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Linkages between forest soils and water quality and quantity

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ABSTRACT

The most sustainable and best quality fresh water sources in the world originate in forest ecosystems. The biological, chemical, and physical characteristics of forest soils are particularly well suited to delivering high quality water to streams, moderating stream hydrology, and providing diverse aquatic habitat. Forest soils feature litter layers and high organic contents, both of which contribute to an abundant and diverse micro- and macro-fauna. Root systems under forests are extensive and relatively deep compared to agricultural lands and grasslands. Together, these biological conditions create soils with high macroporosity, low bulk density, and highly saturated hydraulic conductivities and infiltration rates. Consequently, surface runoff is rare in forest environments, and most rainfall moves to streams by subsurface flow pathways where nutrient uptake, cycling, and contaminant sorption processes are rapid. Because of the dominance of subsurface flow processes, peak flows are moderated and baseflows are prolonged. Conversion of forests to row crops, pastures, or lawns almost always results in deterioration of water quality. In North America, the majority of municipalities ultimately rely on forested watersheds to provide adequate quantities of high quality water for human use. This is particularly true in the western and eastern parts of the continent where human populations are large or growing rapidly. Forest soils provide the perfect conditions for creating high quality water supplies. This paper provides a historical perspective of the linkage between forest soils and water quantity and quality over the past century, and it also makes predictions about research directions in the area of forest soil and water quality linkages.

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1. Introduction

Jenny (1941), building on the seminal work of Russian soils scientist Vasily Dukachaev, described five factors of soil formation: parent material, climate, landscape position, organisms, and time. Forest soils differ from agricultural and urban/suburban soils in terms of organisms. Specifically, forests, tree litter, and the associated fauna fundamentally alter soils in ways that are vital to watershed hydrology, water quality, and stream habitat.

Forests develop deep and extensive root networks, deposit leaf, needle, and limb litter on the soil surface that results in a forest floor with relatively high levels of organic matter. The resulting soil environment is home to a diverse micro- and macro-fauna as evidenced by the many invertebrates, insects, and small vertebrates found in forest soils. Root growth and decay, cracking due to freeze/thaw and wetting-drying processes, animal burrowing, windthrow of weak trees, subsurface erosion, and other natural processes all increase soil porosity (ratio of void space to total soil volume), the number and size of macropores (>0.06 mm in diameter), and the water conductivity of the soil. Leaf litter on the soil surface dissipates raindrop energy and facilitates rainfall infiltration into the soil. Relatively high organic contents of natural soils increase the stability of soil aggregates. Stable aggregates prevent soil crusting by reducing detachment of small soil particles. This helps maintain high surface infiltration rates. For these reasons, most rainfall reaching the forest floor infiltrates, and classical Hortonian overland flow occurs only during very intense rainfall events. Surface runoff occurs mainly as variable source area runoff from low lying areas such as floodplains, wetlands, and ephemeral streams where the water table rises to the soil surface during rainfall. These areas comprise only 5–15% of most forested landscapes. Most of the infiltrated water either is used for plant transpiration needs or reaches streams by subsurface pathways (Fig. 1; Jackson, 2006).

There are five physical, chemical and biological functions common to all watersheds involving the receipt, processing and transfer of water. These are precipitation collection, water storage, chemical processes and transformations, water discharge, and aquatic habitat creation (Black, 2004). Forests and forest soils alter each of these functions relative to other land uses and soil types.

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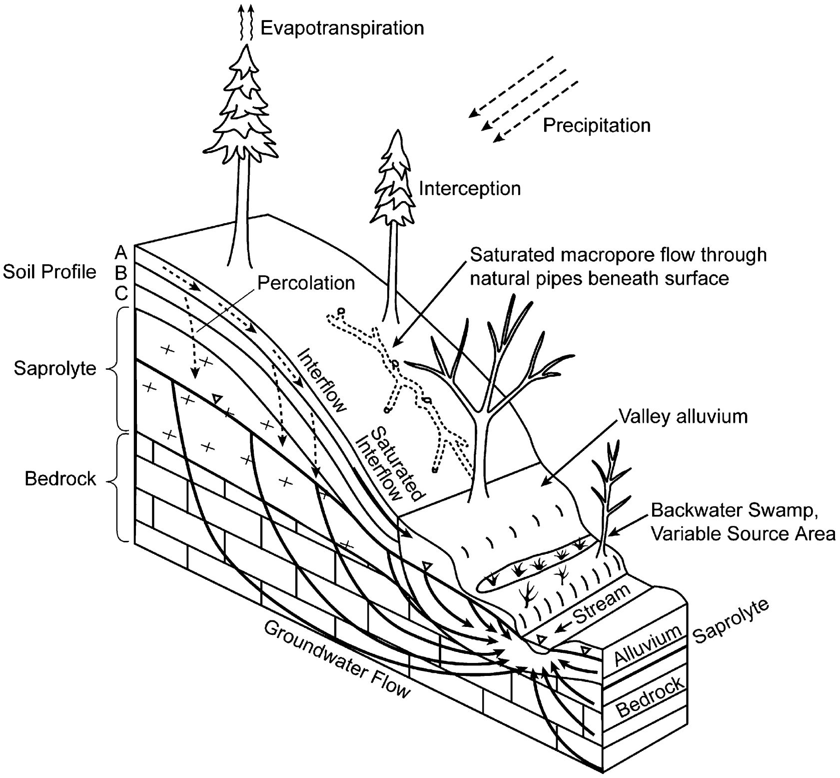

Fig. 1. Water flow pathways in a forested watershed (Adapted from Jackson, 2006).

Due to their high leaf area indices, forests intercept more rainfall than other vegetative assemblages. Deep and well-developed root systems of mature forests efficiently extract soil moisture for tree growth, and also transpire more water than other vegetation types. Nevertheless, because of the high infiltration rates and high soil storage, the hydrologic regime of forests tends to be highly moderated in terms of both peak flows and low flows.

Sediment and nutrient fluxes from forest watersheds are also moderated. The same factors that promote infiltration, subsurface flow, and soil-moisture storage also reduce surface erosion. Even the presence of large wood in streams may reduce stream velocities by increasing channel roughness and promoting sediment storage and nutrient retention (nutrient spiraling) in the stream channel. Tight nutrient cycles in undisturbed forest soils and watersheds result in net gains or small losses of most nutrients compared to other land uses (Hornbeck et al., 1987; Swank and Waide, 1988). Perennial plant uptake and organic matter in forest soils help to retain nutrients. Neary and Leonard (1978), Van Lear et al. (1985) and McBroom et al. (2008) found that forest watersheds retain most nitrogen inputs, even after fertilization and timber harvesting have occurred.

