Chapter 9: Ecoregion 6.2.14 Southern Rockies: Fraser Experimental Forest, Colorado

Alex D. Foster and Alfred A. Basile[1]

Introduction

This chapter is a review and synthesis of research conducted at Fraser Experimental Forest (FEF) on stream chemical nutrients, contributing factors, and biological responses to them. It is intended to inform national and regional water quality regulatory agencies, such as the U.S. Environmental Protection Agency (USEPA) and the Colorado Department of Public Health and Environment (CDPHE), about existing results of relevant scientific studies that are available at FEF, and to identify future field and synthetic research of potential use to regulatory agencies that might be conducted at FEF.

Site Description

FEF is located on the west slope of the Rocky Mountain Front Range (lat. 39.90° N, long. 105.88° W), 7 km southwest of the town of Fraser, Colorado. The experimental forest occupies 9300 ha of federal lands in the Arapaho National Forest, with elevations ranging from 2680 to 3900 m (fig. 9.1). Climate is cool throughout the year. At the FEF headquarters (elevation 2765 m), the annual average temperature is 0.5 °C, and average monthly temperature is -10.0 °C in January and 12.7 °C in July. Mean annual precipitation is 737 mm with more than 65 percent usually occurring as snow.

The west side of FEF is rugged mountains with narrow, steep-sided valleys; whereas the south and east sides have gentle, relatively uniform slopes, and the north side is a broad valley dissected by St. Louis Creek (Alexander and Watkins 1977). Watersheds in the FEF were formerly glaciated, and their streams flow over moraines at varying elevations (Stottlemyer 2001).

Sandy coarse soils are common across FEF and on its east side are primarily derived from a mixture of gneiss and schist metamorphic parent rock types. The soils are very permeable allowing high water infiltration into the soil profile and storing considerable water during snowmelt. At high elevations, especially on the west side, soils are derived from sandstones and are shallow with a high stone content. In areas along the main streams, soils are a mixture of alluvium, glacial till, glacial outwash, and recent valley fill (Alstatt and Miles 1983, Retzer 1962).

---

[1] **Alex D. Foster** is an ecologist, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 3625 93rd Avenue SW, Olympia, WA 98512; **Alfred A. Basile** is a biologist, U.S. Environmental Protection Agency, Region 8, 1595 Wynkoop Street, Denver, CO 80202.

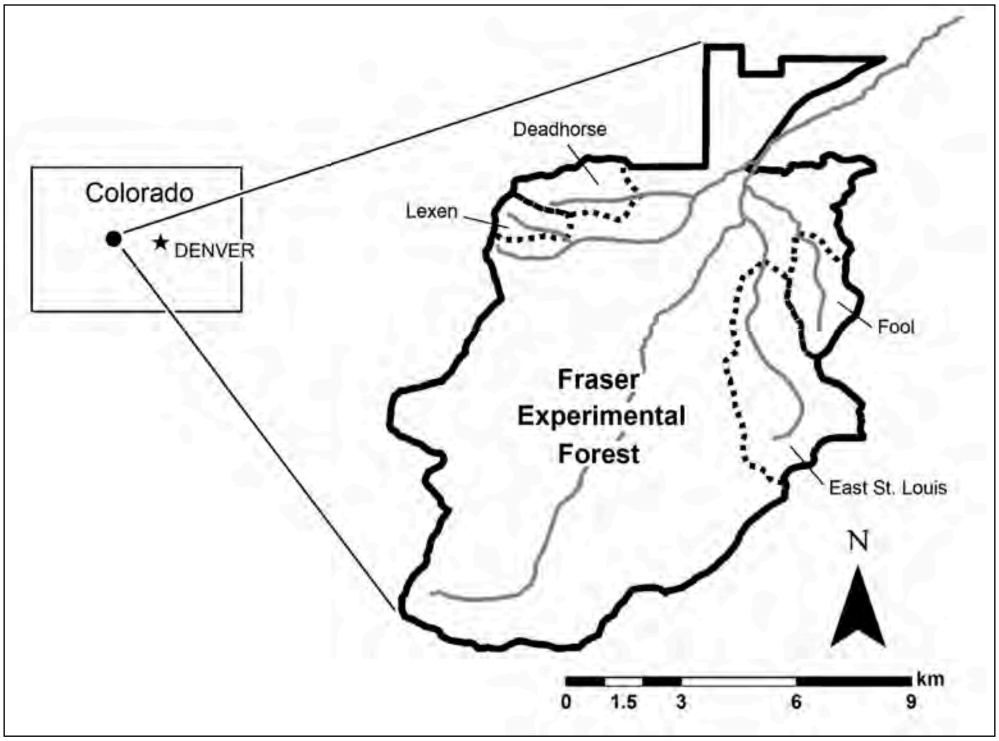

Figure 9.1—Fraser Experimental Forest near Fraser, Colorado, showing the locations of study watersheds.

FEF streams are generally steep with gravel beds and shallow pools, except in constrained reaches where bedrock ledges separate deeper pools. Large wood and boulders typically form roughness elements. The largest stream, St. Louis Creek, is perennial and fish bearing. Snowmelt in late spring and early summer typically dominates the annual hydrograph of St. Louis Creek and its tributaries. Immediately downstream of FEF study watersheds, St. Louis Creek's flow is partially diverted into water diversions for municipal drinking water supply for the city of Denver via a tunnel under the continental divide. Further downstream, St. Louis Creek joins the Fraser River which drains to the upper Colorado River near Granby, Colorado.

Vegetation zones consist of subalpine forests transitioning to alpine tundra at the higher elevations along the St. Louis Creek watershed divide. Below the tree line on north-facing aspects and on moist sites along streams, dominant tree species include Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco), and aspen (*Populus tremuloides* Michx.). Lodgepole pine (*Pinus contorta* Douglas ex Loudon var. *latifolia* Engelm. ex S. Watson) is the dominant tree at lower elevations and on drier, south-facing slopes (Alexander et al. 1985).

Research History

FEF was established in 1937 by the U.S. Forest Service (USFS) and dedicated to research purposes. Continuous air temperature and precipitation data collection at FEF headquarters began in 1939. Initial investigations on FEF focused on timber and watershed research (Alexander 1987). In the 1940s and 1950s, paired watershed experiments were conducted to study effects of timber management on snowpack and water yield (Leaf 1975). Specifically, plot studies were designed to study the effect of differing levels of timber harvest on canopy, understory, litter interception, snowpack accumulation and melt, and soil water storage and depletion (Wilm and Dunford 1948). Continuous hydrologic and meteorological data have been maintained for eight watersheds since those initial experiments, giving FEF some of the longest continuous data records among experimental forests and ranges (EFRs) nationwide (Troendle and King 1985, 1987; Troendle and Reuss 1997). The chemistry of stream water, winter snowpack, soil solution, and precipitation have been monitored since the 1980s (Stottlemyer 1987, 1997; Stottlemyer et al. 1997). Although no formal National Atmospheric Deposition Program (NADP) monitoring has been located on the FEF, NADP protocols have been used at FEF to measure the chemistry of atmospheric deposition (NADP 2019a).

Many subsequent studies have investigated effects on stream chemistry and water cycles of various silvicultural practices at FEF, for example, Troendle and Nilles (1987), Reuss et al. (1997), Stottlemyer and Troendle (1999), and Stottlemyer (2001). Processes that have been examined at FEF include tree canopy interception of atmospheric chemical inputs, effects of clearcutting on nutrient flux, and soil processes occurring under snowpack, such as seasonal carbon dioxide flux (Hubbard et al. 2005, Reuss et al. 1997, Stottlemyer and Troendle 1997). Recent research has investigated the effects of large-scale tree mortality caused by the mountain pine beetle (*Dendroctonus ponderosae* Hopkins) on stream chemistry and water balance, and effects on streams from salvage logging of beetle-killed trees (Hubbard et al. 2014; Rhoades et al. 2013, 2017).

