8 Forest Drainage

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8.1 Introduction

Most of the world's 4030 million ha of forested lands are situated on hilly, mountainous or well-drained upland landscapes where improved drainage is not needed. However, there are millions of hectares of poorly drained forested lands where excessively wet soil conditions limit tree growth and access for harvesting and other management activities. Improved or artificial drainage has been used to improve forest productivity on such lands substantially. Drainage has increased timber growth in natural forests and, applied as a silvicultural practice, enabled harvesting, regeneration and increased production of plantation forests. Improved drainage is needed in regions where precipitation exceeds evapotranspiration (ET) on lands where natural drainage processes are not sufficient to remove the excess. Such conditions frequently occur in northern climates where ET is low and, in the absence of adequate natural drainage, soils remain saturated for long periods of time. Drainage may also be needed in lands that receive runoff and seepage from upslope, and in areas subjected to frequent flooding from adjacent streams. Peatlands, which form under very wet soil conditions, have been drained extensively to facilitate forest production in many parts of the world.

Paavilainen and Päivänen (1995) presented a detailed review of the history, methods and results of forest drainage of peatlands. They date reports of ditching of peatlands to promote tree growth to a 1773 Swedish publication and, based on a review of literature regarding drainage in Russia, the Baltic countries and Germany, noted that drainage to increase tree growth was well known in the region in the mid-19th century. While statistics documenting forest drainage go back to the mid-1800s in Sweden, Norway and Finland, the period of most intensive drainage activity started during the 1920s and 1930s, was inactive during World War II, and resumed in the 1950s and 1960s. In addition to northern and eastern Europe, drainage has been used in the British Isles, Canada and the USA as a relatively economical means of increasing forest productivity (Laine *et al*., 1995; Paavilainen and Päivänen, 1995). Trottier (1991) concluded that, for poorly drained lands, few silvicultural practices can compete with drainage in terms of costs per unit increase of forest yield. By 1995 about 15 million ha of northern peatlands and other wetlands had been drained for forestry (Laine *et al*., 1995). More than 90% of these lands are in Finland, Scandinavia and the former Soviet Union. The peak of forest drainage activity in Sweden was in the 1930s when drainage

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was subsidized by the state to improve forest production while reducing unemployment (Paavilainen and Päivänen, 1995). Peltomaa (2007) reported that 5.5 million ha (more than 20%) of the 26 million ha of forest land in Finland is drained. About 4.5 million ha of the drained forest is peatlands. Beginning in the 1930s, with the greatest activity in the 1960s and 1970s, drainage was subsidized by the Finnish government in an effort to increase forest production. Peltomaa (2007) attributed the positive influence of drainage as one of the main reasons for a 40% increase in growing stock during the 30-year period 1970–2000. Forest products made up as much as 40% of Finnish exports in the 1970s and were still 20% of exports in 2005. Tomppo (1999) reported that drainage of forest lands in Finland had increased annual tree growth by 10.4 million m^3 since the beginning of the 1950s. While forest drainage has been applied on peat soils in Canada (Hillman, 1987), Quebec (Trottier, 1991), Ontario (Stanek, 1977) and Alberta (Hillman and Roberts, 2006), the area drained there and in northern USA states is a small fraction of that drained in northern Europe (Paavilainen and Päivänen, 1995).

The evolution of forest drainage in the US south started with a large-scale drainage project in the Hoffman Forest in eastern North Carolina in the 1930s (Fox *et al.*, 2007). Early observations of improved growth of pine adjacent to drainage ditches on both mineral and peat soils (Miller and Maki, 1957; Maki, 1960) led to field trials and more studies (Terry and Hughes, 1975, 1978), and finally to widespread drainage of forested wetlands. By the mid-1980s, drainage was used to provide access for harvest and regeneration, and to improve production on over 1 million ha of poorly drained forests in the coastal plains of states along the Atlantic and Gulf of Mexico (McCarthy and Skaggs, 1992). Expansion of drainage projects to establish new plantations on wetland forests ended by 1990 because of concern for their effect on jurisdictional wetlands and federal regulations for wetland protection. Government support for drainage was also reduced in other countries. Finland ceased subsidies for new forest drainage projects in 1992, due mostly to ecological concerns. However, in recognition of the economic importance of forest drainage it continued to subsidize maintenance and reclamation of old drainage systems (Peltomaa, 2007).

While forest drainage activity has been reduced substantially compared with 40 years ago, drainage is responsible for substantial increases in production on millions of hectares of natural and plantation forests, and the associated economic and social benefits. Optimum management and operation of existing drainage systems, as well as the design and construction of new systems, is complex since these systems need to address both production and environmental/ecological goals. An understanding of the methods and theory of drainage is needed to optimize drainage systems to achieve competing objectives. This chapter reviews the impacts of drainage on forest production and the hydrology of forested lands.

8.2 Purpose and Impact of Forest Drainage

The purpose and effects of drainage on forest production are well documented in the literature. There are two primary purposes: (i) to enable access and provide trafficable conditions such that planting, harvesting and other field operations can be conducted on time with minimum damage to soil and water resources; and (ii) to remove excess water from the soil profile to improve aeration status and promote tree growth. A related purpose/benefit of forest drainage in cold climates is to remove water from snowmelt and warm soils earlier in the season to promote growth (Peltomaa, 2007).

