EXPERIMENTAL FOREST WATERSHED STUDIES CONTRIBUTION TO THE EFFECT OF DISTURBANCES ON WATER QUALITY

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The most sustainable and best quality fresh water sources in the world originate in forested watersheds (Dissmeyer 2000, Brooks et al. 2003, Barten and Ernst 2004). The biological, chemical, and physical characteristics of forest soils are particularly well suited to delivering high quality water to streams, and moderating the climatic extremes which affect stream hydrology and water quality (Neary et al. 2009). Forest soils are usually characterized by high porosities, low bulk density, and high saturated hydraulic conductivities and infiltration rates (Neary 2011). 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 with high water quality are prolonged (Vertessey 1999, Ice and Stednick 2004).

In much of the world, municipalities ultimately rely on forested watersheds to provide adequate quantities of high quality water for continually growing demand (Lee 1980). This is particularly true in semi-arid regions where water supplies are limited, water quality is affected by high mineral content, and human populations are large or growing rapidly. Forest soils provide the ideal conditions for creating high quality water supplies (Neary et al. 2009). Paired catchment research has provided the scientific basis for understanding disturbance effects on water quality and led to the development of Best Management Practices (BMPs) for sustaining water quality (Ice 2004).

Socio-Economic Importance Of Water Quality

The U.S. Geological Survey's NAWQA studies comparing water quality across land uses have demonstrated that forest lands provide the highest quality supplies (Rosen and Lapham 2008). Much of urbanized America depends on forested catchments to provide stable supplies of high quality water. The Colorado River, that supplies water to major metropolitan areas in Arizona, California, and Nevada, derives the bulk of its flow from forested mountain headwater streams. The quality of water is so high from some forested catchments that cities like Portland, Oregon, utilize unfiltered river water from forested watersheds to supply their residents and businesses (Harr and Fredriksen 1988). New York City has long relied upon forests in the Catskill Mountains to provide one of the highest quality metropolitan drinking water supplies in the world (Pires 2004).

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.

In Canada, the percentage of cities utilizing water from forested catchments is higher due to that country's vast forest area (Bakker 2007). Germany has established Water Conservation Districts (*Wasserschutzgebieten*) for the protection of municipal water supplies (Napier 2000). Australia is one of the driest continents on Earth with less than 1% of the world's freshwater resources. Thus, water supply has always been a major issue for the socio-economic fabric of the country (Pigram 2006). The major cities of Brisbane, Sydney, Canberra, Melbourne, Adelaide, Hobart, and Perth rely on water flow from mostly forested catchments (Foran and Poldy 2002).

Paired Catchment Science

The early 20th Century was unique in that it had the beginnings of paired catchment research in several parts of the world. The Sperbelgraben and Rappengraben experimental catchments were established in 1903 near Emmental, Switzerland (Penman 1963). This was followed by establishment of the Ota watershed study in Japan in 1908 and the Wagon Wheel Gap study in Colorado, USA, in 1910 (Steen1976, Neary 2000). Paired catchment experiments have been reviewed by a

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number of authors (Bosch and Hewlett 1982, Binkley and Brown 1993, Sahin and Hall 1996, Stednick 1996, Neary 2002, Andréassian 2004, Brown et al. 2005). Most of these reviews have dealt with the topic of water yield. However, many of the paired catchment experiments initially designed for water yield research were expanded to include water quality.

This paper is based on a publication produced for a conference on at a meeting of the International Association of Hydrological Sciences in Melbourne, Australia, in 2011 (Neary 2012). It provides a historical perspective of some of the many accomplishments of water quality research over the past century made possible by using the paired catchment methodology. It also examines current research efforts, and makes recommendations about future research directions for water quality science.

PAST CATCHMENT WATER QUALITY RESEARCH

Water quality is a relative concept that is based on measurable physical, chemical, and biological characteristics in relation to specific uses such as human consumption, crop irrigation, livestock watering, fisheries maintenance, and recreational usage (Scatena 2000). As water moves through a catchment, it interacts with ecosystem components and transports dissolved gases, cations and anions, organic compounds, trace metals, sediment particles, and microscopic organisms. The principle parameters of concern in water quality are bacteria and other microorganism contents, suspended sediment, organic matter, dissolved oxygen, nitrogen (N) compounds, anions and cations, trace metals, salts, and pesticides. Temperature, color, and turbidity are physical parameters that round out the concept of water quality. These contaminants and physical conditions then define water quality based on the uses of water mentioned above (Gleick 1993). Understanding of the movement of water through forest catchments provided the scientific foundation for evaluating water quality in both natural and disturbed forests (Swanson et al. 2000). In the USA, there was early interest in water quality research at locations like the Coweeta Hydrologic Laboratory in the 1930s and 1940s, but it did not become well established until the middle of the 20^{th} century when water pollution legislation such as the Federal Water Pollution Act of 1948 was enacted (Douglass and Swank 1975, Swank et al. 2001). By the time the Clean Water Act was enacted in the USA (1972) there was considerable interest in water quality. This aspect of catchment science became fully integrated into hydrologic research.