Streams draining forests tend to have relatively stable channels in quasi geomorphic equilibrium, low concentrations of nutrients and contaminants, and high levels of riparian-stream interaction. Aquatic biodiversity is generally greater in forested streams than in adjacent streams in other land uses (Wallace, 1988; Kratzer et al., 2006). During the process of urbanization, lands are cleared of forest vegetation, slopes and soils are graded for construction, impervious surfaces (rooftops, parking lots, roads) are constructed; and curbs, gutters, and storm drains are created that hasten the flow of surface water off the landscape. The process of clearing and grading compacts the soil, reducing total porosity and macropore volume and thus decreasing infiltration rates. Urban soils typically lack litter layers and have low organic matter contents, so they are susceptible to surface crusting during rainfall. Horton overland flow occurs at lower rainfall rates on these and other disturbed soils. Some altered surfaces have been so degraded that they have infiltration rates approaching zero, thus converting nearly 100% of incident rainfall into overland flow (Fig. 2). Pritchett (1979), in his seminal textbook "*Management and Properties of Forest Soils*" delved into the topics of forest watersheds, and how soil cover and vegetation can be manipulated to increase water yields (Fig. 3). He spent time examining how season, precipitation, precipitation timing, cover, and aspect can affect water yield. His concluding comments highlighted the importance of forests and forest soils in protecting watersheds and water resources.

The U.S. Geological Survey's NAWQA studies (Rosen and Lapham, 2008) comparing water quality across land uses have repeatedly shown that forest lands provide the highest quality stream water (e.g. Frick et al., 1996). Much of urbanized America

Fig. 2. Degraded Typic Hapludult soil in north Georgia following logging and burning of a site with a legacy of agriculture-related desertification (photo by Daniel G. Neary).

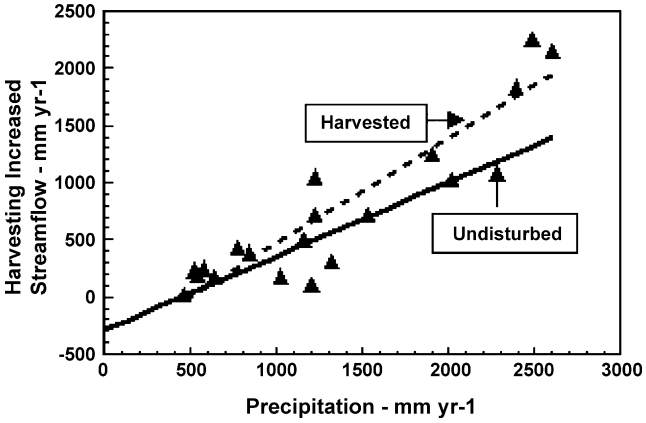

Fig. 3. First-year streamflow increases cross a precipitation gradient from 480 to 2600 mm produced by tree harvesting (Neary et al., 2005).

depends on forested watersheds to provide stable supplies of high quality water. Rivers such as the Colorado that supply water to major metropolitan areas in Arizona, California, and Nevada, derive the bulk of their flows from forested mountain headwater streams. The quality of water is so high from some forested watersheds that cities like Portland, Oregon, utilize unfiltered river water from forested watersheds to supply their residents and businesses. New York City has long relied upon mixed forest/farm watersheds in the Catskill Mountains to provide one of the highest quality metropolitan drinking water supplies in the world.

In the USA, 3400 towns and cities currently depend on National Forest watersheds for their public water supplies (Ryan and Glasser, 2000). An additional 3000 administrative sites such as campgrounds, picnic areas, and historical sites rely on the same or similar sources. It has been estimated that 25% of the people in the USA, predominantly in western regions where the bulk of the National Forest lands are located, rely on streams and groundwater emanating from National Forests for their public water supplies. Since 70% of the forest area in the USA is outside the National Forest System, particularly in the eastern USA, a conservative estimate is that 50–75% of the USA's population relies on forest lands to produce adequate supplies of good quality water. In Canada, the percentage is higher due to that country's vast forest area. In much of the central and northern Mexico area, a semi-arid region with rapidly expanding populations, the situation is similar to the western USA. The more humid regions of southern Mexico and the Yucatan Peninsula are more similar to the eastern USA and Canada.

The intent of this paper is to provide a historical perspective of the linkage between forest soils and water quantity and quality in North America over the past century. This narrative describes the development of this area of watershed science, the key scientists that moved this discipline forward, how it developed, and the breakthroughs that have advanced the understanding of forest soils and watershed science. Lastly, the authors would like to gaze into the crystal ball of watershed "wizardry" to examine potential directions, trends and research needs in this topic area as the 21st Century progresses.

2. Historical understanding of watersheds, soil, and water quality relationships

Watershed management and the importance of forests to water quantity and quality are certainly not new concepts. Watershed management is often thought of as a 20th century development, but its roots go much further back in the history of human civilization. Water and soil have been linked throughout all of human civilization, and poor management of the latter has led to the collapse of numerous societies (Diamond, 2005).

The Chinese began developing an understanding of watershed management, hydrology, and the importance of forest soils as early as 2880 B.C, and forest protection laws were enacted as early as 300 B.C. (Chang, 2003). Indian texts from Vedic times (1000 B.C.) indicated an early understanding of the hydrologic cycle in the development of human civilization, and early development of the concepts upon which the modern science of hydrology and watershed management is based (Chandra, 1990). The development of cities in the Middle East and the Mediterranean Sea basin depended not only upon the agricultural revolution, but also upon water management (Illich, 1985). The Minoan (1700 B.C.) and Mycenaean (1400 B.C.) civilizations of Crete and Greece had a good understanding of water management as indicated by the extensive water facilities they created for their cities (Tainter, 1988). Cities like Ninevah and Troy constricted aqueducts to bring water up to 80 km away from then forested regions in the 7th and 6th centuries B.C. The first aqueduct supplying Rome was built in 312 B.C., and extended out to streams with predominantly forested areas because of a rapidly expanding population and demands for good quality water. By 97 A.D., Rome was a city of over one million with 9 aqueducts 400 km in length bringing in over 1000 L/person/day of fresh water. Population expansion necessitated the construction of an additional five aqueducts by 300 A.D. (Hodge, 2002).

Watershed management and engineering skills declined with the collapse of Rome and the entry of Western European civilization into the Dark Ages. However, recognition of the importance of forests survived since in 1215, King Louis the VI of France promulgated an ordinance called "The Decree of Waters and Forests" in recognition of the interrelationships between water and forests (Kittredge, 1948). The Swiss set aside the first European watershed protection forest in 1342 (Kittredge, 1948). Between 1535 and 1777, another 322 forests were designated as watershed reserves and avalanche protection zones.

By the 19th century, French and Italian scientists published treatises that recognized the relationships between hydrology, vegetation, and climate, and the serious erosion and water impacts of deforestation. (Grebe, 1852; Heyer, 1860; Kittredge, 1948) A remark from the German naturalist Von Humbolt (1849) indicated that the importance of forests for good watershed management. But, as late as 1826, Paris could only supply 3 L/person/day to its population, and London's water supply capacity was only 37 L/person/day in 1936 (Illich, 1985). In contrast, Rome was providing for its population over 30 times that of London in 97 A.D. (Hodge, 2002).

