Impacts of Wildfires on Water Quality and Drinking Water Utilities

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for Post-Fire Impacts on Drinking Water Utilities Webinar
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Objectives

- Provide an overview of the impacts of wildfires on watersheds and drinking water utilities
- Summarize the results from research workshops and selected literature on the impacts on wildfires on water utilities

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Wildfires and Watersheds

- Wildfires can produce dramatic physical and chemical changes in soils and hillslopes that negatively affect downslope and downstream hydrology and water quality

Wildfires and Watersheds

- Magnitude of changes is dependent on several factors including fire severity, intensity, and duration; topography; and post-fire precipitation amount and intensity

Note: Fire severity is a measure of the physical change in an area caused by burning. Although fire intensity is a key component of burn severity, these are two distinct features of fire. Intensity refers to the rate at which a fire produces heat (i.e., temperature and heat yield.) *Fire severity describes the immediate effects of fire on vegetation, litter, and soils.*

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Post-fire changes

- Reduced interception
- Increased rain splash
- Decreased infiltration
- Reduced evapotranspiration (ET)
- Hydrophobic soil

Post-fire effects

Campground in Cable Canyon, southern California, where a debris flow on December 25, 2003, killed two people. A wildfire during the previous October burned hillslopes in the area, and heavy rains triggered the deadly debris flows. Photograph by Sue Cannon.

- Increased total runoff
- Increased peak flow
- Increased flooding
- Increased sediment mobilization (hillslope and channel erosion)
- Transport of ash, partially-burned organic matter
- Debris flow
- Eutrophication and sedimentation
- Smoky taste to water

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Post-fire effects on water quality

- Nutrients – increase after fires
  - Nitrogen (organic nitrogen, nitrate, and ammonium) increases immediately and peaks in the first or second year, slowly declines as vegetation re-establish
  - Phosphorus (dissolved and sediment-associated) concentrations and export are greater

Post-fire effects on water quality

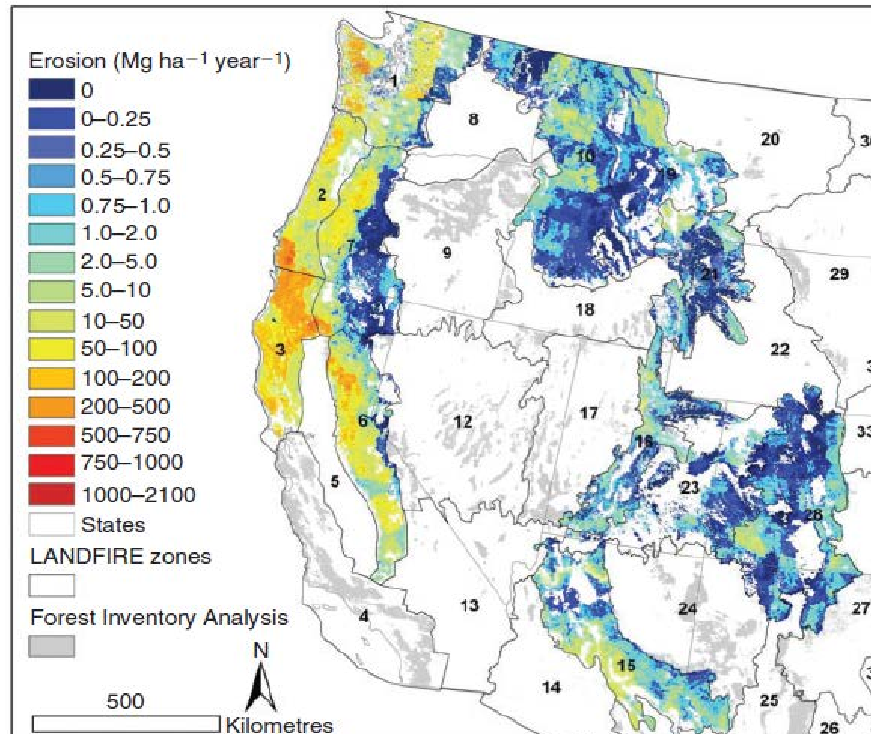
- Organic Carbon – increase after fires
  - Particulate organic carbon (POC) may increase due to deposit of ash
  - Dissolved organic carbon (DOC) may increase as rain and snowmelt percolate through ash; elevated into <u>third and fourth year</u>

Post-fire effects on water quality

- Other chemicals – increase after fires
  - Ash contains oxides of calcium and magnesium, chloride, carbonates of sodium and potassium, polyphosphates of calcium and magnesium, manganese
  - Leaching of ash can mobilize cations and chloride
  - Mobilization of mercury