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 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 water quality.

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 for this paper. Other papers present a much more detailed discussion of these topics (Binkley and Brown 1993, Swanson et al. 2000, Neary 2002, Ice and Stednick 2004).

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 (Tables 1 and 2). Nitrate nitrogen (NO3-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 (Tables

Table 1. Paired catchment comparison of the effects of forest harvesting on mean NO3-N concentrations in streamflow in North America the year after cutting (Adapted from Neary 2002).

Forest Type	Location	NO_3-N Uncut	NO_3-N Cut	Reference
		mg L^{-1}	mg L^{-1}	
Lodgepole Pine	Alberta, Canada	0.2	0.7	Singh & Kalra 1975
Spruce, Fir	British Columbia, Canada	0.1	0.2	Hetherington 1976
Spruce, Fir	British Columbia, Canada	<0.1	0.5	Feller & Kimmons 1984
Spruce, Fir	Colorado, USA	<0.1	<0.1	Stottlemyer 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 Brunswick, Canada	0.1	0.6	Krause 1982
Northern Hardwoods	New Hampshire, USA	0.3	11.9	Pierce et al. 1970
Mixed Hardwoods	North Carolina, USA	<0.1	0.1	Swank et al. 2001
Spruce, Fir, Pine	Nova Scotia, Canada	<0.1	0.3	Vaidya et al. 2008
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
Spruce, Fir, Pine, Birch	Quebec. Canada	<0.1	<0.1	Carignan et al. 2000
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

Table 2. Paired catchment comparison of the effects of forest harvesting on mean NO3-N concentrations in streamflow in Europe, Africa, Asia, and the South Pacific the year after cutting (Adapted from Neary 2002).

Forest Type	Location	NO_3-N Uncut	NO_3-N Cut	Reference
		mg L^{-1}	mg L^{-1}	
Native Beech-Podocarp	Chile	<0.1	<0.1	Oyarzun et al. 2007
Spruce, Fir, Peat	Finland	<0.1	0.1	Ahtiainen & Huttunen 1999
Spruce, Fir, Beech	Germany	0.7	1.0	Bäumler & Zech 1999
Native Hardwoods#	Japan	0.7	1.6	Ohrui & Mitchell (1998)
Radiata Pine	New Zealand	<0.1	0.5	Graynoth 1979
Beech-Podocarp	New Zealand	<0.1	<0.1	O'Loughlin et al. 1980
Radiata Pine	New Zealand	<0.1	0.2	O'Loughlin 1994
Evergreen Forest/Scrub	South Africa	<0.1	0.1	Scott & Lesch 1996
Pine, Spruce, Hardwood	Sweden	0.1	0.2	Rosen 1996
Spruce, Moor	United Kingdom	0.2	0.3	Neal et al. 1992
Eucalyptus spp.	Victoria, Australia	<0.1	<0.1	Hopmans & Bren 2007

4 years after cutting

1 and 2). 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 NO3-N concentration increases. The largest increase reported (Table 1, 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

Table 3. Effects of harvesting and related disturbances on sediment outputs from paired catchments (Adapted from Neary 2002, Diaz-Chavez 2011).

Forest Type	Location	Treatment	Sediment Increase	Reference
			Mg ha^{-1} yr^{-1}	
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
Tropical Forest	Malaysia	Clearcut, Skid	1.200	Malmer 1990
Northern Hardwoods	New Hampshire, USA	Clearcut	0.323	Hornbeck et al. 1987
Beech, Podocarps	New Zealand	Clearcut	0.182	O'Loughlin et al. 1980
Beech, Podocarps	New Zealand	Clearcut, Skid	3.003	O'Loughlin et al. 1980
Douglas-fir	Oregon, USA	Clearcut	0.510	Beschta 1978
Loblolly Pine	South Carolina, USA	Clearcut	0.131	Van Lear et al. 1985
Native Forest	Peru	Clearcut	0.421	Plamondon et al. 1991
Spruce, Douglas-fir	United Kingdom	Clearcut	0.327	Leeks & Roberts 1987
Eucalyptus spp.	Victoria, Australia	Clearcut	0.026	Grayson et al. 1993

atmospheric deposition (Bäumler and Zech 1999), forest harvesting does not significantly raise stream NO_3-N or other nutrient concentrations for long periods of time.

