Chapter 13. Forest management and water in the United States

Daniel G. Neary[33] (dneary@fs.fed.us)

13.1 Introduction

This chapter outlines a brief history of the United States native forests and forest plantations. It describes the past and current natural and plantation forest distribution (map, area, main species), as well as main products produced (timber, pulp, furniture, etc.). Integrated into this discussion is a characterization of the water resources of the United States and the importance of forests for water uses. The chapter presents a review of the most extensive body of research on the relationships of water and forests that has been produced world-wide. Finally, the chapter concludes with a discussion of key forest and water issues, the principal one being a combination of water shortages and excess brought on by a changing climate and human population increases in vulnerable landscapes.

13.1.1 Importance of water

The value of forests in providing stable flows of good quality water was recognized by a number of civilizations (Greece, 1700 BC; India, 1000 BC; Rome, 312 BC; France, 1215 AD; Switzerland, 1535, etc.) (Neary, 2000). By the 19th century, the concept of catchment management and the relationship between forests and water supplies was well developed. For example, in 1849 the German naturalist Alexander Von Humboldt remarked that the concept of catchment management was well developed in European and American scientific circles. He further reflected: "How foolish do men appear destroying the forest cover of the world without regard to consequences, for they rob themselves of wood and water."

In the 21st century, the mission of the US Forest Service, and forestry in as a profession, is in securing favorable water flows for human needs, and riparian and aquatic functions. It is now even more important than in the past two centuries. The population of the USA has expanded from 76 million at the start of the 20th century to 281 million people in 2000, the beginning of the 21st century (Hobbs and Stoops, 2002). Clean and accessible water remains one of the most important resources to sustain this expanding population. One resource that people need every day is water. And every day there are more people in the country that require water. Too often good quality water is taken for granted in developed countries. Across the developing world, the main cause of child mortality is still "dirty water" (Rutstein 2000).

13.1.2 Natural and plantation forest distribution

In 2005, forest land constituted 303.5 million ha of the USA total land area or about 33.3%, similar to both Canada and Mexico (Figure 1). The forests of the eastern USA are predominantly deciduous, while those of the west are mainly coniferous (U.S. Geological Survey 2015). The main eastern USA forest cover types are: white-red-jack pine, spruce-fir, longleaf-slash pine, loblolly-shortleaf pine, oak-pine, oak-hickory, oak-gum-cypress, elm-ash-cottonwood, maple-beech-birch, aspen-birch. Western forest cover types can be grouped into Douglas-fir, hemlock-sitka spruce, ponderosa pine, western white pine, lodgepole pine, larch, fir-spruce, redwood, chaparral, pinyon-juniper, and western hardwoods. Alaska has three cover types of spruce-birch, fir-spruce, and hemlock-sitka spruce. Hawaii's forest cover consists of evergreen broadleaf tropical forest. The southeastern

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[33] USDA Forest Service, Rocky Mountain Research Station, Air, Water, and Aquatic Environments Program, Flagstaff, AZ USA

forests have a large component of yellow pines that form the backbone of the forest industry in that region. Plantation forests dominate the southeastern area forests. Uncolored areas (white in Figure 1) are urban, agriculture, prairie, tundra, ice, water, swamp, desert, or other miscellaneous cover types.

Figure 1. Dominant forest cover types of the USA (From: The National Atlas of the United States of America, US Geological Survey, 2015).

Forest ownership since 2005 is predominantly private in the eastern USA (78%) consisting of many smaller landownerships and fewer numbers of large ownerships (Figure 2). More than half the forest land in the United States (171.2 million ha) is owned and managed by some 11 million private forest owners. Of those private forest owners, 92% (10 million owners) are classified as small "family forest" owners with forest holdings of <4 ha. Industrial and government land holdings for vertically integrated forest products companies have declined in the past several decades in favor of forest management operations run by indigenous, local, or investment enterprises (White and Martin 2002). These private forests are managed under short rotations for sustained production of dimensional timber, pulp and paper feedstocks, furniture, bioenergy feedstocks

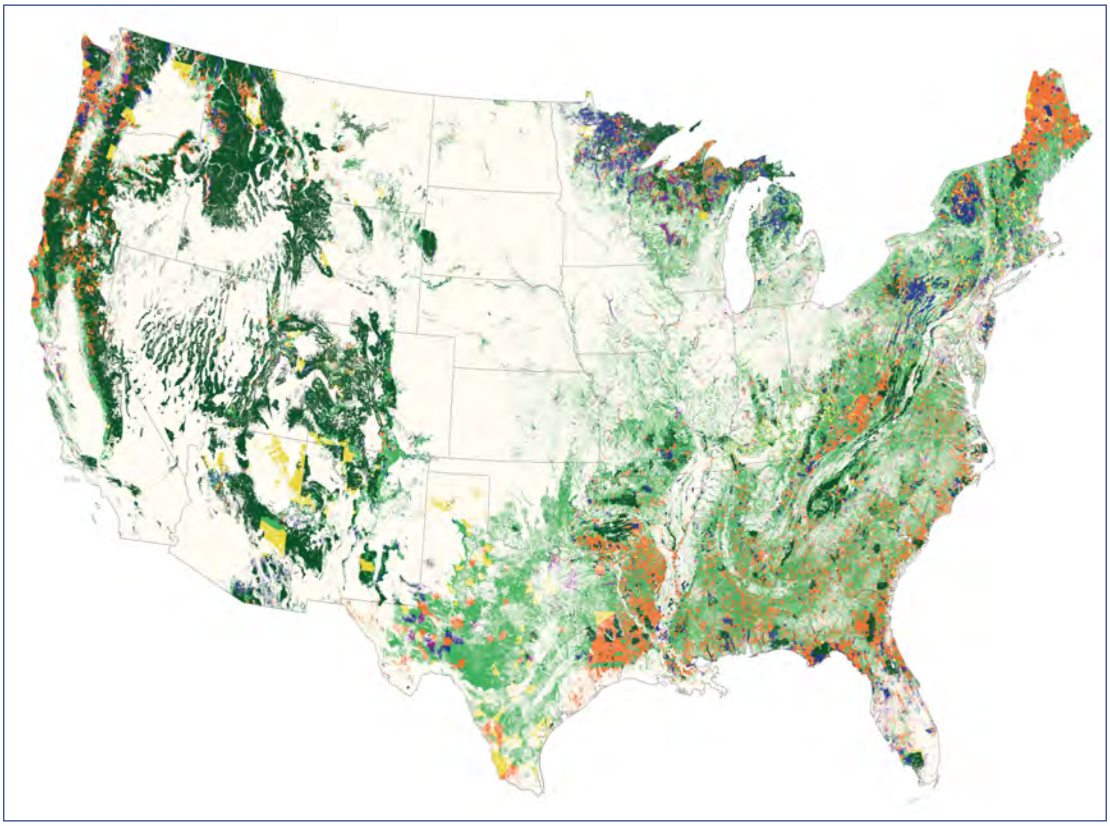

Figure 2. Dominant forest land ownerships of the USA: Dark Green = Federal, Yellow = Tribal, Light Green = non-industrial private, Orange = Industrial; Blue = State and Municipal, White = Non Forest. (From: The National Atlas of the United States of America, US Geological Survey, 2015).