Research on snowpack accumulation and snowmelt dynamics and modeling, including potential responses to alternate climate change scenarios, has also been a recent emphasis (Lisle et al. 2010, Rhoades et al. 2010, Rutter et al. 2009). Snow monitoring at FEF has included an active U.S. Department of Agriculture Natural Resource Conservation Service snow telemetry (SNOTEL) site in operation in the Fool Creek watershed, established October 2011. Another ongoing line of water research at FEF seeks to understand water use, storage, and evapotranspiration dynamics of dominant tree species, such as lodgepole pine, Engelmann spruce, and subalpine fir, to improve understanding of how changes in subalpine tree species composition might affect water yield locally and at the watershed scale (Elder et al. 2006, Kaufmann 1985).

Availability of publications and data—

Although no comprehensive, up-to-date bibliography of FEF scientific publications and research is currently available, bibliographical lists and researcher contact information may be obtained through several websites. The USFS Rocky Mountain Research Station (RMRS) provides general FEF information and contacts, and a search engine for USFS-sponsored research. USFS website links include an overview and personnel contacts for FEF research (USDA FS 2017a). Streamflow, temperature, carbon, and precipitation data can be found at USDA FS (2017b), and publications can be found at the USFS publication search engine (USDA FS 2017c). The RMRS Air, Water and Aquatic Environments Program provides information about various research, data, publications, and biogeochemistry laboratory services (USDA FS 2017d).

The U.S. Department of the Interior Geological Survey (USGS), Fort Collins Science Center provides information about research sponsored by the center, some of which is associated with FEF (USDI GS 2017a). The USGS National Water Information System provides FEF St. Louis Creek water information site data (USDI GS 2017b).

The USEPA STORET water quality data storage and retrieval site contains data collected on St. Louis Creek and adjacent watersheds (US EPA 2017).

Warner College of Natural Resources, Colorado State University in Fort Collins describes its current and past faculty and graduate research, some of which has been done at FEF (CSU 2017).

Grand County Water Information Network provides water quality data archives, which include data collected on St. Louis Creek (GCWIN 2017a, 2017b).

Long-term FEF daily streamflow and meteorological data, formatted for comparison with other EFRs, can be downloaded from the Long Term Ecological Research [LTER] Network (LTER 2017).

Natural Resource Conservation Service SNOTEL (Fools Creek Basin) provides telemetry and snow course data and related products (USDA NRCS 2017).

National Aeronautics and Space Administration National Snow and Ice Data Center provides a link to the Cold Land Processes Field Experiment and related data for FEF (NASA 2017).

Biological Responses to Stream Nutrients N and P

Issues of Concern

As are many mountain watersheds along the Colorado Front Range, FEF is a source of high-quality water for Denver's municipal drinking water system. St. Louis Creek, the main drainage on the FEF, is typical of headwater streams that are the source of 85 percent of the annual yield of water from the Colorado Rockies (Alexander et al. 1985). Excess stream water nitrogen (N) and phosphorus (P) can contribute to poor water quality in drinking water reservoirs and degradation of habitats for desirable fish (Fenn et al. 1998), and can detract from the quality of recreational activities such as swimming, whitewater rafting, and sport fishing, which are economically important in the region.

Nutrients originating from urban, agricultural, and industrial emission sources can be transported through atmospheric pathways and deposited in high-altitude watersheds, potentially contributing to water quality degradation. Periodic disturbances from wildland fires and tree morality from insect attack can also increase stream water nutrient concentrations. Although forest management, such as stand thinning and salvage cutting, may temporarily elevate stream nutrients, these practices are sometimes used to reduce the risks posed to streams and other resources by severe fires and insect outbreaks.

Findings From Studies

Since 1982, streams at FEF have been regularly monitored for ammonium (NH_4^+) and nitrate (NO_3^-) (Stottlemyer 1987, 2001). Stottlemyer and Troendle (1997) analyzed FEF stream water, snowpack, and soil ion concentrations for a variety of chemicals, but did not report results for phosphate (PO_4^{3-}), presumably because concentrations were lower than they could reliably detect.

At FEF, nutrient concentrations in snowpack and stream water increase with elevation, with the highest concentrations of NH_4^+ and NO_3^- in the alpine zone (Stottlemyer 1987, Stottlemyer et al. 1997). For example, water draining the high-elevation, alpine portion of the Lexen Creek reference watershed contained NO_3^- concentrations that were 2 to 10 times higher than stream water in the subalpine portion, at lower elevation in the watershed. As alpine streams transitioned to the subalpine forest, stream water NO_3^- concentrations typically decreased (Stottlemyer 1997). This pattern was explained by postulating that, compared to subalpine forests, alpine areas had more direct routing of snowmelt water to streams via exposed rock and alpine tundra that effectively bypassed storage in groundwater and vegetative nutrient uptake.

In contrast to the alpine areas, most snowmelt in subalpine watersheds is routed through subsurface flow (Stottlemyer 1997, 2001). Soil processes such as ion exchange, biological uptake, overwinter nitrification, and mineralization are probably major factors modifying the chemistry of meltwater before it reaches streams. No correlation was found between soil water chemistry and stream water chemistry, which probably reflects a high variation in distance travelled and degree of chemical processing of soil water as it moves to streams. Alpine stream water ion concentrations change little during snowmelt, suggesting that meltwater passes quickly through porous soils and is well mixed before entering streams. By contrast, in lower elevation subalpine streams, ion concentrations are diluted during snowmelt (Stottlemyer 2001). In subalpine soils, minor changes in the depth of lateral subsurface flow significantly affects the export of ions. Snowmelt apparently changes the depth at which water moves through subalpine soils to streams.

Nutrient effects on aquatic food webs and related factors—
Biological effects of nutrient enrichment and light regimes along a 400-m stretch of West St. Louis Creek were studied by Wellnitz et al. (1996). They examined four light treatments, including artificial shading of a stream reach with no riparian canopy shade, closed canopy, artificial illumination in the closed-canopy reach, and open canopy. To investigate nutrient effects, clay flower pots, filled with cobbles, were placed in streams and received nutrient additions that diffused from agar gels containing 0.5 molar concentrations of nitrate as $NaNO_3$ and phosphorus as KH_2PO_4 either separately or in combination. They found that periphyton and algae abundance responded similarly under open- and closed-canopy treatments. Primary production was reduced in artificial shade, but under artificial lighting it was significantly increased by a factor of two to four. In addition, they found the combined N+P mixture had the greatest effect on periphyton and algal biomass and chlorophyll *a* production under all lighting treatments, suggesting that both nutrients are probably important for eutrophication of mountain streams. Overall, the artificial lighting had a greater effect on the algal community than nutrient enrichment. The artificial light treatment demonstrated that the potential for algal biomass production in West St. Louis Creek was probably not fully achieved owing to photoinhibition. The authors cautioned against extrapolating from their results to conclusions about how the West St. Louis Creek ecosystem would respond to N and P enrichment because their experiment had used nutrient diffusion and artificial substrates.

