Skip all front matter: Jump to Page 1

RAND Environment, Energy, and Economic Development Program

Addressing Climate Change in Local Water Agency Plans

Appendix: Incorporating Fire Impacts

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Prepared for the California Energy Commission

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Appendix: Incorporating Fire Impacts

Overview

Fire can have immediate effects on an agency whose surface supplies derive from a mountainous watershed. The primary effects are through the loss of vegetation that leads to decreased evapotranspiration and increased erosion and sedimentation of surface streams and rivers. In the context of EID, fires can affect EID operations by increasing streamflow and impairing water quality.

As a part of this study, SEI team members explored the feasibility of modeling fire risks within the WEAP modeling framework. This Appendix describes the research involved in developing and incorporating within the WEAP water resources model for EID a routine capable of simulating hydrologic impacts of fire. The goal was to assess the relative impacts of fire against climate and other stressors on EID to develop a robust urban water management plan.

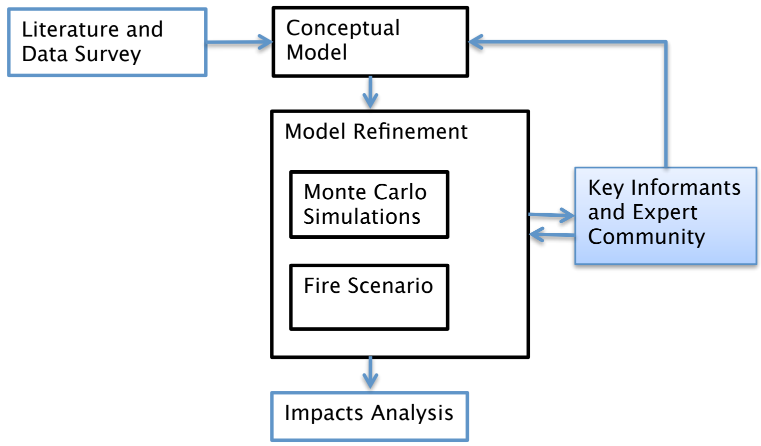
First, a literature and data review were conducted to inform the development of a conceptual model and to identify the status of local data that could assist the effort. A preliminary implementation of the conceptual model within WEAP was then run and shared with key informants in EID as well as outside experts. This feedback provided support for the general approach and also highlighted the great uncertainty in modeling both the occurrence of and impacts of fire, as well as the lack of *local* long-term pre- and post-fire hydrologic data. The implementation was improved by developing a second routine that enabled a stochastic simulation of fire impacts, based on Monte Carlo simulations in which key model parameters were drawn from assumed distributions, resulting in a range of plausible impacts. A second round of discussions with key informants followed, coinciding with the second stakeholder workshop at EID. A specific scenario was then developed that was of particular importance to EID. Results are presented that show the range of increased Jenkinson flows and decreased evapotranspiration (and their evolution over time after a fire) in response to the Monte Carlo simulations of key model parameters.

A major outcome of this research was the development and implementation of routines for evaluating the hydrologic impacts of wildfires—routines that explicitly accounted for uncertainty. However, an important finding was the lack of data (pre- and post-fire *hydrologic* data) to calibrate the routines. This fact, coupled with the complex interactions and feedback among the diversity of fire traits, evolution of recovery, and management, motivated the final subsection of this Appendix—*Future Research Directions*.

Methods

Figure A-1: illustrates the project workflow, which is described in detail below.

Figure A-1: Process Flow Chart



Literature and Data Review

Wildfire regimes describe the general characteristics of fire that occur within a particular ecosystem across long successional time frames, typically on the order of centuries, and are dependent on climate, soils, topography, vegetation, and ignition sources (Neary, Ryan, and DeBano, 2005). Within the broad category of a regime, wildfire events are usually characterized by fire severity (reflecting effects of fire on soil and hydrologic function), extent, intensity (related to the heat energy produced), and fire history, including frequency. For example, in cool moist ecosystems dominated by lodgepole pine, the fire regime may be characterized by long intervals between large, high-severity fires (Schoennagel et al., 2006). In contrast, dry forest stands like ponderosa pine or Douglas fir, typically experience more frequent, low-severity fires.