13.1.3 History of forest use

Watershed management has been an integral part of forestry in the USA since the creation of the National Forests at the end of the 19th century and the beginning of the 20th century (Neary, 2000). The Forest Reserve Act of 1891 created the forest and grassland reserves that were to become the core of the National Forest system (Steen, 1976). During Congressional deliberations on the Forest Reserve Act, Secretary of the Interior John W. Noble personally intervened to include a provision authorizing the President to create forest reserves (Section 24). By the end of 1892, President Harrison had created/authorized 15 reserves totaling 5.3 million ha, primarily to protect water supplies. Additional reserves amounting to 2.4 million ha were added by 1896. The next president, President Cleveland, set off a land reservation furor by increasing the reserves by another 8.5 million ha in early 1897. That same year, the Pettigrew Amendment to the 1897 Sundry Civil Appropriations Bill more fully defined the purpose of the forest reserves (Steen, 1976), stating that the reserves were to be established only to: "...improve and protect the forest within the reservation, or for the purpose of securing favorable conditions of water flows..."

Clearly, by 1897, the interpretation of catchment management within the context of forestry was for water supply and flood prevention. The US Forest Service was established in 1905 with two primary missions, to: (a) manage the nation's forests, and (b) secure favourable conditions of water flow. Today an estimated 80% of the USA freshwater resources originate in forests, with much of the nation's drinking water originating in the 78 million ha that now constitute the National Forest System (Levin *et al*. 2002).

13.1.4 Multiple use forests: wood, water, range, wildlife and recreation

Forest management in the USA has been strongly influenced by the Multiple Use and Sustained Yield Act (MUSY) of 1960 (Cawley and Freemuth 1997). Although MUSY mandates that only National Forests be “administered for outdoor recreation, range, timber, watershed, and wildlife and fish purposes.” The broad directive was extended to other Federal agencies in 1976 by the Federal Land Policy and Management Act of 1976. Other forest land ownerships picked up the concept to some degree. The MUSY Act of 1960 codified the U.S. Forest Service’s management philosophy at the time and named a set of multiple uses: recreation, range, timber, watershed, and wildlife. The Act directed that no single use should be dominant and that resource outputs should be maintained without reductions in land productivity and sustainability. This broad guidance gave the Forest Service a considerable amount of leeway in land management. The objectives of land management under MUSY were community stability, jobs, sustainable supply of fiber, enhanced recreation and hunting opportunities, and sustainable supplies of high quality water for municipal use. These objectives were harmonious and initially there was very little resource conflict.

However, as Cawley and Freemuth (1997) argued, the multiple use concept eventually resulted in management gridlock as single-interest groups inserted their goals into the discussion regarding the management of public lands. They believed that MUSY created a zero-sum game, where the attitude of “*I must restrict or eliminate your use to protect my use*” has been the operative feature and that “*the logic of a zero-sum game encourages the various participants to concentrate their energies on the task of blocking the moves of their opponents rather than on seeking to establish a common ground upon which compromises could be constructed*”. The predictable outcome of a zero-sum game is gridlock (Cawley and Freemuth 1997). This has been a dominant feature of Federal land management decisions for the past half century. Fortunately, private forest land management has not been directly affected by MUSY politics. But, this conflict has resulted in a major shift of forest resource supply from public lands to private ones. The spotted owl dispute has been a major driver in this trend.

13.1.5 USA Water resources and uses

Figure 3. Major watersheds of the United States (From: The National Atlas of the United States of America, US Geological Survey, 2015).

The major drainage basins of the USA are shown in Figure 3 (U.S. Geological Survey 2015). The country has 3,069 km^3 of fresh water reserves, making it the third richest water nation behind Brazil (8,233 km^3) and Russia (4,508 km^3). The Great Lakes account for a large percentage of the USA water wealth. The eastern USA is predominantly humid with the western USA varying from arid and semi-arid to humid, depending wind patterns and topography. The central USA is occupied by the tall grass, middle grass, and short grass prairies that grade from wet to dry along east to west and south to north gradients.

Irrigated lands in the USA total 266,440 km^2. Water withdrawals for all uses add up to 1,583 m^3 person^{-1} yr^{-1}. Forests provide drinking water for many municipalities and small water supply systems. In the USA, over 3400 towns and cities depend on National Forest catchments 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.

13.1.6 Water resource issues in the 21st century

The direction of future water research using paired catchments will depend greatly on the important issues and governmental support for the science. Water research is expensive and it requires the commitment to the long-term that only government entities can afford. Water quantity and quality are going to be increasingly important topics as nations come to grips with water security problems (Vose *et al*. 2011). Human populations are increasing most in regions where the abundance of good quality water is being affected by climate change. The importance of long-term studies will loom large since these studies are good indicators of climate change and its effects (Archer and Predick 2008). Specific topics that require further water quality investigation include wildfire, fire retardant use, atmospheric deposition, trace organic chemicals, oil development, large-scale mining, inter-basin water diversions, and bioenergy.

Water is now an area of keen interest in bioenergy development because of its potential footprint on water supplies and its effects on water quality. Some recent publications have addressed the latter issue (Diaz-Chavez *et al*. 2011a, 2011b). Currently, BMPs offer the best solution to achieving the goal of energy production with biofuels that minimizes the impact on water quality. In some instances, sound research using the paired catchment approach will be needed to convince regulatory authorities that bioenergy feedstock production can co-exist with water quality goals and standards.