Surveys at FEF of stream organisms under ambient nutrient conditions have mainly consisted of fish surveys. Fish species present and their population trends have been periodically monitored by the Arapaho National Forest at an established index reach on St. Louis Creek within FEF. Fish species occurring in St. Louis

Creek and some of its tributaries have historically included native cutthroat trout (*Oncorhynchus clarkii* Richardson), mottled sculpin (*Cottus bairdii* Girard), non-native brook trout (*Salvelinus fontinalis* Mitchill), and rainbow trout (*O. mykiss* Walbaum). The most recent population estimate was approximately 330 fish per kilometer in 2005, primarily brook trout, with no other trout species found (USDA FS 2008). Indigenous cutthroat trout, previously found in FEF streams, may have been extirpated (Elder et al. 2006, Young et al. 1996), although this finding has not been confirmed by extensive field sampling or eDNA analyses. Stream surveys of algae and macroinvertebrates, trophic groups that are often used by water quality regulatory agencies to assess water quality, have not been conducted at FEF.

Other Factors Relevant to Stream Nutrients N and P

Hydrological influences—

In contrast to limited biological monitoring, numerous environmental factors that may affect stream nutrients and biological response have been extensively studied or monitored in FEF. Studies have found that East St. Louis Creek has stable geomorphology under a variety of flow conditions, and woody debris was an important sediment storage element (Adenlof and Wohl 1994, Trayler and Wohl 2000). Although the loading of large wood in East St. Louis Creek was high, the proportion of wood in jams was low because the relatively small contributing area produced flows insufficient to mobilize large wood (Wohl and Jaeger 2009). Earlier research showed that cross-channel logs in Fool and Deadhorse Creeks formed steps by holding back coarse sediment and decreasing flow velocities (Heede 1972), a process that affects stream nutrient cycling. More recent research on streamflow characteristics, channel hydraulics, and reach-level spatial modeling used state-of-the-art technologies, including acoustic Doppler and terrestrial LiDAR on streams at FEF (David et al. 2013, Yochum et al. 2014). These more sophisticated methods not only validated previous work but provided further insights into flow dynamics by quantifying the spectrum of geomorphic change in these high-gradient channel types.

Stream temperature—

Long-term stream temperature monitoring by the Arapaho National Forest is located on St. Louis Creek downstream of the Denver Water Board diversion structure within FEF (fig. 9.1). The timing of snowpack runoff and cool summer temperatures make it rare for St. Louis Creek to exceed water quality standards for temperature. In contrast, the Fraser River, downstream of FEF, is listed as impaired for temperature, and summer maximum water temperatures frequently exceed 16 °C (USEPA 2015).

Signs of changing stream conditions owing to climate warming have been observed at FEF. Jones et al. (2012) reported that spring runoff in recent years at FEF occurs significantly earlier in the season than it did in the mid-20th century, expanding the period of thaw, presumably because the climate has warmed. They also found that minimum daily air temperatures have also increased significantly by several degrees Celsius since 1980. It is not currently known whether increasing ambient air temperature and a longer period of thaw have influenced stream biological communities or their responses to stream nutrients.

Reference Watersheds

Lexen Creek (140 ha) and East St. Louis Creek (940 ha) watersheds on the FEF have been managed for minimal human disturbance since the 1940s and have served as reference watersheds for many studies. These watersheds represent conditions that are probably similar to other relatively undisturbed watersheds along the Front Range that are within a similar elevation range. Streamflow has been continuously monitored from these reference watersheds since the 1940s, and stream nutrients, including NO_3^- and NH_4^+, have been monitored regularly since 1982.

An analysis of trends found significantly increasing stream water NO_3^- concentrations in both FEF reference watersheds from 1997 to 2007 (Argerich et al. 2013). For the same period, streamflow significantly decreased, and NH_4^+ decreased slightly. These findings corroborate those of Baron et al. (2000), who reported increasing NO_3^- in high-altitude streams on the east side of the Colorado Front Range, suggesting this trend in stream NO_3^- may be common in high-altitude streams in this region. Wet deposition of NH_4^+ and NO_3^- measured at FEF did not change significantly from 1987 to 2007 (Argerich et al. 2013).

Onsite meteorology and upland vegetation have also been monitored on these reference watersheds. Upland vegetation has been subject to tree mortality from mountain pine beetles. To maintain minimal human disturbance, no actions have been taken on these reference watersheds to either prevent mortality or remove dead or dying trees. The levels of naturally caused vegetation disturbance on these reference watersheds are probably typical for minimally disturbed watersheds in this region and this altitude range. To date, no surveys or studies have been conducted of the stream biological communities in these undisturbed reference streams. Fish surveys conducted by Arapaho National Forest on the main stem of St. Louis Creek did not extend upstream into these reference basins.

Cross-Site and Regional Studies

The FEF has often been included in regional and national cross-site studies. Studies comparing FEF streams with other, similar mountain streams in Colorado and Wyoming found that bedload transport occurred over a narrow range of discharge, typically between 60 and 100 percent of bankfull flow, and that channels were fairly stable in undisturbed watersheds (Ryan et al. 2005, Troendle and Olsen 1994). Stottlemyer (1997) used data from the Lexen Creek reference watershed in FEF, plus two sites in Michigan, and one in Denali National Park, Alaska, to compare stream water chemistry across a broad geographic range with the objective of finding correlations to atmospheric inputs. Overall, only weak or insignificant correlations were found between precipitation and stream water ionic concentrations including NO_3^-. Atmospheric deposition measurements generated from FEF studies have been compared with measurements from regional NADP sites (Stottlemyer 1987, 2001; Stottlemyer and Troendle 1992; Stottlemyer et al. 1997).

In a cross-site comparison of seven experimental forests from across the United States, Argerich et al. (2013) found that stream water NO_3^- concentrations in FEF reference watersheds, East St. Louis and Lexen Creek, were comparable with the other western site in the study, H.J. Andrews Experimental Forest in Oregon (see chapter 5), but low compared to streams at Hubbard Brook (see chapter 3) and Fernow Experimental Forests (see chapter 13) in the Eastern United States.

In a cross-site analysis of long-term hydrologic response to precipitation and climate among 35 EFR and LTER sites nationwide that included FEF, Jones et al. (2012) found that the higher minimum daily temperatures and a lengthening period of thaw in response to climate warming at FEF were similar to other subalpine sites in the Rocky Mountains.

Dose-Response Studies

The only published dose-response study at FEF has been the work by Wellnitz et al. (1996), which assessed potential effects on stream primary productivity of various N and P enrichments and light regimes using artificial substrates in St. Louis Creek. This study is described in more detail above under the heading "Nutrient effects on aquatic food webs and related factors."

Responses to Forest Management and Natural Disturbances

Research at FEF that investigated effects of silvicultural practices on hydrology has provided a scientific basis for guiding USFS land management practices. Research findings of Troendle and Olsen (1994), for example, were used in the development of forest plan standards and guidelines and best management practices (BMPs) for timber harvest and road design on National Forest System lands. BMPs were intended to mitigate potential effects of timber harvest such as increased runoff and flood flows, which, in turn, may affect channel integrity, sediment loading, riparian vegetation, and water quality.

Timber harvest in subalpine forests at FEF has been found to strongly affect streamflow regimes, potentially affecting nutrient dynamics, sediment flux, and aquatic habitats. A review of historical streamflow records before and for 28 years after a timber harvest in 1956 in the Fool Creek watershed found that in the post-harvest period, seasonal flow increased 40 percent, and spring peak flow increased 20 percent (Troendle and King 1985). Streamflow seasonal variability can have strong effects on bedload movement and nutrient cycling in headwater streams with high-gradient channels and a large stock of woody debris roughness elements. For example, Troendle and King (1985) noted that the duration of bankfull discharge, the most effective discharge for sediment transport, doubled following timber harvest on Fool Creek. Increased sediment transport on the nearby North Fork of Deadhorse Creek was attributed solely to increased discharge and channel scour following partial clearcutting (Troendle and King 1987).

