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Effects of timber management on the hydrology of wetland forests in the southern United States

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Abstract

The objectives of this paper are to review the hydrologic impacts of various common forest management practices that include harvesting, site preparation, and drainage. Field hydrological data collected during the past 5–10 years from ten forested wetland sites across the southern US are synthesized using various methods including hydrologic simulation models and Geographic Information Systems. Wetland systems evaluated include red river bottoms, black river bottoms, pocosins, wet mineral flats, cypress domes, and pine flatwoods. Hydrologic variables used in this assessment include water table level, drainage, and storm flow on different spatial and temporal scales. Wetland ecosystems have higher water storage capacity and higher evapotranspiration than uplands. Hydrologic impacts of forest management are variable, but generally minor, especially when forest best management practices are adopted. A conceptually generalized model is developed to illustrate the relative magnitude of hydrologic effects of forest management on different types of wetlands in the southern US. This model suggests that in addition to soils, wetland types, and management practice options, climate is an important factor in controlling wetland hydrology and the magnitude of disturbance impacts. Bottomland wetlands, partial harvesting, and warm climate usually offer conditions that result in low hydrologic impact.

Keywords: Forested wetlands; Groundwater; Hydrology; Forest harvesting; Forest management

1. Introduction

The effects of forest management on upland forest hydrology are relatively well understood (Bosch and Hewlett, 1982). Studies suggest that vegetation removal generally results in increased water yield of 10, 25, 40 mm per 10% reduction in cover for scrub, deciduous hardwood, and pine and eucalypt forests, respectively. A recent long-term watershed study in eastern Kentucky of the southern Appalachian region suggested that forest clear-cutting caused increased water yield for at least 8 years (Arthur et al., 1998). Associated with increase in water yield and stream flow peaks, forest practices, without best management practices (BMPs) or under intense storms, have potential to degrade water quality by elevating concentration of suspended sediment.

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In contrast, little information is available about hydrologic responses of timber management in forested wetlands (Shepard et al., 1993). Reports on forest wetland hydrology in the southern US were limited in the 1980s (Heimburg, 1976; Riekerk et al., 1989). However, the 1990s have seen a dramatic increase in the literature on wetland hydrology research (McCarthy et al., 1991; Skaggs et al., 1991; Ewel and Smith, 1992; Shepard et al., 1993; Burger, 1994; Lockaby et al., 1994; Crownover et al., 1995; Chescheir et al., 1995; Dube et al., 1995; Sun et al., 1995; Amatya et al., 1996; Preston, 1996; Perison, 1997). Studies or syntheses on a regional scale on forested wetland hydrology in the southern US are rare (Riekerk et al., 1989).

This paper reviews how timber management of wetland forests affects hydrology in the southern US. It uses data gathered in projects supported by the forest industry wetlands research program in the past decade, as well as information from the literature. Specifically, this study asks: (1) To what extent are wetlands affected by various forest management practices under different climatic, soil, and geographic conditions? (2) Is there any correlation between hydrologic effects and environmental gradients (i.e. wet versus dry season; flat versus sloping landscape)? (3) What are the controlling factors/variables behind these differences?

2. Methods

2.1. Data acquisition

This study focuses on but is not limited to raw and published data collected from ten forested wetland research projects located in the southern US during the past 5–10 years (Table 1).

The following common forest management practices were evaluated to study the potential impacts on wetland hydrology:

1. forest harvesting: clear-cut or partial-cut by different wood removal systems (i.e. skidder and helicopter),
2. site preparation (chopping, burning, bedding, mole plowing and soil tillage),
3. controlled drainage (surface and subsurface drainage).

2.2. Processes of hydrologic perturbation due to forest management

The hydrologic effect of forest management on wetland water table at any time interval may be described mathematically as

$$\Delta h_{\mathrm{eff}} = \frac{\Delta \mathrm{Inflow}_{\mathrm{eff}} - \Delta \mathrm{Outflow}_{\mathrm{eff}} - \Delta \mathrm{ET}_{\mathrm{eff}}}{S_{\mathrm{y}}} \quad (1)$$

where Δh_{eff}=water table effect due to forest harvest=water storage change under disturbance conditions over time−water storage change under non-disturbance conditions over time, S_{y} is the effective soil specific yield (i.e. drainable soil porosity) with values varying from 0.0 to 1.0.; $\Delta \mathrm{Inflow}_{\mathrm{eff}}$ the wetland inflow change due to forest management; $\Delta \mathrm{Outflow}_{\mathrm{eff}}$ the outflow change due to forest management; $\Delta \mathrm{ET}_{\mathrm{eff}}$ the evapotranspiration change due to forest management.

