Geomorphic Responses of Burned Watersheds in the Modern Fire Regime: Floods, Debris Flows and Long-Term Recovery

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Outline
• Fire Regimes and Trends
• Post-fire Hydrologic Changes
• Post-fire Geomorphic Responses
• Post-Fire Erosion and Rainfall Regimes across the Western US
• Post-fire Water Quality
• Post-fire Disturbance Regimes and implications for Watershed Recovery

Fire Regimes: Tree Ring Data

Fire Regimes: Pre-settlement

Fire Regimes: Tree Ring Data

Fire Regimes: Pre-settlement

Largest Arizona Wildfires, 1990-2011 (SWCC Historic Data)

... leaving forests devastated
With huge canopy holes

... leaving forests devastated
With huge canopy holes
SEVERITY VS. INTENSITY


Soil Burn Severity

Burn Severity: On the Ground

Low severity: Little change
- <50% litter consumption
- Needles and leaves intact

Moderate severity: Up to 80% litter consumption
- Needles and leaves recognizable or leaf/noodle fall

High severity: <20% remaining groundcover
- Nearly all litter and dust consumed
- Little to no leaf or needle fall to shield ground

Burn Severity: Soil Structure

Low severity: Little change
- No aggregate deterioration

Moderate severity: Slightly altered
- Consumption of organic matter in top 1 cm

High severity: Aggregates destroyed
- Loose / single grained soil
- Consumption of organic matter in top 5 cm

Burn Severity: Vegetation

Low severity: Scorched fuels at ground level
- 5-30% canopy scorching
- <1 m char height

Moderate severity: Understory vegetation consumed
- Canopy scorching but not consumed
- 3-5 m char height

High severity: Surface fuels and veg. consumed
- >2-4 m char height
- 90-100% canopy charred

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2010 Schultz Fire

Slide: Deb Martin, USGS
HYDROLOGIC CYCLE:
Runoff = Rainfall – Infiltration – Storage

Post-fire Hydrologic Changes

20% Interception

Unburned watershed
Burned watershed

Post-fire Runoff
Garden variety storms can produce post-fire debris flows.

Water repellency is ubiquitous in the western United States, especially when conditions are dry!

Unburned --STORAGE--Burned

Quick review:
Fire Effects on Landscape Susceptibility (particularly water routing)
- Loss of storage
- Surface Sealing
- Fire-induced water repellency
- Change in surface roughness
- Change in connectivity
Slope Effects
Runoff Generation

2004 Willow Fire, Arizona

- Increased Runoff on steep slopes = increased erosion
- Channels often scour to bedrock => decreased bank or channel storage
- Subsequent storms will have flashier hydrographs

Runoff Magnitude and Timing

Rate of Runoff or Rainfall

Hyetograph

Time lag

Hydrograph from burned watershed

Hydrograph from unburned watershed

Time

Wallow Fire, 10 Aug 2011
11.6 mm rainfall, $I_{30} = 11$ mm hr$^{-1}$

Video: J. Wagenbrenner

Wallow Fire Peak flows
$(11 \text{ L s}^{-1} \text{ km}^{-2} = 1 \text{ ft}^3 \text{ s}^{-1} \text{ mi}^{-2})$

- S. Thomas
- W. Willow
- N. Thomas

Pre-fire maxima

$1$-yr $I_{30}$

Runoff from Burned Watersheds

A function of:

- HEAT (effects quantified as BURN SEVERITY)
  - Loss of soil cover (storage + protection)
  - Changes to soil (fire-induced water repellency)
- SLOPE, GEOLOGY
- WHAT HAPPENS AFTER THE FIRE
  (sequence, magnitude, and location of rain events)

Slide: Deb Martin, USGS

Slide: J. Wagenbrenner

POST-FIRE PEAKFLOWS
0 - 900 TIMES > THAN UNBURNED
(Neary et al. 2005)

After the 2011 Wallow Fire Wagenbrenner et al. found a 5 – 18X increase in runoff after <1 yr storms

How do you visualize that?

UnBurned

Burned
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Why do we care about post-fire flooding and erosion?