Over the span of the 20th Century, the perception of what constitutes watershed management and hydrologic science has grown considerably. At the beginning of the century, it was mostly concerned with the development and maintenance of water supplies. Water quality was a big issue then and it still is. At the beginning of the 21st Century, it is probably best defined as a comprehensive understanding of the components of watersheds and their physical, chemical, and ecological interactions to produce high quality water in sufficient supply to meet human demands (Reimold 1998). This definition also reflects thinking on the discipline at the end of the 20th Century that watershed management and hydrologic science incorporates the holistic approach to a watershed as an ecosystem, and not just manipulation of physical processes. The goal of watershed management is to assess the effects of current and future land uses on soil and water resources, determine the potential social and ecological impacts, and provide solutions to watershed problems.

As Rango (1995) pointed out, the increase in the world's human population (now at 7 billion) will cause the demand, scarcity, price, and need for high quality water to expand on a global scale into the foreseeable future. He forecast that, in this era of "Global Hydrology" for hydrologic science and watershed management, worldwide emphasis will be placed on large area assessments using modeling, remote sensing, watershed management expertise, and the best hydrologic science. The technological tools and paired catchment infrastructure are in place. The key to the future success of these endeavors lies in watershed management professionals using their expertise and understanding of paired catchment science to develop positive outcomes for human populations of all countries.

13.2 Literature review

13.2.1 Water and natural processes

Although the initial focus of early catchment research was water yield, the adoption of the paired catchment approach set the stage for examining physical, chemical, and biological processes that controlled nutrient cycling and other water quality related functions of forest catchments (Bormann and Likens 1967). The untreated half of catchment study pairs provided the opportunity to study natural processes that controlled water yield and quality. However, the disturbances to these processes produced by practices such as harvesting, site preparation, road construction, fire, fertilization, herbicide use and insect outbreaks provided the real insight into natural catchment processes that affect both water quantity and quality.

13.2.2 Water yield

Forest harvesting affects many water cycle processes (Figure 4). The specific hydrologic effects are summarized in Table 1. Changes in baseflow and stormflow definitely affect the quantity of water delivered from forested catchments, and can ultimately alter water quality. The following discussion is a general summary of the effects, not a site-specific analysis. Remember, the occurrence and magnitude of these effects is a function of the general climate, precipitation, aspect, latitude, severity of disturbance, and the percentage of the watershed harvested.

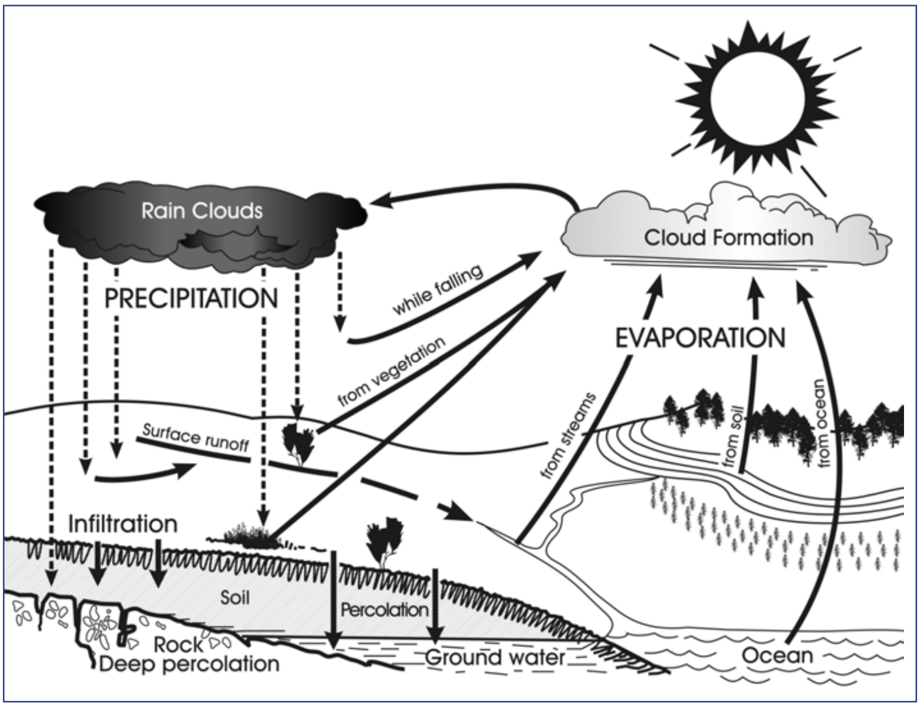

Figure 4. Hydrologic cycle processes (From Neary and Koestner 2012).

13.2.2.1 Water quantity – total yield

Watershed responses to forest harvesting are very ecosystem specific. Water quantity increases are normally the highest the first year after harvesting (Brooks *et al.* 2003). Thereafter water yields decline as vegetation recovers and leaf area index returns to levels that occurred before harvesting. This recovery period is very short (3-4 years; Brown *et al.* 1974) in forests with high evapotranspiration rates and low precipitation, and over 10 years in ecosystems with high rainfall and low evapotranspiration.

The amount of water yield increase after forest harvesting is a function of the proportion of a watershed that is cut, the amount of precipitation, and site factors such as aspect, soils, and vegetation cover (Neary and Koestner 2012). Aspect, which is a good indicator of potential evapotransiration, has a strong effect on water quantity responses to forest harvesting (Figure 4). Slopes oriented normal to solar radiation receive the highest solar loadings and have the highest evapotranspiration. In general, mean annual streamflow increases as the percentage harvest of a forest stand or watershed approaches 100%. Streamflow is usually minimal at the low end of the precipitation range for forest ecosystems, but it is substantial in forests that occur in high precipitation zones.

Table 1. A summary of the changes in hydrologic processes after harvesting and other disturbances that change stand basal area, cover type, soil conditions, etc. (Adapted from Neary 2002).