Post-fire effects on water quality

- Suspended sediments and turbidity – increase after fires

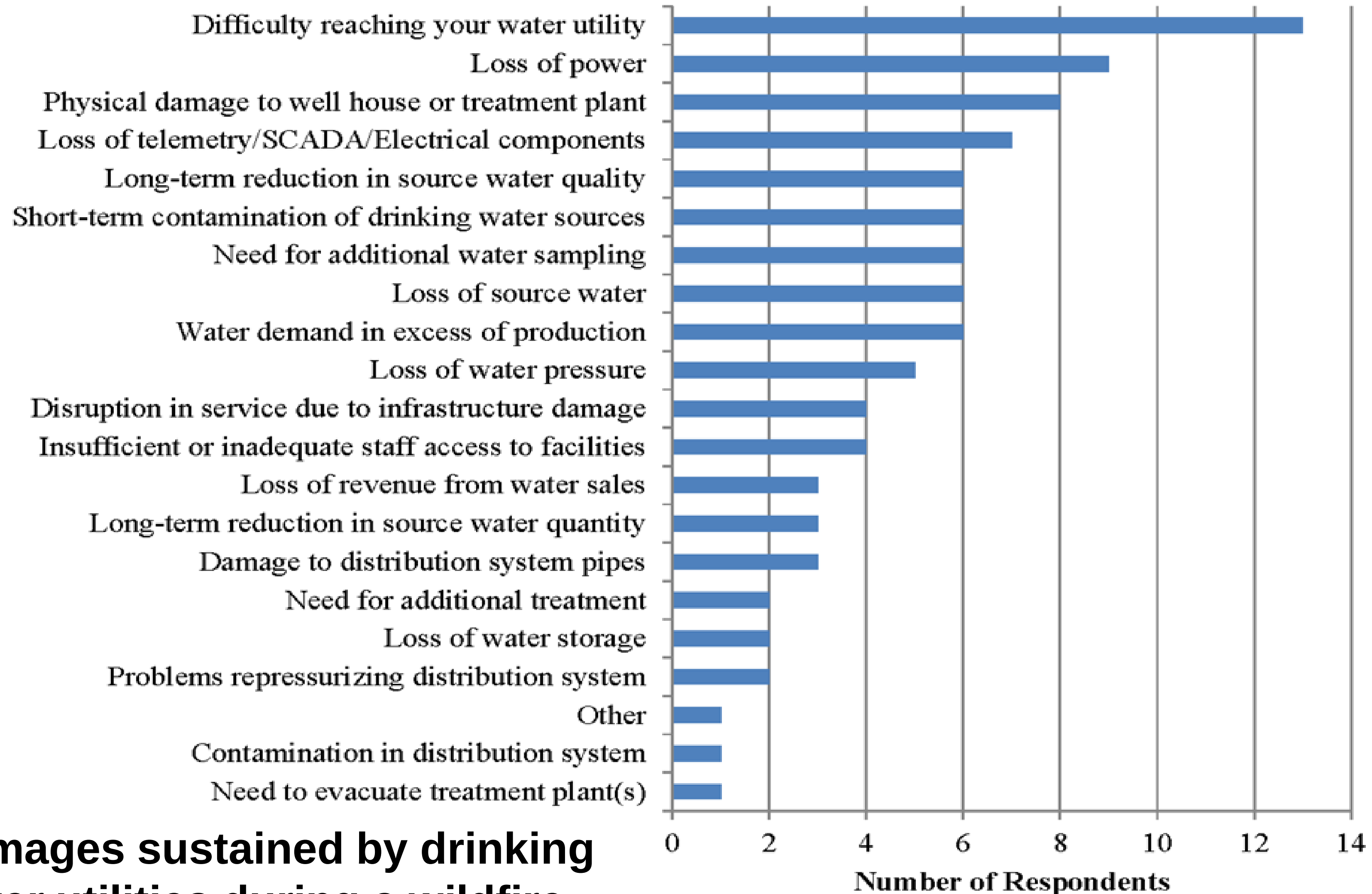


Predicted post-fire erosion one year after wildfire

References for Overview:

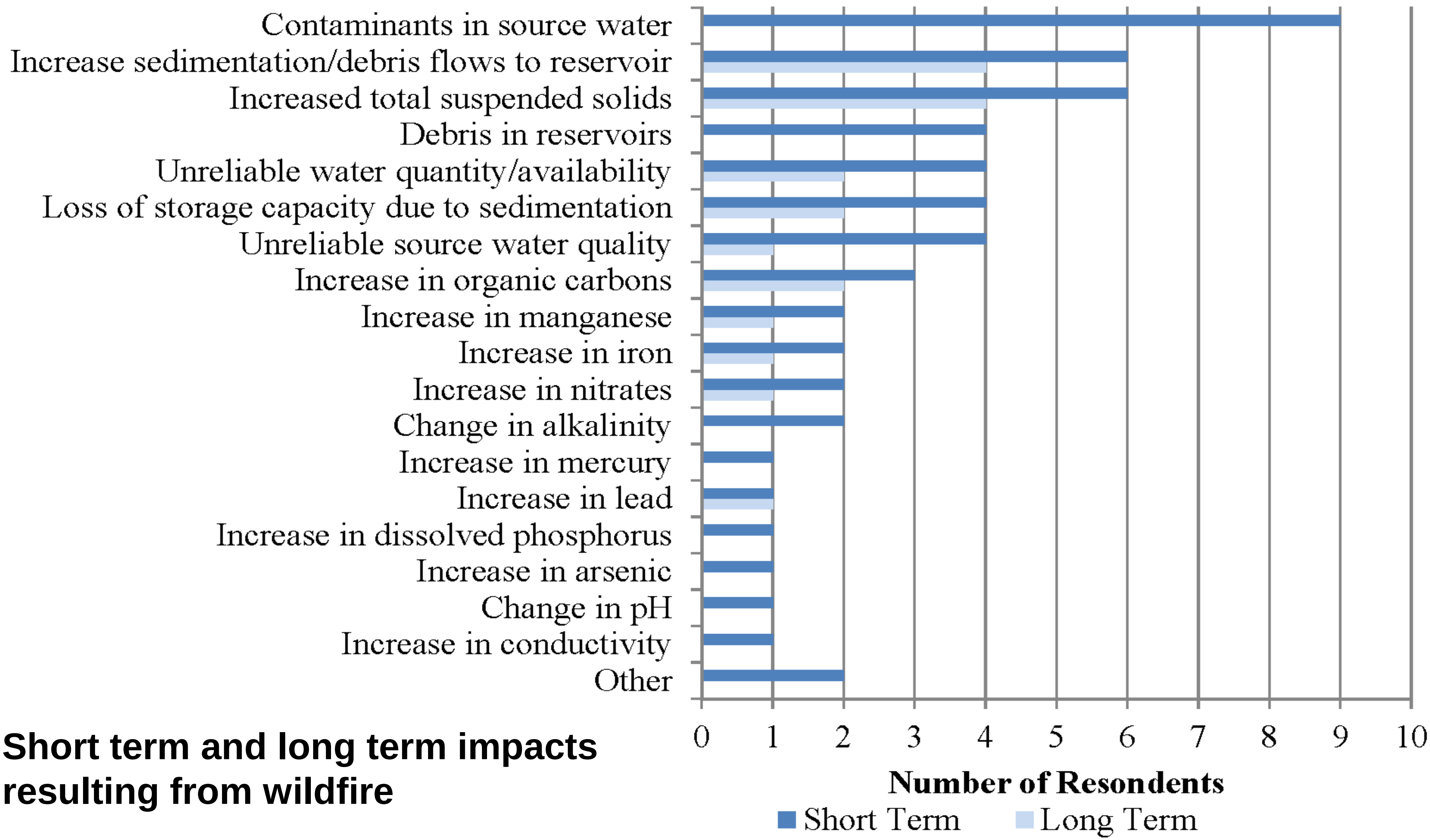
- Water Research Foundation. 2013. Effects of Wildfire on Drinking Water Utilities and Best Practices for Wildfire Risk Reduction and Mitigation. Available at: http://www.waterrf.org/PublicReportLibrary/4482.pdf
- Water Research Foundation. 2014. Wildfire Impacts on Water Supplies and the Potential for Mitigation: Workshop Report. Available at: http://www.waterrf.org/PublicReportLibrary/4529.pdf
- Martin, D.A. 2016. At the nexus of fire, water and society. Philosophical Transactions Royal Society B, 371: 20150172. http://dx.doi.org/10.1098/rstb.2015.0172