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 (Rosen 1984). 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 (e.g. O'Loughlin et al. 1980, Swanson et al. 1986, Heede 1987), highly erosive soils (Beasley and Granillo 1988), and steep terrain (Beschta 1978) (Table 3).

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 (Terrene Institute 1993). 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 3). However, adequate BMPs can significantly limit increases in sediment delivery to streams (Grayson et al. 1993, Neary et al. 2011).

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. 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

Table 4 Paired catchment studies of the effects of forest harvesting on stream temperature (Adapted from Binkley and Brown 1993, Binkley et al. 1999, Moore et al. 2005).

Location	Temperature			Time	Reference
	Control	Cut	Change		
	°C	°C	°C		
Clear Cut, No Buffer					
Brit. Columbia, Canada	17.9	21.8	3.9	Mean Annual	Feller 1981b
New Hampshire, USA	16.0	20.0	4.0	Mean Daily 30 Days AUG	Likens et al. 1970
New Zealand	12.4	15.0	2.6	Mean Annual	Quinn & Stroud 2002
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
New Zealand	16.8	20.0	3.2	Mean 10 Minute OCT-JAN	Boothroyd et al. 2004
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 Maximum	Harris 1977
Tasmania, Australia	8.2	9.0	0.8	3 Year Mean	Ringrose et al. 2001

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 4).

Forest Fertilizers: Forest fertilization is another management disturbance that has the potential to

Table 5. Paired catchment comparison of the effects of forest fertilization on maximum NO3-N concentrations in streamflow (Adapted from Binkley and Brown 1993, Binkley et al. 1999).

Location	Temperature			Time	Reference
	Control	Cut	Change		
	°C	°C	°C		
Clear Cut, No Buffer					
Brit. Columbia, Canada	17.9	21.8	3.9	Mean Annual	Feller 1981b
New Hampshire, USA	16.0	20.0	4.0	Mean Daily 30 Days AUG	Likens et al. 1970
New Zealand	12.4	15.0	2.6	Mean Annual	Quinn & Stroud 2002
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
New Zealand	16.8	20.0	3.2	Mean 10 Minute OCT-JAN	Boothroyd et al. 2004
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 Maximum	Harris 1977
Tasmania, Australia	8.2	9.0	0.8	3 Year Mean	Ringrose et al. 2001

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 (Table 5). Higher stream concentrations are usually associated with higher fertilizer application rates (e.g. >200 kg–N ha^{-1}) (Smith et al. 1994) or aerial applications that fly over or near monitored streams (Grip 1982, Hetherington 1985, Helvey et al. 1989, Göethe et al.

Table 6. Paired catchment comparisons of sediment yield the first year after prescribed fires and wildfire (Adapted from Neary et al. 2005, Shakesby and Doerr 2006, and Smith et al. 2011)