Hydrologic Process	Type of Change	Specific Effect
1. Interception	Reduction	Moisture storage smaller
		Greater runoff in small storms
		Increased water yield
2. Litter Storage of water	Litter Reduced	Less water stored (0.5 mm cm^{-1})
	Litter Not Affected	No change
	Litter Increased	Storage increase
3. Transpiration	Temporary Elimination	Baseflow increase
		Soil moisture increase
4. Infiltration	Reduced	Overland flow increase
		Stormflow increase
	Increased	Overland flow decrease
		Baseflow increase
5. Streamflow	Changed	Increase in most ecosystems
		Decrease in snow systems
		Decrease in fog-drip systems
6. Baseflow	Changed	Decrease with less infiltration
		Increase with less transpiration
		Summer low flows (+ and -)
7. Stormflow	Increased	Volume greater
		Peakflows larger
		Time to peakflow shorter
8. Snow accumulation	Changed	Cuts <4 ha, increase snowpack
		Cuts > 4 ha, decrease snowpack
		Snowmelt rate increase
		Evaporation/sublimation greater

A considerable amount of research has been conducted in the past on the effects of forest harvesting for the purpose of increasing water supplies or determining the impacts on watershed hydrology (Tables 2 and 3). These studies have been very costly and required considerable dedication to their continuity. The earliest paired watershed experiments were installed in Switzerland, Japan, and the USA in the first decade of the 20th century (Neary 2000). Some have been in existence since the 1930s. Researchers in the USA have examined various intensities and harvesting configurations and timing. In doing so they have produced the largest body of works in existence on the relationships between forests and water quantity and quality.

With a 100% clearcut, first-year water yield increases reported in the literature generally range from 21 to 80%. One exception to this generalization occurs with high evapotranspiration and low rainfall (<480 mm) where harvesting has not produced increased streamflows (Clary *et al*. 1974). Another exception to this trend occurs in areas with high evapotranspiration and high rainfall. Increases in water yield of 0 to 280% have been reported after harvesting (Table 2; Clary *et al*. 1974, Neary *et al*. 1982). These higher values probably resulted from temporary removal of overstory and understory vegetation with high transpiration rates where rainfall was high. Although the absolute water yield increase the first year after harvesting increases with total precipitation, the percentage increase is not related to precipitation amount but the absolute amount is strongly related to the average annual rainfall.

Table 2. First year streamflow responses to forest harvesting in the United States, 450 to 1200 mm precipitation forest ecosystems. (Adapted from Neary 2002) .

Forest type	**Location**	**Ppt.** mm	**Mean annual streamflow** mm	**Cut** %	**1st year increase** mm	**Percent increase** %	**Reference**
Pinyon-juniper	Arizona USA	457	20	100	0	0	Clary *et al*. 1974
Aspen-conifer	Colorado USA	536	157	100	34	22	Reinhart *et al*. 1974
Ponderosa pine	Arizona USA	570	153	100	96	63	Brown *et al*. 1974
Oak woodland	California USA	635	144	99	33	23	Lewis 1968
Spruce-fir-pine	Colorado USA	770	340	40	84	25	Leaf 1975
Aspen - birch	Minnesota USA	775	107	100	45	42	Verry 1972
Slash pine	Florida USA	1020	48	74	134	280	Neary *et al*. 1982

In semiarid areas, where annual precipitation falls below 500 mm, forest cutting does not produce any additional increases in mean annual streamflow (Table 2; Clary *et al*. 1974). Evaporation is such a powerful factor in low precipitation climates, that basin-wide vegetation management or species conversion does not have much effect on streamflow.

The fact that harvesting of forest stands increases water yield has been used as the basis for municipal water supply augmentation (Bosch and Hewlett 1982, Brooks *et al*. 2003). The duration of the response is dependent on a number of factors. Generally, the increase in total water yield from harvesting is not of sufficient magnitude to produce adverse hydrologic or ecosystem effects. A more important parameter of concern is flood peak flows.

13.2.2.2 Water quantity – peak flows

Examination of the literature indicates that harvesting of forests produces a mixed peakflow response (Table 4). In locations where snowmelt runoff is an important component of annual hydrographs, declines in peakflows up to 35% have been reported after cutting (Pierce *et al*. 1970, Verry 1972). Some investigators have reported no peakflow response to harvesting (Kochenderfer *et al*. 1997). In other locations, watershed, vegetation, and climatic characteristics have produced peakflow increases of up to 1,400%. But that sort of response is rare, and more often produced by disturbances like wildfire. However, some combinations of terrain and geology may combine to create localized hazards (Neary and Hornbeck 1994).

Table 3. First year streamflow responses to forest harvesting in the United States, 1200 to 2600 mm precipitation forest ecosystems (Adapted from Neary 2002).

Forest type	Location	Ppt. mm	Mean annual streamflow mm	Cut %	1st year increase mm	Percent increase %	Reference
Coastal redwoods	California USA	1200	67		34		Keppler and Ziemer 1990
Mixed hardwoods	Georgia USA	1219	467	100	254	54	Hewlett and Doss 1984
Northern hardwoods	New Hampshire USA.	1230	710	100	343	48	Hornbeck *et al*. 1987
Loblolly pine	Arkansas USA	1317	214	100	101	47	Miller *et al*. 1988
Slash pine	Florida USA	1450	169	74	134	79	Swindel *et al*. 1982
Mixed hardwoods	W. Virginia USA	1524	584	85	130	22	Patric and Reinhart 1971
Mixed hardwoods	N. Carolina USA	1900	880	100	362	41	Swift and Swank 1980
Cascade Douglas-fir	Oregon USA	2388	1376	100	462	34	Rothacher 1970
Coastal Douglas-fir	Oregon USA	2483	1885	82	370	20	Harr 1976

Flood peakflow responses are important to understand from a watershed management and human health and safety viewpoint. Major changes in stream channel geomorphology and damage to cultural resources are a function of the magnitude of the peakflow. Peakflow responses from harvesting have been measured to be less than one order of magnitude greater than peakflows of undisturbed and forested lands (Table 4). They compare to the lower end of peakflow responses measured after wildfires (1 to 4 orders of magnitude increase) (DeBano *et al*. 1998). Floods after major, severe wildfires often produce significant channel degradation, sedimentation of reservoirs and low-gradient channels, damage to transportation systems, personal property damage, and can be a significant cause of human and livestock death and injury. Although peakflows increase after harvesting, they are not of the same level of concern as wildfire-induced peakflow increases.

Table 4. Effects of tree harvesting on peakflows (Q_{pt}). (Adapted from Neary 2002) .