2013 Survey on the Impacts of Wildfire on Drinking Water Systems



Damages sustained by drinking water utilities during a wildfire

2013 Survey on the Impacts of Wildfire on Drinking Water Systems



Short term and long term impacts resulting from wildfire

Selected Findings and Summary of the Kananaskis Workshop

- Water utility wildfire preparedness and response plan
  - Identify potential alternate sources of water; range of potential impacts of wildfire on water quality; additional drinking water treatment infrastructure and analytical capacity
  - Develop treatment plan technological and operational response options
  - Include a knowledge mobilization strategy

Challenges to water utilities- active fire period (Martin 2016)

- Difficulty reaching water facilities
- Loss of electricity and communication functions
- Physical damage to infrastructure
- Loss of water pressure
- Accidental water contamination from firefighting chemicals
- Additional personnel costs

Challenges to water utilities- short-term post-fire (days to months)

- Treatment issues related to high turbidity, DOC, nutrients, manganese, iron, taste issues
- Increased risk of algal and cyanobacterial blooms in reservoirs
- Legacy sediments from previous land-use and post-fire deposition mobilized by high peak flows
- Increased personnel, monitoring, and water-treatment costs
- Loss of revenue

Challenges to water utilities- short-term post-fire (days to months)

- Infrastructure damage from sediment and debris
- Damage to distribution system pipes
- Problem re-pressurizing distribution pipes
- Increased hydrologic and water-quality variability
- Altered seasonality of hydrological and chemical export from burned catchment

Challenges to water utilities- long-term post-fire (decades)

- Loss of reservoir capacity
- Seasonal release of manganese from reservoir sediments

Effects of fire-related constituents on water-treatment processes

- Turbidity
  - Additional settling and filtration
- DOC
  - Need for additional filtration, potential to form disinfection by-products, additional sludge production from coagulation processes
- Taste issues
  - Problematic (water can smell and taste smoky), algae can contribute to taste & odor, oxidation or adsorption processes required

Effects of fire-related constituents on water-treatment processes

- Nutrients – potential to form nitrogen-containing disinfection by-product, difficult to maintain adequate disinfectant
- Manganese – additional oxidation required, manganese can be released from reservoir bottom sediments during dredging, by storm events, or as a result of anoxia

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Adaptation to increase resiliency of water utilities to fire disruptions

- Preparation
  - Establish contingency plans,
  - Identify alternate water sources,
  - Identify critical source water areas,
  - Build collaborations,
  - Identify vulnerabilities and system deficiencies,
  - Pre-fire fuel thinning,
  - Pre-fire modeling to determine areas at greatest risk of flooding, erosion, and deposition,
  - Develop real time monitoring networks,
  - Plan and get permits to construct pre-sedimentation basins

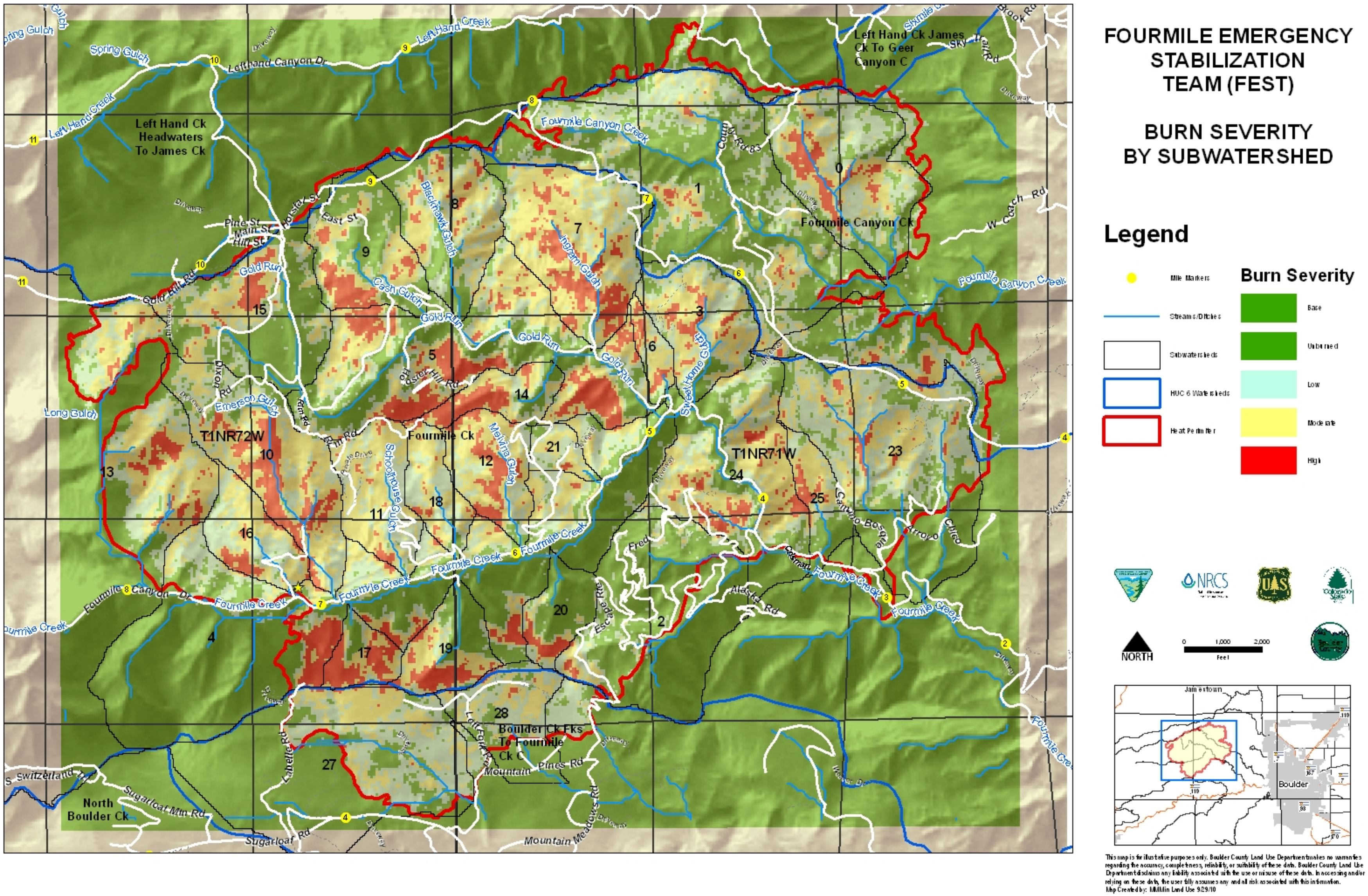
Adaptation to increase resiliency of water utilities to fire disruptions