When $\Delta h_{\mathrm{eff}}>0$, the site is getting wetter, otherwise it is getting drier or remains unchanged. Management practices (biological or engineering methods) affect both ET and the flow regimes.

The above equation suggests that the responses of groundwater table are controlled by four factors: runoff changes, ET change (i.e. canopy interception+soil evaporation+transpiration change), and specific yield, S_{y}. All these four variables are functions of water table levels. If Δh_{eff} is >0, groundwater table is elevated by forest management; if Δh_{eff} is <0, the groundwater table is decreased due to disturbance; if Δh_{eff} is not significantly different from 0, then disturbance has no effect on the water table level.

3. Results and discussion

3.1. Harvesting and associated soil disturbance

3.1.1. Bottomlands

Riverine bottomland forests have the largest acreage among other forest wetlands in the southern US (Cubbage and Flather, 1993). Most of this ecosystem is found along streams and drainage ways, particularly prevalent in the lower Mississippi River alluvial valley.

Harvesting bottomland forests usually has little long-term effect on hydroperiod if BMPs are followed (Lockaby et al., 1997a). The common hydrologic change following harvesting of bottomlands is

Table 1
Forest wetlands research projects in the southern US

Location	Wetland type	Experimental design	Experimental period		Hydrologic data	Major References
			Pre-harvest	Post-harvest		
Alabama	Black river bottomland	Randomized complete block; three 4 ha replicates	None	March 1991	Groundwater water table (WT)	Lockaby et al. (1994)
Georgia	Red river bottomland	Randomized complete block; three 8 ha plots; treatments: clear-cut, partial cut, control	None	1993	WT; Crest gage	Lockaby et al. (1997a)
South Carolina	Black river bottomland	Randomized complete blocks; five replicates; treatments: helicopter, simulated rubber-tired skidder, control	None	1991	Three WT recorders and PVC wells; soil and GW chemistry	Perison (1997)
Texas	Bottomland hardwood	Randomized complete plot; three 8 ha plots; treatment: clear-cut, partial cut and control	None	1992–1994	WT, soil chemistry, GW and surface water chemistry	Wang (1996)
Virginia	Riparian wetland mixed upland pine-hardwood forest	Paired watershed with three 8–10 ha each; treatment: clear-cut, BMPs and control	October 1991–January 1994	February 1994–spring 1997	Hourly flow	Mostaghimi et al. (1996)
Alabama	Cypress–tupelo swamp	Latin Square of four treatment with nine replicates: clear-cut and wood removal by: helicopter, helicopter+2-year glyphosate herbicide, simulated rubber-tired skidder, control	None	1986	WT 1 and 7 years after clear-cut harvesting	Aust et al. (1997)
North Carolina	Wet pine flat, loblolly pine plantations	Three 25 ha drained watersheds	1988–1990 (calibration) 1990–1994 (controlled drainage)	July 1995 (a) harvesting (b) orifice–weir	Hourly flow, soil moisture, WT, water quality	McCarthy et al. (1991), Amatya et al. (1996)
South Carolina	Wet pine flat, loblolly pine	Randomized complete block; treatments: dry, wet harvests and three site preparation methods: bedding, mole plow and non	1991–1993	Fall 1993, spring1994 November 1995	Intensive WT (n=1125) Soil and GW chemistry	Preston (1996)
Virginia	Wet pine flat, loblolly pine	Randomized complete block with three replicates; four treatments: clear-cut chop and burn; chop, burn, windrow and bedding; chop and burn and deep drainage; control	None	1969–1971 re-measured 1991–1992	WT soil chemistry Fertilization response	Andrews (1993)
Florida	Flatwoods cypress swamp–slash pine plantations	Randomized complete block; treatments: clear-cut, pond cut only, control	1992–April 1994	May 1994–December 1996	WT, runoff, ET, water chemistry	Crownover et al. (1995), Sun et al. (1995)

elevation of the water table (Aust and Lea, 1992; Wang, 1996; Perison, 1997; Lockaby et al., 1997b) due to reduction of ET. However, one exception has been reported that the water table in dark-colored organic soils dropped 20–40 cm during the post-harvest period (Lockaby et al., 1994). The water table drop was attributed to greater soil evaporation from dark-colored organic soils and possibly increased transpiration from newly developed plants.