Forest Type	Location	Ppt. Mean	Peakflow (Q_{pt}) Change 1-3 Years Post Harvest	References
Ponderosa pine	Arizona USA	570	Rainfall: Q_{pt} +167%	Brown et al. 1974
Lodgpole pine, Engelmann spruce	Colorado USA	762	Snowmelt: -23 to + 50% change in Q_{pt}	Goodell 1958
Aspen	Minnesota USA	775	Rainfall: Q_{pt} Doubled Snowmelt: Q_{pt} –35 to +1,400%	Verry 1972
Loblolly pine	Georgia USA	1219	Rainfall: Q_{pt} Tripled	Hewlett and Doss 1984
Northern hardwoods	New Hampshire USA	1230	Rainfall: -13 to +170% Rain +snowmelt: -21 to +23% change in Q_{pt}	Pierce *et al*. 1970
Loblolly and shortleaf pine	Arkansas USA	1317	Rainfall: Q_{pt} increased +16 to +247%	Miller *et al*. 1988 Beasley and Granillo 1988
Slash pine	Florida USA	1450	Rainfall: Q_{pt} increased six-fold	Swindel *et al.* 1983
Mixed hardwoods	W. Virginia USA	1524	Rainfall: No effect on Q_{pt}	Kochenderfer *et al*. 1997
Mixed hardwoods	North Carolina USA	1900	Rainfall: increased 9%	Hewlett and Helvey 1970
Douglas–fir and hemlock	Oregon USA	2300	Rainfall: Q_{pt} increased 1% Snowmelt: Q_{pt} –16%	Harr and McCorison 1979

13.2.3 Disturbance effects

Most of the forest catchment water quality studies reported in the literature deal with tree harvesting and post-harvest site preparation since much of the early interest in paired catchment science related to vegetation management to increase water yield. In addition, these practices were considered to produce the most disruptions to ecological processes and therefore the most influence on water quality. Since forest fertilization has been a basic feature of intensive forest management throughout the world, the impact of fertilizers on water quality has been an issue easily addressed by paired catchment research (Binkley *et al*. 1999). Paired catchments provided a sound basis for acid deposition research in the 1980s and 1990s (Likens *et al*. 1996), and continue to support scientific endeavors on climate change in the 21st Century (Bouraouii *et al*. 2004).

A number of water quality parameters are affected by disturbances, but only nutrients, sediments, and temperature will be discussed in the limited space available in this chapter. Other papers present a much more detailed discussion of these topics (Swanson *et al*. 2000, Neary 2002, Ice and Stednick 2004).

13.2.3.1 Harvesting and site preparation – nutrients

Neary (2002) summarized a number of paired catchment studies looking at N losses in streamflow after harvesting and site preparation (Table 5). Nitrate nitrogen (NO_3-N) dynamics are considered to be very susceptible to disturbance and NO_3-N concentration is a commonly accepted indicator of catchment health and water quality throughout the world since low levels (10 mg L^{-1}) can affect infant health (Neary 2002). For the most part, large increases in NO_3-N levels in streams draining harvested catchments have not been observed. Certainly there is no general indication that the World Health Organization (2006) water quality standard (10 mg L^{-1} NO_3-N) is commonly breached by post-harvesting NO_3-N concentration increases. The largest increase reported (Pierce *et al*. 1970) was measured in an experiment where herbicides were used to suppress vegetation regrowth. Other causes of increased NO_3-N losses in forested catchments have been documented where severe fire occurred (DeBano *et al*. 1998), nitrogenous fertilizers were used during regeneration (Neary and Hornbeck 1994), or N saturation of ecosystems has reached a critical level due to atmospheric deposition (Aber *et al*. 1989). Paired catchments have been instrumental in demonstrating that, except in rare instances of delayed vegetation regrowth (e.g. Pierce *et al*. 1970) or forest ecosystems impacted by atmospheric deposition, forest harvesting does not significantly raise stream NO_3-N or other nutrient concentrations for long periods of time.

Table 5. Paired catchment comparison of the effects of forest harvesting on mean NO_3-N concentrations in streamflow in North America the year after cutting (Adapted from Neary 2002).

Forest Type	Location	NO_3-N Uncut mg L^{-1}	NO_3-N Cut mg L^{-1}	Reference
Spruce, Fir	Colorado, USA	<0.1	<0.1	Stottlemeyer 1992
Slash pine	Florida, USA	<0.1	0.3	Riekerk *et al.* 1980
Loblolly Pine	Georgia, USA	0.1	0.1	Hewlett & Doss 1984
Mixed Conifer	Idaho, USA	0.2	0.2	Snyder *et al.* 1975
Aspen, Birch, Spruce	Minnesota, USA	0.1	0.2	Verry 1972
Mixed Conifer	Montana, USA	0.1	0.2	Bateridge 1974
Northern Hardwoods	New Hampshire, USA	0.3	11.9	Pierce *et al.* 1970
Mixed Hardwoods	North Carolina, USA	<0.1	0.1	Swank & Douglass 1975
Douglas-fir	Oregon, USA	<0.1	0.2	Fredrickson *et al.* 1975
Mixed Conifers	Oregon, USA	<0.1	0.2	Fredrickson *et al.* 1975
Oak-Maple	Pennsylvania, USA	0.1	5.0	Corbett *et al.* 1975
Loblolly Pine	South Carolina, USA	<0.1	<0.1	Van Lear *et al.* 1985
Mixed Hardwoods	West Virginia, USA	0.1	0.5	Aubertin & Patric 1974

13.2.3.2 Harvesting and Site Preparation – Sediment

After forest harvesting, forest catchments produce sediments yields that are highly variable depending on factors such as soils, climate, topography, ground cover, road networks, and catchment condition. Although sediment yields increase after harvesting due to the physical disturbance of soil, they are usually transient due to vegetation re-growth (Neary 2002). There is a large body of literature that reported using paired catchments to assess the effects of harvesting and site preparation on the sediment component of water quality (Binkley and Brown 1993, Neary 2002). The largest increases documented in the literature have been associated with post-harvest mechanical site preparation (Beasley 1979), slope instability (O'Loughlin and Pearce 1976), road construction and maintenance (Heede 1987), highly erosive soils (Beasley and Granillo 1988), and steep terrain (Beschta 1978) (Table 6).

Table 6. Effects of harvesting and related disturbances on sediment outputs from paired catchments (Adapted from Neary and Hornbeck 1994, Neary 2002, Diaz-Chavez 2011).