In the Western Hemisphere, early Native American cultures made substantial achievements in watershed management. Between 200 B.C. and 700 A.D., the Huari and Tiahuanaco empires of Peru and Bolivia built extensive irrigation canals and agricultural terracing to create a large artificial agricultural landscape to support their burgeoning populations (Tainter, 1988). The Inca civilization that followed these two empires had cities of 200,000 people supplied with water by lengthy aqueducts from forests in the Andes Mountains (Kerr, 1960). The Mayan culture (1000 B.C. to 1000 A.D.) of the Southern Lowlands of Mexico modified their landscapes extensively to provide water for agriculture (Tainter, 1988), but drought, forest clearing, and soil degradation caught up with this society and contributed to its collapse.

The Hohokam culture that occupied areas of the Sonoran Desert in Arizona from 600 to 1200 A.D. was noteworthy among North American native peoples for water management (Reid and Whittlesey, 1997). Hohokam living near the present day city of Phoenix irrigated their corn, bean, and squash crops in the Sonoran Desert, a location that averaged less than 200 mm of annual precipitation. They used fresh water originating in forested watersheds of the Salt and Verde Rivers (McGuire, 1982).

Watershed management in the USA gained a strong foothold with the creation of the National Forests. The Forest Reserve Act of

Table 1
Locations and themes of the eleven North American Forest Soils Conferences, with total oral papers and those dedicated to forest soil and water linkages.

No.	Year	Location	Theme	Oral Papers Presented (Water)
1	1958	East Lansing, MI	None	31 (1)
2	1963	Corvallis, OR	Forest Soil Relationships	35 (0)
3	1968	Raleigh, NC	Tree Growth and Forest Soils	38 (1)
4	1973	Quebec City, QB	Forest Soils and Land Management	42 (8)
5	1978	Fort Collins, CO	Forest Soils and Land Use	33 (7)
6	1983	Knoxville, TN	Forest Soils and Treatment Impacts	25 (1)
7	1988	Vancouver, BC	Sustained Productivity of Forest Soils	30 (0)
8	1993	Gainesville, FL	Carbon Form and Function in Forest Soils	27 (0)
9	1998	Sault Ste, Marie, ON	Forest Soils and Ecosystem Sustainability	31 (0)
10	2003	Tahoe City, CA	Forest Soils Research	23 (2)
11	2008	Blacksburg, VA	Forest Soil Science: Celebrating 50 Years	23 (5)

1891 created the reserves that were to become the core of the National Forest system (Steen, 1976). By the end of 1892, President Harrison had added 15 reserves totaling 5.3 million ha, primarily to protect water supplies. In 1896, the forest reserves were up to 8.1 million ha. President Cleveland set off a land reservation further by adding another 8.5 million ha in early 1897 with the Pettigrew Amendment to the 1897 Sundry Civil Appropriations Bill (also known as the Organic Act of 1897). This legislation clearly defined the purpose of the forest reserves stating that the reserves could be established only to improve and protect forests or secure favorable water flows (Steen, 1976; Ice and Stednick, 2004).

Forest soils are of paramount importance to successful watershed management and the continuity of civilization as we know it (Montgomery, 2007): In 2008, the Congress of the United States finally recognized this important role in providing clean water through a Senate Resolution that now declares that soils are an “essential” natural resource, placing soil on par with water and air. The Senate Resolution acknowledges the work of soil scientists and soil professionals to continue to enrich the lives of all Americans by improving stewardship of the soil, combating soil degradation, and ensuring the future protection and sustainable use of air, soil, and water resources in the United States (Congressional Record, 2008).

3. Forest soil science and connections to water quantity and quality

3.1. *Influential textbooks*

Pritchett (1979) commented that the science of Forest Soils developed slowly in North America during the 20th Century because of the lack of incentive during what has been labeled as the period of exploitive technological forestry (Stone, 1975; McFee and Kelly, 2005). Although the Forest Reserve Act of 1891 and the Organic Act of 1897 had already acknowledged the importance of water, it was only after World War I that the management of forests for other uses came into vogue.

Pritchett (1979) went on to say that the greatest stimulus to the development of Forest Soils in North America as a scientific discipline was simultaneous publications of text books on the subject by Lutz and Chandler (1946) and Wilde (1946). Two European textbooks preceded these books (Ramann, 1893; Henry, 1908, cited in Comerford, 2006), and several from Sweden and Germany followed in the early 1950s. However, language differences limited their use in North American forestry. Although there is a large body of research on forest soils and water, any discussion of the development of forest soil science and its linkage to water must include the North American texts that Pritchett (1979) mentioned, as well as more recent ones. These include texts by Kittredge (1948), Armson (1977), Pritchett and Fisher (1987), Kimmons (1987), and Fisher and Binkley (2000).

A number of forest hydrology textbooks also chronicle progress in the understanding of forest soils and their influence on water. They document the close association between forest soil science and forest hydrology science that has led to the currently well-developed state of knowledge. This group of textbooks include those by Sopper and Lull (1967), Hewlett and Nutter (1969), Brown (1980), Lee (1980), Swank and Crossley (1988), Black (1990), Brooks et al. (1991), Ward and Elliot (1995), Chang (2003), Ward and Trimble (2004), and Stednick (2008).

3.2. *North American forest soils conference proceedings*

The North American Forest Soils Conferences (NAFSC) began in 1958 (Table 1). They were, and still are viewed, as a means to summarize and highlight advances in forest soil science every 5

Table 2
Forest soil and water linkage papers in the North American Forest Soil Conferences 1958 to 2008.

NAFSC	YEAR	TOPIC	Number of Papers
1	1958	Soil Moisture	2
		Forest Soils and Watersheds	1
2	1963	Soil Moisture	1
		Forest Soils and Watersheds	1
		Nutrient Cycling	1
		Erosion	1
3	1968	Nutrient Cycling	2
		Pesticide Movement	1
4	1973	Soil Moisture	1
		Nutrient Cycling	3
		Water Quality	5
		Wastewater Recycling	1
5	1978	Forest Soils and Watersheds	3
		Nutrient Cycling	3
		Erosion	1
		Wastewater recycling	1
		Slope Stability	3
		Mining and Water	1
6	1983	Atmospheric Deposition	5
		Grassland Soils and Watersheds	1
7	1988	Nutrient Cycling	5
		Atmospheric Deposition	1
8	1993	Nutrient Cycling	7
9	1998	Soil Moisture	1
		Nutrient Cycling	7
10	2003	Nutrient Cycling	3
		Erosion	1
		Groundwater	1
		Water Quality	1
11	2008	Forest Soils and Watersheds	3
		Nutrient Cycling	1