Wildfires are dynamic and variable, shaping plant community assemblages, wildlife habitat, and biodiversity, as well as affecting soils and water quality and quantity (Schoennagel et al., 2006; Neary, Ryan, and DeBano, 2005; Barro and Conard, 1991; Dwire and Kauffman, 2003). Field observations on post-fire hydrologic impacts have consistently found increased runoff and erosion rates, due to a combination of lower infiltration rates from increased hydrophobicity and decreased evapotranspiration from devegetation (Wittenberg et al., 2007; Vadilonga et al., 2008; Shakesby et al., 2007; U.S. Forest Service, 2009; Rulli and Rosso, 2007; Robichaud, 2000; Pierson et al., 2008; Neary, Ryan, and DeBano, 2005; Moody and Martin, 2001; Mayor et al., 2007; Martin and Moody, 2001; Letey, 2001; Huffman, MacDonald, and Stednick, 2001; González-Pelayo et al., 2006; DeBano, 2000; Cerda, 1998). Most of the literature on hydrologic impacts is based on post-fire field measurements in small catchments; very little work has been done on linking fire impacts on large watershed scale modeling (Cydzik and Hogue, 2009) that is directly linked to water systems infrastructure, the objective of this research. This gap in the literature stems from the scarcity of long-term soil-hydrologic monitoring at watershed scale that could provide the necessary data both pre- and post-fire to inform modeling efforts.

The study area falls largely in the drainage of the south fork of the American River, with the El Dorado National Forest (ENF) forming the major forested catchment of the south fork. The ENF maintains, as part of its forest management activity, a spatiotemporal database of fire occurrences and characteristics that goes back almost a hundred years. The Highway 50 corridor has played a dominant role in recent large fires in the region. For example, Fred's Fire burned more than 700 acres north of Kyburz in 2004, killing 75-90 percent of the trees in the area and resulting in high sedimentation rates, erosion, and loss of wildlife habitat and old growth forest. Restoration efforts were estimated to cost $2.5 million (U.S. Forest Service, 2009). Other large, stand-replacing fires in the ENF include Pilliken's Fire (1973, 10,000 acres), Wright's Fire (1981, 3,800 acres) and the Cleveland fire (1992, 24,000 acres). Apart from ENF's local fire occurrence data, a coarser, state-level simulation of fire risks in response to changing climate has been developed on a 1/8 degree grid (Westerling et al., 2009). While state- and local-level information of fire occurrence and characteristics exists, it should be noted that there is no long-term, pre- and post-fire hydrologic data from within the ENF.

Conceptual Model

WEAP's hydrological routine, consisting of a lumped soil moisture balance, is described in Yates (1996) and Yates et al. (2005). The impacts of fire on the hydrologic cycle can be simulated through impacts on soil and vegetative function (Beeson, Martens, and Breshears, 2001; Cydzik and Hogue, 2009; Elliott et al., 2005; McMichael and Hope, 2007; Rulli and Rosso, 2007). This is incorporated into the modeling framework by (1) finding a parsimonious set of new parameters that can conceptually simulate the ecosystem (primarily soil and vegetation) impact and recovery trajectory, and (2) relating the same to a fire's characteristics. Fire severity is the characteristic that is most linked to effects on soil properties and hydrologic function (Neary, Ryan, and DeBano, 2005). In this context, the closest modeling analog to WEAP's lumped soil moisture model is the modification of the Natural Resources Conservation Service runoff numbers to reflect both the immediate post-fire impact on soil and vegetative function, as well as the recovery time of those ecosystem functions (Cydzik and Hogue, 2009; Elliott et al., 2005). In WEAP, the most parsimonious set of parameters to be modified in a similar fashion to capture the soil-hydraulic response are the runoff resistance factor (RRF), which controls surface runoff (SRO) generation, and the crop coefficient (Kc), which controls evapotranspiration (ET). Four new parameters were used to modify RRF and Kc, with the functional forms dictating the trajectory of recovery of function.