Forest Type	Location	Treatment	Sediment Increase Mg ha^{-1} yr^{-1}	Reference
Mixed Conifers	Arizona, USA	Clearcut	0.003	Heede 1987
Mixed Conifers	Arizona, USA	Cut, Road	0.081	Heede 1987
Loblolly Pine	Arkansas, USA	Clearcut	0.225	Beasley & Granillo 1988
Slash Pine	Florida, USA	Clearcut, Bed	0.033	Riekerk *et al.* 1980
Northern Hardwoods	New Hampshire, USA	Clearcut	0.323	Hornbeck *et al.* 1987
Douglas-fir	Oregon, USA	Clearcut	0.510	Beschta 1978
Loblolly Pine	South Carolina, USA	Clearcut	0.131	Van Lear *et al.* 1985

Sediment movement to and within stream systems is a constant environmental concern in managed forest catchments, but it also occurs naturally without management. Herein rests the importance of paired catchment analyses. Catchments can vary greatly in their natural suspended and bedload sediment characteristics (Trimble and Crosson 2000). Both natural and anthropomorphic erosion material can be re-entrained after initial deposition in ephemeral or perennial stream channels, and move downstream with streamflow for long time periods and distances. The cumulative effects of erosion and sedimentation that occurred centuries ago from agriculture or forestry can present forest managers with many challenges. Sediment is an important water quality parameter since it can harm aquatic organisms and habitats, and render water unacceptable for drinking water supply or recreation purposes (Table 6). However, adequate BMPs can significantly limit increases in sediment delivery to streams (Neary *et al*. 2011).

13.2.3.3 Harvesting and site preparation – temperature

Forest vegetation shades stream channels from solar radiation, thereby producing stream temperatures that are cooler and less variable than for unshaded sites. Increases in temperature that result from forest harvesting affect physical, chemical, and biological processes (Table 7). Thus, temperature is a critical water quality characteristic of many streams and aquatic habitats. Temperature controls the survival of certain flora and fauna in the water that are sensitive to water temperature. The removal of streambank vegetation by burning can cause water temperature to rise, causing thermal pollution to occur, which in turn can increase biological activity in a stream (DeBano *et al.* 1998, Brooks *et al.* 2003). Increases in biological activity place a greater demand on the dissolved oxygen content of the water, one of the more important water quality characteristics from a biological perspective.

In the USA there are no established national standards for the temperature of drinking water (Dissmeyer 2000). However, under the Clean Water Act, States are required to develop water quality standards to protect beneficial uses such as fish habitat and water quality restoration. The U.S. Environmental Protection Agency provides oversight and approval of these State standards. One of the problems with these standards is identifying natural temperature patterns caused by vegetation, geology, geomorphology, climate, season, and natural disturbance history. Also, increases in stream water temperatures can have important and often detrimental effects on stream eutrophication. Acceleration of stream eutrophication can adversely affect water quality by adversely affecting the color, taste, and smell of drinking water. Severe wildfires can function like streamside timber clearcuts in raising the temperature of streams due to direct heating of the water surface (Neary *et al*. 2005, Table 7).

Table 7. Paired catchment studies of the effects of forest harvesting on stream temperature (Adapted from Binkley & Brown 1993, Binkley *et al.* 1999, Moore *et al.* 2005).

Location	Temperature			Time	Reference
	Control °C	Cut °C	Change °C		
Clear Cut, No Buffer					
New Hampshire, USA	16.0	20.0	4.0	Mean Daily 30 Days AUG	Likens *et al.* 1970
North Carolina, USA	18.3	21.7	3.4	Mean Daily 30 Days AUG	Swift & Messer 1971
Oregon, USA	13.3	15.6	2.3	1 Day - JUL	Brown *et al.* 1971
Oregon, USA	20.6	28.3	7.7	1 Day - JUL	Brown *et al.* 1971
Oregon, USA	14.4	22.8	8.4	Mean Daily 30 Days AUG	Levno & Rothacher 1969
Oregon, USA	12.2	22.2	10.0	Mean Daily 30 Days AUG	Brown & Krygier 1970
Pennsylvania, USA	17.8	25.0	7.2	Mean Daily 30 Days AUG	Rishel *et al.* 1982
Clear Cut, With Buffer					
Georgia, USA	21.1	25.0	3.9	Mean Daily 30 Days AUG	Hewlett & Fortson 1982
Oregon, USA	14.4	15.0	0.6	1 Day - July	Brown *et al.* 1971
Oregon, USA	16.7	18.3	1.6	1 Day - July	Brown *et al.* 1971
West Virginia, USA	14.4	16.1	1.7	Mean Weekly – Growing Season	Aubertin & Patric 1974
Partial Cut With Buffer					
Pennsylvania, USA	19.4	20.6	1.2	Mean Daily 30 Days AUG	Rishel *et al.* 1982
Oregon, USA	12.0	15.0	3.0	Mean Daily 21 Days AUG	Harr & Fredriksen 1988
Oregon, USA	12.5	14.4	2.0	Mean Monthly Max. (APR-OCT)	Harris 1977

13.2.4 Forest fertilizers

Forest fertilization is another management disturbance that has the potential to affect stream water quality because of the additions of N, phosphorus (P), cations, etc. to forest catchments (Binkley *et al.* 1999, Neary 2002). Streams originating in agricultural areas have about 9 times the load of N and P than forested catchments so the water quality of forested areas is highly valued. The growth of tree plantations in high production silviculture regions of the world is often limited by soil nutrient availability (Fox *et al.* 2007). Hence, fertilization is a common silvicultural practice in these high-intensity production forests. Fertilizer applications are rarely incorporated in stand management in slower growing forests due to economic limitations. Nitrogen and P fertilizers are the most frequently used but, in some locations, cations and micronutrients are applied to deal with local deficiencies. Here again, paired catchments have been invaluable in understanding the water quality implications of this management practice). Higher stream concentrations are usually associated with higher fertilizer application rates (e.g. >200 kg–N ha^{-1}) or aerial applications that fly over or near monitored streams (Helvey *et al*. 1989). Nitrogen saturation of soils from atmospheric deposition (Aber *et al*. 1989) can predispose forest stands to leak highly mobile NO_3-N if it is not utilized by vegetation (Pierce *et al*. 1970). Paired catchments provide investigators the ability to sort out fertilizer water quality effects from those produced by other processes (e.g. herbicide suppression of vegetation regrowth, N saturation of soils, naturally high N soils, inputs from agricultural areas, etc.).