Referring to Eq. (1), assuming $\Delta\text{Inflow}_{\text{eff}}$ and $\Delta\text{Outflow}_{\text{eff}}$ are minor, a positive of $-\Delta\text{ET}_{\text{eff}}$ or reduction of ET, results in a positive value of Δh_{eff}, or rise of water table. Tree removal reduces water loss from canopy interception and plant transpiration. However, the exposure of forest floors can significantly increase soil temperature up to 11°C at noon (Wang, 1996; Lockaby et al., 1997b) and may also increase wind speed and convection at the harvest site, resulting in more soil/water evaporation loss from a managed wetland system than the non-disturbed site. The compound effects of the above two scenarios determine the magnitude of water table rise (drop) and how long it persists (Lockaby et al., 1997a). The extent of the water table effects are most pronounced during the first two growing seasons (Lockaby et al., 1997b). Wang (1996) reported that clear-cutting and partial-cutting of a bottomland hardwoods forest in Texas caused an average significant and non-significant increase of the water table of 19 and 15 cm, respectively, in the first year. However, only an insignificant increase of 6 cm for the second year was observed. The second year's relative decrease in water table level was believed to be caused by ET recovery from rapid growing tree seedlings and herbaceous vegetation. Minimum soil disturbance was achieved during harvesting operations of this experiment. Monthly measurements of surface soil (0–15 cm) moisture did not show seasonal patterns and treatment effects, reflecting its high variability in wetlands (Wang, 1996).

Harvesting activities may cause hydrologic impacts by affecting soil physical properties. As the specific yield (S_y) or drainable porosity of the surface soils decreases due to compaction, h_{eff} increases, and the water table is elevated (ref. Eq. (1)).

In one study, saturated hydraulic conductivity was reduced by 50–90% with bulk density increase of 0.1 g cm^{-3} in ruts associated with rubber-tired skidder traffic (Lockaby et al., 1997b). One study on tupelo–cypress wetlands in the Mobile–Tensaw River delta in Alabama concluded that soil hydraulic conductivity was greatly affected by harvesting activities (Aust and Lea, 1992). However, a follow-up study found that soil disturbance did not affect productivity and tree growth (Aust et al., 1997).

A study in a blackwater bottom wetland forest in South Carolina found that removing trees by helicopter and skidder methods caused limited water table elevation (Perison, 1997). The 20–40 cm deep skidder ruts, that covered 20% of the area, increased surface water storage and elevation of water table by blocking surface and subsurface drainage (Perison, 1997). In this study, surface soil bulk density increased. Periodical flooding at the research site might have masked the effects of vegetation difference on ET among the treatments even during the dry period.

3.1.2. Cypress wetland–pine flatwoods

Cypress wetlands (swamps, ponds) often occur in isolated depressions with different sizes (1–100 ha) or in linear stands along rivers ranging from eastern Louisiana to southern Virginia. Hydrologic impacts of three management scenarios, maximum (no BMPs), minimum (with BMPs) disturbance harvesting and no harvesting, have been studied at the Bradford Forest on a cypress–pine flatwoods landscape in northern Florida since the late 1978 (Riekerk, 1989). Three watersheds (50–140 ha) were isolated by dikes and instrumented with water table recorders and long-throated recording flumes for data collection. Highlights of this long-term watershed research are:

1. During the first year of treatment (1979), maximum disturbance caused a 15 cm or 150% increase in water yield while the minimum disturbance resulted in only an insignificant increase of 3 cm in water yield. Water table rose significantly for both treatments, especially during the drought months (Riekerk, 1989).
2. In the sixth year (1985) of post-treatment, runoff from the maximum disturbance watershed was still significantly higher, but was reduced from 150 to 65% of predicted from a regression equation; groundwater tables in both disturbance sites remained higher than the control.
3. The simulation model, FLATWOODS (Sun et al., 1998a), suggests it requires about 10 years for a

clear-cut flatwoods watershed to return to its pre-harvest hydrologic conditions (Sun et al., 1998b).

Hydrologic impacts of harvesting a cypress ponds/pine flatwoods mosaic have been studied in greater detail in a north-central Florida site (Crownover et al., 1995; Sun et al., 2000). On the 42 ha research site, two harvesting treatments, wetland-harvest-only (treatment 1) and wetland+upland harvest (treatment 2) and control, were imposed on three separate blocks during April–May 1994 after 2 years of calibration. Bedding and planting were done from September 1994 to January 1995. Three wetlands and associated uplands located in the center of each experimental block were intensively monitored for water balances. Major results from this study are summarized as following:

1. Water tables in the two wetlands were elevated up to 130 cm by treatments 1 and 2. The water table in the upland was elevated for 40 cm by treatment 2, but not affected by treatment 1. The increase occurred immediately following the harvest activities in the dry summer months in 1994. The rise was reduced and was not significant during the wet year of 1995. However, it appeared again with a maximum rise of 120 cm in the wetland (treatment 1) and 25 cm in the upland (treatment 2) in the dry period (February, March, June, and July) of 1996.
2. Average annual open-water evaporation from harvested wetlands increased about 21–800 mm per year following the harvest. Total ET from wetlands was reduced by 20 and 28% in treatments 1 and 2, respectively.
3. Outflow from treatment wetlands was significantly increased by 21–27% for treatments 1 and 2. The runoff effect was apparently compounded with water table rise.
4. Harvesting did not alter the general flow directions from the pre-harvest on flatwoods landscape.
5. Simulations by the FLATWOODS model suggested treatment 2 had greater hydrologic effect than treatment 1. The effects were more pronounced during drought years/seasons (Sun et al., 1998b).

Data presented above generally agree with other studies in the region. Williams and Lipscomb (1981) found a water table rise of 15–35 cm after partial cutting a coastal pine forest on sandy soils. In contrast, Rodriguez (1981) concluded that clear-cutting a wet savanna watershed did not significantly alter the hydrology.

3.1.3. Wet pine flats

Harvesting under wetland conditions, such as wet pine flats may cause degradation of soil hydrologic properties (e.g. hydraulic conductivity, macropores) from soil compaction, rutting, and puddling (Greacen and Sands, 1980). Aust et al. (1993) reported that a salvage timber harvesting on a wet pine flat in South Carolina caused a significant water table rise of 5–31 cm. This ‘watering up’ was due to trafficking and soil puddling instead of a reduction in ET, because there was no precipitation observed between pre-harvest and post-harvest. It was found that total porosity and saturated hydraulic conductivity (K_s) were significantly reduced by 10 and 50–90%, respectively, in the disturbed areas. Those areas with reduced porosity and K_s had impeded lateral subsurface water movement in the porous surface soil horizons above a clay layer, resulting in a water table rise. Soil compaction, rutting and puddling impact become greater with increased soil wetness, clay content, and traffic (Green et al., 1983). However, Aust et al. (1995) found that the hydrology of poorly- and very poorly-drained soils was less altered by skidding than that of moderately-well-drained or somewhat-poorly-drained soils. This finding suggests lateral subsurface water movement is important in evaluating hydrologic impacts on wet pine flats, especially for fine-textured soils.

An ongoing study on wet pine flats in South Carolina examined the hydrologic and site productivity impacts of two harvesting schemes, wet-weather harvesting and dry harvesting (Burger, 1994; Preston, 1996). Site hydrology of three replicate 19 ha treatment blocks of 20-year old loblolly pine plantations was monitored monthly with a 20 m×20 m grid of water table wells for 18 months prior to treatment installation. During the pre-harvest period, the water table depth followed a uniform pattern throughout the sites with seasonal fluctuation between 5 cm (spring) and 75 cm (summer) below the soil surface. During the post-harvesting period prior to site preparation, water tables in the control plots were significantly lower than the wet- and dry-weather harvesting plots (Miwa, 1997). The average water table level for the wet harvest site was 13 cm higher than that for the dry harvest site due to increased disturbance on the former site. The maximum water table depths occurred during the dry period (October–May) (Preston, 1996). The wetter conditions in the summer at the wet-weather harvest site were due to soil disturbances as illustrated in Aust et al. (1993, 1995), but the drier conditions in the winter were a result of higher soil evaporation compared to the dry-weather harvest site. Within wet-harvest areas, only churning and some deep rutting resulted in a significant effect on the water table compared to undisturbed area. Within the dry-harvest areas, disturbance did not significantly change the water table depth. Further, analysis of soil physical properties concluded that bulk density, macroporosity and hydraulic conductivity were significantly affected by all levels of wet-harvesting disturbance. Bulk density increased to an average of 1.44 g cm^{-3} compared to the undisturbed level of 1.24 g cm^{-3}. Macroporosity decreased to an average of 7% compared to the undisturbed level of 14%. Total porosity was reduced from 51.5 to 46.4%. The average K_s value on disturbed sites dropped to an average of 14 cm per day compared to 81 cm per day for undisturbed sites. Dry-weather harvesting also degraded the three soil physical properties. From a spatial perspective, wet-weather harvest created a much higher degree and extent of impact compared to dry-harvest. Similar changes of soil physical properties due to harvest and regeneration were also reported for a wet pine flat site in North Carolina where soil macroporosity was reduced by half within a 200 cm profile (Blanton et al., 1998).

