Effects of flow regime on stream turbidity and suspended solids after wildfire, Colorado Front Range

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Abstract Wildfires occur frequently in the Colorado Front Range and can alter the hydrological response of watersheds, yet little information exists on the impact of flow regime and storm events on post-wildfire water quality. The flow regime in the region is characterized by base-flow conditions during much of the year and increased runoff during spring snowmelt and summer convective storms. The impact of snowmelt and storm events on stream discharge and water quality was evaluated for about a year after a wildfire near Boulder, Colorado, USA. During spring snowmelt and low-intensity storms, differences in discharge and turbidity at sites upstream and downstream from the burned areas were minimal. However, high-intensity convective storms resulted in dramatic increases in discharge and turbidity at sites downstream from the burned area. This study highlights the importance of using high-frequency sampling to assess accurately wildfire impacts on water quality downstream.

Key words wildfire; water quality; turbidity; Colorado Front Range; Fourmile Canyon fire; flow regime; convective storms

INTRODUCTION

Wildfire size, fire severity and length of fire season have increased in recent years, largely due to effects from climate variability, including extreme droughts, forest disease outbreaks, and changes in precipitation patterns (Westerling *et al.*, 2006; Holden *et al.*, 2007). Wildfires can drastically alter the hydrological and soil properties of watersheds (Moody & Martin, 2001), leading to increased flooding, erosion, and sediment loads. Large erosion events, such as those caused by wildfire, are short-lived on geological time scales, but can dominate the long-term sediment yield response (Kirchner *et al.*, 2001). Wildfires can impair water quality and are a major disturbance in many terrestrial and aquatic ecosystems. Studies of surface waters after wildfire have reported increases in turbidity, nutrients, organic carbon, sulfate, major ions and trace metals (e.g. Tiedemann *et al.*, 1979; Gresswell, 1999). Water quality effects from wildfire vary substantially depending on several factors including, amongst others, the proportion of watershed burned, steepness of watershed slopes, geology, and post-fire precipitation type, timing and intensity (Beschta, 1990; Neary *et al.*, 2005).

The Fourmile Canyon Fire burned 2600 hectares and destroyed more than 160 homes in Boulder County, Colorado, USA in September 2010. The wildfire burned 23% of the Fourmile Creek Watershed (Fig. 1). As a result of high winds and rapid movement of the fire front, burn severity ranged from low to severe (Keeley, 2009; Fourmile Emergency Stabilization Team, 2010). The Fourmile Creek watershed consists largely of steep, rugged terrain and the wildfire has left the area at risk of substantial erosion, including debris flows (Ruddy *et al.*, 2010). The watershed also contains abandoned waste rock and tailings piles from historical mining, many of which have been exposed by the wildfire. Fourmile Creek discharges to Boulder Creek about 3 km upstream from the city of Boulder, Colorado. Fourmile Creek and Boulder Creek are sources for water supply for local communities. Several other wildfires have occurred in this region in the past 25 years (Fig. 1). Therefore, an in-depth study of the hydrological and hydrochemical responses of this watershed was warranted to assess how watershed processes are affected and to determine the increase in risks of flooding, debris flows and water quality impairment.

The flow regime in this watershed, as is typical in the Colorado Front Range and many watersheds in the western USA, is characterized by base-flow conditions during much of the year, with increased runoff during spring snowmelt and high-intensity summer convective storms.