Both the need for and the effectiveness of improved subsurface drainage in providing trafficable soil conditions are depicted in Fig. 8.1, where soil on a poorly drained site (upper right of the picture, above the road) was severely puddled during the harvest operation. By contrast, the drainage ditch below and left of the road lowered the water table and significantly reduced compaction and puddling. Soil damage resulting from harvesting or site preparation during wet site conditions can reduce growth rates significantly and may be only partially offset by subsequent amelioration (Terry and Campbell, 1981). Terry and Hughes (1978) discussed the impacts of drainage on both natural stands and new pine plantations. They noted that drainage installation at least 1 year prior to

Fig. 8.1. Picture of soil conditions after harvesting on a plantation pine site, contrasting subsurface drainage (left of the road) with that without improved drainage (right of the road). Note severe puddling of soil in contrast with soil conditions on left of the road, where drainage had been improved. (Photo by Joe Hughes, 1981.)

harvest extends the logging season and minimizes soil damage, and concluded that about half of the cost of preharvest ditching was offset by reduced logging and site preparation costs, reduced site damage and increased site preparation effectiveness. Use of conventional equipment for both harvesting and site preparation on undrained sites is limited to dry seasons. Drainage extends the season for harvesting and makes it possible to conduct needed field operations in a timely fashion without damaging the soil.

While the impact of drainage on tree growth and yield has been studied by a number of researchers over the years (Miller and Maki, 1957; Graham and Rebuck, 1958; Maki, 1960; Klawitter *et al*., 1970; White and Pritchett, 1970; Brightwell, 1973; Terry and Hughes, 1975; Trottier, 1991; Hillman and Roberts, 2006; Jutras *et al*., 2007; Socha, 2012), published data on the subject are relatively limited. A number of articles by Weyerhaeuser scientists (Terry and Hughes, 1975, 1978; Campbell, 1976; Campbell and Hughes, 1991) reported results of a programme initiated in 1972 to improve drainage for the production of high-yield loblolly pine. Results originally summarized for pine by Terry and Hughes (1975) are given in Table 8.1, which has been expanded to include results published in recent years and for other regions. Results reported by Miller and Maki (1957), Klawitter *et al*. (1970), White and Pritchett (1970) and Terry and Hughes (1975) showed that drainage increased annual growth on very poorly drained mineral soils by 3.6 to 8.9 m^3/ha. These results are similar to those reported for peatlands in northern Europe and for bogs and poorly drained mineral soils in Quebec (Trottier, 1991). Annual increases in yield were typically more than 100% and in some cases much greater (Table 8.1). However, for cases where trees had negligible volume or rate of growth prior to drainage, large percentage increases may not be particularly meaningful (Payandeh, 1973). Growth responses to drainage not only differed among species, but also among stand ages. Socha (2012) determined that drainage

Table 8.1. Summary of results of studies to determine effects of drainage on tree growth and yield.

Study	Soil	Species	Age (years)	Units	Tree growth: Drained	Tree growth: Undrained	Increase (%)	Notes
Miller and Maki (1957)[a]	Portsmouth sl	Loblolly pine (*Pinus taeda*)	0–17	m^3/ha/year	4.7	0.34	4.4 (1300)	
Klawitter *et al.* (1970)[a]	Plummer Rains ls	Slash pine (*Pinus elliottii*)	19–22	m^3/ha/year	9.0	4.9	4.1 (84)	
White and Pritchett (1970)[a]	Leon s	Slash pine (*P. elliottii*)	0–5	m^3/ha/year	14.6	5.7	8.9 (160)	Water table depth (WTD) = 46 cm
					13.3	5.7	6.6 (120)	WTD = 92 cm
		Loblolly pine (*P. taeda*)			7.6	1.3	6.3 (490)	WTD = 46 cm
					4.9	1.3	3.6 (280)	WTD = 92 cm
Terry and Hughes (1975)[a]	Bayboro-Bladen	Loblolly pine (*P. taeda*)	0–13	m^3/ha/year	4.3	0.54	3.8 (700)	
Socha (2012)	Peatland	Scots pine (*Pinus sylvestris*)	0–100	m^3/ha/year	10	8	2 (25)	Modelled
Hillman and Roberts (2006)	Peatland	Black spruce (*Picea mariana*)	30–60	m^3/ha/year	0.59	0.11	0.48 (440)	Average from two sites
		Tamarack (*Larix laricina*)	50–60		0.87	0.74	0.13 (180)	Average from two sites
Trottier (1986) as cited in Hillman (1987)	Peatland	Black spruce (*P. mariana*)	30	m^3/ha/year	1.78	0.5	1.28 (250)	40 m drain spacing
Hökkä and Ojansuu (2004)	Peatland	Scots pine (*P. sylvestris*)	8–228	m^2/ha/year	12.5	5	7.5 (150)	Basal area

Continued

Table 8.1. Continued.

Study	Soil	Species	Age (years)	Units	Tree growth: Drained	Tree growth: Undrained	Increase (%)	Notes
Jutras *et al.* (2007)	Peatland	Black spruce (*P. mariana*)	45–75	mm/year (diameter)	1.37 0.85 0.65	0.44 0.42 0.45	0.93 (210) 0.43 (100) 0.2 (44)	Spacing = 20 m Spacing = 40 m Spacing = 60 m
Payandeh (1973)	Peatland	Black spruce (*P. mariana*)	79–119	m^3/m^2/year	0.005	0.00006	(8200)	Before and after drainage
Graham and Rebuck (1958)[a]		Pond pine (*Pinus serotina*)	0–22	m^2/ha/year	0.74	0.41	0.33 (80)	
Walker *et al.* (1961)	Bladen cl	Slash pine (*P. elliottii*)	0–2	m/year (height)	0.41	0.1	0.31 (310)	Seedlings
		Loblolly pine (*P. taeda*)			0.49	0.21	0.28 (140)	
Langdon (1976)	Myatt, Rains,	Loblolly pine	0–5	m/year	3.1	2.0	1.1 (55)	These three studies
Andrews (1993)	Lynchburg sl	(*P. taeda*)	0–21	(height)	14.1	11.7	2.4 (20)	conducted on the same site.
Kyle *et al.* (2005)			21–33	m^3/ha/year	334	341	–7 (–2)	Cumulative growth at three ages