In contrast to the Florida pine flatwoods study, a recent watershed study suggested that tree harvesting with or without BMPs did not significantly affect total water yield, storm flow peaks, and storm volume (Mostaghmi, personal communication). However, concentrations of several water quality parameters for the watershed with BMPs were found significantly lower than those without BMPs and had no difference from the undisturbed watershed. This 44-month experiment was conducted on a mixed pine-hardwoods landscape in the coastal plain (2% in slope) of Virginia.

3.2. Drainage (ditching)

Drainage may have on-site and off-site impacts on wetland hydrology. Campbell and Hughes (1991) reported that free drainage in pine plantations resulted in a water table drop of 30–60 cm compared to undrained pocosins during wet seasons. The standing water was minimized but soil saturation was still maintained with a less fluctuating water table. Drainage did not change the basic hydrologic cycle or convert wetlands to uplands. A retrospective study in Virginia found that ditching significantly lowered water table in 0–3 year old pine plantations on wet flats during wet seasons when the water table was close to soil surface (Andrews, 1993). However, at age 23, the ditching effect was dramatically reduced during the growing season. A study on the ditching effect on water table level in Pomona sand in Florida suggested that ditching affected water table levels up to 45 m from the ditch (2 m deep and 3 m wide) for high and average water table condition (80 cm from surface) (Segal et al., 1986). About 28% of precipitation was removed from drained loblolly pine plantations by drainage in the North Carolina coast (McCarthy et al., 1991; Amatya et al., 1996, 1997). Hughes et al. (1990) reported no apparent difference in flow volume and seasonal hydrographs among 16-year old plantation, unditched natural timber, full stocked pine plantations, mixed plantation/natural watershed, and a ditched natural stand. Simulation by DRAINMOD suggested that ditch spacing had major effects on the composition of runoff from forest lands, but limited change in total flow volume (Skaggs et al., 1991).

Controlled drainage, the practice of regulating the water table to conserve water for tree use but minimize detrimental effects down streams, has been implemented by some forest products companies, especially in the lowlands of the Carolina in the past 15 years. Extensive forest hydrology research has been conducted on controlled drainage practices on loblolly pine plantations in the North Carolina coast (McCarthy et al., 1991; Amatya et al., 1996, 1997). Major results from this ongoing research include:

1. Controlled drainage outflow volumes were reduced by 15–30% compared to free drainage (Amatya et al., 1996).
2. Controlled drainage reduced peakflow rates,

especially when ditches were plugged during the spring (Amatya et al., 1996).

3. Controlled drainage did not change the fluctuation patterns of the water tables and runoff (Amatya et al., 1996).
4. Compared to free drainage with V-notch weir, orifice–weir water table management not only reduced daily, seasonal and annual drainage outflows but also significantly dampened the peak drainage rates during large events of the early spring (Amatya and Skaggs, 1997).
5. Harvesting (clear-cut) raised the water table during the dry periods from April to July. The effect was most pronounced when the water table was 100 cm below the soil surface. Total outflows also increased as a result of tree removal and site preparation (Blanton et al., 1998).

4. Discussion

As a summary of the study results presented above, a regional conceptual model is presented to provide a general picture on the effects of wetland management on hydrology (Fig. 1). This model illustrates the interactions of topography (wetland type), climate, and forest management practice types in affecting the hydrology of forested wetlands.

Compared to uplands, because of depression and flat topography, wetlands have higher water storage capacity resulting in lower flow rates. Water yield from wetlands is expected to be low since ET is near potential when the water table depth is less than 30 cm below the surface (Verry, 1997). In contrast, water tables in steep uplands rarely reach the surface but the water yield is much higher, often >50% of precipitation. The magnitude of increase in runoff from coastal flatwoods due to forest management was considerably lower than the 25–30 cm increase from upland watersheds. The overall hydrologic impact of silvicultural operations on wet soils is much less than in areas having greater relief and shallow soils (Fisher, 1981). Storm peak flows may be reduced significantly with increasing percentage of wetlands in a basin (Amatya et al., 1995). For bottomland wetlands bordering large rivers, the hydroperiod is mostly determined by upstream precipitation events. Interactions between groundwater and surface water (e.g. floodwater, tidal water) are frequent in natural bottomlands systems. However, under human engineering influences (i.e. dams), bottomlands hydrology has been altered and is heavily determined by local precipitation. In this case, bottomlands show similar hydrologic characteristics as wet pine flats in the lower coastal plain. Tree removal does not necessarily result in reduction of