KcFire

This parameter is a multiplier of the pre-fire crop coefficient Kc, (restricted to between 0 and 1). Its purpose is to simulate the immediate impact of the fire on vegetative (transpiration) function as a fraction of pre-fire function.

VRT

The vegetation recovery time (VRT) parameter simulates the recovery of the vegetative (transpiration) function. It is the time, in years, over which transpiration function can be assumed to recover to pre-fire state—i.e., the time over which post-fire Kc, starting from KcFire*Kc, returns to pre-fire Kc. The form of this recovery is modeled as a function of fire severity. Mild fires are mapped to a logistic growth, moderate fire to a linear growth, and severe fire to an exponential growth.

RRF Fire

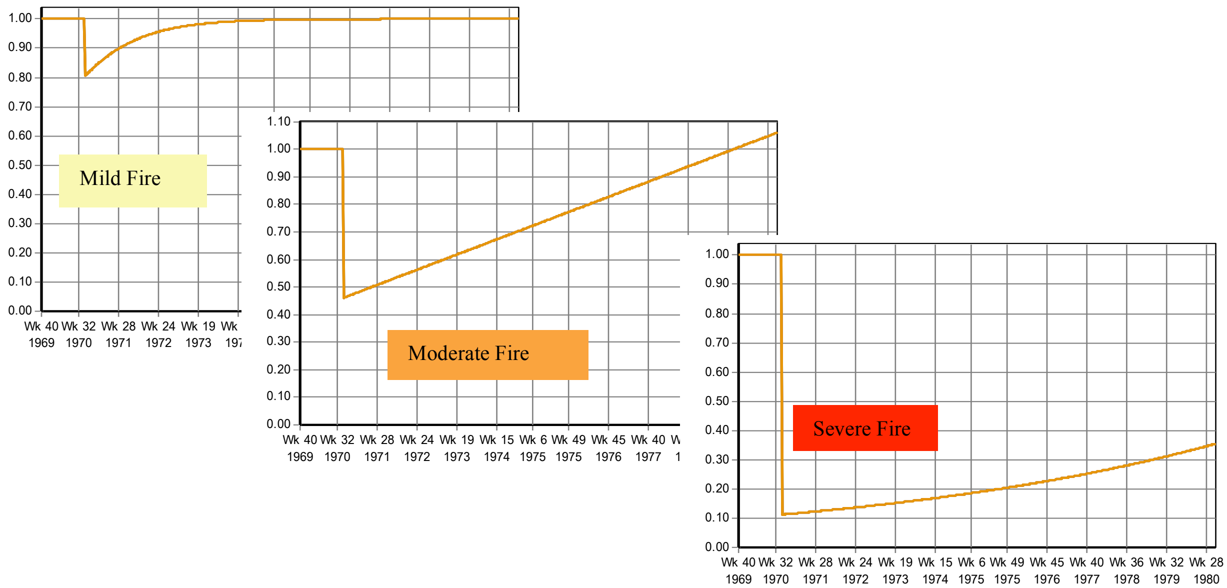
This parameter is a multiplier of the pre-fire RRF, (restricted to between 0 and 1). Its purpose is to simulate the cumulative immediate impact of the fire on soil-hydraulic function as a fraction of pre-fire function.

Soil Recovery Time (SRT)

The SRT parameter simulates the recovery of the vegetative (transpiration) function. It is the time over which soil hydraulic function can be assumed to recover to pre-fire state—i.e., the time over which post-fire RRF, starting from RRF Fire*RRF, returns to pre-fire RRF. The form of this recovery is modeled as a function of fire severity. Mild fires are mapped to a logistic growth, moderate fire to a linear growth, and severe fire to an exponential growth.

The evolution of the soil-vegetation function as a function of fire severity (as the chosen fire characteristic) was simulated by imposing, respectively, exponential, linear, and logistic growth functions on RRF and Kc in response to a mild, moderate, and severe fire. Figure A-2 provides an illustration of the same, where in response to a severe fire, the immediate impact is much higher and takes longer to recover from than a mild fire.