[a]After Terry and Hughes (1975).

increased yields of Scots pine planted after drainage of a peatland in Poland by 25%, as compared with 15 and 6% increases for trees 30 and 40 years old, respectively, at the time of drainage. Langdon (1976) and Andrews (1993) reported significant increases of tree growth at ages 5 and 21 years for a drained loblolly pine stand in the coastal plain of Virginia, USA. However, Kyle *et al*. (2005) reported no significant tree volume increase for the same site at a stand age of 33 years. These results may have also been impacted by the natural drainage condition of the site. The soils on the site are classified as 'poorly drained' as opposed to the 'very poorly drained' soils of most of the other studies. Increased ET with stand age could have reduced the difference of water table depth between drained and undrained plots and hence the response to drainage (Kyle *et al*., 2005). Hökkä and Ojansuu (2004) found that drainage increased site productivity by over 80% on a pine fen in northern Finland, but had only a moderate effect on another site with better natural drainage. In other cases tree growth responded well to drainage, but narrow ditch spacings were required to increase yields significantly. Jutras *et al*. (2007) found that drainage had little impact beyond 15 m from the ditch in a black spruce stand in Quebec.

8.3 Drainage Systems and Their Function

Most forest drainage systems can be characterized as one of two types or a combination of the two: (i) natural or systems that use and often enhance existing drainage patterns, branches, creeks and streams developed as a result of the watershed topography; and (ii) a grid system of parallel ditches such as that shown in Fig. 8.2. Where there is enough relief, natural drainage systems may provide a sufficient outlet for needed drainage. Additional ditches may be necessary to increase drainage intensity (DI) in some cases, but the basic drainage patterns are unchanged. The grid pattern is used in broad, poorly drained areas. Its regular pattern with relatively straight rows increases efficiency of site preparation, planting and harvesting. The drainage system for either a natural forest or a plantation will often be a combination of both types (Terry and Hughes, 1978). The drainage system may also be characterized as to whether it provides primarily surface drainage, subsurface drainage, or a combination of the two. The system shown in Fig. 8.2 provides primarily subsurface drainage through parallel ditches about 1 m deep and typically spaced 100 to 200 m apart. The tree seedlings are planted on beds, about 30 cm in height, which provide protection from flooded conditions and good soil–root contact. The water standing between the beds in Fig. 8.2 is the result of more than 150 mm of rainfall during a hurricane. In this case the furrows between the beds are not connected to the ditches; thus, the intensity of surface drainage is very low. Although there may be some runoff during extreme events, annual surface runoff is small and nearly all of the drainage water is removed by relatively slow subsurface flow. This has the advantage of reducing outflow rates from these watersheds during large storms and of preventing sediment and associated contaminants from moving into the ditches and on downstream. It also tends to keep water from intense runoff-producing rainfall events on the site making more of it available for ET.

For tight soils, subsurface drainage is slow and surface drainage may be the best option for removing excess water. In this case the furrows in Fig. 8.2 would be connected to the ditches such that most of the surface water would run off the site during the storm event. The beds would still provide protection from waterlogging and the water table would subsequently be drawn down by ET. Annual surface runoff would be greatly increased compared with a site with intensive subsurface drainage, as will be shown in a later example. The intensity or quality of surface drainage may be defined as the average depth of depression storage (i.e. the average depth of water stored on the surface at the time surface runoff ceases following a large rainfall event). For drainage of existing stands, beds are usually not an option. The intensity of surface drainage in that case is still dependent on depressional storage and is generally inversely proportional to ditch spacing, but is improved by distributing the ditch spoil such that entry of surface water is not impeded.

A schematic of the drainage system showing the evolution of the water table and its effect

Fig. 8.2. Drained pine plantation in the coastal plain of North Carolina, USA. Picture taken 1 day after rainfall of over 150 mm from hurricane Dennis, August 1981. Beds protect young seedlings from drowning. Note furrows between beds are not connected to ditches, virtually eliminating surface runoff in all but the most extreme rainfall events. (Photo by Joe Hughes, 1981.)

on drainage rates following a rainfall event is given in Fig. 8.3. Drainage rate is plotted as a function of water table elevation midway between the drains, *m*, in Fig. 8.3b. Drainage rates for specific water table positions 1–6 (Fig. 8.3a) are denoted in Fig. 8.3b. Exact solutions for this case may be obtained by numerically solving the governing equations for combined saturated and unsaturated flow (Skaggs and Tang, 1976). An approximate approach is to use a combination of methods as follows. When the profile is saturated and water is ponded on the surface (position 1), the drainage rate may be calculated by equations developed by Kirkham (1957) (denoted by DK in Fig. 8.3b). After the depth of surface water recedes due to drainage and evaporation to a depth below the top of the beds, water can no longer move across the surface to the vicinity of the drains (position 2) and the Kirkham equation is no longer applicable. Drainage rates continue to decline as the ponded water drains through the profile until the water table midway between the drains is just coincident with the surface (position 3). At this point the drainage rate can be estimated with the steady-state Hooghoudt equation (Bouwer and van Schilfgaarde, 1963), which may be written for ditches as:

$$q = 4K_e m(2d + m)/L^2, \qquad (8.1)$$

where q is drainage rate (cm/h), m is midpoint water table elevation above the drain, K_e is the equivalent lateral hydraulic conductivity of the profile (cm/h), d is the depth from the drain to the restrictive layer (cm) and L is the drain spacing (cm) (Fig. 8.3a). For drain tubes used in agricultural applications an equivalent depth d_e rather than the actual depth, d, is used to compensate for radial head losses near the drain. The drawdown process as the water table falls from position 3 to position 4 and finally to drain depth (position 5) is obviously not steady state but, in most cases, proceeds slowly, and the drainage rate can be estimated by the Hooghoudt equation. The water table may continue to recede (position 6) due to ET and/or seepage, but the drainage rate would be zero when the water