13.2.5 Roads

Best Management Practices for roads are most effective on minimizing sediment impacts to water quality when properly planned and implemented prior to, during, and after harvesting (Neary *et al*. 2011). Most of these guidelines relate to designing, constructing, and maintaining major access roads, logging roads, skid trails, and landings. Permanent roads and associated temporary roads are the primary sources for 90% of the sediment generated by harvesting (Swift 1988). The underlying principles of road BMP guidelines are to minimize disturbances in streamside zones, reduce the erosive power of runoff on bare road surfaces, and to maintain the normally high infiltration capacity of forest soils (Neary *et al*. 2011).

13.2.6 Fire

A major disturbance to catchment hydrology, geomorphology, and water quality in fire-prone regions like the western USA, the Mediterranean Basin, and Australia is wildfire (Shakesby and Doerr 2006). The random nature of wildfires and their characteristic severities rarely gives researchers the opportunity to used paired catchment techniques to assess impacts on water quality. Prescribed fires are much more amenable to paired catchment comparisons because they are easier to manage. However, even the best-managed paired catchment study of prescribed fire can produce surprises (Gotttfried *et al*. 2012). Wildfire impacts on water quality evaluations reported in the literature have been a mixture of paired catchment methods and before-fire and after-fire approaches using the same catchment (DeBano *et al*. 1998, Neary *et al*. 2005, Smith *et al*. 2011).

Post-fire sediment yields can vary widely from <0.001 to over 204 Mg ha^{-1} yr^{-1} depending on the type of fire (prescribed or wildfire), fire severity, topography, fuel type, and climate. The highest soil erosion values usually involve intense rainfall on steep terrain (Glendening *et al*. 1961, Moody and Martin 2001, Neary *et al*. 2012). Wright *et al*. (1976) demonstrated the effect of slope with his study in juniper stands in Texas. As slope increased from zero to the 43-54 % range, the annual prescribed fire sediment losses rose from about 0.029 to 8.443 Mg ha^{-1} yr^{-1} compared to a range of 0.013 to 0.025 Mg ha^{-1} yr^{-1} in unburned paired catchments.

Usually post-fire maximum NO_3-N levels are in the 0.1 to 0.6 mg L^{-1} range since wildfires volatilize most of the N in the fuels they consume and prescribed fires are usually low-level disturbances (Neary *et al*. 2005). One of the few and the most striking response of water quality streamflow to fire was observed in southern California, where N loadings from atmospheric deposition are relatively high, and the frequent wildfires in the chaparral shrublands are characterized by high fire severity (Riggan *et al*. 1994). Severe burning of a catchment in the Mediterranean-type chaparral resulted in a maximum NO_3-N level of 15.3 mg L^{-1} in streamflow compared to 2.5 mg L^{-1} peak in streamflow from an unburned control watershed. The maximum concentration for a moderately burned catchment was 9.5 mg L^{-1}. These results represent an “unusual response” because the catchments studied were subject to a chronic atmospheric deposition of air pollutants from the Los Angeles basin that are among the highest recorded in the USA.

13.2.7 Pesticides

Another water quality parameter of considerable concern that has been amenable to study with the paired catchment approach is herbicide and insecticide residue environmental fate. Michael and Neary (1993) discussed this topic in considerable detail. A study by Neary *et al*. (1983) that utilized four 1.0 ha chemically-treated catchments plus an untreated control was adopted as a template for required herbicide registration studies in the USA by the U.S. Environmental Protection Agency. Since that study, paired watersheds have been an integral part of forestry pesticide environmental fate studies the past three decades (Neary *et al*. 1993). Virtually all monitoring protocols now require use of untreated control watersheds. Any future research on newly developed forestry pesticides must incorporate paired-watershed methodology. Despite the frequent criticisms of pesticides like herbicides, they should be kept as tools that can achieve vegetation or other pest management goals and maintenance of water quality (Neary and Michael 1996).

Additional research conducted by Michael and Neary (1993) and Neary *et al*. (1993) expanded on the work of Norris (1970). However, it incorporated newer, rapidly degrading pesticides. They enhanced 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 the low toxicity of the chemicals, infrequent use over the rotations of conventional forest stands, the lack of bioaccumulation by these 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, their tendency to migrate into streams is limited by forest soil biological and chemical processes. Although herbicides, especially water soluble ones like picloram and hexazinone, have been measured to move through forest soils, they do so in small non-toxic amounts because of the biological and chemical actions of organic matter in forest soils (Neary *et al*. 1985).

13.3 Politics

13.3.1 Key environmental regulations, laws, and policies related to forestry and water

The legal support for maintaining forest ecosystem sustainability and conservation is complicated since there is no national policy to guide lawmakers and land managers at all levels of governance. Most land-use regulations are not forestry specific but deal with general environmental concerns.

National Environmental Policy Act of 1969

This act requires all federal agencies proposing major land management activities that may substantially affect the environment to follow an analysis and reporting process. Agencies must produce an environmental analysis through either environmental assessments or environmental impact statements.

Clean Air Act of 1970

This comprehensive federal law regulates air emissions from area, stationary, and mobile sources. Its purpose is to protect and enhance the quality of the nation’s air resources. It authorizes the Environmental Protection Agency to establish National Ambient Air Quality Standards to protect public health and the environment. The original Clean Air Act was passed in 1963, but the current air pollution control program is based on the 1970 version of the law. Substantial revisions of the 1970 law were made in the 1990 Clean Air Act Amendments.

Clean Water Act of 1972

The Clean Water Act established a regulatory system for navigable waters in the United States, whether on public or private land. It is intended to eliminate discharge of water pollutants into navigable waters, to regulate discharge of toxic pollutants, and to prohibit discharge of pollutants from “point” sources (e.g., pipeline effluent) without permits. The legislation was amended in 1977, 1981, and 1987 and is currently being refined by Executive Order.

Endangered Species Act of 1973

This law instructs federal land management agencies to conduct programs to sustain endangered and threatened species and to protect the ecosystems that are critical for supporting these species. Threatened or endangered species receive additional legal protection under the auspices of the Act. Specific management procedures are designed to restore populations to sustainable levels.

The National Forest Management Act of 1976

This legislation requires the US Forest Service to develop land management plans for every National Forest. The agency must consider each unit under the principles of multiple use and sustained yield, factoring in both traditional and non-traditional uses and outputs. A key component of the planning process is public participation.

Forest Land Policy and Management Act of 1976

This legislation is directed at the Bureau of Land Management for management of Federal forest and range lands under the agency’s pervue. It was crafted in the same fashion as the National Forest Management Act of 1976.