Figure A-2: Illustration of Soil-Vegetation Recovery Under Three Qualitative Fire Severity Scenarios



NOTES: The y-axis is the ratio of the soil hydraulic function value to its pre-fire value. In this illustration, under a severe fire, the soil-vegetative function does not recover to its original state.

Testing the Model

An initial test was implemented in the WEAP model of the EID system. The implementation was tested using two separate approaches: (1) coding the new parameters and equations using Python scripting and (2) using WEAP only built-in features using new variables and expressions. After evaluating the pros and cons of each approach, the WEAP-only implementation was chosen, primarily because the Python scripting approach would require stakeholders interested in running the model to have Python installed and knowledge of the programming language.

Initial results were evaluated for 10-year test runs (instead of the complete 56-year duration). These evaluations showed that the model performed to expectation under assumed impacts and recovery times (Figure A-3 and Figure A-4).

Incorporating Uncertainty: Monte Carlo Simulations

In response to the lack of data of long-term hydrologic impacts that could inform the model parameterization as well as the inherent variability of the response, the model was enhanced to run a Monte Carlo simulation which involved (1) incorporating the uncertainty in both process and model parameters by assuming a probability distribution on each of the new parameters and (2) running the model 100 times for 56 years each time, drawing the four parameter values from the random normal distribution each time. The assumed distributions for each parameter are illustrated in Figure A-5 and summarized below:

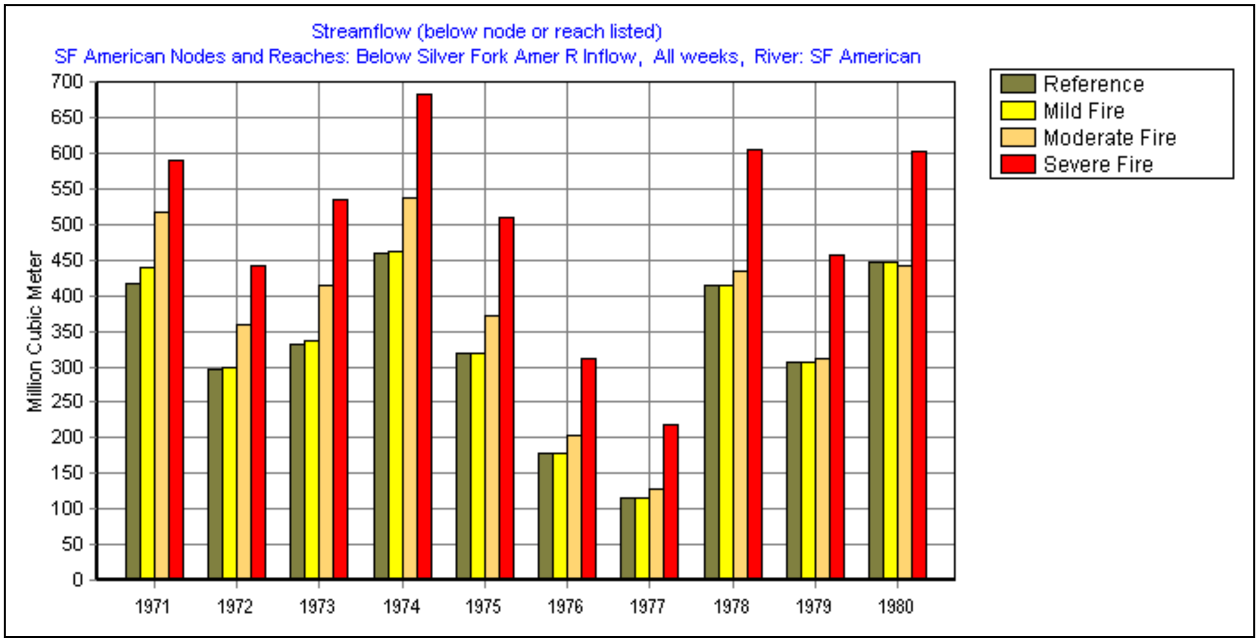
- **KcFire ~ N(0.3,0.05)**
  Immediate post-fire Kc is assumed to drop to 30 percent of pre-fire Kc on average, with a standard deviation (sd) of 5 percent.
- **Vegetation Recovery Time ~ N(40,10)**
  Evapotranspiration function is assumed to recover in 40 years on average with an sd = ten years.
- **RRF Fire ~ N(0.5,0.05)**
  Immediate post-fire (soil-hydraulic) runoff function is assumed to drop to 50 percent of pre-fire function with an sd = 5 percent.
- **SRT ~ N(10,2)**
  Recovery of (soil-hydraulic) runoff function is assumed in ten years on average with an sd = two years.