- Loss of soil resources
- Effects on humans and infrastructure
- Effects on water quality and aquatic ecosystems

Post-fire Geomorphic Responses

High frequency (<1-5 RI), low magnitude storms can result in tremendous post-fire responses.

On this day Miller Canyon received 1.64” in an hour (2-yr, 60 minute storm)
 Peak 15-minute intensity = 0.92”
 Peak 30-minute intensity = 1.36” (2-yr RI)

Miller Canyon, 10 July 2011

- July 10, 2011 Marshall Canyon debris flows (this same canyon had debris flows after the 1977 Carr Fire)
- Other Miller Canyon debris flows
- 1.6” rainfall in ~1 hr (2 yr storm)
- First significant monsoon rain
- Damage to Beatty’s and Tombstone water pipe (again)

Miller Canyon, 10 July 2011

Debris flows initiate in channels on steep, severely burned hillslopes
Scour to bedrock in larger channels
Deposit coarse boulder fans
Post-fire debris flows:
- Intense runoff
- Channel bank failure
- Channel scour

Marshall Canyon channel reloaded since 1977 and had enough sediment for debris flows in 2011.
Post-fire flow in CA

Non post-fire debris flow but important to see

Burned Willow Fire watersheds along SR87 after July 23, 2004, storm

Compared NWS-Mt Ord ALERT gage; Radar over estimated ~30%
Radar rainfall estimates over SR-87 basins = ~2-2.5”
Reduces to ~1.4-1.75”/hr NOAA Atlas 14 = 2- to 5-yrs

Post-Aspen Fire Flood in Romero Canyon

Aspen Fire June 17 to July 14, 2003
Post-fire flood event on July 24, 2003

Radar 2.35” basin average 1-hour rainfall
63% radar-indicated precip reached ALERT gages
0.85 correction factor = 2.00” adj basin ave 1-hour rainfall
~80% fell within 30 min = 1.60” adj basin ave 30-min rainfall
NOAA Atlas 14 = 10 yr 30-min basin ave pptn freq

Post-Aspen Fire Flood in Romero Canyon

<table>
<thead>
<tr>
<th>Rain Gauge</th>
<th>ALERT Gauge Data</th>
<th>NWS Radar Data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Start</td>
<td>End</td>
</tr>
<tr>
<td>Green Mountain</td>
<td>6:15 PM 6:55 PM</td>
<td>0:40:05 2.24 2.17</td>
</tr>
<tr>
<td>White Tail</td>
<td>6:21 PM 7:17 PM</td>
<td>0:56:07 2.17 1.81</td>
</tr>
<tr>
<td>Mt. Lemmon</td>
<td>6:35 PM 7:37 PM</td>
<td>1:02:24 0.91 0.74</td>
</tr>
<tr>
<td>Cargodera Canyon</td>
<td>6:42 PM 7:31 PM</td>
<td>0:49:09 1.42 1.14</td>
</tr>
</tbody>
</table>

Quick review: Post-fire floods and debris flows:

- Can be generated from high frequency, low magnitude (garden variety) storms
- Flood magnitudes can be many magnitudes greater than pre-fire flows (documented up to 900x greater)
- Debris flows are very destructive and tend to occur quickly after a storm starts
- Antecedent soil moisture is typically not a factor in generating these flows

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A Rogues’ Gallery of Post-Fire Response

Rainfall regimes based on rainfall types associated with different air masses and rainfall intensities based on a 2-yr 30-min storm.

Source: Moody and Martin, 2009, Synthesis of sediment yields after wildland fire in different rainfall regimes in the western United States, IJWF.