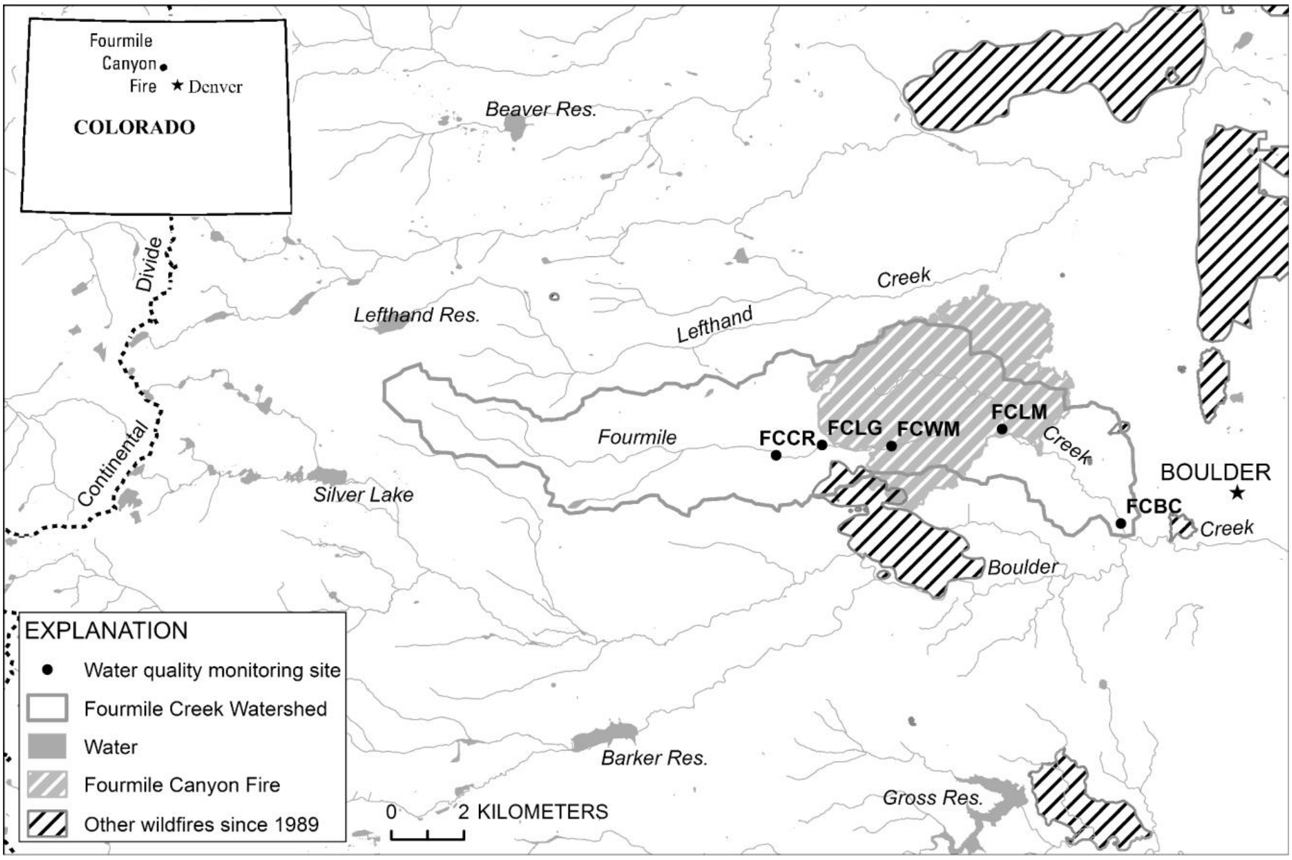

Fig. **1** Map showing the study location (wildfire areas from Boulder County Land Use Department).

Water quality is closely tied to this annual regime, yet little information exists on the impact of snowmelt and convective storms on water quality after wildfire. Weekly or monthly water-quality sampling is not sufficient to capture effectively the relation between watershed hydrology and streamwater chemistry (Kirchner *et al.*, 2004), but the remote locations of many wildfires make frequent manual sampling difficult. This study focused on high-frequency water-quality sampling at several locations in the Fourmile Creek watershed for the purpose of understanding the coupling of hydrological and chemical processes, and to evaluate the effects of snowmelt runoff and summer convective storms on water quality. Specifically, this paper focuses on post-wildfire turbidity and total suspended solids. The export of carbon and nitrogen is discussed in Writer *et al.* (2012).