- Response
  - **Participate on USFS Burned Area Emergency Response (BAER) teams**
  - Implement post-fire rehabilitation measures to stabilize hillslope, channels and infrastructure
  - Monitor rain predictions
  - Be prepared to shut off water intakes and diversions
  - Install high-frequency chemical and turbidity sensors
  - Post-fire modeling to identify potential flooding, erosion, and deposition
  - Construct pre-sedimentation basins (based on analysis)
- Recovery
  - Strengthen existing infrastructure
  - Build new infrastructure

Assessment of post-fire conditions

- Burn severity – affect organic matter loss
  - Fuel properties and behavior
  - Soil moisture, texture and properties
- Landscape susceptibility
- Variability in space and time
- Timing, magnitude, duration, and location of storms after wildfire
- "A series of unfortunate events" – e.g., timing of storms

Post-fire burn severity mapping



Burn severity– surface and soil

GROUND COVER

Parsons et al., 2010

SOIL STRUCTURE

Low severity:

Little change
<50% litter consumption
Needles and leaves intact
Soil structure unchanged

Moderate severity:

Up to 80% litter consumption
Needles and leaves recognizable or leaf/ needle fall
Soil structure slightly altered

High severity:

<20% remaining ground cover
Nearly all litter and duff consumed
Little to no leaf or needle fall to shield
Soil structure reduced or destroyed