Clearcut harvesting experiments at FEF found that snowpack runoff and stream water quality were affected by increasing snowpack peak water equivalent by an average of 36 percent over reference uncut forests, and by increasing peak stream discharge (Troendle and King 1985, 1987; Troendle and Reuss 1997). In addition, clearcut logging increased NO_3^- concentrations in the snowpack compared to forested areas, whereas NH_4^+ concentrations were lower in snowpack in clearcuts (Stottlemyer and Troendle 2001). A companion study found that, compared to uncut reference watersheds, which typically served as sinks for atmospherically deposited N, clearcut harvesting elevated NO_3^- concentrations in drainage water and caused significant stream export of N at the onsite and hillslope scales (Reuss et al. 1997). Taken together, these findings suggested that clearcutting increased N export by both increasing NO_3^- deposited to snowpack and decreasing biological assimilation and retention of NO_3^- released during snowmelt at FEF.

Salvage logging of beetle-killed trees may alter future forest diversity and fuel types by promoting conditions more favorable to lodgepole pine and aspen regeneration than to subalpine fir (Pelz et al. 2015). This shift in tree species may have implications on future water yield, water chemistry, and fire hazards (Collins et al. 2011, 2012).

Wildland fire, the primary source of natural disturbance to forests in this region, can alter stream nutrient levels. For example, the Hayman Fire of 2002, Colorado's largest historical wildfire, increased postfire stream water NO_3^- concentrations (Rhoades et al. 2006). Temporary postfire nutrient enrichment, coupled with increases in solar radiation and temperature from postfire loss of vegetative canopy cover, can produce a short-term increase in aquatic primary productivity.

Wildland fires in the subalpine spruce and lodgepole pine forests at FEF were historically infrequent, but occasionally severe, and stand replacing. Using average tree cohort age as a surrogate, Huckaby and Moir (1995) estimated that historical wildfire return intervals ranged from 64 to 389 years. The establishment of fire suppression measures at FEF effectively eliminated wildland fire as a major disturbance mechanism since the early 1900s. The lack of wildland fire has resulted in overstocked forest conditions, which, along with periodic droughts, may increase the risk of severe, stand-replacing fires in the future.

These ecological conditions have also stressed trees, making them vulnerable to mortality from the mountain pine beetle, which is common along the Front Range. Beetle infestation levels at FEF peaked around 2007. Research has assessed pre- vs. postinfestation tree mortality effects on water chemistry and water yield. For example, stream water total dissolved inorganic N was higher in old-growth reference watersheds with extensive beetle kill compared to the pre-beetle outbreak period, yet NO_3^- concentrations were unaffected in mixed-age forest stands (Rhoades et al. 2017). Nutrient demand by understory and live overstory trees in upland and riparian areas may balance the elevated soil nutrients measured beneath beetle-killed trees thus neutralizing effects on export to streams. Compared to wildland fires, increases in stream water NO_3^- concentrations after beetle-caused tree mortality were moderate (Hubbard et al. 2014; Rhoades et al. 2008, 2013). The modest response to beetle kill was attributed to a combination of lower atmospheric N deposition locally in the beetle-kill area, gradual tree mortality spread over multiple years, and high compensatory capacity of residual vegetation and soils. An FEF watershed with substantial beetle-induced mortality showed a response in stream NO_3^- flux that was smaller than the response that followed a partial harvest (30 percent of area harvested) in a nearby watershed (Rhoades et al. 2013).

Reliability and Limitations of Findings

FEF data and research findings are of high quality and are probably most applicable to high-elevation forests near the subalpine-alpine transition of the Colorado Front Range. Outside of these conditions, or where additional accuracy is required, validation studies or monitoring might be advisable at other locations to test how well FEF represents local conditions.

Research Needs

An important science gap at FEF and the highest priority research need related to nutrient pollution is characterization of biological communities, including algae, macroinvertebrates and fish, in undisturbed reference streams on the FEF, and better understanding of how these communities respond to increases in stream nutrient concentrations. Filling this science gap is important because surveys of stream community composition at FEF might be used to confirm or extend what is known about reference conditions in other minimally disturbed Colorado montane streams (e.g., Lewis and McCutchan 2010). FEF studies might also be used to determine at what threshold levels, and after how much time, reference stream communities change in response to nutrient enrichment. Such studies might also investigate whether other factors, such as temperature, might be controlling nutrient response in these mountain streams. Filling this gap would require conducting surveys of stream biological communities in FEF reference streams. These surveys would be most valuable if substrate type, stream width, streamflow, canopy cover, total and dissolved N and P, pH, dissolved oxygen, alkalinity, and water temperature were included in the analysis. Community responses to nutrient enrichment might be inferred by comparing reference communities in FEF streams with biotic communities in other, more enriched, Colorado montane streams. Experimental stream enrichments might also be useful to determine response thresholds, especially if they included effects of adding both N and P, in various combinations and concentrations. Studies should be continued long enough (>5 years) to detect delayed biological and food web responses similar to those observed by Davis et al. (2010) at Coweeta Hydrologic Laboratory (see chapter 14). Utilizing multivariate data analytical tools, such as those of Baker and King (2010), might make community effects of nutrient enrichment more detectable, especially in contrast to aggregating community data into univariate responses, such as diversity and richness, as were evaluated by Lewis and McCutchan (2010).

Other research questions of interest that might be filled at FEF include (a) what are the effects of observed increasing ambient air temperature at FEF on stream temperature and biological response to stream nutrients, and (b) to what degree is stream water NO_3^- concentration driven by atmospheric deposition of N?

Potential Utility to Water Quality Regulatory Agencies

The FEF and other experimental forests and ranges provide extremely valuable long-term data that might be used to define reference or near-reference conditions. A great challenge in deriving numeric nutrient criteria for any waterbody is identifying lowest concentrations of N and P that produce undesirable impairment from attainment of designated uses, such as fishing, swimming, and protection of aquatic life. This threshold is to some degree subjective, and how far it may deviate, if at all, from a reference or near-reference condition is debatable. Ultimately, the criteria are based upon a judgment of what is needed to protect designated uses. To minimize risk to aquatic biota, some states are developing nutrient criteria to maintain the natural condition in their highest quality waters. Enrichment above naturally occurring levels departs from conditions to which biota have evolved over a very long time, and when species and unique assemblages are lost, restoration can be extremely difficult, expensive, and improbable in most cases. Maintaining the natural condition would require understanding the physical, chemical, and biological conditions that exist in reference streams. The FEF and other experimental forests and ranges provide an extensive record of documented natural stream conditions in carefully maintained reference watersheds.

Another challenge is how to include in the development of water quality criteria, observations that background conditions in reference watersheds have not been static, but have undergone changes from regional or global-scale anthropogenic or natural influences. Research results and long-term monitoring datasets at FEF may be useful in addressing this issue because they provide scientific evidence that, even in high-altitude reference watersheds that have been scrupulously protected from onsite human disturbance, stream water NO_3^- concentrations have increased in recent decades (Argerich et al. 2013). Therefore, the importance of FEF as a natural laboratory to examine the effects from natural and anthropogenic disturbances cannot be overstated. Continued monitoring will allow us to assess current conditions, provide early warning if conditions decline, and monitor effects of various environmental disturbances.