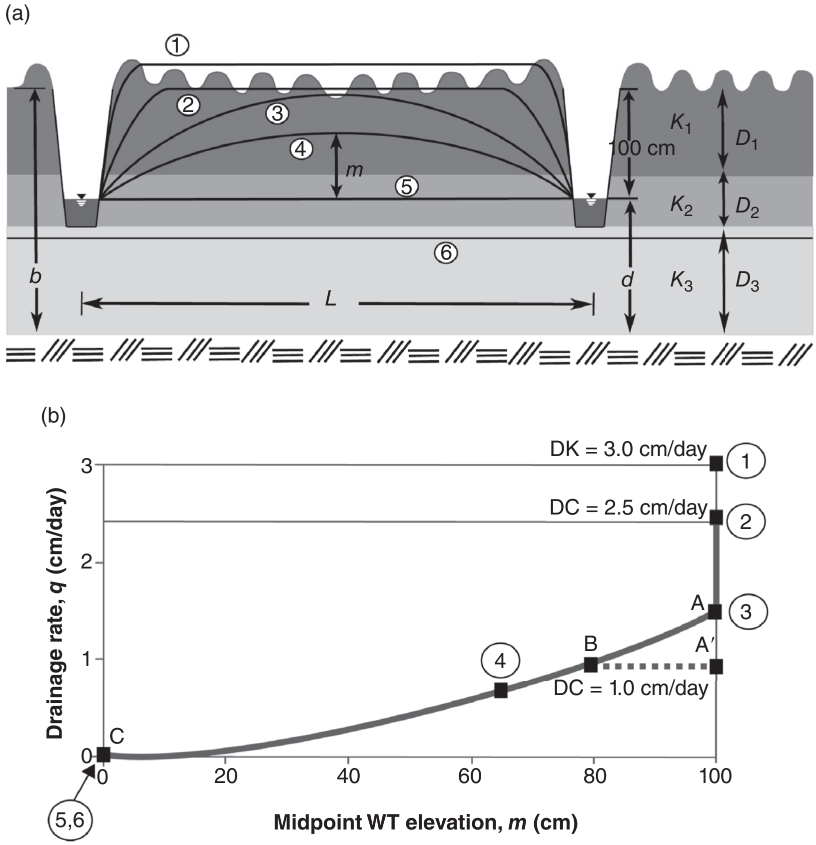

Fig. 8.3. (a) Schematic of a parallel subsurface drainage system with 1 m deep ditches spaced a distance *L* apart in a layered soil profile. (b) Drainage rates, *q*, corresponding to water table (WT) positions 1 to 6 shown in (a) are plotted as a function of the WT elevation, *m*, midway between the ditches. Drainage rates may be limited by the hydraulic capacity, DC, of the outlet, as shown.

table falls below drain depth. The drainage rate when the water table midway between the drains is at the surface (position 3) may be defined as the subsurface DI. DI is thus a function of the drain spacing and depth, and the thickness and hydraulic conductivity of the profile.

The values predicted by the Kirkham and Hooghoudt equations quantify the rate of water movement through the soil to the drains for given water table elevations. Most of the time, the water table is below the soil surface, drainage rates follow curve ABC in Fig. 8.3b and may be calculated with Eqn 8.1 above. The quality or intensity of subsurface drainage for a given site is typically quantified by the DI as defined above. However, in some cases the drainage rate may be limited not by the rate that water will move from the soil profile to the drain, but by the rate water will move through the ditch network to the drainage outlet; that is, by the hydraulic capacity of the system. The hydraulic capacity is called the drainage coefficient (DC) and depends on the size of the area being drained and the capacity of the outlet works, which is dependent on the size, slope and hydraulic roughness of the main drain or, in the case of pumped outlets, the pumping capacity. For example, let us assume the hydraulic capacity is 2.5 cm/day. When the profile is saturated and water is ponded on the surface such that it could theoretically drain through the soil at a rate of DK = 3.0 cm/day (Fig. 8.3b), the actual rate would be limited by the outlet capacity to DC = 2.5 cm/day. Once the water table falls to position 3 in Fig. 8.3b, q = DI = 1.5 cm/day which is smaller than DC, so the drainage event would follow curve ABC from there forward. In this example, DI < DC < DK, but DC may be greater than DK or less than DI, depending on the capacity of the outlet. For the case where DC is less than DI, say DC = 1.0 cm/day, the drainage rate for water table position 3 would be 1.0 cm/day and flow rates during a drainage event would follow A′BC in Fig. 8.3b. In this case water would back up in the ditches, the water table would become flatter and the flow rate from field to ditch would equilibrate with the DC.

Subsurface drainage rates may be reduced by obstructions in the ditches or downstream in outlet canals. In some cases obstructions such as weirs may be placed in the ditches to purposely reduce drainage rates. This practice is called controlled drainage (CD) and may be applied in both agricultural and forested lands to conserve water and reduce nutrient losses. Drainage rates for these cases may still be calculated with Eqn 8.1 as discussed above, with the value of m in Fig. 8.3 defined as the distance from the top of the weir in the ditch to the water table midway between drains. This approach could also be used to determine drainage rates when there is an obstruction or partial fill of the ditch.