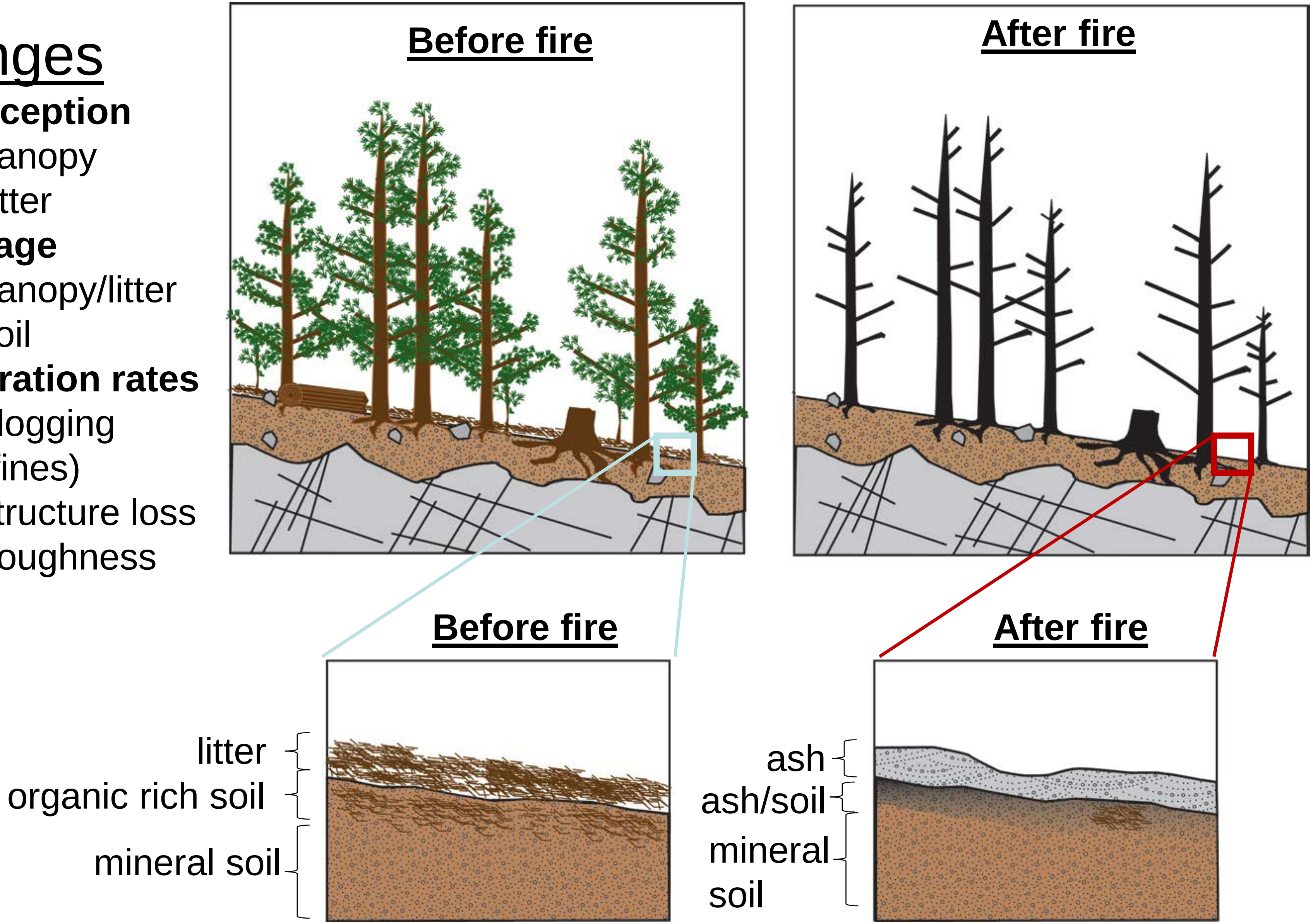
Credit; Deborah Martin

Scientific basis for mulching: restore surface cover

Source: Ebel, 2012

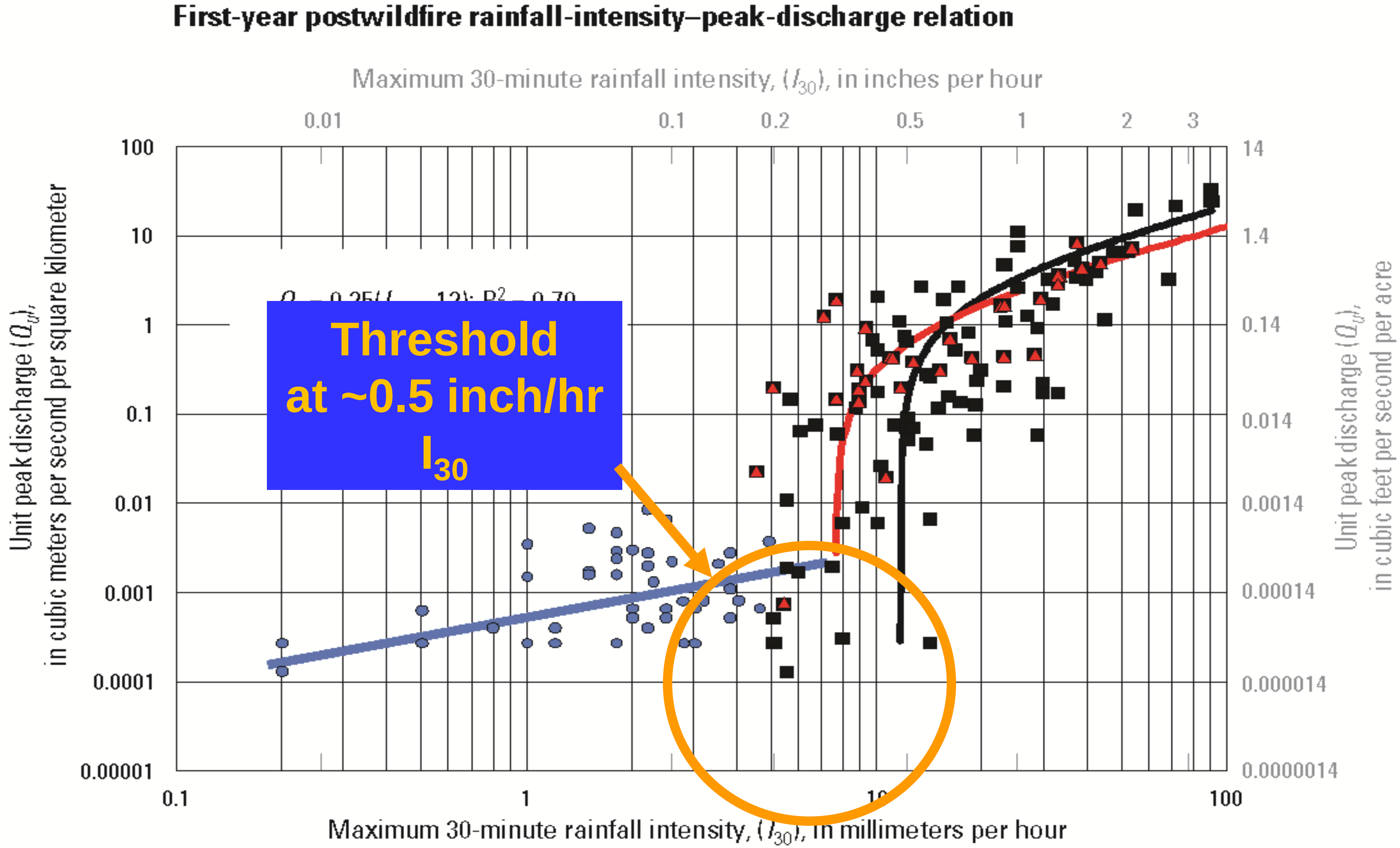
Changes

- **Interception**
  - Canopy
  - Litter
- **Storage**
  - Canopy/litter
  - Soil
- **Infiltration rates**
  - Clogging (fines)
  - Structure loss
  - Roughness



Most common post-fire stabilization technique: Mulching with straw or wood strand

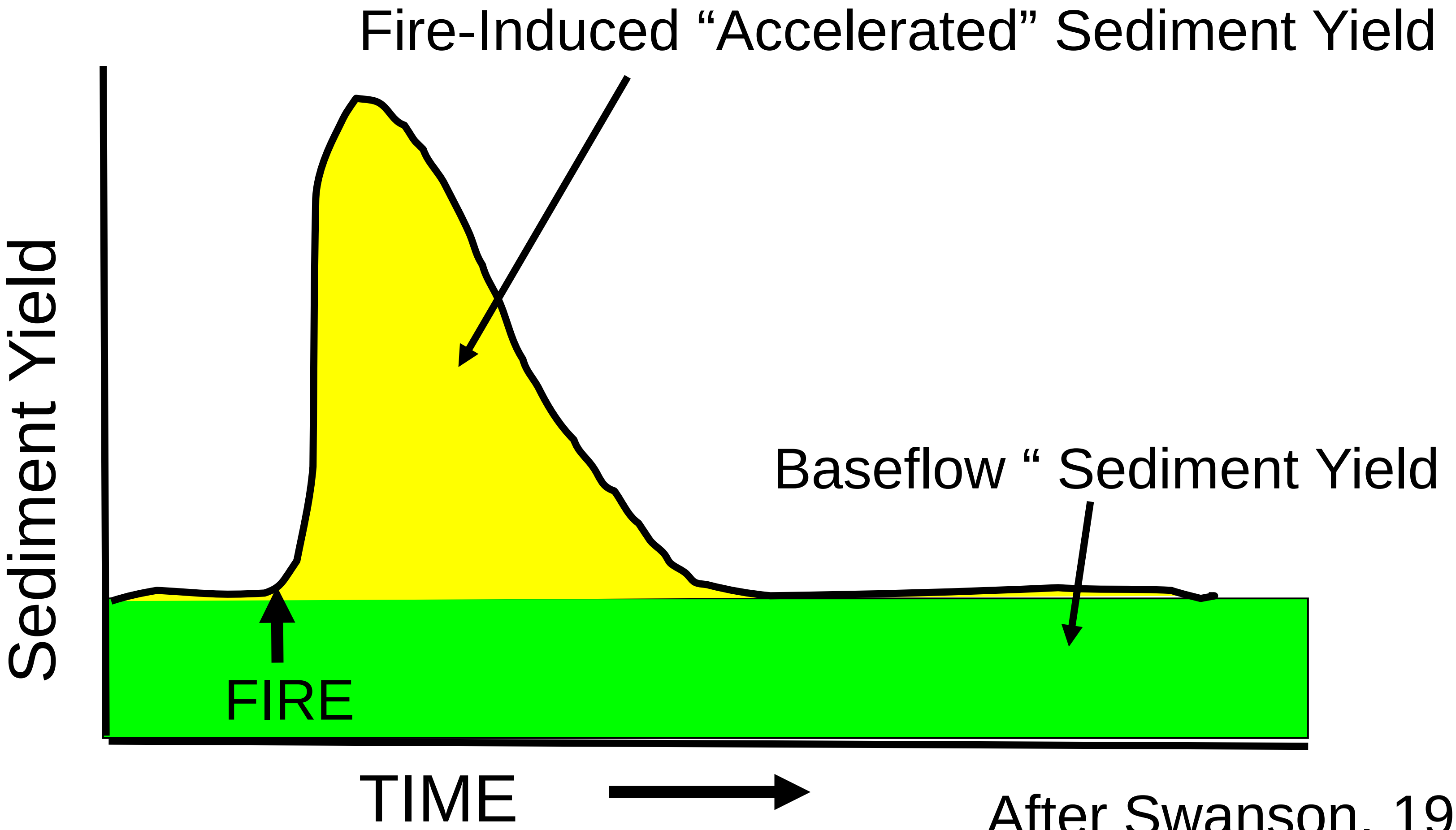
Impacts of rainfall intensity on discharge



Source: Moody, 2012. An analytical method for predicting post-fire peak discharge.