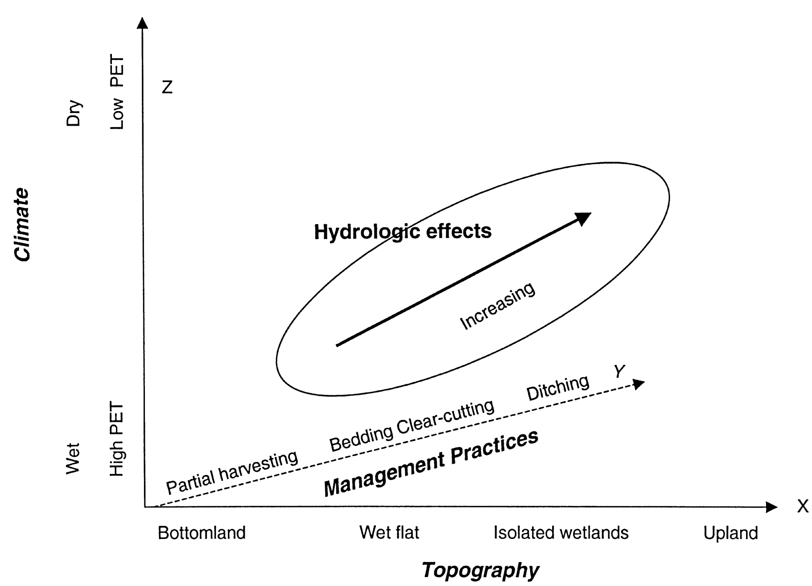

Fig. 1. A conceptually generalized model for the effects of management on wetlands hydrology, southern US.

ET since the harvested sites might experience a higher soil/water evaporation under an open canopy and the emerging plants with high vigor may recover to their growth potential within two growing seasons. Harvesting resulted in greater water table rise in the depression cypress swamps than in the pine uplands. Soil compaction, rutting and churning are common problems related to wet-weather harvesting in forest wetlands, and these soil disturbances contribute to hydrologic responses of forest management.

Climate gradient is also a factor to be considered to evaluate the effects of timber management on hydrology because climate directs how vegetation recovers and how environmental conditions change due to forest disturbances. Effects of harvesting in colder climate may last longer simply because it takes longer for a forest to establish (Verry, 1986). However, past studies on northern peatlands suggest the hydrologic responses were rather variable (Verry, 1986). The scenario that water table was decreased after tree removal (Lockaby et al., 1994) was also found in northern fens (Verry, 1997). Compared to the southern states, northern wetlands may experience greater change in solar radiation due to canopy removal, and this may explain the high variability of hydrologic response. For all the wetlands reviewed, water table responses were found to be most pronounced during dry periods when the water table was deep.

Different forest management practices also have different effects on wetland hydrology. Data suggested that ditching or 'minor drainage' has the most significant effects on both drainage volume and peakflow rates during wet periods. However, many studies show that drained wetlands of fully stocked pine plantations have little impact on hydrology. The 'biological drainage' or ET from closed canopy plays a key role in regulating water storage of drained forests (Heikurainen, 1980). Control drainage systems can conserve water for tree use during dry periods in the growing season, therefore, reduce down-stream negative impacts in the non-growing season (generally wet season).

5. Conclusions

Studies in the past two decades in the southern US suggested that timber management practices in wetlands generally cause little impact on wetland hydrology in terms of both magnitude and duration. This is especially true when forest BMPs guide lines are followed. In general, the short-term change of hydroperiod of forested wetlands were found within natural variations and may not result in negative long-term concerns in wildlife habitats and plant regeneration. Hydrologic responses of forested wetlands to timber management are generally less pronounced than that of uplands.

Timber management should consider the spatial and temporal features of wetland hydrology. Partial harvests or selection cut may be used to reduce water table rise and soil disturbance. Harvesting during dry periods in the spring when the water table is deep may cause less soil damage and reduce equipment costs. Fertilization in spring or dry seasons is recommended when surface flow is usually minor. Controlled drainage systems are effective for poorly drained flatwoods to reduce negative hydrologic impacts, but maintaining proper tree stocking, thus, natural 'biological drainage' is also important.

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References

Amatya, D.M., Skaggs, R.W., 1997. Predicting effects of an orifice–weir structure at the outlet of a drained pine forest. In: Proceedings of Application of Emerging Technology on Hydrology Research. ASAE, pp. 149–152.

Amatya, D.M., Chescheir, G.M., Skaggs, R.W., 1995. Hydrologic effects of wetland location and size in an agricultural landscape. In: Campbell, K.L. (Ed.), Versatility of Wetlands in the Agricultural Landscape. Am. Assoc. Agric. Eng., pp. 477–487.