The effect of drainage on water table depth is shown in Fig. 8.4 for a site in eastern North Carolina, USA. Measured water table depths for a drained loblolly pine plantation, an undrained forested wetland and a drained agricultural cropland are plotted for a 3-year period (1993–1995). Annual precipitation was 1004 mm (77% of average) in 1993, about average in 1994 (1284 mm) and 1368 mm in 1995. Very dry conditions during summer 1993 caused the water table to recede to depths greater than 1.2 m in the cropland site and to even greater depths in the deeper-rooted wetland and drained forested sites. The water table in the wetland was at or above the surface for extended periods in the winter and spring months of all three years and, except for the very dry summer 1993, well above the water tables in both the drained cropland and managed forest. Drainage from the wetland was mostly surface runoff, with minor subsurface drainage to widely spaced shallow natural drains. The average water table depth (1.54 m) on the drained forested site was much deeper and receded more rapidly than on the cropland site (0.75 m) or the undrained site (0.55 m). Drainage is the obvious reason for deeper water table depths in the forested compared with the wetland sites. Difference in ET is the reason for the greater water table depths on the drained forested versus the cropland site. Rooting depths are greater and the ET demand continues all year for the pine forest. The ditch depth was only 0.9 m but ET caused the water table to be drawn down to a maximum depth of more than 2 m for the drained forest, compared with only about 1.4 m for the agricultural site.

The response to drainage shown in Fig. 8.4 is in contrast to that reported for less permeable soils at other locations. For example, Jutras *et al*. (2007) reported that while drainage increased the annual growth rate of the diameter of black spruce close to the ditches in a peatland, it had only minor effects more than 15 m from the ditch. They concluded that narrow ditch spacing would be necessary to transform unproductive sites into productive ones. Such differences in response to drainage may be partly due to differences in climate, but are more likely due to differences in soil properties. The soil property having the greatest effect on drainage is the saturated hydraulic conductivity, K (Eqn 8.1). Paavilainen and Päivänen (1995) presented a summary of published measurements on a wide range of undisturbed peat soils. The K values varied from 4×10^{-2} to 9×10^{-8} cm/s (35 to 8×10^{-5} m/day), with magnitudes generally decreasing with increasing decomposition of peat. Published K values for mineral soils are roughly dependent on soil texture and vary from about 6×10^{-2} to 2×10^{-6} cm/s (Smedema *et al*., 2005). The effect of K on response to drainage is shown in Table 8.2 for a 3 m deep homogeneous profile with parallel 0.9 m deep drainage ditches. Results show that profiles with K_e values less than 10^{-6} cm/s would have minimal response to subsurface drainage. Ditches spaced less than 2 m apart would be required for DI values of 5 mm/day. Depending on profile depth, K_e greater than 10^{-4} cm/s (0.36 cm/h) would be necessary for a typical forest drainage ditch spacing (40 m or greater) to result in a DI of just 1 mm/day. For soils with very low K_e values, the best alternative may be to provide drainage to remove surface water so that the water table can be lowered by ET. This will make runoff events flashier, but not have a great effect on annual catchment drainage (Robinson, 1986; Holden *et al*., 2006).

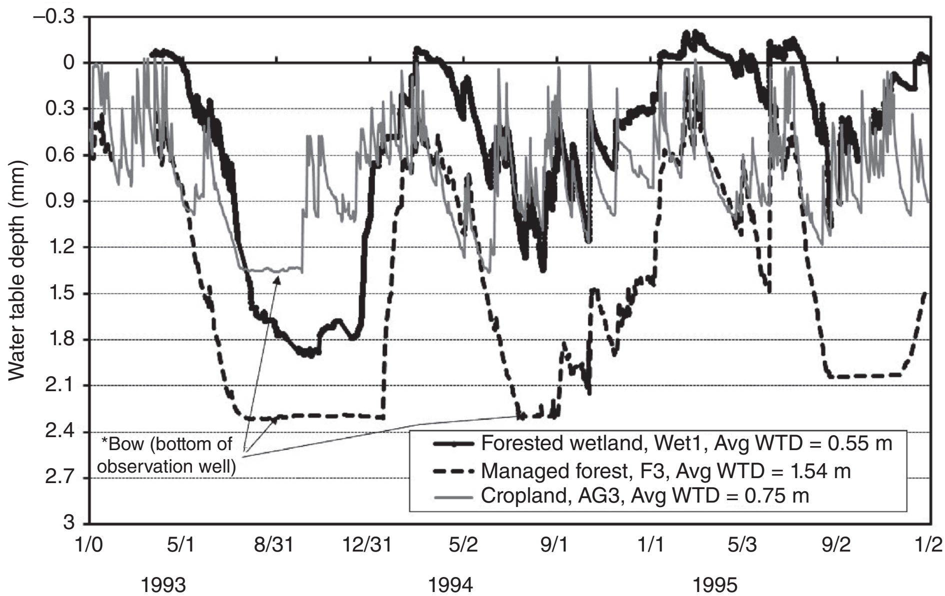

Fig. 8.4. Measured water table depths (WTD) for a drained loblolly pine plantation (F3), an undrained forested wetland (Wet1) and a drained agricultural field (AG3) near Plymouth, North Carolina, USA. Soils on the three sites (all located within a 3 km radius) are mineral (Portsmouth and Cape Fear sl and scl). (After Skaggs *et al.*, 2011.)

Table 8.2. Effect of hydraulic conductivity (K_e) on ditch spacing required for drainage intensity (DI) of 5 mm/day and on DI for a 40 m ditch spacing (L). Calculations made with Eqn 8.1 for ditch depth of 0.9 m and 3 m deep homogeneous soil profile (Fig. 8.3a).