Post-fire Action: ? Install sediment basins ?

Sediment Yield after Wildfire



After Swanson, 1981

Landscape susceptibility

Findings and summaries of recent research efforts (included)

- Focus on post-fire changes
- Take home lessons:
  - No two watersheds or burned areas are the same
  - Need quick assessments (BAER team) to help identify rapid response
  - It will take time to recover
  - Appropriate actions will help
  - There are many resources – USFS and USGS

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Questions?

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Additional findings and summaries of recent research efforts

- Fire-induced changes in soil properties from low temperatures were not as drastic as high temperature, but that reductions in surface soil water repellency in high temperature burns may increase infiltration relative to that from low temperature burns – Wieting et al., 2017
  - Low-temperature burned areas may enhance runoff generation

.

Additional findings and summaries of recent research efforts

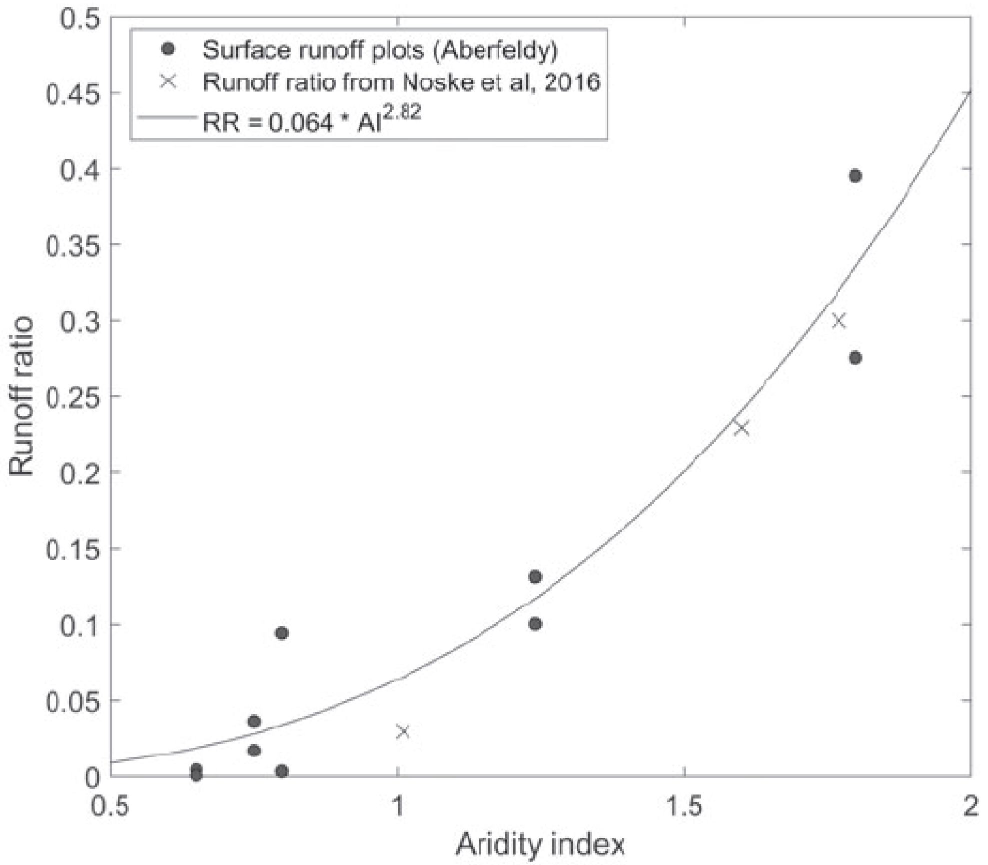
- Suggests that bulk density and loss on ignition at 0–1 cm have residual direct impacts from the wildfire heat impulse – Ebel et al., 2018
- Burn severity impacts on soil properties and surface runoff Suggests that gravel-rich soils may have increased resilience to sustained surface runoff generation and erosion following wildfire

Additional findings and summaries of recent research efforts

- Recovery of small-scale infiltration and erosion after wildfires – Larson-Nash et al., 2018.
  - High severity wildfire for 5 years after the 2003 Hot Creek Fire in Idaho
  - Low vegetation recovery due to severity of the fire
  - Total infiltration on burned plots were persistently lower than control plots
  - Infiltration analyses suggest that measurements at shallow depths (compared to soil surface) may be better to estimate infiltration during a short-duration high-intensity storm (therefore, for post-fire erosion models)

Additional findings and summaries of recent research efforts

- Post-wildfire surface runoff is strongly associated with landscape aridity – Van der Sant et al., 2018
  - Aridity index (AI) = Ep/P where Ep is potential evaporation and P is annual precipitation



Additional findings and summaries of recent research efforts

- Wildfires enhanced annual river flow in the western regions with a warm temperate or humid continental climate – Hallema et al., 2018
  - Increases in annual river flow – highest in semi-arid Lower Colorado region
  - Prescribed burns in the subtropical Southeast did not significantly alter river flow

Additional findings and summaries of recent research efforts

- Hydrologic response to wildfires in mountainous regions – Havel et al., 2018.
  - Use of the Soil and Water Assessment Tool (SWAT) to evaluate hydrologic responses of the upper Cache la Poudre Watershed in Colorado to the 2012 High Park and Hewlett wildfire events
  - Generally, higher surface runoff and decreased subsurface flow were observed under post-wildfire conditions
  - Flow duration curves developed for burned sub-watersheds using full streamflow statistics showed that less frequent stream flows become greater in magnitude
  - Positive correlation was determined between runoff increase and percentage of burned area upstream
  - Wildfires had a higher effect on peak flows, which may increase the risk of flash floods in post-wildfire conditions

Additional findings and summaries of recent research efforts

- Large, high-severity wildfires alter the physical and biological conditions of watersheds – Rhoades et al.,2018.
  - 14 years after Hayman Fire (Colorado), TDN remained elevated and related to burned extent

Table 2. Stream Nitrate and Turbidity 1 year Prior to the 2002 Hayman Fire, During 5 Post-fire Years, and the 13–14-Year Post-fire Resampling

Period	Burn extent	Nitrate–N ($mg\ l^{-1}$)			Turbidity (NTUs)			Catchments
		Mean	SD	Max	Mean	SD	Max	
Pre-fire (2001)	Unburned	0.04	0.0	0.1	3.4	2.7	11.3	Brush, Sugar, No-Name
Post-fire period 1 (1–5 years)	Unburned	0.04	0.0	0.2	7.8	9.4	43.0	Sugar, No-Name
	Low burn extent	0.25	0.3	2.1	30.2	55.4	220.3	Wigwam, West
	High burn extent	0.69	0.6	2.3	81.1	120.1	481.0	Brush, Fourmile
Post-fire period 2 (13 and 14 years)	Unburned	0.05	0.0	0.1	2.1	3.2	17.0	Sugar, Fern
	Low burn extent	0.22	0.1	0.5	1.7	1.8	7.5	Wigwam, Cabin
	High burn extent	0.62	0.5	1.6	2.0	3.3	19.0	Brush, Fourmile

Pre-fire period sampling included streams that were both burned (Brush) and unburned (Sugar, No-Name) by the Hayman Fire. West and No-Name were excluded from post-fire period 2 analysis due to their large or small catchment size relative to the other monthly sample catchments.