Amatya, D.M., Skaggs, R.W., Gregory, J.D., 1996. Effects of controlled drainage on the hydrology of drained pine plantations in the North Carolina coastal plain. J. Hydrol. 181, 211–232.

Amatya, D.M., Skaggs, R.W., Gregory, J.D., Herrmann, R.B.,

1997. Hydrology of a drained forested pocosin watershed. J. Am. Water Resour. Assoc. 33, 1–12.

Andrews, L.M., 1993. Loblolly pine response to drainage and fertilization of hydric soils. M.S. Thesis, Virginia Polytechnic Institute and State University, Blacksburg.

Arthur, M.A., Coltharp, G.B., Brown, D.L., 1998. Effects of best management practices on forest stream water quality in eastern Kentucky. J. Am. Water Resour. Assoc. 3, 481–495.

Aust, W.M., Lea, R., 1992. Comparative effects of aerial and ground logging on soil properties in a tupelo–cypress wetland. For. Ecol. Manage. 50, 57–73.

Aust, W.M., Reisinger, T.M., Burger, J.A., Stokes, B.J., 1993. Soil physical and hydrological changes associated with logging a wet pine flat with wide-tired skidders. South. J. Appl. For. 1, 22–25.

Aust, W.M., Tippett, M.D., Burger, J.A., McKee Jr., W.H., 1995. Compaction and rutting during harvesting affect better drained soils more than poorly drained soils on wet flat pines. South. J. Appl. For. 19, 72–77.

Aust, W.M., Schoenholtz, S.H., Zaebst, T.W., Szabo, B.A., 1997. Recovery status of a bald cypress–tupelo wetland seven years after harvesting. For. Ecol. Manage. 90, 161–170.

Blanton, C.D., Skaggs, R.W., Amatya, D.M., Chescheir, G.M., 1998. Soil hydraulic property variations during harvest and regeneration of drained coastal plantation. Presented at the 12–16 July meeting, Paper No. 982147, ASAE, 2950 Niles Rd., St. Joseph, MI 49085–9659, USA, p. 6.

Bosch, J.M., Hewlett, J.D., 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. J. Hydrol. 55, 3–23.

Burger, M.A., 1994. A wetland trafficability hazard index based on soil physical properties and site hydrology evaluations. M.S. Thesis, Virginia Polytechnic Institute and State University, Blacksburg.

Campbell, R.G., Hughes, J.H., 1991. Impacts of forestry operations on pocosins and associated wetlands. Wetlands 11, 467–479.

Chescheir, G.M., Amatya, D.M., Skaggs, R.W., 1995. Monitoring the water balance of a natural wetland. In: Campbell, K.L. (Ed.), Versatility of Wetlands in the Agricultural Landscape. Am. Assoc. Agric. Eng., pp. 451–462.

Crownover, S.H., Comerford, N.B., Neary, D.G., 1995. Water flow patterns in cypress–pine flatwoods landscapes. Soil Sci. Soc. Am. J. 59, 1199–1206.

Cubbage, F.W., Flather, C.H., 1993. Forested wetland area and distribution — a detailed look at the South. J. For. 91, 35–40.

Dube, S., Plamondon, A.P., Rothwell, R.L., 1995. Watering up after clear-cutting on forest wetlands of the St. Lawrence lowland. Water Resour. Res. 7, 1741–1750.

Ewel, K.C., Smith, J.E., 1992. Evapotranspiration from Florida pond cypress swamps. Water Resour. Bull. 28, 299–304.

Fisher, R.F., 1981. Impact of intensive silviculture on soil and water quality in a coastal lowland. In: Lal, R., Russell, E.W. (Eds.), Tropical Agricultural Hydrology. Wiley, New York.

Greacen, E.L., Sands, R., 1980. Compaction of forest soils — a review. Aust. J. Soil Res. 18, 163–189.

Green, W.D., Stuart, W.B., Perumpral, J.V., 1983. Skidder and tire size effects on soil compaction. ASAE Paper No. 83–1620, Am. Soc. Agric. Eng., St. Joseph, MI, p. 16.

Heimburg, K., 1976. Hydrology of some north-central Florida cypress domes. M.S. Thesis, University Florida, Gainesville.

Heikurainen, A.L., 1980. Effect of forest drainage on high discharge. The influence of man on the hydrological regime with special reference to representative and experimental basins. In: Proc. Helsinki Symp. 23–26 June 1980. IAHS-AISH Pub. No. 130, pp. 89–96.

Hughes, J.H., Bergman, J.B., Campbell, R.G., Farnum, P., Herrmann, R.B., White, W.M., 1990. Research on the effects of minor drainage and forest management on the hydrology of a forested wetland and adjacent estuary. NCASI Tech. Bull. No 583, 48–57.