VOLCANIC
Rattlesnake Fire
Chiricahua Mountains
Arizona

CHANNEL EROSION
RR: Arizona, high

VOLCANIC
Cerro Grande Fire
New Mexico

HILLSLOPE EROSION
(Rainsplash Impact)
RR: Arizona, medium

VOLCANIC
Cerro Grande Fire
New Mexico

HILLSLOPE EROSION
CHANNEL EROSION
RR: Arizona, medium
**CHANNEL DEPOSITION**  
(Alluvial Fan Formation)  
RR: Sub-Pacific, low

**SEDIMENTARY**  
Oregon Coast Range  
RR: Pacific, medium  
(Dry Ravel)  
50% of sediment released within 24 hours  
Photos thanks to Joshua Roering  
Univ. of Oregon

**GRANITIC**  
Idaho Batholith  
RR: Sub-Pacific, low

**SEDIMENTARY**  
Vaseux Lake Fire  
Canada  
CHANNEL EROSION  
CHANNEL DEPOSITION

**GRANITIC**  
Mojave National Monument  
California  
RR: Sub-Pacific, low

**SEDIMENTARY**  
Vaseux Lake Fire  
Canada  
CHANNEL EROSION  
CHANNEL DEPOSITION

**Volcanic**  
1977 Carr Fire and 2011 Monument Fire  
Arizona  
CHANNEL EROSION and DEPOSITION (Debris Flow)  
RR: Arizona, extreme

**Volcanic**  
2011 Schultz Fire  
Arizona  
CHANNEL EROSION and DEPOSITION (Debris Flow)  
RR: Arizona, medium
Quick review: Effects of rainfall and geology on Landscape Susceptibility

- Rain is not the same everywhere
- Rainfall intensity, timing and storm type influence erosion
- Geology plays a key role in post-fire erosion
- ~20% of post-fire eroded sediment comes from hillslopes, the rest from channels

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WATER QUALITY EFFECTS OF FIRE

- Gasses
- Sediment
  - Fire retardants/fire suppression chemicals
  - ASH and partially burned organic matter

Input of particulates and gases while fire is burning

Use of fire retardants
Sediment is a major water-quality issue.

*Photo: John Moody, USGS

Buffalo Creek Fire: Coarse organic debris etc.

*Slide: Deb Martin, USGS

**ASH** is another major water quality issue.

Pikes Peak YMCA Camp, Four Mile Creek

*Photo by Greg Smith, USGS, CWSC

**ASH** chemistry is a function of:

- Type of vegetation
- Underlying geology
- Temperature and duration of heat pulse
- Atmospheric deposition
  - Short term
  - Long-term
  - Long-range

Post-Aspen Fire Flooding

*Slide: S. E. Desilets

Suspension sediment rating curves

\[ C_s = a Q^b \]

*Monsoon 2003

*Cs = a Q^b*

*Slide: S. E. Desilets*
\[ C_s = a Q^b \]

**Suspended sediment rating curves**

Seasonally different runoff-generating mechanisms

**Movement of elements during fire:**

- Volatilization
- Ash convection
- Ash reposition
- Ash left in situ

**Water quality variables most affected by fire:**

**Short term:**
- Discharge
- Temperature
- Dissolved oxygen
- Turbidity and TSS
- Nitrate
- Phosphorus
- Total organic carbon
- Manganese
- Mercury

**Longer term:**
- Discharge
- Turbidity and TSS
- Nitrate
- Total organic carbon
- Mercury

**Wildfire Effects on Aquatic Environments**

- Increased solar radiation
- Increased water temperatures
- Change in water chemistry including ash
- Increased erosion and sedimentation
- Increased water yields

**Fourth order**

Effects on stream shading depends on stream order

**Second order**

- Increased solar radiation
- Increased water temperatures
- Change in water chemistry including ash
- Increased erosion and sedimentation
- Increased water yields

Example from the 1996 Buffalo Creek Fire

**Wildfire Effects on Aquatic Environments**

- Increased solar radiation
- Increased water temperatures
- Change in water chemistry including ash
- Increased erosion and sedimentation
- Increased water yields

Example from the 1996 Buffalo Creek Fire
Quick review: Fire effects on water quality

- Magnitude and timing of peak flows changes with fire
- Surface sealing is major factor determining runoff in granitic environments [and elsewhere]
- Sediment is main water quality effect
- Chemistry of ash is function of type of vegetation, heat, underlying geology, legacy of atmospheric deposition
- Watershed size and %burned matters

Disturbance and Temporal Scales

- Monthly (immediately following the fire)
- Decadal
- Centennial
- Millennial
- Millions of years