Additional findings and summaries of recent research efforts

- Impacts of wildfires and extreme events on stream chemistry – Murphy et al., 2018
  - 5-year post-wildfire study in the Fourmile Creek watershed in Colorado
  - Drought and two extreme rainfall events
  - Reduced infiltration, increased overland flow – transport ash and soil into streams leading to elevated concentrations of Ca, K, Mg, alkalinity, DOC, sediment, and nitrate; and lower concentrations of Na and SiO2
  - During droughts, concentrations of sediment, DOC, and Ca fell below average but SiO2 did not

Additional findings and summaries of recent research efforts

- Wildfire effects on influent water quality were observed through statistically significant spatial differences for turbidity, nutrients, and dissolved organic matter (DOM) – Hohner et al., 2016
  - Post-fire source water remained treatable by conventional processes, although water utilities will likely need to apply a higher coagulant dose.
  - Rainstorms can affect treatability – minimal DOC removal and high DBP formation.

Additional findings and summaries of recent research efforts

- Impact of a moderate/high-severity prescribed eucalypt forest fire on soil phosphorous stock and partitioning – Santin et al., 2017.
  - Led to net phosphorous losses of ≈7 kg/ha from litter and surface soil
  - Increased inorganic P stocks, but only a minor proportion was bioavailable
  - ≈2 kg/ha total P was transferred from litter and soil to the highly-erodible ash
  - Higher maximum temperatures in the burning litter layer (e.g., T > 650°C) are associated with higher TP concentration in the ash

Additional findings and summaries of recent research efforts

- Wildfire impacts on nitrogen concentrations and production from headwater streams in Alberta – Bladon et al., 2008
  - During the first postfire year, nitrate, DON, and TN concentrations in severely burned watershed streams were 6.5, 4.1, and 5.3 times greater
  - Rapid decline in mean watershed concentrations and production of nitrate, DON, TDN, and TN was observed from burned watersheds over the 3 seasons post-fire
  - Nitrate, TDN, and TN concentrations and product were still elevated during snowmelt freshet and following precipitation events

Additional findings and summaries of recent research efforts

- Wildfire and salvage logging impacts on nutrient runoff – Silins et al., 2014
  - P concentrations – 2 to 13 times greater in burned and post-fire salvage-logged areas
  - Algal production – 5 to 71 times greater in streams within burned watersheds and persist for 5 years
  - Changes in ecology may be long-lived because of slow recovery of P regimes

Additional findings and summaries of recent research efforts

- Significant increases in nutrient, major-ion, and metal fluxes within first 5 years after fire; with dissolved ions and metals decrease after 5 years whereas particular matter continues to increase – Rust et al., 2018.

Additional findings and summaries of recent research efforts

- Effects of a high-severity wildfire and post-fire straw mulching on nitrogen dynamics – Fernandez-Fernandez et al., 2017.
  - Burning opened up the N cycle and increasing the ecosystem N losses.
  - Straw mulching effective in reducing post-fire erosion.
  - In the short term, straw mulching slightly mitigates the effects of fire on the N cycle

Additional findings and summaries of recent research efforts

- Turbidity responses from wildfire and post-fire logging – Lewis et al., 2018
  - Turbidity increased in six burned watersheds that were logged after the fire, as compared to unburned watersheds
  - Unusually high turbidity were very rare before fire but began to appear in the first year after fire and were more frequent in the first 9 months after salvage logging

Additional findings and summaries of recent research efforts

- Post-fire changes in streamflow are variable across western U.S. with some patterns – Saxe et al., 2018.
  - Low flows, high flows, and peak flows increase in the first 2 years following a wildfire and decrease over time
  - NDVI, aridity index, percent of a watershed's precipitation that falls as rain, and slope are positively correlated with post-fire streamflow response
  - Negative correlation between response and the soil erodibility factor, watershed area, and percent low burn severity
  - Slope and percent area burned as significant watershed parameters controlling response

Additional findings and summaries of recent research efforts

- Post-fire thunderstorms and spring snowmelt in Colorado increased DOC and DBP concentrations; alum coagulation effectively reduced DOC concentration and DBP formation – Writer et al, 2014.
  - The Fort Collins water treatment facility responded to the High Park Wildfire by increasing environmental monitoring, using multiple water supplies, and constructing a pre-sedimentation basin to effectively deliver high-quality drinking water to its customers in the year following the fire.

Additional findings and summaries of recent research efforts

- Water Research Foundation Project 4590
  - Wildfire Impacts on Drinking Water Treatment Process Performance: Development of Evaluation Protocols and Management Practices
- Journal AWWA July 2018 Feature Article
  - Preparing for wildfires and extreme weather: plant design and operation recommendations
- Environmental Science: Water Research & Technology (2017)
  - Water treatment process evaluation of wildfire-affected sediment leachates by Hohner et al.

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References (1)

Bladon, K.D., Silins, U., Wagner, M.J., Stone, M., Emelko, M.B., Mendoza, C.A., Devito, K.J., and S. Boon (2008). Canadian Journal of Forest Research 38:2359-2371.

Ebel, B.A. (2012). Impacts of wildfire and slope aspect on soil temperature in a mountainous environment Vadose Zone Journal, v. 11, vzj2012.0017.

Ebel, B.A., Romero, O.C., and D.A. Martin (2018). Thresholds and relations for soil-hydraulic and soil-physical properties as a function of burn severity four years after the 2011 Las Conchas Fire, New Mexico, USA. Hydrological Processes 32 (14):2263-2278.

Emelko, M. and C.H. Sham (2014). Wildfire Impacts on Water Supplies and the Potential for Mitigation Workshop Report. Canadian Water Network and Water Research Foundation, 25 p. http://www.waterrf.org/PublicReportLibrary/4529.pdf

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References (2)

Fernandez-Fernandez, M., Rutting, T., and S. Gonzalez-Prieto (2017). Effects of a high-severity wildfire and post-fire straw mulching on gross nitrogen dynamics in Mediterranean shrubland soil. Geoderma 305:328-335.