Vegetation	Location	Fire Type	Sediment Yield		Reference
			Control	Post-Fire	
			$Mg\ ha^{-1}\ yr^{-1}$	$Mg\ ha^{-1}\ yr^{-1}$	
Ponderosa Pine	Arizona, USA	WF Low[1]	0.003[C]	0.080	Campbell et al. 1977
Ponderosa Pine	Arizona, USA	WF Mod[1]	0.003[C]	0.300	Campbell et al. 1977
Ponderosa Pine	Arizona, USA	WF High[1]	0.003[C]	1.254	Campbell et al. 1977
Chaparral	Arizona, USA	Wildfire	0.175[C]	204.000	Glendening et al. 1961
Chaparral	Arizona, USA	Wildfire	0.096[C]	28.694	Pase & Ingebo 1965
Shortleaf Pine	Arkansas, USA	Prescribed	0.036[C]	0.237	Miller et al. 1988
Mixed Conifer	B.C. Canada	Wildfire	0.005[S]	0.008[S]	Petticrew et al. 2006
Chaparral	California, USA	Wildfire	0.880[C]	146.000	Krammes 1960
Ponderosa Pine	California, USA	Prescribed	<0.00[C]	<0.001	Biswell & Schultz 1965
Chaparral	California, USA	Wildfire	0.043[C]	28.605	Wells et al.1981
Ponderosa Pine	Colorado, USA	Wildfire	0.280[P]	68.000	Moody & Martin 2001
Oak spp.	Mississippi, USA	Prescribed	0.470[C]	1.142	Ursic 1970
Hardwoods	Oklahoma, USA	Prescribed	0.022[C]	0.246	Daniel et al. 1943
Fynbos Scrub	South Africa	Prescribed	0.013[C]	0.420	Scott 1993
Fynbos	South Africa	Wildfire	0.013[C]	7.800	Scott 1993
Loblolly Pine	South Carolina, USA	Prescribed	0.027[C]	0.042	Van Lear et al. 1985
Loblolly Pine	Texas, USA	Prescribed	0.112[C]	0.806	Pope et al. 1946
Juniper 0% Slope	Texas, USA	Prescribed	0.025[C]	0.029	Wright et al. 1976
Juniper 15-20%	Texas, USA	Prescribed	0.076[C]	1.874	Wright et al. 1976
Juniper 43-54%	Texas,USA	Prescribed	0.013[C]	8.443	Wright et al. 1976
Eucalyptus spp.	Victoria, Australia	Wildfire	0.230[P]	2.960	Lane et al. 2006
Radiata Pine	Victoria, Australia	Wildfire	0.744[P]	12.300	Smith et al. 2012
Eucalyptus spp.	Victoria, Australia	Wildfire	0.057[P]	0.110	Smith et al. 2012
Mixed Conifer	Washington, USA	Wildfire	0.008[P]	0.120	Helvey 1980

[P] Pre-fire data; [C] Control catchment data; [1] Fire Severity: Low Moderate, High; [S] Seasonal Suspended Sediment

1993). 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.).

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). Lane and Sheridan (2002) clearly pointed out the role of stream crossings in routing sediment into streams that Swift (1988) alluded to. They employed an above and below approach rather than a paired catchment method. In Lane and Sheridan's (2002) study of unsealed road stream crossings in Victoria, Australia, suspended sediments increased 3.5 times below crossings.

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 (Table 6). The highest soil erosion values usually involve intense rainfall on steep terrain (Glendening et al. 1961, Moody & 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 NO3-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.

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).

PRESENT CATCHMENT WATER QUALITY RESEARCH

The present level of paired catchment water quality research is quite varied world-wide depending on funding levels and personal commitments and dedication of individual scientists. As an example, Neary et al. (2012) mentioned 180 gauged catchments that are currently active in the U.S. Forest Service's Experimental Forests and Ranges network. However not all of these catchments are engaged in providing data for water quality research. Some topics researched in the past have been suspended because the forestry practices are not being used or decisions were made that sufficient information exists on the topic. These include clearcutting, fertilizer use, road construction, and pesticide application.

Present water quality science is more aligned with the objectives of long-term programs like the Long Term Ecological Research (LTER) program that has international sites, and the Europe-based International Cooperative Program on Assessment and Monitoring of Air Pollution (ICP2). A series of new ICP2 sites added to the network in the USA are based on U.S. Forest Service Experimental Forest and Range sites that have actively-gauged paired catchments. Paired catchments also can be used for climate change research. Although they do not provide the control vs treated comparisons in a classical sense, they can be used for replications within an ecosystem and comparisons between sites/ecosystems.

Fire impacts on water quality are currently another major area of concern because of adverse effects on municipal water supplies (Neary et al. 2005, Smith et al. 2011). Prescribed fire effects on water quality are being studied at sites that have paired catchments (Gottfried et al. 2012). Wildfires rarely present the opportunity to use a paired catchment approach to study water quality effects because of the random nature of these events and their unpredictability.

FUTURE WATER QUALITY RESEARCH USING PAIRED CATCHMENTS

The direction of future water quality research using paired catchments will depend greatly on governmental support for the science. This type of water quality 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.

SUMMARY AND CONCLUSIONS

This paper provides an overview of the role of paired catchment science in the understanding of water quality in forest ecosystems. Many cities throughout the world rely on forested catchments for the source of their water supplies. This resource is constantly being stressed due to burgeoning demand for high quality water. The current level of knowledge of how forest management has affected water quality has been dependent on science conducted on a large array of catchment studies in mainly Europe, North America, Asia and the South

Pacific. These studies have been expensive to establish in the past, but their value to future water resources science is invaluable. They need to be supported to address important science topics and water management concerns of the 21st century.

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