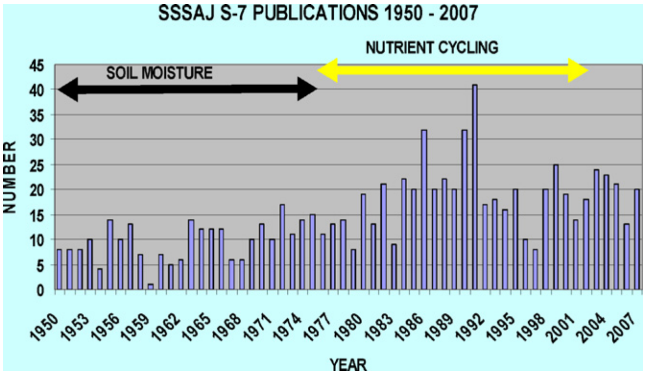

Fig. 4. Soil Science Society of America Journal articles related to forest soils (Division S-7) and water quantity or quality.

years. The NAFSC has always produced books or special editions of journals to circulate the conference proceedings as widely as possible (Michigan Agricultural Experiment Station, 1958; Youngberg, 1965; Youngberg and Davey, 1970; Bernier and Winget, 1975; Youngberg, 1978; Stone, 1984; Gessel et al., 1990; McFee and Kelly, 1995; Boyle and Powers, 2000; Gale et al., 2005). There has been and ebb and flow of water-related papers throughout the 50 years of the NAFSC that has reflected scientific interest, funding, and political interest in the topic. A list of the topics and numbers of papers is shown in Table 2.

3.3. *Soil Science Society of America and other journal publications*

A number of journals have published papers that deal with the topic of the linkages between forest soils and water quality. These include the Soil Science Society of America Journal (SSSAJ), the Canadian Journal of Soil Science, Soil Science, Forest Science, Canadian Journal of Forest Research, Journal of Environmental Quality, Southern, Western, and Northern Journals of Applied Forestry, and Forest Ecology and Management. A large number of U.S. Forest Service publications have also dealt with the topic. It is beyond the space constraints of this paper to deal with all sources of published literature, so only publications in the SSSAJ will be addressed.

Publications primarily in Division S-7 (Forest, Range, and Wildland Soils) of the SSSAJ on water and forest soils since 1950 are presented in Fig. 4. There have been 859 publications that addressed the water quantity and quality theme. The peak in water-related papers in SSSAJ occurred during the 1960s when they made up 19% of the total S-7 Division papers published. In the current decade the proportion of water-related papers is 11%, with nutrient cycling papers comprising nearly half of the manuscripts. These papers constitute a substantial part of the science behind the linkages between forest soils and water. From 1950 to about 1977, the major water theme was soil moisture. A small number of papers (<2/year) were in other topic areas such as water quantity/quality, nutrient cycling, macropores, ground water, erosion, evapotranspiration, subsurface flow, and watershed studies. After 1977, there was a theme shift. Nutrient cycling became the dominant topic with similar low numbers of papers in the other categories mentioned above, including soil moisture. These themes and their change in importance reflected both scientific interest and funding direction.

4. Forest soils and watershed science development

Much of the development of the science that links forest soils and the water flowing from forested watersheds was developed by

Table 3
Major North American long-term forest watershed studies (From Ice and Stednick, 2004).

Watershed Study	Forest Type	Location	Est.	Ownership
United States of America				
Alsea Basin	Douglas-fir	Oregon	1959	USFS[a]
Bear Brook	N. Hardwoods/Spruce/Fir	Maine	1987	Private
Beaver Creek	Ponderosa Pine/Juniper	Arizona	1956	USFS
Belle Baruch	Marsh/Swamp/Pine	South Carolina	1969	Private
B.F. Grant	Loblolly Pine	Georgia	1973	State
Bradford Forest	Slash Pine	Florida	1977	Private
Caspar Creek	Mixed Conifer	California	1962	USFS
Caribou-Poker Creeks	Birch/Spruce Taiga	Alaska	1963	State
Coweeta	S. Hardwoods	North Carolina	1934	USFS
Entiat	Pond. Pine/Douglas-fir	Washington	1957	USFS
Fernow Forest	Mixed Hardwoods	West Virginia	1934	USFS
Fraser Forest	Sub-alpine Spruce/Fir	Colorado	1937	USFS
H.J. Andrews	Douglas-fir/W. Hemlock	Oregon	1948	USFS
Hubbard Brook	N. Hardwoods/Spruce-fir	New Hampshire	1955	USFS
King's River	Red Fir/Mixed Conifer	California	2002	USFS
Luquillo	Broadleaf Tropical	Puerto Rico	1956	USFS
Marcell Forest	Peatland/Hardwoods	Minnesota	1960	USFS
NC Coastal Plains	Loblolly Pine/Wetlands	North Carolina	1960	Private
Oxford Gulf Coast	Loblolly Pine	Mississippi	1956	USFS
Ouachita	Loblolly Pine	Arkansas	1977	USFS
San Dimas	Chaparral	California	1933	USFS
Santee Forest	Mixed Pine/Hardwoods	South Carolina	1937	USFS
Sierra Ancha Forest	Chaparral/Mixed Conifer	Arizona	1932	USFS
Tenderfoot Creek	Sub-alpine Fir	Montana	1961	USFS
Walker Branch	Oak-Hickory	Tennessee	1978	USDOE[b]
Canada				
Carnation Creek	Hemlock/Fir/Red Cedar	British Columbia	1970	Province
Hayward Brook	Hardwood/Conifer	New Brunswick	1994	Province
Pockwock-Bowater	Red & Black Spruce	Nova Scotia	1997	Private
Turkey Lakes	Maple/Birch	Ontario	1979	Province
Western Boreal Plains	Spruce/Aspen/Pine	Alberta	2001	Province

[a] USFS: U.S. Forest Service.
[b] USDOE: U.S. Department of Energy.

soil scientists and hydrologists working on collaboratively on long-term forest watershed studies (Table 3). Chang (2006) lists 49 sites in the continental USA that contain a total of 441 experimental watersheds. The bulk of these studies are Federal Government-funded, principally by the U.S. Forest Service, because of the long-term commitment and funding needed to operate them. National Science Foundation programs such as the Long-Term Ecological Research network (LTER) and the more recent National Ecological Observatory Network (NEON) also provide support for these long-term watershed studies.

The science synergy that occurred on these studies was a natural result of what Hendricks (1962) identified as the critical requirement for understanding water in relation to earth processes like soil science—a collaboration of many disciplines. Continuation of this collaboration will be critical for advances in the forest soil and forest hydrology sciences in the next 50 years. This is particularly true for emerging science issues like climate change.

5. Breakthroughs and important concepts

Black (1996) defined a number of critically important concepts that underlay the art and science of forest hydrology. These include evaporation, condensation transpiration, interception, photosynthesis, respiration, storm return period, time of concentration, environmental water, water budget, infiltration, antecedent moisture conditions, and variable source area. The latter three concepts directly pertain to the linkages and interactions between soils and water quantity and quality at a watershed scale. Some others which merit mention include landslides and debris flows, water repellency, macropores, and watershed models that incorporate soil processes. The important ones will be highlighted here. The key papers are listed in Table 4.