Hallema, D.W., Sun, G., Caldwell, P.V., Norman, S.P., Cohen, E.C., Liu, Y., Bladon, K.D., and S.G. McNulty (2018). Burned forests impact water supplies. Nature Communications 9 (1307): 1-9.

Havel, A., Tasdighi, A., and M. Arabi (2018). Assessing he hydrologic response to wildfire in mountainous regions. Hydrology and Earth System Sciences 22:2527-2550.

Hohner, A.K., Cawley, K., Oropeza, J., Summer, R.S., and F.L. Rosario-Ortiz (2016). Drinking water treatment response following a Colorado wildfire. Water Research 105:187-198.

References (3)

Larson-Nash, S.S., Robichaud, P.R., Pierson, F.B., Moffet, C.A., Williams, C.J., Spaeth, K.E., Brown, R.E., and S.A. Lewis (2018). Recovery of small-scale infiltration and erosion after wildfires. Journal of Hydrology and Hydromechanics 66(3):261-270.

Lewis, J., Rhodes, J.J., and C. Bradley (2018). Turbidity responses from timber harvesting, wildfire, and post-fire logging in the Battle Creek Watershed, Northern California. Environmental Management. DOI: 10.1007/s00267-018-1036-3

Martin, D. A. (2016). At the nexus of fire, water and society. Phil. Trans. R. Soc. B 371: 20150172 http://dx.doi.org/10.1098/rstb.2015.0172

Moody, J.A. (2012). An analytical method for predicting post-wildfire peak discharges U.S. Geological Survey Scientific Investigations Report 2011–5236, 36 p.

References (4)

Murphy, S.F., McCleskey, R.B., Martin, D.A., Writer, J.H., and B.A. Ebel (2018). Fire, flood, and drought: extreme climate events alter flow paths and stream chemistry. Journal of Geophysical Research G: Biogeosciences. DOI: 10.1029/2017JG004349.

Parsons, A., Robichaud, P.R., Lewis, S.A., Napper, C., and J.T. Clark (2010). Field guide for mapping post-fire soil burn severity. General Technical Report RMRS-GTR-243. Fort Collins, CO U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 49 p.

Rhoades, C.C., Chow, A.T., Covino, T.P., Fegel, T.S., Pierson, D.N., and A.E. Rhea (2018). The legacy of a severe wildfire on stream nitrogen and carbon in headwater catchments. Ecosystems. DOI: 10.1007/s10021-018-0293-6.

Rust, A.J., Hogue, T.S., Saxe, S., and J. McCray (2018). Post-fire water quality response in the western United States. International Journal of Wildland Fire 27(3):203-216.

Santín, C.; Otero, X.L. Doerr, S.H., and C.J. Chafer (2018). Impact of a moderate/high-severity prescribed eucalypt forest fire on soil phosphorous stocks and partitioning. Science of the Total Environment 621:1103-1114.

References (5)

Saxe, S., Hogue, T.S., and L. Hay (2018). Characterization and evaluation of controls on post-fire streamflow response across western US watersheds. Hydrology and Earth System Sciences 22:1221-1237.

Sham, C.H., Tuccillo, M.E., J. Rooke (2013). Effects of Wildfire on Drinking Water Utilities and Best Practices for Wildfire Risk Reduction and Mitigation. Web Report #4482. Denver, CO: Water Research Foundation, 98 p. http://www.waterrf.org/PublicReportLibrary/4482.pdf

Silins, U., Bladon, K.D., Kelly, E.N., Esch, E., Spence, J.R., Stone, M., Emelko, M.B., Boon, S., Wagner, M.J., Williams, C.H.S., and I. Tichkowsky (2014). Five-year legacy of wildfire and salvage logging impacts on nutrient runoff and aquatic plant, invertebrate, and fish productivity. Ecohydrology 7(6): 1508-1523.

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References (6)

Van der Sant, R.E., Nyman, P., Noske, P.J., Langhans, C., Lane, P.N.J., Lane, N.J., and G.J. Sheridan (2018). Quantifying relations between surface runoff and aridity after wildfire. Earth Surface Processes and Landforms 43 (10):2033-2044.

Wieting, C., Ebel, B.A., and K. Singha (2017). Quantifying the effects of wildfire on changes in soil properties by surface burning of soils from the Boulder Creek Critical Zone Observatory. Journal of Hydrology: Regional Studies 13:43-57.

Writer, J.H., Hohner, A., Oropeza, J., Schmidt, A., Cawley, K.M., F.L. Rosario-Ortiz (2014). Journal American Water Works Association 106(4):E189-E199.

References (extra 1)

Ager, A.A., Vaillant, N.M., and A. McMahan (2013). Restoration of fire in managed forests a model to prioritize landscapes and analyze tradeoffs. Ecosphere 4(2)29. http//dx.doi.org/10.1890/ES13-00007.1

Emelko, M.B., Silins, U., Bladon, K.D., and M. Stone (2011). Implications of land disturbance on drinking water treatability in a changing climate: Demonstrating the need for "source water supply and protection" strategies. Water Research 45 (2), 461-472

Murphy, S. F., Writer, J. H., R McCleskey, R. B., and D.A. Martin (2015). The role of precipitation type, intensity, and spatial distribution in source water quality after wildfire. Environmental Research Letters 10(8). doi:10.1088/1748-9326/10/8/084007

References (extra 2)

Oropeza, J.; & Heath, J., 2013. Five Year Summary Report (2008–2012) Upper Cache la Poudre River Collaborative Water Quality Monitoring Program. City of Fort Collins Utilities, City of Greeley, Tri-Districts. https://www.fcgov.com/utilities/img/site_specific/uploads/2012_Five_Year_Summary_Report_Upper_CLP.pdf

Ruddy, B.C., Stevens, M.R., Verdin, K.L., and J.G. Elliott (2010). Probability and volume of potential post-wildfire debris flows in the 2010 Fourmile burn area, Boulder County, Colorado: U.S. Geological Survey Open-file Report 2010–1244, 5 p.

Swanson, F.J., 1981, Fire and geomorphic processes, in Mooney, H.A., Bonnicksen, T.M., Christensen, N.L., Lotan, J.E., and W.A. Reiners, eds., Fire Regimes and Ecosystem Properties, Proceedings of the Conference: Honolulu, Hawaii, U.S. Department of Agriculture, U.S. Forest Service General Technical Report WO-26, p. 401–420.