Finally, in addition to the value of FEF streams for documenting reference conditions, existing long-term datasets and research results from other streams on the FEF may be used to evaluate impacts from forest management practices. Research results from forest management experiments at FEF may be of practical use for developing BMPs that provide guidance for protecting water quality during forest management activities in other high-altitude basins. Outside of FEF, carefully controlled studies of the effects of active forest management on streams are rare along the Front Range, in part because management experiments are difficult to implement or are not permitted in some other study watersheds in the region, for example, those managed as wilderness or in national parks.

Key points:

- FEF has publicly available, high-quality, and long-term hydrology, temperature, meteorological, and stream water N data.
- Forestry-related effects on stream water flows and N chemistry have been well studied at FEF, resulting in many reports and published articles.
- Apart from fish surveys along St. Louis Creek, and a study of stream algal response to nutrient enrichment on artificial substrates by Wellnitz et al. (1996), there has been relatively little research on aquatic biology at FEF, providing many opportunities for future study.
- The highest priority research need, for the purpose of addressing nutrient pollution, is to characterize existing biological communities, including algae, macroinvertebrates, and fish in relatively undisturbed reference streams on the FEF, and to determine at what threshold levels, and after how much time, reference stream communities change in response to nutrient enrichment.

Biological Responses to Stream Nutrients Other Than N and P

Issues of Concern

Currently, there are also water quality concerns related to other nutrients, such as sodium (Na) and selenium (Se), in the region; however, levels in atmospheric deposition at FEF for nutrients other than N, P, and heavy metals have historically been low. Deposition of some of these elements, however, could increase in high-altitude ecosystems along the Front Range, including FEF, if air emissions from fossil fuel production and combustion increase in regions upwind. For example, atmospheric deposition of sulfur (S), if high enough, could contribute to the acidification of stream systems.

Atmospheric deposition of S might also contribute to increased accumulation of mercury (Hg), a neurotoxin, in apex predators of aquatic food chains, which includes fish commonly consumed by people. Research in wetlands at Marcell Experimental Forest (see chapter 2) has found that, under some circumstances, deposition of the nutrient sulfur, as sulfate (SO_4^{2-}), can increase uptake of Hg in food chains (Jeremiason et al. 2006). Thus, although Hg is not itself a nutrient, the risk this toxin poses to humans is amplified by stream food chains and, under some circumstances, might be further heightened by ambient levels of the nutrient S.

Ground-disturbing activities, such as mining, have not occurred within FEF, but in some parts of the Front Range, drainage from mines and mine spoil has degraded water quality with pollutants, including high acidity, SO_4^{2-}, heavy metals, and sediment loads. These water pollutants can negatively affect fish and other aquatic biota, and may also affect use of streams for water-contact recreation and drinking water supply. FEF has the potential to provide important information on background stream conditions in high altitude Front Range basins in the absence of mining disturbance.

Findings From Studies

Metals and bacteria—
Since the mid 1980s, stream water, snowpack, soil solution, and atmospheric deposition at FEF have been monitored for calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), chloride (Cl^-), and SO_4^{2-}, along with pH, electrical conductivity, and acid neutralizing capacity (ANC).

In addition, three water quality monitoring sites, station numbers 12165, 12165B, and 12165C, have been maintained within FEF by the CDPHE on St. Louis Creek (CDPHE WQCC 2010). At these sites, stream water has been monitored for major metallic cations, including copper (Cu), iron (Fe), manganese (Mn), Se, and zinc, plus the bacteria Escherichia coli and fecal coliform. As expected, these data indicate that levels of these metals in streams within FEF, which has not been mined, are low compared to streams draining some mining areas. Other than a single fecal coliform detection in 1997, bacteriological monitoring has found no contamination.

Other Factors Relevant to Stream Nutrients N and P

Other factors that might affect biological response to stream nutrients other than N and P are the same as those related to N and P that are described above under "Biological Responses to Stream Nutrients N and P."

Reference Watersheds

The nutrients Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, and SO_4^{2-} have been monitored in streams on FEF reference watersheds since the early 1980s. Variations in stream chemistry observed among FEF watersheds, including the reference watersheds, were correlated with basin lithology. For example, the mean pH of St. Louis Creek and its tributaries is 7.8 standard unit (SU) and ranges from 7.4 to 8.1 SU, with higher values in streams on sedimentary bedrock. Also, pH, Ca^{2+}, Mg^{2+}, ANC, and electrical conductivity of stream water were higher in basins with mixed geology (Nelson et al. 2011). Concentrations of nutrients other than N and P in FEF reference streams did not show any significant trends over time.

Cross-Site and Regional Studies

Atmospheric deposition of SO_4^{2-} at FEF, measured by Stottlemyer (1987, 1997), was similar to other high-elevation NADP stations in the Rocky Mountains.

Mercury has not been measured in deposition, stream water, or food chains at FEF, and regional analyses are contradictory about what levels might be expected. The Western Airborne Contaminants Assessment Project (2002–2007) measured deposition of heavy metals, such as Hg, and of semivolatile organic compounds, including pesticides, across 20 western national parks and monuments (Hageman et al. 2010, Landers et al. 2018). The nearest site studied was Rocky Mountain National Park, about 65 km north of FEF. Sites on the eastern side of Rocky Mountain National Park had elevated Hg levels in snowpack, along with some of the highest levels of semi-volatile organic compounds in the survey. In contrast, NADP maps of regional Hg deposition predict relatively low Hg deposition ($<9\ \mu g/m^2$) in the vicinity of FEF (NADP 2019b). These maps are based on NADP Hg monitoring sites, the closest of which is Fort Collins, 100 km northeast of FEF. Whether current environmental levels of Hg at FEF are high, as Western Airborne Contaminants Assessment Project results suggest, or low, as NADP deposition maps seem to indicate, may remain unresolved until measurements of Hg in deposition, stream water, and food chains are made at FEF.

Responses to Management and Natural Disturbances

Clearcut timber harvest at FEF increased Ca^{2+}, Mg^{2+}, $Na^+$and K^+ ions in stream water (Reuss et al. 1997), but in snowpack, clearcut logging produced concentrations of K^+ and H^+ that were lower than in forested areas (Stottlemyer and Troendle 2001).

The primary source of natural disturbance to forests in this region, wildland fire, can alter levels of nutrients other than N and P in streams. For example, the Hayman Fire of 2002, which occurred about 100 km southeast of FEF, increased postfire stream water Ca^{2+}, K^+, and ANC and decreased stream SO_4^{2-} and Cl^- (Rhoades et al. 2006). Studies of beetle-caused mortality of trees at FEF (Hubbard et al. 2014, Rhoades et al. 2008) did not examine stream nutrients other than N and P.

Research Needs

From a water quality perspective, there are no research needs of high priority related to nutrients other than N and P that need to be filled at FEF at this time. Most current management efforts are focused on N and P because they are considered to be the principal drivers of eutrophication.

Potential Utility to Water Quality Regulatory Agencies

Existing FEF datasets and research findings on atmospheric deposition of pollutants might be helpful in determining whether measures to control such pollutants are effective for protecting water quality in high-elevation streams along the Front Range. In the future, continued environmental monitoring at FEF might serve as an early warning for changes in atmospheric deposition and whether such changes have the potential to affect water quality.