Description of a Relevant Fire Scenario

Further engagement with the EID community resulted in the description of a fire scenario more relevant to EID's water supply, that *(1) limits the fire simulation to the Upper Cosumnes River, from which water is transferred to Jenkinson Lake via the Camp Creek tunnel and (2) to focus the impact analysis on key results that are important for EID, i.e., impacts on the hydrology of the Upper Cosumnes, plus inflows to Jenkinson Lake and Camp Creek tunnel flows under current operating rules on the use of the infrastructure.*

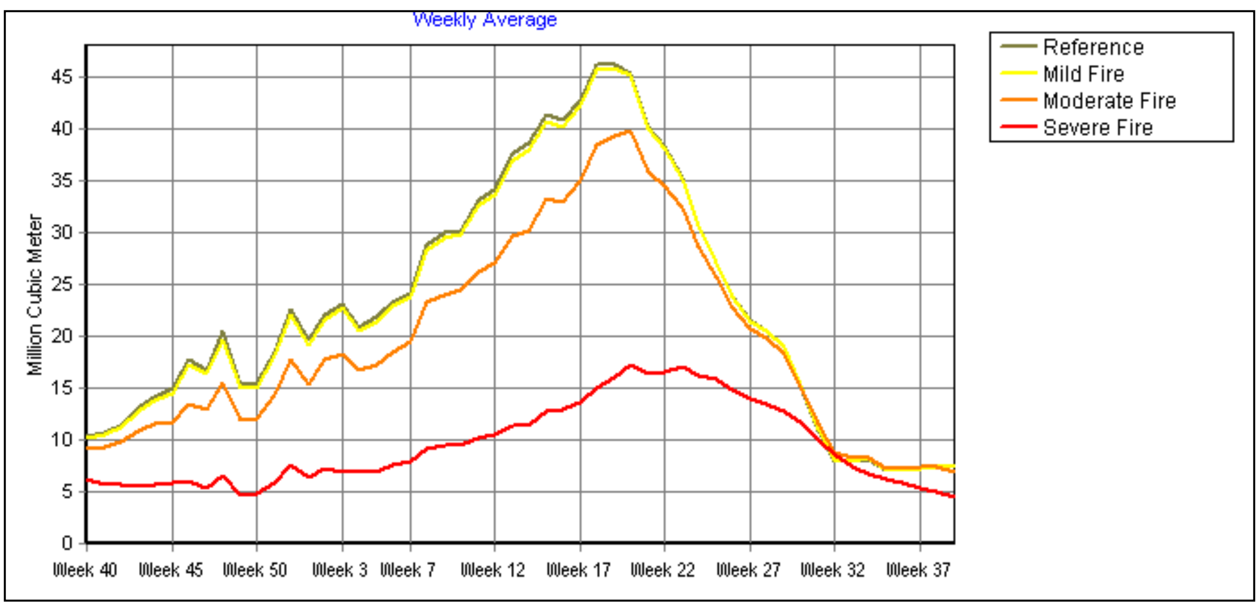
Monte Carlo simulations were run by implementing the parameter sampling only for the Upper Cosumnes catchments (thereby simulating a fire in those catchments), and the results of this run are shown in Figure A-5. These results reflect the general behavior of the initial model run—that of increased streamflows and reduced evapotranspiration. As a result, both Camp Creek flows and Jenkinson inflows are increased in the early years after a fire. Baseflows are also slightly higher despite more water being routed to surface runoff than infiltration, reflecting that the reduction in ET makes up for it.