K_e (cm/s)	Ditch spacing (m) for DI = 5 mm/day	DI (mm/d) for L = 40 m
10^{-8}	0.15	0 .0001
10^{-6}	1.5	0.01
10^{-4}	15	1
10^{-2}	150	100

8.4 Long-term Forest Drainage and Water Management Case Study

A long-duration watershed-scale study of forest drainage was conducted at the Carteret 7 site in Carteret County, North Carolina, USA. Initiated in 1986, the research site consists of three artificially drained experimental watersheds (D1, D2 and D3), each about 25 ha in size. Deloss fine sandy loam soil on the site is classified as very poorly drained with a shallow water table under natural conditions; the topography is nearly flat with slopes less than 0.1%. Each watershed is drained by four parallel lateral ditches about 1.2 m deep, spaced 100 m apart. A pump was installed on the outlet ditch to provide a reliable drainage outlet so that flow measurements could be made and water quality samples collected with minimum interference from elevated water levels in the outlet canal. The site was instrumented and water table and outflow data collection began in 1988 when the loblolly pine trees were 15 years old. Watershed D1 was maintained as the control with standard drainage practices from 1988 through 2009. Paired watershed studies were conducted to determine the hydrological and water quality impacts of several silvicultural and water management practices over the 21-year period 1988–2008.

After a 2-year calibration period, CD treatments were implemented on watersheds D2 and D3 to evaluate the impacts on water balance and storm event hydrology (Amatya *et al.*, 1996, 2000). In 1995, watershed D2 was harvested to study the impacts of harvesting, site preparation and regeneration on hydrology and water quality. At the same time, an orifice weir was installed on watershed D3 to study the performance of a weir arrangement that would extend drainage flow events and reduce peak flow rates (Amatya *et al*., 2003). Watershed D3 was thinned in 2002 to study the impact of thinning on hydrology and drainage water quality (Amatya and Skaggs, 2008). The 21-year data set collected on the site was used to develop and test simulation models for predicting the hydrology of drained forested watersheds under the treatments referenced above.

8.4.1 General hydrology

Observations on the Carteret 7 watersheds indicated that the principal hydrological components for drained forested watersheds in the coastal plain are rainfall, ET and subsurface drainage. These processes are dominated by shallow water tables that result from the combination of very low relief, micro-topography that produces high surface detention storage, and aquitards within a few metres of the surface. A restrictive layer that begins at an average depth of about 2.8 m limits vertical seepage, which was estimated to be less than 3% of precipitation (Amatya *et al*., 1996). Surface depressional storage is large on the bedded watersheds causing surface runoff to be small and, except for large tropical storms and hurricanes, negligible. Analysis of data for a 17-year period (1988–2005) on the control watershed (D1) showed that annual rainfall ranged from 852 to 2331 mm with an average of 1538 mm (Amatya and Skaggs, 2011). The large range in annual rainfall resulted from tropical storms and hurricanes in some years and drought in others. The annual runoff coefficient, defined as the ratio of outflow to rainfall, averaged 0.32 for the 17-year period. It ranged from 0.05 in the very dry year 2001 to 0.56 in the year of highest rainfall, 2003. Outflow on these watersheds is primarily subsurface flow to drainage ditches. Outflow rates were greater, more continuous and longer in duration in winter than in other seasons. Winter outflow was 59% of rainfall on average. The water table tended to be close to the surface during winter and early spring when ET demands are low, and during summer when hurricanes and tropical storms produced large outflows. However, it was drawn down to depths much deeper than the ditch depth during long dry periods in the summer and autumn. Annual ET, calculated as the difference between rainfall and outflow, averaged 1005 mm, which was close to the Penman–Monteith based average annual potential ET for a grass reference.

8.4.2 Effects of controlled drainage on hydrology of drained pine plantations

The DI needed for agricultural and silvicultural production varies with season and stage of the production cycle. For plantation forest the most critical stage is during harvest, site preparation for planting, and in the first years after planting when the seedlings require protection from high water table and excessive soil water conditions. ET is reduced during the seedling and early stage of growth, so drainage to lower the water table and provide suitable conditions for tree growth is more critical than later in the production cycle. For similar reasons, drainage is more critical in winter than in summer when the water table may be relatively deep due to ET alone (e.g. Fig. 8.4). Drainage in excess of that needed should be avoided as it removes water that could be used by the growing trees. Drainage can be reduced or managed on a temporal basis through the process of CD. CD may be applied in forested lands by the installation of a weir in the drainage outlet ditch such that the water level in the ditch must exceed the elevation of the weir for drainage water to leave the system.

Watershed D1 was maintained in conventional drainage with the weir level 1 m below the surface. CD to conserve water during the growing season was practised on D2 and CD to reduce drainage outflows during the spring was applied on D3. Results from the 3-year treatment period indicated that CD increased both ET and seepage and reduced outflows from D2 and D3 by 25 and 20 %, respectively, compared with the conventional drainage (Amatya *et al*., 1996). The CD treatment on watershed D2 resulted in rises in water table elevations during the summer. But the rises were small and short-lived due to increased ET rates as compared with the spring treatment with lower ET demands. Spring-time CD on watershed D3 also reduced freshwater outflows substantially, minimizing off-site water quality impacts. CD significantly reduced storm outflows for all events, and peak outflow rates for most events. In some events, flows did not occur at all in watersheds with CD. When outflows occurred, duration of the event was reduced sharply because of reduced effective ditch depth. While sediment and nutrient transport from these flat forested watersheds is low compared with other land uses (Chescheir *et al.*, 2003), CD was effective in reducing those loads to surface waters (Amatya *et al.*, 1998).

8.4.3 Effect of harvesting, bedding and planting on hydrology

Watershed D2 was harvested in July 1995 at a stand age of 21 years. Continuous flow and water table records were analysed to determine the hydrological effects and their change with time after replanting. The biggest effect of harvesting is the removal of growing plants, which substantially reduces ET. This reduced water table depth and increased drainage outflow and runoff coefficient compared with the control (D1), which was not harvested. Harvesting and regeneration reduced annual ET by 28% and increased outflow by 49% during the 5-year period 1995–1999 (Skaggs *et al.*, 2006). The average runoff coefficient for the period was increased from 0.32 to 0.51. Analysis of the long-term flow and water table data indicated that differences in both drainage outflows and water table depths between D2 and the control (D1) had returned to normal by 2004, 7 years after replanting in 1997.