Key points:

- Reference watersheds with minimal anthropogenic disturbance provide important opportunities to study water quality changes that may result from atmospheric deposition of pollutants from offsite sources, in addition to changes from other disturbances such as insect outbreaks and warming climate.
- Continued monitoring at FEF might be useful by providing early warning of changes in atmospheric deposition that could potentially affect water quality in mountain streams.
- For purposes of addressing nutrient pollution, there are no research needs of high priority related to nutrients other than N and P at this time.
- The FEF has publicly available, high-quality and long-term hydrology, temperature, meteorological, and stream chemical data.
- The FEF is an important reference site in the region and has also been used in nationwide comparison studies.
- Low levels of anthropogenic disturbance maintained at FEF provide useful opportunities to monitor effects of contaminant deposition from atmospheric pathways and provide early warning of changes that could affect aquatic ecosystems.
- Controlled forestry management experiments on the FEF are useful for developing science-based BMPs designed to protect water quality and aquatic ecosystems.
- The highest priority research need at FEF, for the purpose of addressing nutrient pollution, is to characterize existing biological communities, including algae, macroinvertebrates, and fish in relatively undisturbed reference streams, and to determine at what threshold levels, and after how much time, reference stream communities change in response to enrichment with N and P.

Overview and Synthesis

The study watersheds at FEF are typical of the high-altitude, snow-dominated basins that produce ~85 percent of the water yield from the Colorado Rocky Mountains Front Range. These alpine basins are especially important because they provide not only a primary source of high-quality drinking water in this region but other beneficial uses such as habitat for aquatic life, fishing, boating, and swimming. They are also used for agricultural purposes and by local businesses. Although these alpine ecosystems are well adapted to survive the harsh mountain climate, and are relatively isolated from many human activities, they may be susceptible to a variety of influences that could alter water quality in mountain streams. Decades of research and monitoring at FEF have measured water quantity and water quality impacts from common forest management practices and natural disturbances in these high-altitude basins. Controlled investigations of the effects of forest management practices on FEF streams may help to better inform BMP strategies to protect stream systems. Studies at FEF may also be useful for investigating how regional and global influences such as deposition of air pollution and climate warming might affect water quality and aquatic communities in reference watersheds. Evidence that NO_3^- concentrations in FEF reference streams have significantly changed over recent decades raises questions about how to incorporate "baseline" reference conditions that are not static into the development of water quality criteria. Finally, the highest priority research need at FEF to address nutrient pollution is to characterize existing biological communities including algae, macroinvertebrates, and fish in relatively undisturbed reference streams, and to determine at what threshold levels, and after how much time, reference stream communities change in response to enrichment with N and P.

References

Adenlof, K.A.; Wohl, E.E. 1994. Controls on bedload movement in a subalpine stream of the Colorado Rocky Mountains, U.S.A. Arctic and Alpine Research. 26: 77–85.

Alexander, R.R. 1987. Early history of St. Louis Creek and the Fraser Experimental Forest: a narrative. In: Troendle, C.A.; Kaufmann, M.R.; Hamre, R.H.; Winokur, R.P., eds. Management of subalpine forests: building on 50 years of research. Proceedings of a conference. Gen. Tech. Rep. RM-149. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 1–11.

Alexander R.R.; Troendle, C.A.; Kaufmann, M.R.; Shepperd, W.D.; Crouch, G.L.; Watkins, R.K. 1985. The Fraser Experimental Forest, Colorado: research program and published research 1937–1985. Gen. Tech. Rep. RM-118. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 46 p.

Alexander, R.R.; Watkins, R.K. 1977. The Fraser Experimental Forest, Colorado. Gen. Tech. Rep. RM-40. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 32 p.

Alstatt, D.; Miles, R.L. 1983. Soil survey of Grand County area, Colorado. Fort Collins, CO: U.S. Department of Agriculture, Soil Conservation Service and Colorado Agricultural Experiment Station. Washington, DC: U.S Government Printing Office. 174 p.

Argerich, A.; Johnson, S.L.; Sebestyn, S.D.; Rhoades, C.C.; Greathouse, E.; Knoepp, J.D.; Adams, M.B.; Likens, G.E.; Campbell, J.L.; McDowell, W.H.; Scatena, F.N.; Ice, G.G. 2013. Trends in stream nitrogen concentrations for forested reference catchments across the USA. Environmental Research Letters. 8 p. doi:10.1088/1748-9326/8/1/014039. 8 p.

Baker, M.E.; King, R.S. 2010. A new method for detecting and interpreting biodiversity and ecological community thresholds. Methods in Ecology and Evolution. 1: 25–37. doi:10.1111/j.2041-210X.2009.00007.x.

Baron, J.S.; Rueth, H.H.; Wolfe, A.M.; Nydick, K.R.; Allstott, E.J.; Minear, J.T.; Moraska, B. 2000. Ecosystem responses to nitrogen deposition in the Colorado Front Range. Ecosystems. 3: 352–368.

Collins, B.J.; Rhoades, C.C.; Battaglia, M.A.; Hubbard, R.M. 2012. The effects of bark beetle outbreaks on forest development, fuel loads, and potential fire behavior in salvage logged and untreated lodgepole pine forests. Forest Ecology and Management. 28: 260–268.

Collins, B.J.; Rhoades, C.C.; Hubbard, R.M.; Battaglia, M.A. 2011. Tree regeneration and future stand development after bark beetle infestation and harvesting in Colorado lodgepole pine stands. Forest Ecology and Management. 261(11): 2168–2175.

Colorado Department of Public Health and Environment, Water Quality Control Commission [CDPHE WQCC]. 2010. 5 CCR 1002-93, Regulation #93, Colorado Section 303(D) List of Impaired Waters and Monitoring and Evaluation List.

Colorado State University [CSU]. 2017. Warner College of Natural Resources. http://warnercnr.colostate.edu/. (25 October 2017).

David, G.C.L.; Legleiter, C.J.; Wohl, E.; Yochum, S.E. 2013. Characterizing spatial variability in velocity and turbulence intensity using 3-D acoustic Doppler velocimeter data in a plane-bed reach of East St. Louis Creek, Colorado, USA. Geomorphology. 183: 28–44.

Davis, J.M.; Rosemond, A.D.; Eggert, S.L.; Cross, W.F.; Wallace, J.B. 2010. Long-term nutrient enrichment decouples predator and prey production. Proceedings of the National Academy of Science. 107(1): 121–126.

Elder, K.; Dwire, K.; Hubbard, R.; Rhoades, C.; Ryan, S.; Young, M.; Porth, L.; Dixon, M.; Goodbody, A. 2006. Disturbance and water related research in the Western United States. In: Fowler, D.L., comp. Second interagency conference on research in the watersheds: challenges and opportunities in watershed research. Ashville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station: 3–21. https://www.srs.fs.fed.us/pubs/28765. (1 March 2021).

Fenn, M.E.; Poth, M.A.; Aber, J.D.; Baron, J.S.; Bormann, B.T.; Johnson, D.W.; Lemly, A.D.; McNulty, S.G.; Ryan, D.F.; Stottlemyer, R. 1998. Nitrogen excess in North American ecosystems: predisposing factors, ecosystem responses, and management strategies. Ecological Applications. 8: 706–733.

Grand County Water Information Network [GCWIN]. 2017a. Data. http://www.gcwin.org/. (1 March 2021).

Grand County Water Information Network [GCWIN]. 2017b. Ambient Water Quality Monitoring System (AWQMS). https://www.gcwin.org/data. (6 May 2019).

Hageman, K.J.; Hafner, W.D.; Campbell, D.H.; Jaffe, D.A.; Landers, D.H.; Massey-Simonich, S.L. 2010. Variability in pesticide deposition and source contributions to snowpack in western U.S. National Parks. Environmental Science and Technology. 44: 4452–4458.