METHODS

Precipitation data from raingauges within and surrounding the burned area were obtained from the Urban Drainage and Flood Control District (UDFCD) and the National Atmospheric Deposition Program (NADP) (Fig. 1). The gauges operated by UDFCD (2011) are 1-mm tipping-buckets and the tips were summed to obtain daily precipitation, storm totals and maximum 30-minute rain intensity (which was converted to units of mm h^{-1} and is abbreviated here as I_{30}). Daily precipitation at five raingauges in, or near to, the burned area was averaged to estimate average daily precipitation in the region for the period June–September (these raingauges are not designed to record snow, which commonly occurs from October to May). Data from the NADP Sugarloaf station is recorded by an ETI Total Precipitation Gauge NOAH IV, which is an all-weather precipitation gauge that weighs the entire contents of an internal collection container. Both daily and 15-minute precipitation data are reported (NADP, 2011) from this gauge. These daily data were used to estimate precipitation in the region for the period October–May. Daily minimum temperature was also obtained from the NADP Sugarloaf station (NADP, 2011).

Five sites on Fourmile Creek were monitored for water quality and quantity for over a year following the wildfire (Fig. 1), and four of these were instrumented to obtain continuous discharge data. Historical (1947–1953, 1983–1995) mean daily discharge and peak discharge data from USGS stream-gauging station 06727500 (located 0.4 km upstream from Boulder Creek at site FCBC; Fig. 1) were obtained from the US Geological Survey (USGS, 2011). A stream-gauging station was re-installed at this location by the USGS Colorado Water Science Center in 2011. An additional station (06727410) was installed on Fourmile Creek at Logan Mill Road about 5.8 km upstream of Boulder Creek (at the FCLM site) in 2011. These two stations reported discharge every five minutes from 1 April to 30 September 2011. Vented water-level loggers (Global Water, model WL16U) were deployed at sites FCCR and FCWM (and FCLM and FCBC prior to the installation of USGS stream-gauging stations) to monitor stage. Prior to deployment, the water-level loggers were calibrated by measuring instrument response at 0.1-m intervals for water depths from 0 to 1.1 m. The water level loggers were housed within 1.5-m long sections of 5-cm diameter, perforated PVC pipe anchored to the streambed with rebar. Data were downloaded from the instruments at approximate 30-day intervals. Stream discharge was measured periodically with a pygmy meter using standard US Geological Survey protocols (Rantz *et al.*, 1982), and these measurements were used to generate a rating curve for each site, and to subsequently estimate stream discharge from stage readings.

The four sites monitored for continuous stream discharge (FCCR, FCWM, FCLM, and FCBC; Fig. 1) were also instrumented with conductivity loggers from Onset Corporation (Hobo data logger U24-001) to monitor continuously electrical conductivity and temperature. Water samples were collected monthly during base-flow conditions and twice weekly during snowmelt runoff. Electrical conductivity (Amber Science, Model 2052) and pH and temperature (Orion, 3-Star pH/temperature meter) were measured in the stream. Water samples were collected in pre-cleaned 1-L Teflon bottles and immediately returned to the USGS National Research Program laboratory in Boulder, Colorado for filtering, preservation, and measurement of turbidity (within 4 hours). Water samples were collected at more frequent intervals using automatic samplers (ISCO, models 6700 and 6712) during, or immediately after, substantial precipitation events (12 October 2010; 15–17 April 2011; 18–20 May 2011; 19–21 June 2011; 7–8 July 2011; 13–14 July 2011; and 7 September 2011) at sites FCCR, FCWM, FCLM, and FCBC. Automatic samplers were either triggered manually or when water level reached a pre-set stage. These samples were collected in pre-cleaned 1-L polyethylene sampling bottles and were delivered to the laboratory for measurement of electrical conductivity and turbidity, filtration, and preservation within 48 hours. The turbidity of unfiltered samples was measured using a Hach 2100Q portable turbidimeter, which was calibrated with 20, 100 and 800 nephelometric turbidity unit (NTU) formazin standards provided by the manufacturer (Hach Company, 2010). If the turbidity of the sample exceeded the range of the instrument (1000 NTU), the sample was diluted with de-ionized water, agitated, and re-analysed. A subset of samples was analysed for total suspended solids (TSS). The mass of dried sediment suspended on a 0.4-micrometer pore size filter, plus the mass of sample passed through the filter were recorded, and the mass of water sample was converted to volume assuming a water density of 1 g cm^{-3} (very turbid samples may have a greater density, but by comparing sample volume to mass, the maximum error related to this assumption was determined to be less than 7%). The relation between turbidity and TSS was calculated using a simple linear regression, as described below. Filtered samples were analysed for dissolved organic carbon, nutrients, major cations and anions, plus metals (McCleskey *et al.*, 2012).