Hydrological data collected in the Carteret 7 studies provided clear evidence that land use and operations such as harvesting and site preparation for new planting may substantially impact soil properties that may also result in further hydrological changes. Recorded water table and drainage flow data were analysed to determine the relationship between q and m (e.g. Fig. 8.3b) for various stages of the production cycle. The measured $q(m)$ relationship was used with Eqn 8.1 to calculate the field effective saturated hydraulic conductivity for a range of water table elevations (m). Then the field effective saturated hydraulic conductivity was determined for the three principal layers of the soil profile above the restrictive horizon. Results are summarized in Table 8.3.

Results indicate that the field effective hydraulic conductivity (K) in the top 80 cm of the soil profile prior to harvest of the 21-year-old loblolly pine was 20 to 30 times greater than values given in the county soil survey for the Deloss soil series. The K value of 1.6 m/day for depths greater than 80 cm was apparently unaffected as it remained within the range given in the soil survey for Deloss throughout the preharvest to postharvest period. The high K values in the shallower layers are attributed to the presence of large pores that result from tree roots and biological activity that is uninterrupted for many years in a forest. Similar high K values were reported for an organic soil on the Parker tract in eastern North Carolina (Grace *et al.*, 2006) and for a mineral soil on the same tract (Skaggs *et al.*, 2011). All sites were in plantation forest. Hydraulic conductivity (K) determinations based on water table and drainage outflow measurements after harvest in 1995, but prior to site preparation for the new plantation in October 1996 (postharvest in Table 8.3), were the same as obtained for the preharvest

Table 8.3. Field effective hydraulic conductivity (m/day) by layer for the soil profile on Carteret 7 watershed D2 prior to and following harvest, bedding and planting. Transmissivity (T) of the soil profile is also shown. Values published in the county soil survey for Deloss soil series on the site are given in parentheses for reference and are considered typical for agricultural land uses. (After Skaggs *et al.*, 2006.)

		D2			
Depth (cm)	K, Deloss soil survey	Preharvest	Postharvest	Post bedding	7 years post planting
0–50	3.6 (1.2–3.6)	60	60	3.6	50
50–80	1.6 (0.36–1.6)	55	55	1.6	20
80–280	1.6 (0.36–1.6)	1.6	1.6	1.6	1.6
T (m^2/d)	5.5	50	50	5.5	34

condition. However, after bedding and planting, drainage rates were substantially reduced and the field effective K values determined from field data after bedding were in good agreement with the range of values published in the soil survey (Table 8.3). Apparently the bedding process destroyed the macropores in the surface layers such that the profile had effective K values similar to that expected for agricultural land use. These results indicate that K values needed for drainage design on plantations can be estimated from soil survey data. These values may be conservative as field effective K values in the top part of the profile may increase as the trees grow, only to return to original values after harvest and site preparation for new plantings. Other studies have found that drainage may change soil physical properties (possibly reducing K), through subsidence and compaction, and chemical properties, including decreased pH (Minkkinen *et al*., 2008), decomposition rates of soil organic matter (Domisch *et al*., 2000) and soil C stock (Minkkinen and Laine, 1998; Laiho, 2006).

8.5 Application of a Forest Drainage Simulation Model

Computer models can be applied for simulating hydrological processes and their interactions in drained forests. The models include DRAINMOD (Skaggs *et al*., 2012), FLATWOODS (Sun *et al*., 1998), SWAT (Arnold *et al*., 1998) and MIKE SHE (Abbott *et al*., 1986). As an example, an application of DRAINMOD is presented to illustrate impacts of subsurface DI on forest hydrology. DRAINMOD was developed in the 1970s to describe the performance of agricultural drainage systems. It is based on a water balance in the soil profile and uses the methods discussed in Section 8.3 to calculate drainage rates. Components of the water balance are simulated on an hourly basis for several years of weather record. The model used here is DRAINMOD-FOREST (Tian *et al*., 2012, 2014), an enhanced version of DRAINMOD for forested landscapes; the model is briefly described in Chapter 9 (this volume). Simulations were conducted for the Deloss soil on the Carteret 7 site with mid-rotation (age 15 years) pine for DI ranging from 0.5 to 32 mm/day (corresponding to ditch spacing varying from 800 to 100 m), while other parameters were kept the same as in Tian *et al*. (2012). Results of the simulations show the effects of drainage system design on drainage objectives and the hydrology of drained watersheds. The effect of DI on average number of days with soil water and weather conditions suitable for field work is shown in Fig. 8.5a for three different periods of the year. A day was counted as a working day if the predicted water table depth was at least 0.6 m and the precipitation during the day was less than 10 mm. The number of working days increases sharply with increase of DI from 0.5 to 8 mm/day (Fig. 8.5a). Based on these results, a DI of between 5 and 8 mm/day would be recommended for this location. This would provide an average of 55 to 65 working days suitable for harvesting and site preparation during January–March, the wettest 90 days of the year. A DI of 5 to 8 mm/day is less than half of that required for agricultural production, which is about 15 mm/day for eastern North Carolina (Skaggs, 2007).