Heede, B.H. 1972. Influences of a forest on the hydraulic geometry of two mountain streams. Water Resources Bulletin. 8: 523–530.

Hubbard, R.M.; Elder, K.; Rhoades, C.C.; Hays, P.; Sims, B. 2014. Small bugs with big impacts: ecosystem and watershed-level responses to the MPB epidemic. In: Matonis, M.; Hubbard, R.M.; Gebert, K.; Hahn, B.; Miller, S.; Regan, C., eds. Future forests webinar series, webinar proceedings and summary: ongoing research and management responses to the mountain pine beetle outbreak. Proceedings RMRS-P-70. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 61–72. Chapter 7.

Hubbard, R.M.; Ryan, M.G.; Elder, K.; Rhoades, C.C. 2005. Seasonal patterns in soil surface CO_2 flux under snow cover in 50 and 300 year old subalpine forests. Biogeochemistry. 73: 93–107.

Huckaby, L.S.; Moir, W.H. 1995. Fire history of subalpine forests at Fraser Experimental Forest, Colorado. In: Brown, J.K.; Mutch, R.W.; Spoon, C.W.; Wakimoto, R.H., eds. Proceedings: symposium on fire in wilderness and park management. Gen. Tech. Rep. INT-GTR-320. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 205–210.

Jeremiason, J.D.; Engstrom, D.R.; Swain, E.B.; Nater, E.A.; Johnson, B.M.; Almendinger, J.E.; Monson, B.A.; Kolka, R.K. 2006. Sulfate addition increases methylmercury production in an experimental wetland. Environmental Science and Technology. 40: 3800–3806. doi:10.1021/es0524144.

Jones, J.A.; Creed, I.F.; Hatcher, K.L.; Warren, R.J.; Adams, M.B.; Benson, M.H.; Boose, E.; Brown, W.A.; Campbell, J.L.; Covich, A.; Clow, D.W.; Dahm, C.N.; Elder, K.; Ford, C.R.; Grimm, N.B.; Henshaw, D.L.; Larson, K.L.; Miles, E.S.; Miles, K.M.; Sebestyen, S.D.; Spargo, A.T.; Stone, A.B.; Vose, J.M.; Williams, M.W. 2012. Ecosystem processes and human influences regulate streamflow response to climate change at Long-Term Ecological Research sites. BioScience. 62(4): 390–404. doi:10.1525/bio.2012.62.4.10.

Kaufmann, M.R. 1985. Annual transpiration in subalpine forests: large differences among four tree species. Forest Ecology and Management. 13: 236–246.

Landers, D.H.; Schwindt, A. Hageman, K.; Blett, T.; Simonich, S.; Schreck, C.; Usenko, S.; Erway, M.M.; Jaffe, D.; Kent, M.; Ackerman, L.; Geiser, L.; Hafner, W.; Schrlau, J.; Campbell, D.H.; Taylor, H.E.; Rose, N.; Christie, S. 2018. The fate, transport, and ecological impacts of airborne contaminants in western national parks (USA). Western Airborne Contaminants Assessment Project final report. EPA/600/R-07/138. Environmental Protection Agency (EPA). Corvallis, Oregon. https://irma.nps.gov/DataStore/Reference/Profile/660829. (6 May 2019).

Leaf, C.F. 1975. Watershed management in the Rocky Mountain subalpine zone: the status of our knowledge. Res. Pap. RM-137. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 31 p.

Lewis, W.M., Jr.; McCutchan, J.H., Jr. 2010. Ecological responses to nutrients in streams and rivers of the Colorado mountains and foothills. Freshwater Biology. 55: 1973–1983.

Lisle, T.E.; Adams, M.; Reid, L.M.; Elder, K. 2010. Hydrologic influences of forest vegetation in a changing world: learning from Forest Service experimental forests, ranges, and watersheds. In: Adams, M.; NcNeel, J.; Rodriguez-Franco, C., eds. Meeting current and future conservation challenges through the synthesis of long-term silviculture and range management research. Gen. Tech. Rep. WO-84. Washington, DC: U.S. Department of Agriculture, Forest Service: 37–49.

Long Term Ecological Research Network [LTER]. 2017. Climate and hydrology database projects (CLIMDB/HYDRODB). http://climhy.lternet.edu/. (1 March 2021).

National Aeronautics and Space Administration [NASA]. 2017a. Cold Land Processes Field Experiment (CLPX) data server. http://nsidc.org/data/clpx/clpx_data.html. (1 March 2021).

National Atmospheric Deposition Program [NADP}. 2019a. National Trends Network http://nadp.slh.wisc.edu/ntn/. (1 July 2019).

National Atmospheric Deposition Program [NADP]. 2019b. Annual NDM [Mercury Deposition Network]. maps. http://nadp.slh.wisc.edu/MDN/annualmdnmaps.aspx (1 July 2019).

Nelson, M.L.; Rhoades, C.C.; Dwire, K.A. 2011. Influence of bedrock geology on water chemistry of slope wetlands and headwater streams in the southern Rocky Mountains. Wetlands. 31: 251–261.

Pelz, K.A.; Rhoades, C.C.; Hubbard, R.M.; Battaglia, M.A.; Smith, F.W. 2015. Species composition influences management outcomes following mountain pine beetle in lodgepole pine-dominated forests. Forest Ecology and Management. 336: 11–20.

Retzer, J.L. 1962. Soil survey of Fraser alpine area. Colorado Soil Survey 1956. No. 20. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Soil Conservation Service and Colorado Agriculture Experiment Station. Washington, DC: U.S. Government Printing Office. 47 p.

Reuss, J.O.; Stottlemyer, R.; Troendle, C.A. 1997. Effect of clearcutting on nutrient fluxes in a subalpine forest at Fraser, Colorado. Hydrology and Earth System Sciences. 1: 333–344.

Rhoades, C.C.; Elder, K.; Greene, E. 2010. The influence of an extensive dust event on snow chemistry in the southern Rocky Mountains. Arctic, Antarctic, and Alpine Research. 42(1): 98–105.

Rhoades, C.C.; Elder, K.; Hubbard, R.M.; Dixon, M. 2008. Streamwater chemistry and nutrient export during five years of bark beetle infestation of subalpine watersheds at the Fraser Experimental Forest. Eos: Transactions of the American Geophysical Union. 89(53): Fall Meeting Supplement, Abstract H13C-0929.

Rhoades, C.C.; Entwistle, D.; Butler, D. 2006. Initial streamwater response to the Hayman fire, Colorado Front Range. In: Fowler, D.L., comp. Second interagency conference on research in the watersheds: challenges and opportunities in watershed research. Ashville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. https://www.srs.fs.fed.us/pubs/28765. (16 November 2017).

Rhoades, C.C.; Hubbard, R.M.; Elder, K. 2017. A decade of stream water nitrogen and forest dynamics after a mountain pine beetle outbreak at the Fraser Experimental Forest, Colorado. Ecosystems. 20: 380–392. doi:10.1007/s10021-016-0027-6.

Rhoades, C.C.; McCutchan, J.H., Jr.; Cooper, L.A.; Clow, D.; Detmer, T.M.; Briggs, J.S.; Stednick, J.D.; Veblin, T.T.; Ertz, R.M.; Likens, G.E.; Lewis, W.M., Jr. 2013. Biogeochemistry of beetle-killed forests: explaining a weak nitrate response. Proceedings of the National Academy of Sciences. 110: 1756–1760.