5.1. Variable source area and streamflow

The Variable Source Area concept was an important breakthrough in the understanding of water movement in forests through soils and into streams (Hewlett and Troendle, 1975). It was a radical departure from the previously held Hortonian concept of overland flow dominating watershed response to rainfall (Horton, 1933). According to the Hortonian concept, overland flow of water occurs more or less simultaneously over a watershed when rainfall exceeds the infiltration capacity of the basin. Horton (1933) maintained that such overland flow was a major contribution to the rapid rise of river flow levels, and was the prime cause of soil erosion. Hortonian flow is distinct from subsurface flow since it involves no movement of underground water back to the surface. Subsequent research indicates that the Hortonian model is not widely applicable. Beginning with observations by Hursh (1936), forest hydrologists and soil scientists began to demonstrate that Horton overland flow did not describe most stormflow production in forested watersheds. Rigorous development of the variable source area concept began with Hewlett's (1961) initial work on soil moisture as a source of baseflow in forest watersheds, and later collaboration with A.R. Hibbert (Hewlett and Hibbert, 1963). In this concept (Fig. 5, Adapted from Hewlett, 1982), watershed runoff response to precipitation in low order basins typical of forested regions is a combination of two simultaneous and independent processes: slope soil water movement and channel expansion.

Table 4
Key breakthrough papers in the linkages of forest soils to water quantity and quality.

Breakthrough topic	Key paper
5.1 Variable source area and streamflow	Hewlett and Hibbert (1963)
5.2 Macropore flow and water movement	Hursh (1944)
5.3 Interflow and subsurface topography	Hewlett (1961)
5.4 Water flow and soil erosion	Trimble and Weitzman (1953)
5.5 Landslides and soil management	Froehlich (1978)
5.6 Nutrient cycling and water quality	Henderson and Harris (1975)
5.7 Water repellency	DeBano (1981)
5.8 Forest floor and the environmental fate of pesticides	Norris (1970)
5.9 Best Management Practices	Singer and Maloney (1977), Stone (1973)

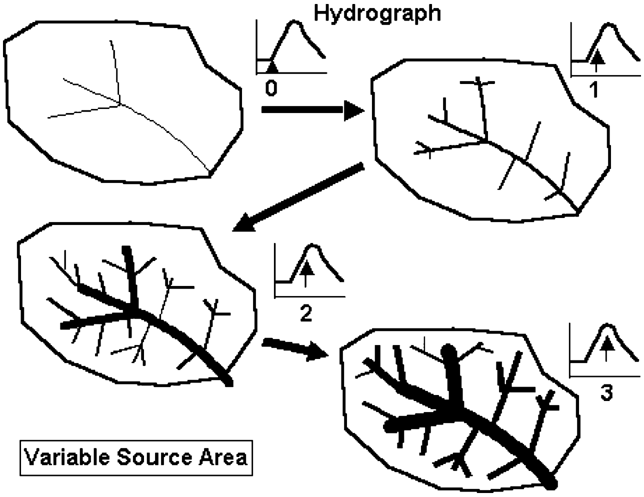

Fig. 5. Variable source area concept of streamflow response to rainfall at three time steps (Adapted from Hewlett, 1982).

Precipitation falling directly into channels is increased by water flowing directly through large soil pores into channels or by upslope displacement of water stored in the soil or in weathered saprolite (Hewlett and Nutter, 1969; Hewlett and Troendle, 1975). As rainfall continues, infiltration capacities of soils near the channel are exceeded, causing an upslope expansion of the water surface areas in ephemeral channels that can expand the perennial reach by 10–20 times. The variable source area concept was popularized after the strikingly descriptive mapping of saturated area expansion and contraction conducted by Dunne and Black (1970a,b) and Dunne et al. (1975). A detailed description of the development of the variable source area concept was presented by Hibbert and Troendle (1988) at the Coweeta Hydrologic Laboratory 50th anniversary symposium.

The importance of the variable source area lies in the linkage between forest soils and how watersheds respond to storm events. Because of the properties of forest floor organic materials and the generally high porosity of forest soils, more water infiltrates into the soil, thereby reducing surface runoff, erosion, and flashy responses to storm rainfall. This process also produces more baseflow that supports streamflow between storm events and improves water quality.

5.2. Macropore flow and water movement

Macropores in soils are crucial to hillslope hydrologic and biogeochemical processes because they allow soil water to rapidly bypass the soil matrix when the soil is saturated or nearly saturated. These large pores are created by roots, soil fauna, shrinking/drying, soil aggregate development, and by subsurface erosion forming soil pipes. As reported by Beven and Germann (1982), the recognition of the importance of macropores dates back over 145 years at least to Schumacher (1864), "the permeability of a soil during infiltration is mainly controlled by big pores, in which the water is not held under the influence of capillary forces." Hursh (1944), an early thinker on the variable source concept, also realized that macropores in the upper soil horizons could cause increases in lateral transmission rates as soils saturate from below. He realized that in natural soils, macropores created by biological processes such as roots, worm burrowings, or insect tunnels could significantly govern water movement through a substantial volume of soil.

Beven and Germann (1982) provided an excellent review of the science and importance of macropores, and their paper stimulated a renewed interest in the hydrologic and biogeochemical roles of macropores. Since 1990, nearly 600 journal articles have been published on the subject. Because of the continued difficulty in mapping, monitoring, and modeling macropores at different scales, it is expected that macropores will continue to be an active area of forest soil research (Sidle et al., 1995). Macropores are an important linkage to water flow in forest soils since they provide routes of subsurface rapid water movement to either surficial aquifers or stream channels. These pores develop as a result of the process of tree root growth and decay and burrowing by soil animals of various sizes.

5.3. *Interflow and subsurface topography*

Interflow is shallow lateral subsurface flow moving nearly parallel to the soil surface and flowing over a soil or bedrock layer featuring low hydraulic conductivity. While the concept of interflow appears in early hydrologic texts, the mechanisms and importance of interflow remain a subject of research and debate. Hewlett (1961) and Hewlett and Hibbert (1963) conducted the first experimental investigation of interflow at the Coweeta Hydrologic Laboratory in western North Carolina. They sought to understand why small mountain streams with very small alluvial aquifers maintained flows during long periods without precipitation. To evaluate the hypothesis that interflow through the thin soil mantle overlying bedrock on steep slopes provided water to replenish the alluvial aquifer and sustain streamflows, they constructed linear concrete troughs, approximately 1 m wide and 1 m deep on 40% slopes, saturated the troughs, covered the tops with plastic to prevent evapotranspiration, and then monitored outflow from the base of the trough. A 14 m long trough sustained flows for 145 days, clearly demonstrating the hillslope interflow could be a dominant contributor of baseflow in steep terrain. Saturated flow from most of the hillslope ceased after only 36 h, and unsaturated flow sustained the saturated wedge at the base of the trough for the remainder of the experiment (Hewlett and Hibbert, 1963).