Federal Insecticide, Fungicide, and Rodenticide Act of 1948 (amended 1996)

This legislation was designed to allow provide federal regulation over the development, registration, sale, and application of pesticides. Since forestry is a minor use of pesticides, the law is primarily aimed at agriculture uses. However, forestry uses still fall under the regulation provided by the U.S. Environmental Protection Agency.

Increases in fire activity, area, and severity since 1995 have brought an increased focus on national fire management and budgeting requiring new sets of Federal and State legislation.

13.3.2 Additional State Regulation

Regulations formulated by individual States provide additional governance over forest management and water use. Some States have adopted forest practices laws. The most commonly used are forestry Best Management Practices (BMP) codes and guidelines (Aust and Blinn 2004, American Forest and Paper Association 2006, Shepard 2006, Georgia Forestry Commission 2009, Neary *et al*. 2013, National Association of State Foresters 2016). Implementation for forest management is variable from State-to-State depending on the level of commercial forest industry. The National Association of State Foresters (2016) maintains up-to-date information as to the status of state BMP regulations as regulatory, quasi-regulatory, or voluntary. As of 2016, 10 states had regulatory BMPs, 19 operated under quasi-regulatory BMPs, and 20 used non-regulatory BMPs. Seventy five percent of the states west of the Mississippi River are non-regulatory BMP states. State and Federal agencies involved in BMP policy and regulation monitoring vary from state to state. The most recent guidelines are posted on the web site *Forestry Best Management Practices by State* (National Association of State Foresters 2016).

13.3.3 Role of Forest Certification Systems in Managing Water Quantity and Quality.

The key environmental laws relating to forestry and water at the National level in the USA include the National Environmental Policy Act of 1969, the Clean Water Act of 1972, the National Forest Management Act of 1976, and the Forest Land Policy and Management Act of 1976 (See Section 3.1 above). Individual states are also free to implement additional regulations and policies as deemed necessary by local conditions. Enforcement has traditionally been the responsibility of a mix of State and Federal agencies. Implementation of new regulations and practices to protect water resources relies on landowner cooperation in both the public and private forestry sectors. Forest certification systems have been very successful in disseminating knowledge and encouraging incorporation of BMPs that protect water and other forest resources through sustainable forest management (Rametsteiner *et al*. 2003).

In contrast to national Criteria and Indicators developed by the 1998 Montreal Process (Castañeda 2000), forest certification is designed for use by individual forest landowners for marketing purposes as well as ensuring good forest land stewardship by establishing proof of sustainable forest management. There are over 50 forest certification systems world-wide. The main certification systems in North America are the American Tree Farm System (ATFS), the Sustainable Forest Management System Standard of the Canadian Standards Association (CSA), the Sustainable Forestry Initiative (SFI), the Program for Endorsement of Forest Certification (PEFC), and the Forest Stewardship Council Standards (FSC). The two largest certification systems are FSC and PEFC. Presently, PEFC is mostly based in Europe and is certifying the largest area. The FSC program is the fastest growing. Certification systems are currently being utilized mainly by industrial and non-industrial private forest land owners. As the area of forests under certification management increases, the benefits to water resources will likewise increase. The main benefits will certainly be in improved water quality.

13.4 Climate change and the future of forestry and forest research

13.4.1 Effects of climate change in the USA

Climate change is certain to exert a large impact on USA forests and water yields produced by those forests. The most profound impacts will be exhibited through alteration of the frequency, intensity, duration, and timing of natural disturbances beyond anything observed in the past several centuries (Dale *et al*. 2001). Unprecedented drought, flooding, wildfire, insect outbreaks, and exotic species infestations are already announcing the presence of climate change. Since water integrates the impacts of natural and human disturbances, significant changes in water resources can be expected. The IPCC Scenario A1 for 2050 forecasts a 20% decrease in water availability for the Southwest, the Great Plains, the Upper Midwest, and the Northeast. If these projections occur, the impact on water resources will be the greatest where water is already in short supply and the demands from a growing population are high. Impacts on aquatic and riparian ecosystems are likely to be high and the interactions with wildfire certain to aggravate an already out-of-bounds fire regime.

13.4.2 Area occupied by forest plantations

About 303.5 million ha of the USA total land area, or 33.3% of the land base, is classified as forest (Zhang and Stanturf 2008). Two thirds of this forest land is classified as timberland, forests capable of producing >1.5 m^3 ha^{-1} yr^{-1} (Smith *et al*. 2002). Plantation forests account for only 11% of the USA timberland and most are found in the southern part of the country. Common plantation species are *Pinus* spp., *Pseudotsuga menziesii*, *Populus* spp., *Quercus* spp., *Larix* spp., *Salix* spp., and *Eucalyptus* spp. The intensity of plantation management varies by ownership, region, and tree species. High intensity silviculture is most likely to be practiced on forest industry and corporate investment sites. Government-owned plantation forests and small ownership stands typically have the least intensive management prescriptions. Plantations are likely to become more important for future wood supplies in the USA due to reduced availability of wood products from Federal forests (Haynes 2002). However, international market forces and competition from Canadian and South American sources may have an impact on reducing American plantation demands. Rising demand for bioenergy feedstocks from wood pellets may offset reductions due to off-shore competition.

13.4.3 Future research and management practices to improve water quality and water yield.

Through achievements in the 20th Century, the USA has been able to supply its residents with reliable supplies of safe drinking water. Much of this supply originates in forest lands which constitute 33% of the national land base. As the nation enters into the 21st Century there are numerous challenges to maintaining the high quality of water supply that will require future research investments and development or refinement of management practices (Levin *et al*. 2002). Some of these challenges are:

- Insufficient resources to deal with infrastructure deterioration
- Modernization of water economics and ownership
- Groundwater and surface water changes due to climate change
- Spread of water borne infectious diseases
- Sharing of water resources on regional and national basis
- Remediation strategies for depleted and contaminated groundwater
- Sub-standard quality of surface waters due to sediment
- Nutrient contamination of surface waters in agricultural areas
- Deterioration of water quantity and quality due to increased wildfires
- High technology water monitoring tools
- Updating regulatory requirements and procedures
- Development of and implementation of BMPs
- Training of adequate numbers of hydrologists and water managers needed to cope with water resource issues in forest lands, agricultural lands, municipalities, and other parts of the national landscape.

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