RESULTS AND DISCUSSION

The historical (1947–1953, 1983–1995) mean daily discharge of Fourmile Creek at FCBC ranged from 0.025 to 0.96 $m^3 s^{-1}$ (USGS, 2011). Discharge in April and the first half of May 2011 was lower than the historical mean, as a result of low snowfall (Fig. 2(a)). Discharge rose sharply in mid-May after minimum air temperatures rose above 0°C and two substantial precipitation events occurred (Fig. 2(b), Table 1). Several large storms in June and July led to discharge values that were higher than the historical daily mean. A convective storm on 13 July 2011 resulted in a peak discharge of 23 $m^3 s^{-1}$ at site FCLM, downstream from the burned area (Fig. 3(a)). This storm conveyed a substantial amount of sediment to Fourmile Creek, which moved through the stream system over the next few weeks, causing uncertainty in discharge values in late July to early August as sediment moving through the system modified the stream bed (and rating curve).

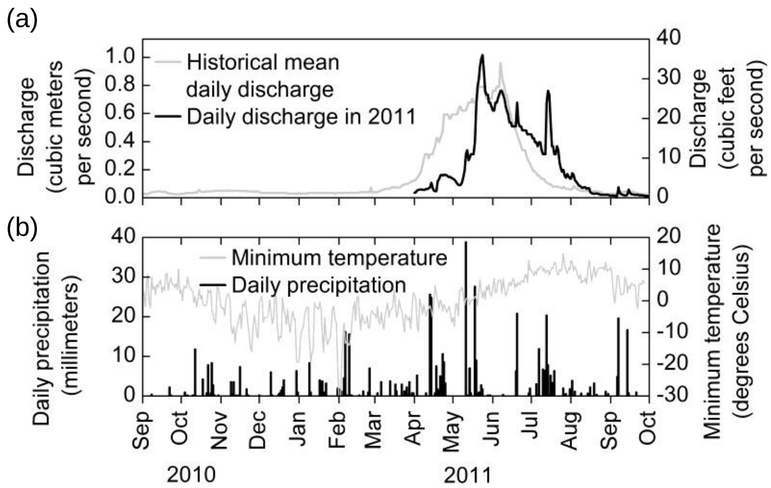

Fig. 2 (a) The historical mean daily discharge (1947–1953, 1983–1995) and mean daily discharge in 2011 of Fourmile Creek (at USGS streamflow-gauging station 06727500; USGS, 2011). (b) Precipitation and minimum daily air temperature, 1 September 2010 to 30 September 2011 (1 September 2010–31 May 2011 precipitation from Sugarloaf station, National Atmospheric Deposition Program (2011); 1 June–1 October 2011 precipitation from average of five Urban Drainage and Flood Control District raingauges in or near the burned area; temperature from Sugarloaf station (NADP, 2011)).

Table 1 Storms with daily precipitation totals greater than 10 mm, September 2010–September 2011.

Date	Type of precipitation	Total precipitation (mm)	Maximum I_{30}* (mm h^{-1})
12-Oct-10	rain	14	4
6-Feb-11	snow	16	--
9-Feb-11	snow	16	--
13-Apr-11	snow	26	--
14-Apr-11	snow	25	--
23-Apr-11	snow	11	--
24-Apr-11	snow	9	--
11-May-11	mix	39	--
18-May-11	mix	28	--
19-May-11	mix	9	--
19-Jun-11	rain	6	
20-Jun-11	rain	21	16 †
7-Jul-11	rain	12	46
13-Jul-11	rain	20	40
7-Sep-11	rain	20	8
14-Sep-11	rain	17	8

Dates with <10 mm included if part of the same storm as previous or following day; from Sugarloaf NADP station for dates with snow or mixed; average of 5 stations closest to the burned area for dates with rain only. *I_{30}, maximum 30-minute rainfall intensity at any of five gauges nearest the burned area (calculated for rain-only events)]

† Maximum value on 19 or 20 June 2011.