Finite difference and finite element modeling of Richards' equation has elucidated many aspects of hillslope flow, including interflow. Using such a model, Zaslavsky and Sinai (1981) demonstrated that the initial flow direction of infiltrating water is perpendicular to the soil surface, but that interflow commences when the wetting front reaches an impeding layer. Isotope analysis of rainwater, stream water, soil water, and groundwater has revealed that stormflow in streams is often dominated by "old" water, or water that was in the hillslope prior to rainfall (e.g. Brammer and McDonnell, 1996). Pressure waves, or "piston flow" as it was originally described by Hewlett (1961), are a likely explanation for the old water paradox (Rasmussen et al., 2000).

Recent investigations have demonstrated the importance of subsoil or bedrock topography on hillslope flow mechanisms. On broader scales, subsurface topography roughly usually reflects surface topography, but subsurface topographic variation at smaller scales can cause zones of subsurface flow accumulation not evident from surface topography. These areas saturate before the rest of the hillslope, initiating rapid macropore flow, as reflected in the "fill and spill" hypothesis (Tromp-Van Meerveld and McDonnell, 2006a,b). The fill and spill hypothesis has substantial implications for threshold responses of hillslope flow to precipitation (e.g. Lehmann et al., 2007).

5.4. *Water flow and soil erosion*

Soil scientists long ago realized and demonstrated that soil cover strongly affects infiltration rates, and particularly that raindrops hitting bare soils cause aggregate breakdown and the formation of a crust that inhibits infiltration (Duley, 1939; Ellison, 1947). Reduced infiltration rates increase the likelihood of Hortonian overland flow and the resulting surface erosion. It is not overly simplistic to say that the study of nonpoint source pollution from forestry activities has largely been a study of runoff and erosion from bare soil areas created for roads, landings, skid trails, fire breaks, and also bare soils created by site preparation fires.

In all forested areas of the United States (except for flat coastal plain areas), roads, landings, and skid trails have been repeatedly implicated as the primary source of sediment from silvicultural operations (e.g. Hoover, 1952; Trimble and Weitzman, 1953; Megahan and Kidd, 1972; Rivenbark and Jackson, 2004). Much of the research program at the Fernow Experimental Forest in West Virginia was oriented toward the development of minimum road standards for safe and durable forest access roads that minimized sediment inputs to streams (Kochenderfer, 1970). Decades of research across the country showed that road-related soil loss could be reduced by vegetating cut and fill slopes (Hursh, 1942; Swift, 1988; Burroughs and King, 1989), by improving road surfaces (Reid and Dunne, 1984; Swift, 1984a,b), by dispersing water onto hillslopes via broad based dips, turnouts and relief culverts (Cook and Hewlett, 1979; Luce and Black, 1999), by scheduling traffic during dry periods (Bilby et al., 1989), and by providing filter strips between roads and streams (Swift, 1986). Megahan and Kidd (1972) also determined that road erosion is highest just after road construction and that it decreases with age.

In small basins, forest roads increase peak flows and stormflow volumes due to the surface runoff produced by roads (Wemple and Jones, 2003). Road cutslopes on steeper slopes may also intercept interflow moving downslope, short-circuiting the natural hydrologic system (Wemple et al., 1996). Using a distributed hydrologic model, Wigmosta and Perkins (2001) and Bowling and Lettenmaier (2001) both estimated that forest road networks can increase peak flows by 10–12% in small basins (less than 280 ha), and that roading networks (main roads, temporary roads, and skid trails) and clearcutting can increase 2-yr, 5-yr, and 10-yr recurrence interval peak flows. This increase in stormflow depends on factors such as flood magnitude, road flow diversions onto forest soils, vegetation, road condition, etc.

In much of the eastern United States, and in some parts of the West, forests are now growing on lands that were previously used for row crop agriculture, pasture, and mining. Even after decades of forest growth, water quality conditions in streams draining these areas reflect legacy effects of the prior land use. For example, almost all of the southeastern Piedmont was cleared for row crop agriculture during the 1800s and early 1900s. Due to the high erodibility of Piedmont soils, the high rainfall erosivity of the area, and poor farming practices, erosion was severe (Richter and Markewitz, 2001). Trimble (1974) estimated that 10–30 cm of native topsoil were lost as a consequence across the region. This type of agricultural erosion was not limited to the southeastern Piedmont (Knox, 2006), and mining activities in parts of the Appalachian Mountains also contributed large quantities of sediment to streams (Leigh, 1994). The cotton-farming era ended abruptly in the 1930s, and since then, much of the southeastern Piedmont reverted to or was planted to forest. However, the historical land use is currently reflected in remnant hillslope gullies, thin topsoils with low carbon contents, altered valleys, unstable streams, and altered steam biological communities (Richter and Markewitz, 2001). Happ (1945) described the situation for the South Carolina Piedmont which suffered soil losses of up to 15 cm. A sediment budget conducted 55 years later in a forested watershed found stable terraces with unstable streams downcutting through the legacy agricultural sediments and determined that in stream erosion accounted for 60–80% of current sediment export (Jackson et al., 2005).

Much of the cotton-era erosion occurred as gully erosion (Ireland et al., 1947), and remains of these gullies are still ubiquitous on forested Piedmont hillslopes (Richter and Markewitz, 2001; Galang et al., 2007). These gullies can reactivate after timber harvest (Rivenbark and Jackson, 2004), potentially delivering significant quantities of sediment to the valley floor (Ward and Jackson, 2004). Because of the potential problems associated with reactivated agricultural gullies, the Georgia Forestry Commission has recently developed gully BMPs for forestry operations.

The legacy sediment and geomorphological effects of past land use are also transmitted to the stream biological communities. Harding et al. (1998) found that current aquatic communities in the southern Appalachians were best predicted by 1950s land use. Even after five decades of forest growth, stream biology still reflected the prior land use. These legacy effects need to be understood in order to understand the water quality status of watersheds.

Forest soils are reforming in new forests planted on abandoned agricultural lands but their rate of formation is slow, creating a few centimeters of new ‘‘A Horizon’’ in a half century (Van lear et al., 1995). As these forest soils redevelop, Hortonian surface flow has dramatically declined, sediment delivery to channels has dropped, nutrient fluxes into streams are lowered, and stormflows are less flashy (Jackson et al., 2005). Delivery of legacy sediment downstream continues to be a problem but overall water quality has improved because of conversion of agricultural lands back to forests.

5.5. Landslides and soil management

Shallow landslides or other mass soil movements, such as earthflows and debris torrents (water-charged failures moving in the stream channel) occur naturally in forest watersheds (Froehlich, 1978; Swanson et al., 1981). In steep regions, such as the Pacific Northwest, scientists have found that these mass soil failures are essential to maintaining health fish habitat because they introduce wood and complexity to streams (Everest and Meehan, 1981) and create off-channel fish habitat (Miller and Benda, 2000). While these events occur naturally and can be important for creating fish habitat, forest management activities can accelerate when a failure will occur. Highly accelerated soil-related landslides may damage channels and water quality. Some potential mechanisms by which forest management can accelerate landslides include:

- Reduced soil strength (loss of root re-enforcement and root anchoring) with timber harvesting,
- Increased soil–water pore pressure (increased net precipitation, reduced evapotranspiration, re-routing of road runoff),
- Altered slope configuration (over-steepened cut-slopes and unconsolidated sidecast along roads).