Lockaby, B.G., Thornton, F.C., Jones, R.H., Clawson, R.G., 1994. Ecological response of an oligotrophic floodplain forest to harvesting. J. Environ. Qual. 23, 901–906.

Lockaby, B.G., Stanturf, J., Messina, M.G., 1997a. Effects if silvicultural activity on ecological processes in floodplain forests of the southern United States: a review of existing reports. For. Ecol. Manage. 90, 93–100.

Lockaby, B.G., Clawson, R.G., Flynn, K., Rummer, R.B., Meadows, J.S., Stokes, B., Stanturf, J.A., 1997b. Influence of harvesting on biogeochemical exchange in sheetflow and soil processes in a eutrophic floodplain forest. For. Ecol. Manage. 90, 187–194.

McCarthy, E.J., Skaggs, R.W., Farnum, P., 1991. Experimental determination of the hydrologic components of a drained forest watershed. Trans. ASAE 5, 2031–2039.

Miwa, M., 1997. Hydrologic responses to harvesting and site preparation operations. In: Sustaining the Productivity and Function of Intensively Managed Forests. Project Progress Report to NCASI, Virginia Polytechnical and State University, p. 98.

Perison, D.M., 1997. The effects of timber harvest and soil disturbance on soil processes and water quality in a South Carolina blackwater swamp. Ph.D. Dissertation, North Carolina State University, Raleigh, NC, p. 86.

Preston, D.P., 1996. Harvesting effects on the hydrology of wet pine flats. M.S. Thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Riekerk, H., 1989. Influence of silvicultural practices on the hydrology of pine flatwoods in Florida. Water Resour. Res. 25, 713–719.

Riekerk, H., Neary, D.G., Swank, W.T., 1989. The magnitude of upland sivilcultural nonpoint source pollution in the South. In: Hook, D.D., Lea, R. (Eds.), The Forested Wetlands of the southern United States. USDA Forest Service General Technical Report SE-50, Asheville, NC, p. 168.

Rodriguez, H.M., 1981. Impact of the intensive slash pine management on the hydrology of a coastal, wet savanna watershed. M.S. Thesis, University Florida, Gainesville, FL.

Segal, D.S., Neary, D.G., Best, G.R., Michael, J.L., 1986. Effect of ditching, fertilization, herbicide application on groundwater levels and groundwater quality in a flatwood spodosol. Proc. Soil Crop Sci. Soc. Florida 46, 14–16.

Shepard, J.P., Lucier, L.A., Haines, L.W., 1993. Industry and forest wetlands: cooperative research initiatives. J. For. 5, 29–33.

Skaggs, R.W., Gilliam, J.W., Evans, R.O., 1991. A computer simulation study of pocosin hydrology. Wetlands 11, 399–416.

Sun, G., Riekerk, H., Korhnak, L.V., 1995. The hydrology of cypress wetland–upland ecosystems in Florida flatwoods. In: Campbell, K.L. (Ed.), Versatility of Wetlands in the Agricultural Landscape. Am. Assoc. Agric. Eng., pp. 489–500.

Sun, G., Riekerk, H., Comerford, N.B., 1998a. Modeling the forest hydrology of wetland-upland ecosystems in Florida. J. Am. Water Resour. Assoc. 34, 827–841.

Sun, G., Riekerk, H., Comerford, N.B., 1998b. Modeling the hydrologic impacts of forest harvesting on flatwoods. J. Am. Water Resour. Assoc. 34, 843–854.

Sun, G., Riekerk, H., Korhnak, L.V., 2000. Groundwater table rise after forest harvesting on cypress–pine flatwoods in Florida. Wetlands, in press.

Verry, E.S., 1986. Forest harvesting and water: the lake states experience. Water Resour. Bull. 22 (6), 1039–1047.

Verry, E.S., 1997. Hydrological processes of natural, northern forested wetlands. In: Trettin, C.C., Jurgensen, M.F., Grigal, D.F., Gale, M.R., Jeglum, J.K. (Eds.), Northern Forested Wetlands: Ecology and Management. Lewis Publishers, New York, pp. 163–188.

Wang, Z., 1996. Effects of harvesting intensity on water quality, nitrogen mineralization, and litter decomposition in a bottomland hardwood floodplain forest in southern Texas. Ph.D. Dissertation, Mississippi State University, Mississippi State, MS.

Williams, T.M., Lipscomb, D.J., 1981. Water table rise after cutting on coastal plain soils. South. J. Appl. For. 5, 46–48.