The effect of DI on average annual outflow for the 21-year simulation period (1988–2008) is shown in Fig. 8.5b. Results are shown for surface depression storages of 150 mm (characteristic of a bedded surface as shown in Fig. 8.2) and 25 mm, which is the minimum expected surface storage on either natural or non-bedded plantation forests on these nearly flat lands. For the bedded condition, average annual predicted subsurface drainage varied from a low of 420 mm for DI = 0.5 mm/day to 510 mm for DI = 32 mm/day. That is, the large majority of outflow from these bedded lands occurs as subsurface flow, even for wide ditch spacing and low DI. This is not the case when surface storage is small (25 mm). Increasing the DI from 0.5 to 32 mm/day for that case decreased predicted average annual surface runoff from 390 to 30 mm and increased annual subsurface drainage from 60 to 480 mm (Fig. 8.5b). Increasing the DI reduced predicted average annual ET and increased total outflow by about 60 mm (4% of annual precipitation) for both surface storage values considered. The 60 mm predicted increase in annual flow is about the same as reported by Robinson (1986) following the installation of a dense network of 0.5 m deep plough ditches on upland clay and peat soils in northern England. Drainage outflows accounted for about two-thirds of precipitation and ET one-third – almost exactly the reverse of the situation at Carteret where drainage accounts for about

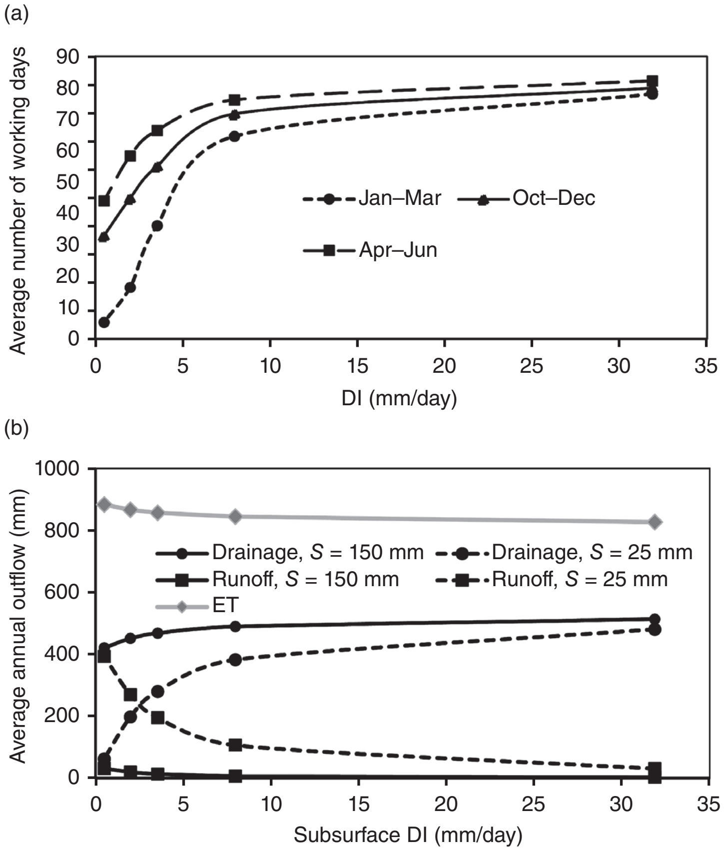

Fig. 8.5. (a) Effect of drainage intensity (DI) on predicted average number of days suitable for harvesting and site preparation during indicated periods. (b) Effect of subsurface DI on annual average drainage and surface runoff for average surface depression storages (*S*) of 15 cm and 2.5 cm. Results predicted by 21-year DRAINMOD-FOREST simulations for a Deloss sandy loam in Carteret County, North Carolina, USA (ET, evapotranspiration).

one-third of annual rainfall and ET roughly two-thirds. While the magnitude of increase in outflows was about the same as predicted for Carteret, the mechanisms were very different. The dense network of shallow ditches on the England site increased baseflows, quickly removed surface runoff, and increased peak flow rates and sediment loss. However, except for the zone very close to the ditch, drainage had limited effect on soil moisture (Robinson, 1986).

8.6 Summary

Drainage is used to improve access and yields on a small percentage of the world's forested lands. However, it has had a big impact on the millions of hectares on which it is applied. Drainage has increased timber yields on poorly drained peatlands and mineral soils in northern Europe, Canada and the southern USA. Substantial yield responses to drainage have been reported on both natural and plantation forests, with typical annual increases of 2 to 8 m^3/ha. In some cases yields have not responded to drainage due to climate, soil physical properties or fertility issues. First applied in the mid-1700s, forest drainage has a long history with the most active periods in the 1930s and from 1950 to about 1985. In recent years forest drainage has been de-emphasized because of concerns about its effects on ecology, biodiversity and related environmental issues.

Government programmes to subsidize forest drainage have been phased out in most countries, and new drainage projects to enhance forest production on wetland soils have been greatly reduced or effectively terminated by regulations to protect wetlands. In most countries exemptions to the regulations or special government programmes allow replanting on, and continued maintenance of, existing forest drainage systems. It is perhaps unreasonable to assume that the needs for wood and wood products for over 7 billion people can be provided without some ecological and environmental costs. Recognizing that, in spite of regulations limiting forest drainage, drained forests are here to stay, Lõhmus *et al*. (2015) suggested:

> Forest drainage can be seen as a scientifically exciting case for ecosystem management which must use novel approaches to reconcile timber production, water management and biodiversity conservation in functional forest–wetland mosaics and their hydrological networks.

Research has increased our understanding of the impacts of forest drainage and the response of hydrology, soils and tree growth to their design and management. For some cases, it is possible to control drainage outlets to conserve water during periods when drainage is not needed and remove excess water when it is. Simulation models have been developed for predicting, on a day-to-day basis, the effects of drainage management on hydrology, primary productivity, water quality and C stock. Their reliability and range of application will likely improve as we go forward. Future models may be run in real time to manage drainage on wetland forests to enhance both production and ecological objectives. While it may not be possible to economically produce timber and other forest products on forested wetlands without some impact on biodiversity and the environment, to do so in ways that create a sustainable balance between economic and environmental/ecological objectives appears to be a reasonable and achievable goal.

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