Side-cast roads on steep slopes and roads with inadequate culvert capacity on steep streams have high probabilities of failure and can produce landslides and debris flows with large effects on local stream systems. Landslide inventories conducted on two Idaho National Forests following major climatic events found 88% (Megahan et al., 1978) and 57% (McClelland et al., 1997) of all landslides were associated with roads. Better road placement and design can greatly reduce landslide risks from roads (Sessions et al., 1987)

A complete discussion of landslides is beyond the scope of this paper, but it is important to note that the linkages of forest soils, geology, vegetation, management, and water contribute to slope failure risks. WRENS (USDA Forest Service, 1980) lists factors contributing to both slump-earthflow and debris avalanche/debris flow type failures. Some factors to consider for the later type of soil failure include: slope gradient, soil depth, surface drainage characteristics, soil texture, bedding structure and orientation of geology, surface slope configuration, precipitation input, vegetation cover, roads and skidways, and harvest system (summarized in Ice, 1985). Clearly soil factors are a key consideration for slope failures and are strongly influenced by local hydrology. Risks rise when forest soils are shallow, soil moisture content is high, soil internal drainage is slow, slopes are steep, woody vegetation is removed, roads divert water on to slopes, and precipitation is high. The shear strength needed to hold soils on slopes can be compromised by soil saturation due to rain or road runoff diversions, death of tree roots due to harvesting, fire, or insect outbreaks, slope steepness, changes in vegetation type.

A review of landslide inventories for the Pacific Northwest (Ice, 1985) found a number of examples where landslide rates associated with forest management, particularly roads, had declined from earlier inventories. This is probably a result of improved road construction (avoidance or removal of side-cast road construction methods, better drainage, full-bench road construction, improved culvert sizing, etc.) and maturing of the road system. Robison et al. (1999), in a study of the 1996 floods and landslides in Oregon, reported that most landslides in forest were related to roads. The road associated landslides found in this study were typically about four times larger in volume than non-road associated landslides. Some State forest practice rules, notably those in Washington and California, also address harvest units and require special planning or restrict harvesting in high landslide-risk locations. These rules continue to be monitored and evaluated for their effectiveness.

5.6. Nutrient cycling and water quality

An important breakthrough in forest soil and watershed science was the establishment of the linkage between nutrient cycles in forest ecosystems and the quality of water in streamflow. Nutrient cycling was the second major theme of scientific effort in understanding the linkages between forest soils and water (Fig. 4). Development of this linkage largely arose from research being conducted at major watershed research facilities (Swank and Waide, 1988; Table 3). Efforts such as the Clean Water Act of 1977 in the USA and similar legislation in Canada, the Acid Rain Program in the late 1970s as well as the National Science Foundation's LTER program stimulated and funded forest soil science research dealing with the linkage between nutrient cycling and water quality. Controversy over forest harvesting in the late 1960s and into the 1970s also stimulated nutrient cycling research.

Several publications have reviewed the literature on the linkages of disturbances to forest vegetation and soils and water quality (Brown, 1980; Brown and Binkley, 1994; Neary and Hornbeck, 1994; Dissmeyer, 2000; Neary, 2002). Site-specific nutrient cycling syntheses have been done for individual research watersheds like Coweeta (Swank and Waide, 1988), Walker Branch (Johnson and Van Hook, 1989), Hubbard Brook (Likens and Bormann, 1995), and Fernow Experimental Forest (Adams and Kochenderfer, 2007), to mention a few. In addition, this topic is covered in greater detail in the paper by Van Miegroet and Johnson (in this volume).

5.7. Water repellency

Many forest soils have developed in the presence of fire, including those in forested wetlands (Neary et al., 2005). Understanding linkages with water flow through forest ecosystems is important in the management of fire in forests. A key fire process in soils is water repellency. The creation of water repellency in soils involves both physical and chemical processes. Although hydrophobic soils have been observed since the early 1900s (DeBano, 1981, 2000a, 2000b), fire-induced water repellency was first identified on burned chaparral watersheds in southern California in the early1960s. Watershed scientists were aware of it earlier, but it had been referred to simply as the ''tin roof'' effect because of its effect on infiltration. In southern California, both the production of a fire-induced water repellency and the loss of protective vegetative cover played a major role in the post-fire runoff and erosion. Normally, dry soils have an affinity for adsorbing liquid and vapor water because there is strong attraction between the mineral soil particles and water. In water repellent soils, however, the water droplet ''beads up'' on the soil surface where it can remain for long periods and in some cases will evaporate before being absorbed by the soil. Water repellency has been characterized by measuring the contact angle between the water droplet and the water-repellent soil surface. Wettable dry soils have a liquid–solid contact angle of nearly zero degrees. In contrast, water-repellent soils have liquid–solid contact angles of 90° (Fig. 6).

Water repellency is produced by soil organic matter that forms hydrophobic substances during natural or fire-induced heating that coat mineral particles. It can be found in both fire and non-fire environments (DeBano, 2000a,b; DeBano et al., 1998). The magnitude of fire-induced water repellency depends upon several parameters, including the severity of the fire, the type and amounts of organic matter, temperature gradients in the mineral soil, soil texture, and antecedent soil moisture. Soil heating during a fire produces a water-repellent layer at or near the soil surface that further impedes infiltration into the soil. The severity of the water repellency in the surface soil layer decreases over time as it is exposed to moisture; in many cases, it does not substantially affect infiltration beyond the first year. Water repellency can have a particularly significant effect on water quantity and quality because it produces surface runoff-dominated precipitation responses. This reduces soil moisture, increases watershed peakflows, and dramatically increases hillslope and channel erosion (Neary et al., 2005; MacDonald and Huffman, 2004; Larsen and MacDonald, 2007).

Fig. 6. Fire-induced water repellent soil showing water drops beaded on the surface of mineral soil. (DeBano, 1981; Neary et al., 2005; Photo by Leonard DeBano).

5.8. Forest floor and the environmental fate of pesticides

Apart from clearcutting, the single most divisive issue in forestry related to water quality has been the use of silvicultural chemicals. Research by Norris (1970) pointed out the importance of the forest floor in adsorbing pesticides and preventing leaching and surface runoff. Fredriksen et al. (1975) noted in their research that most cases of herbicide contamination of water in forest watersheds involve the application phase. Their work clearly demonstrated that the organic matter of the forest floor and surface mineral horizons is the ''*single most important soil characteristic*'' influencing adsorption and retention of pesticide residues on-site in forest soils.