Figure A-3: Test Implementation of the Conceptual Model—Annual Streamflow



NOTE: SF = streamflow.

Figure A-4: Test Implementation of the Conceptual Model—Average Weekly Evapotranspiration Under Different Fire Scenarios over a Year



NOTE: The horizontal axis is the week number of a calendar year, e.g., week 1 is the first week in January.

Two key results emerge from the Monte Carlo simulation: (1) this approach allows for a range of plausible outcomes to emerge, rather than a fixed and rather unrealistic deterministic value; and (2) the initialization of a fire is an important consideration. In the current run illustrated in Figure A-4, from 1950–1999, the fire was assumed to be initiated at the first time step, in 1950—and as per the parameters, the response reaches values prior to the fire in about 40 years. While the approach captures the system dynamics of recovery time from an immediate post-fire impact, it is not yet informed as to when to initiate a fire.

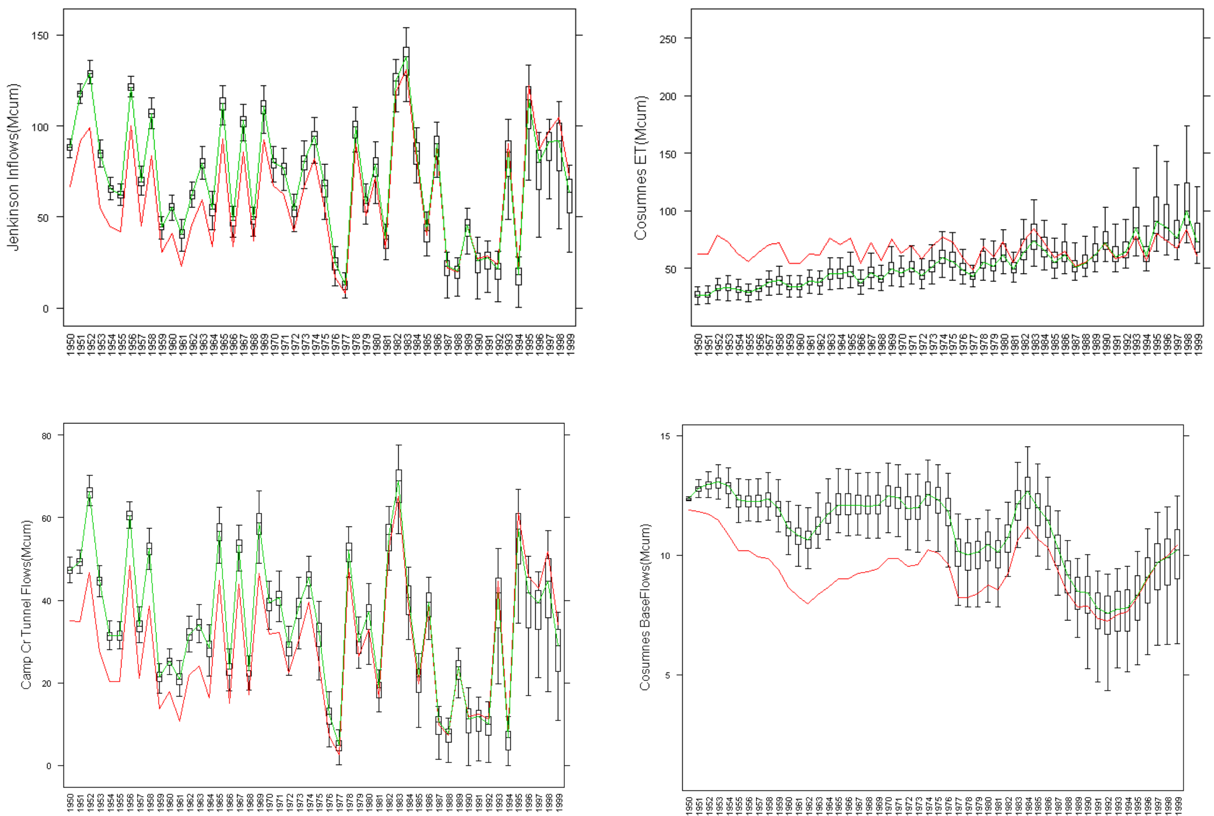
Stakeholder Engagement

Stakeholder engagement throughout this effort spanned key informants in EID and the expert community, comprising forest service staff and scientists from ENF, U.S. Department of Agriculture (USDA) Southwest Pacific Research Station, and academics engaged in similar research. The key stages of interaction and response were illustrated in Figure A-1+ and are summarized here.

Data Search

Both communities (i.e., EID and experts) were engaged in the literature and data review in this process, through electronic correspondence, teleconferences, and in-person meetings. These interactions were instrumental to identify key literature and to obtain the local- and state-level fire data. Three important conclusions are that (1) there is no long-term, pre- and post-fire **hydrologic** data, (2) the Westerling 1/8 degree gridded data on projected fire risk are too coarse for our immediate objectives, and (3) there is a very high degree of uncertainty on impacts of fire on hydrology, beyond the ordinal relationships between impacts and fire severity. These conclusions led to a refinement of the model application that could handle a stochastic simulation of impacts through Monte Carlo simulations (see *Model Refinement* above).

Figure A-5: Boxplots from Monte Carlo Simulations of Fire Impacts: Annual Streamflow, Tunnel Flows, Evapotranspiration, and Baseflow



NOTE: Mcum = million cubic meters.

Feedback on the Model