Post-fire Effects: Time

Sediment Response to Fire

Fire-Induced “Accelerated” Sediment Yield

“Baseflow” Sediment Yield

“Punctuated Sediment Supply” (Benda and Dunne, 1997 a,b)
Also called “pulsed disturbance”
Immediately after fires – trampoline channels

Aspen Fire, Lower Romero Canyon
Monthly: 10/03 – 3/04

Monument Fire
Marshall Canyon Debris Fan, July – September, 2011
View up-fan to the apex and channel.
July 11, 2011
August 3, 2011
September 1, 2011

Decadal Time Scale: 1996-2005
Spring Creek Watershed

Spring Creek Channel Recovery
Mouth at confluence with the South Platte River

Chiricahua – 1994 Rattlesnake Fire
Decadal: 1996-2011

Photo UofA Tree Ring Lab (photo from 1996 but erosion occurred during the monsoon after the fire in 1994)
Decadal → Centennial Time Scale

SEDIMENT:
1/3 in reservoir
2/3 still in watershed
RESIDENCE TIME
300 YEARS

Centennial Time Scale: 1800’s – 1900’s Spring Creek Watershed

Modern view: More (burned) trees!!

Millennial Time Scale
Buffalo Creek Watershed

So what does this mean for “Watershed Recovery”?
“Post-fire recovery in ~3-5 years”
What Does Recovery Mean?
Vegetation + ~pre-fire Qp, levels = Recovery??
What about riparian zones?
Sediment pulses and channel conditions?
Cerro Grande Watershed...major flooding 3 yrs later.
Hayman Fire...major flooding 8 yrs later.

Hydrological response of burned watersheds:
Cerro Grande Fire

YEAR 1
Photo: Thomas Trujillo

YEAR 3
Photo: John Hogan

Elliott and Parker, 2001
Post-fire Recovery

Declines in post-fire sedimentation if a function of:

- Soil Texture
- % bare soil
- Rainfall Intensity

![Graph showing sediment yield vs. percent bare soil](image)

- McDonald, L.H., Robichaud, P.R. 2008, Post-fire erosion and the effectiveness of emergency rehabilitation treatments over time, Stream Notes, Rocky Mountain Research Station, 1-6

Campo Bonito

August 14, 2003, 1 mo after containment of Aspen Fire
1.51” in 30 min, RI = 10 yr, 30 min
One death
Q_p = 1,900 cfs

Sept 1, 2005
Longer duration storm
Similar 30-minute intensity
Q_p = 680 cfs

Possible Effects of Climate Change on Post-fire Erosion

- “Bigger, hotter fires”, i.e. greater extent of high severity areas
- Extensive areas of tree mortality from insects and drought -> stand-replacing fires
- As more precipitation falls as rain instead of snow, larger window for erosion
- Higher rainfall intensities

How can information about potential for post-fire erosion inform pre-fire management

- Pre-fire fuel reduction
- Pre-fire planning
  - Permits for debris/sediment basins
  - Strategies for closing intakes and diverting fire-affected water
  - Pre-disaster mitigation; floodplain planning, building code and ordinance updating
  - Land-use decisions

Conclusions

- Fires trends increasing in size and severity
- Fires significantly change basin hydrology
- Rainfall regimes and geology influence post-fire erosion
- Different components of the watershed recover at different rates
  - Veg Recovery ≠ Hydrologic Recovery
  - Veg + Hydro Recovery ≠ Ecosystem or Riparian Recovery
  - Sediment pulses

Photo: D. Greenspan, Schultz Fire from Humphrey's Peak
Acknowledgements

Deb Martin, USGS
Karletta Chief, UofA
Sue Cannon, USGS
John Moody, USGS
Sharon Desilets
Karen Koestner, RMRS
Dan Neary, RMRS

Jim Washburn, UofA
Joe Wagenbrenner, RMRS
Phil Pearthree, AZGS
Jess Clark, RSAC

Online resources

• Inciweb.org
• GeoMac
• Google Earth
• GeoSetter (http://www.geosetter.de/en/)
• USGS Watersheds (http://water.usgs.gov/GIS/huc.html)
• NOAA Atlas 14 http://dipper.nws.noaa.gov/hdsc/pfds/
• GeoSetter http://www.geosetter.de/en/

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