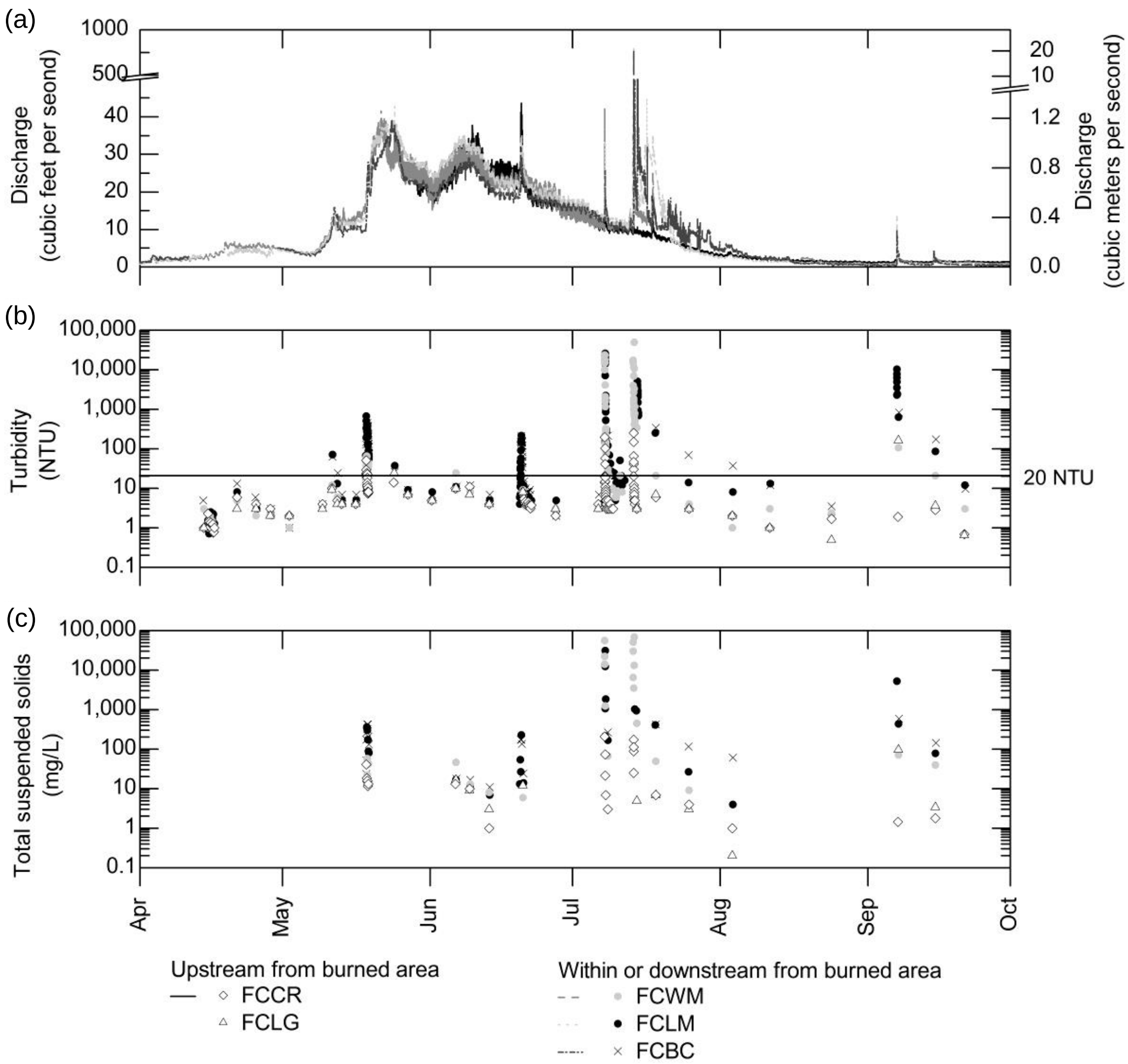

Fig. **3** Discharge, turbidity, and TSS measured in Fourmile Creek, 1 April to 30 September 2011.