Rutter, N.; Essery, R.; Pomeroy, J.; Altimir, N.; Andreadis, K.; Baker, I.; Barr, A.; Bartlett, P.; Boone, A.; Deng, H.; Douville, H.; Dutra, E.; Elder, K.; Ellis, C.; Feng, X.; Gelfan, A.; Goodbody, A.; Gusev, Y.; Gustafsson, D.; HellstrÖn, R.; Hirabayashi, Y.; Hirota, T.; Jonas, T.; Koren, V.; Kuragina, A.; Lettenmaier, D.; Li, W.-P.; Luce, C.; Martin, E.; Nasonova, O.; Pumpanen, J.; Pyles, R.D.; Samuelsson, P.; Sandells, M.; Schädler, G.; Shmakin, A.; Smirnova, T.G.; Stähli, M.; Stöckli, R.; Strasser, U.; Su, H.; Suzuki, K.; Takata, K.; Tanaka, K.; Thompson, E.; Vesala, T.; Viterbo, P.; Wiltshire, A.; Xia, K.; Xue, Y.; Yamazaki, T. 2009. Evaluation of forest snow processes models (SnowMIP2). Journal of Geophysical Research 114: D06111. doi:10.1029/2008JD011063.

Ryan, S.E.; Porth, L.S.; Troendle, C.A. 2005. Coarse sediment transport in mountain streams in Colorado and Wyoming, USA. Earth Surface Processes and Landforms. 30: 269–288.

Stottlemyer, R. 1987. Natural and anthropic factors as determinants of long-term streamwater chemistry. In: Troendle, C.A.; Kaufmann, M.R.; Hamre, R.H.; Winokur, R.P., tech. coords. Management of subalpine forests: building on 50 years of research. Gen. Tech. Rep. RM-149. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station: 86–94.

Stottlemyer, R. 1997. Stream water chemistry in watersheds receiving different atmospheric inputs of H+, NH_{4+}, NO_{3-}, and SO_4^{2-}. Journal of the American Water Resources Association. 33(4): 767–779.

Stottlemyer, R. 2001. Processes regulating watershed chemical export during snowmelt, Fraser Experimental Forest, Colorado. Journal of Hydrology. 245: 177–195.

Stottlemyer, R.; Troendle, C.A. 1992. Nutrient concentration patterns in streams draining alpine and subalpine catchments, Fraser Experimental Forest, Colorado. Journal of Hydrology. 140: 179–208.

Stottlemyer, R.; Troendle, C.A. 1999. Effect of subalpine canopy removal on snowpack, soil solution, and nutrient export, Fraser Experimental Forest, CO. Hydrological Processes. 13: 2287–2299.

Stottlemyer, R.; Troendle, C.A. 2001. Effect of canopy removal on snowpack quantity and quality, Fraser Experimental Forest, Colorado. Journal of Hydrology. 245: 165–176.

Stottlemyer, R.; Troendle, C.A.; Markowitz, D. 1997. Change in snowpack, soil water, and streamwater chemistry with elevation during 1990, Fraser Experimental Forest, Colorado. Journal of Hydrology. 195: 114–136.

Trayler, C.R.; Wohl, E.E. 2000. Seasonal changes in bed elevation in a step-pool channel, Rocky Mountains, Colorado, U.S.A. Arctic, Antarctic and Alpine Research. 32: 95–103.

Troendle, C.A.; King, R.M. 1985. The effect of timber harvest on the Fool Creek watershed, 30 years later. Water Resources Research. 21: 1915–1922.

Troendle, C.A.; King, R.M. 1987. The effect of partial and clearcutting on streamflow at Deadhorse Creek, Colorado. Journal of Hydrology. 90: 145–157.

Troendle, C.A.; Nilles, M.A. 1987. The effect of clearcutting on chemical exports in lateral flow from different depths on a subalpine forest slope. In: Swanson, R.H.; Bernier, P.Y.; Woodard, P.D., eds. Forest hydrology and watershed management. IAHS Publ. No. 167. Washington, DC: International Association of Hydrologic Sciences: 423–432.

Troendle, C.A.; Olsen, W.K. 1994. Potential effects of timber harvest and water management on streamflow dynamics and sediment transport. In: Covington, W.W.; DeBano, L.F., tech. coords. Sustainable ecological systems: implementing an ecological approach to land management. Gen. Tech. Rep. RM-247. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station: 34–41.

Troendle, C.A.; Reuss, J.O. 1997. Effect of clear cutting on snow accumulation and water outflow at Fraser, Colorado. Hydrology and Earth System Sciences. 1: 325–332.

U.S. Department of Agriculture, Forest Service [USDA]. 2008. Monitoring and evaluation report of the 1997 revision of the Land and Resource Management Plan for fiscal year 2008. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Arapaho and Roosevelt National Forests and Pawnee National Grassland. 35 p.

U.S. Department of Agriculture, Forest Service [USDA]. 2017a. Fraser Experimental Forest. http://www.fs.usda.gov/fraser. (25 October 2017).

U.S. Department of Agriculture, Forest Service [USDA]. 2017b. Research data archive. http://www.fs.usda.gov/rds/archive/Catalog?freesearch=fraser&searchfield=. (1 March 2021).

U.S. Department of Agriculture, Forest Service [USDA]. 2017d. Rocky Mountain Research Station Air, Water and Aquatic Environments Program (AWAE). http://www.fs.fed.us/rm/boise/awae_home.shtml. (1 March 2021).

U.S. Department of Agriculture, Forest Service [USDA]. 2017c. Treesearch: publication search engine. https://www.fs.usda.gov/treesearch/. (1 March 2021).

U.S. Department of Agriculture, Natural Resources Conservation Service [USDA NRCS]. 2017. Natural Resource Conservation Service Snow Telemetry SNOTEL. http://www.wcc.nrcs.usda.gov/snow/. (1 March 2021).

U.S. Department of the Interior, Geological Survey [USDI GS]. 2017a. Fort Collins Science Center. https://www.fort.usgs.gov/. (1 March 2021).

U.S. Department of the Interior, Geological Survey [USDI GS]. 2017b. National Water Information System. https://waterdata.usgs.gov/co/nwis/inventory/?site_no=09026500. (1 March 2021).

U.S. Environmental Protection Agency [USEPA]. 2015. Impaired waters and total maximum daily loads. http://water.epa.gov/lawsregs/lawsguidance/cwa/tmdl/. (1 March 2021).

U.S. Environmental Protection Agency [USEPA]. 2017. STORET water quality data. https://www.epa.gov/storet/dbtop.html. (1 March 2021).

Wellnitz, T.A.; Rader, R.B.; Ward, J.V. 1996. Importance of light and nutrients in structuring an algal community in a Rocky Mountain stream. Journal of Freshwater Ecology. 11: 399–413.

Wilm, H.G.; Dunford, E.G. 1948. Effect of timber cutting on water available for streamflow from a lodgepole pine forest. Tech. Bull. 968. Washington, DC: U.S. Department of Agriculture, Forest Service. 43 p.

Wohl, E.; Jaeger, K. 2009. A conceptual model for the longitudinal distribution of wood in mountain streams. Earth Surface Processes and Landforms. 34: 329–344.

Yochum, S.E.; Bledsoe, B.P.; Wohl, E.; David, G.C.L. 2014. Spatial characterization of roughness elements in high-gradient channels of the Fraser Experimental Forest, Colorado, USA. Water Resources Research. 50: 6015–6029.

Young, M.K.; Schmal, R.N.; Kohley, T.W.; Leonard, V.G. 1996. Conservation status of Colorado River cutthroat trout. Gen. Tech. Rep. RM-282. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 32 p.