More recent work by Michael and Neary (1993) and Neary et al. (1993) expanded on the work of Norris (1970) using newer, rapidly degrading pesticides. They augmented the earlier findings regarding the importance of forest soils in protecting water quality. Neary et al. (1993) and Neary and Michael (1996) concluded that the risks to water quality posed by modern silvicultural chemicals is very low due to infrequent use over the rotation of a forest stand, lack of bioaccumulation by the pesticides, and the function of forest soil organic matter and microorganisms in adsorbing and decomposing pesticide residues. If forest pesticides are not applied directly to water during application, their propensity to move into streams is limited by forest soil processes. Although herbicides, especially water soluble ones, can move through forest soils, they do so in small amounts because of the organic matter in the forest floor, roots, and organic coatings on mineral particles (Neary et al., 1985). Herbicide molecules sorbed onto organic matter can then be taken up by target plant roots or degraded by soil microorganisms. Some herbicides like glyphosate are so tightly sorbed onto organic complexes that they do not leach at all (Michael and Neary, 1993).

5.9. Best management practices—understanding soil and water linkages

The U.S. Environmental Protection Agency (USEPA) coined the term ''Best Management Practices'' (BMPs) in the mid-1970s as the agency developed guidance for achieving nonpoint pollution control objectives of the 1972 Amendment of Water Pollution Control Act (known as the Clean Water Act). While BMPs are not direct linkages between forest soils and hydrology, they have been developed, and are generally successful, because of the improved understanding of the actual linkages between forest soils and water (Stone, 1973). Singer and Maloney (1977) defined BMPs as operational practices that prevent or reduce the amount of nonpoint source pollution in keeping with water quality objectives. BMPs are relatively low cost measures to reduce nonpoint pollution developed from science and professional judgment. These techniques are fundamentally interdisciplinary, involving all aspects of water quality, forest hydrology, forest soils, aquatic and terrestrial biology, and forest engineering. Commercial forestry is regulated largely at the State level, and in the late 1970s and early 1980s, states began publishing the first forestry BMP guidance documents. These guidance documents have evolved over time in response to emerging research, operational experiences, changing technology, economics, and social values.

While BMP specifics vary from state to state, all forestry BMPs share the same following basic strategies (adapted from Jackson et al., 2004; Olszewski and Jackson, 2006; Jackson and Miwa, 2007): (1) Minimize soil compaction and bare ground coverage, (2) Separate exposed bare ground from surface waters, (3) Separate fertilizer and herbicide applications from surface waters, (4) Inhibit hydraulic connections between bare ground and surface waters, (5) Avoid disturbance in steep convergent areas, (6) provide a forested buffer around streams, and (7) Engineer stable road surfaces and stream crossings. Any forester who keeps these principles in mind and broadly understands forest soils and water quality can do a good job minimizing nonpoint pollution.

6. Directions, trends, and research needs

In regards to future directions, trends, and research needs for the topic of forest soils and water in the next five years or even half-century, the outlook is both clear and cloudy, depending on whose "Crystal Ball" one gazes into. One trend that is crystal clear and inexorable is that the importance of water quantity and quality will increase as the 21st Century unfolds. This is driven by climate change and population growth. By 2030, the current projection is that 47% of the world's population will face severe water shortages (OECD, 2008). The management of forests and grasslands for drinking water supplies will continue to be a major activity for Federal and other land management agencies (Dissmeyer, 2000). Forest soil science will have to maintain its pace to satisfy information needs of forest land managers under pressure to supply adequate amounts of high quality water.

A future direction in forest soils and water is increased usage of forest watershed simulation models. These models are tools for evaluating water quantity and quality issues related to forest management and disturbance. They also provide a management tool for extending research results and a research method for prioritizing research and focusing work on important problems in the fields of forest soils and forest hydrology. There are numerous forest watershed models because of differences in their approaches and application (Brooks et al., 2003). In the early 1980s, there were at least 75 hydrologic simulation models that were available and deemed suitable for small watersheds (Renard et al., 1982). Since the computer technology revolution in the early 1980s, the numbers and variations on these watershed models have in creased exponentially.

Some forest watershed models are mathematical rather than scaled physical models. These models can be lumped or spatially distributed across watersheds and their soils, and be empirical or physically based. The temporal resolutions of their simulations can be single event or continuous in nature. A comprehensive and detailed review of existing forest watershed models and how they incorporate soil processes is certainly beyond the scope beyond the scope of this paper. Some models do not incorporate soil processes at all, except in a very general way, and some simulate soil water movement in considerable detail. But, the sheer numbers, specific adaptations, and incorporations of soil processes in these models indicate the high degree of the advancement in the science in the past 50 years.

Several models are worth pointing out to illustrate the degree of soil processes incorporation into forest watershed models. FORWADY (Forest Water Dynamics, 2008) is a new model developed by B. Seeley and J.P. Kimmons constructed around an earlier model, FORHYM, developed by Arp and Yin (1992). This model routes infiltrated water through the forest floor, A and B soil horizons, and the subsoil to produce runoff, interflow, and soil water storage. FLATWOODS (Sun et al., 1998) is a forest hydrologic model developed for USA coastal plain forests based on the COASTAL model (Sun, 1985). The subsurface component of FLATWOODS incorporates soil moisture characteristic curves, saturated hydraulic conductivity, specific yield, soil moisture content, water table, and root density for multiple soil horizons.

A number of authors have looked at future directions in forest soil science relative to the linkages between forest soils and water (Dissmeyer, 2000; Ice and Stednick, 2004; Fisher et al., 2005; McFee and Kelly, 2005). Fisher et al. (2005) pointed out the need to maintain a balanced mix of basic and applied research. McFee and Kelly (2005), in a summary of the 10th NAFSC, made a plea for seeking new approaches to old problems within the framework of team approaches to forest soil science. They reminded their readers that "exciting things" often happen on the interfaces between scientific disciplines like hydrology and forest soils.

A number of emerging issues like climate change and water quantity and quality will undoubtedly frame, and provide the funding for, new and continued research in this arena of forest soil science. Some key research issues and needs will be:

- Training an adequate number of scientists with expertise in the forest soil–water linkage;
- Maintaining funding for long-term watershed studies;
- Increasing the "network" of long-term watershed studies;
- Refining the "natural range of variability" of water yield and quality in forest landscapes;
- Determining if climate change will affect soil processes that affect water yield and quality;
- Determining if the current understanding of the linkages between forest soils and water quantity and quality hold up in a changing climate;
- Measuring long-term cumulative effects of forest soil management relative to water;
- Improving and validating soil process-based hydrologic models at a watershed scale;
- Refining BMPs and streamside management zone guidelines specific to water quality protection;
- Developing innovative approaches to quantify the function of soil organic matter in nutrient cycling and the linkage to water quality.

There are many challenges ahead in operating at the interface between forest hydrology and forest soils. However, this is a critical arena of endeavor for scientific, sociological, and economic reasons. The science of the past 50 years has laid a good foundation for supporting the work of the next 50 years.

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