Discharge at four locations along Fourmile Creek was similar during this study (Fig. 3(a)), suggesting that most of the water in the creek at all sampling locations is derived from upstream. Fourmile Creek has few major tributaries – the most substantial is the ephemeral Gold Run (Fig. 1) – and snowfall is greater in the upper reaches of the watershed. Summer rain storms varied in extent, total precipitation and intensity, and thus affected discharge at the monitoring sites differently. A large frontal storm on 19–20 June 2011 delivered an average of 27 mm precipitation to the five raingauges in, or near, the burned area (Table 1). This was the largest storm total in June/ July 2011; however, this storm had a relatively low rainfall intensity (maximum I_{30} of 16 mm h^{-1}; Table 1). This storm also had a relatively consistent intensity across the Fourmile Creek watershed. In contrast, convective storms on 7 and 13 July 2011 had lower precipitation totals (average values of 12 and 20 mm, respectively), but much higher rainfall intensities (maximum I_{30} values of 46 and 40 mm h^{-1}, respectively). These two convective storms were much smaller in extent, and were centred on different areas of the Fourmile Creek watershed. The 7 July 2011 storm was centred upstream from and within the western part of the burned area, near sampling sites FCCR, FCLG, and FCWM. Prior to the storm, discharge at all Fourmile Creek sites was between 0.29 and 0.34 m^3 s^{-1}

(Fig. 3(a)). During the storm, discharge at FCCR (located upstream from the burned area) increased to 0.4 $m^3 s^{-1}$ (49% increase), while discharge at FCWM and FCLM (within or downstream from the burned area) increased to 1.2 $m^3 s^{-1}$ (313% increase) and 0.93 $m^3 s^{-1}$ (175% increase), respectively (Fig. 3(a)). The 13 July 2011 storm was centred on Gold Run, which discharges to Fourmile Creek between sites FCWM and FCLM (Fig. 1). Pre-storm discharge at all sites was between 0.26 and 0.28 $m^3 s^{-1}$. During the storm, discharge at FCCR increased to 0.35 $m^3 s^{-1}$ (36% increase), discharge at FCWM increased to more than 1.0 $m^3 s^{-1}$ (at least 281% increase) and discharge at FCLM increased to 23 $m^3 s^{-1}$ (8100% increase) (Fig. 3(a)). Maximum discharge from Gold Run during the 13 July storm has been estimated at 8.2 $m^3 s^{-1}$ (R. D. Jarrett, USGS, written communication, 20 July 2011). These two convective storms had recurrence intervals of about 2 to 5 years (for 30-minute intervals; Miller *et al.*, 1973), i.e. have a 20–50% chance of occurring each year. Despite the relatively low storm totals, the 13 July 2011 event resulted in an increase in discharge that was about three times greater than ever recorded on Fourmile Creek (7.3 $m^3 s^{-1}$; USGS, 2011). Wildfires reduce the threshold precipitation intensity at which overland flow occurs; a 5-year recurrence interval storm in a burned forest can produce the same runoff response as that of an unburned forest during a 30-year recurrence interval storm (Wondzell & King, 2003).

During periods of no precipitation, including during snowmelt runoff, turbidity and TSS at all sites were low, and similar from site to site (Fig. 3). During precipitation events, turbidity and TSS at all sites typically increased, but turbidity and TSS at sites within and downstream from the burned area showed greater increases than upstream sites; dissolved organic carbon showed similar trends (Writer *et al.*, 2012). These increases were substantially greater during the high-intensity convective storms in July; turbidity and TSS values were as high as 50 000 NTU and 68 000 milligrams per litre (mg L^{-1}), respectively, within the burned area. These TSS values fall within a range of maximum reported TSS concentrations measured globally during stormflows in the first year after fire (11 to 500 000 mg L^{-1}; Smith *et al.*, 2011). Due to the large amount of sediment delivered to Fourmile Creek, particularly downstream from Gold Run, turbidity values downstream from the burned area remained elevated for several weeks after the storms – even when no precipitation occurred – as base flows continued to transport sediment through the system. A rain event on 7 September 2011, which had an I_{30} of only 8 mm h^{-1} (Table 1), remobilized stream sediment and led to turbidity values of 10 000 NTU at site FCLM (automatic samplers at other sites did not trigger during this event). Our findings that post-wildfire erosion was most significant during high-intensity storm events (in this case, 10 months after the wildfire) are similar to those of Benavides-Solorio & MacDonald (2005), who found that 90% of the sediment delivered after wildfire was generated by summer convective storms. These high-intensity storms led to substantial erosion in the study watershed, despite post-fire stabilization efforts that included aerial straw mulching and seeding of native plants (Boulder County, 2012). It was beyond the scope of this study to determine if these mitigation efforts were effective in decreasing erosion. Straw mulching can be significantly effective at reducing sediment yield, but effectiveness can be decreased due to uneven application and redistribution related to wind conditions, hillslope steepness and standing trees (Robichaud *et al.*, 2010), all of which are factors in the Fourmile Creek watershed.

The values for TSS showed a strong correlation with turbidity (Fig. 4). The relation for all samples was TSS = 1.5 × turbidity + 80, with an r^2 of 0.86 (Fig. 4(a)). In order to assess the error introduced by processing and diluting high-turbidity samples, we subdivided the samples into categories greater or less than the highest turbidity standard (800 NTU). When including only samples with turbidity <800 NTU, the correlation between turbidity and TSS improved to an r^2 value of 0.92 (TSS = 1.1 × turbidity + 4.8) (Fig. 4(b)). For samples with turbidity >800 NTU (which were all collected during the storm events of 7, 13 and 14 July, and 7 September 2011), the correlation decreased to an r^2 value of 0.769 (TSS = 1.5 × turbidity + 1300). These results suggest that measurement of turbidity, a much easier parameter to measure than TSS, may be used to estimate TSS and hence sediment loading in the study watershed. In-stream turbidimeters, however, may not accurately record the largest sediment loads in this watershed because these instruments have saturation limits that may be exceeded during storm events (Anderson, 2005).

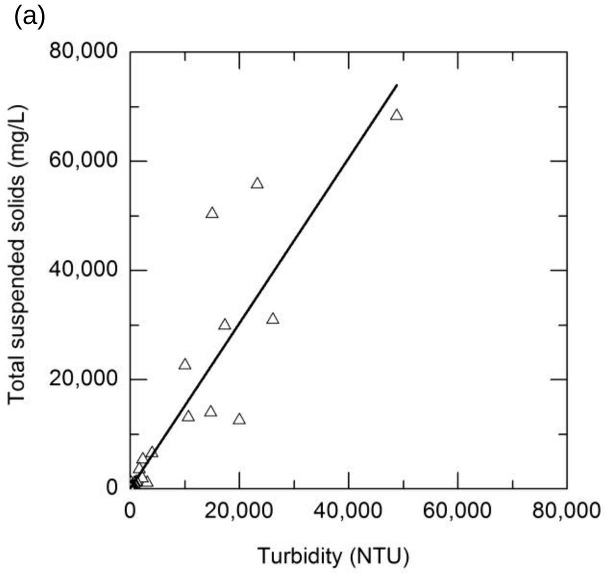

Fig. **4** Relation of TSS and turbidity for: (a) all samples and (b) samples with a turbidity < 800 NTU.

CONCLUSION

During periods of no precipitation, including during snowmelt runoff, turbidity and TSS values at sites upstream and downstream from a burned area in the Colorado Front Range were low and typically similar among sites. Low-intensity storm events often led to increases in turbidity and TSS at all sites, but the increases were greater at sites within or downstream from the burned area. High-intensity convective storms resulted in up to 80-fold increases in stream discharge downstream from the burned area, whereas discharge upstream from the burned area increased only 0.4-fold. These high-intensity convective storms mobilized sediment from hillslopes and led to substantial increases in turbidity and TSS in the local streams. The re-working of sediment deposits within the stream channel commonly resulted in elevated turbidity levels for weeks after the high-intensity convective storms. Subsequent, low-intensity rain events remobilized additional stream sediment. The results from this study suggest that dramatic water quality changes can occur during and immediately after high-intensity storms. A network of high-density precipitation stations and stream gauges is necessary to understand more fully water quality and quantity issues related to such events in a landscape impacted by wildfire.

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