Feedback on the initial implementation of the conceptual model was first sought from the expert community, including ENF staff (facilitated by Tony Valdez), the USDA Pacific Southwest Research Station (facilitated by Richard Stein and Seth Bigelow), and the academic community in the fire modeling group at the University of Washington. The response to the approach was positive and enthusiastic, supporting the conceptual model. There were two important conclusions from this effort. First, forest service modeling efforts (using spatially distributed simulation tools for fire spread) are geared toward supporting forest management efforts, especially in managing fuel loads and prescribed burns. The focus (understandably) is not directly on water supply concerns and hydrologic impacts. Second, the expert community saw value in this research, especially because of the direct link it could draw between fire and impacts on people through water supply concerns.

Feedback on the initial model results was also gained at the second EID stakeholder workshop in January 2010. This response was varied and is described elsewhere. The key messages from the workshop were that (1) there is a diversity of values associated with forests and roles of wildfires in the forest ecosystem that determine impacts, and (2) the importance of understanding fire impacts on water supply is widely acknowledged among the public, but that erosion and water quality concerns ran alongside water quantity concerns. Impacts on erosion and water quality are however outside the scope of the current research.

Future Research Directions

In this Appendix, we describe the key components of a future research program that builds upon the results of the current effort. While this report focuses on fire impacts, the same approach could be at least theoretically extended to forest management treatments—including prescribed fires, selective logging, thinning, clear-cutting, and afforestation. The future research program documented below includes these effects and is not limited to wildfire-only impacts on water resources.

Knowledge Synthesis

As detailed in Section 4, although the modeling framework to link forest management with water resources has been built into WEAP, a major constraint is uncertainty in the parameters to adopt. This uncertainty comes from a combination of (1) a lack of long-term pre- and post-fire hydrological **monitoring** (at least in the ENF), and (2) inherent **variability** in impacts of a particular treatment across a **diversity** of site characteristics (e.g., climate, forest types, management history, and pressures).

Two formal methods of knowledge synthesis are proposed here that address these problems. These go beyond the classical, narrative-led literature reviews, into the realm of *systematic reviews.* The USDA Forest Service's "Wildland Fire in Ecosystems: Effects of Fire on Soils and Water" (Neary, Ryan, and DeBano, 2005) remains the "state-of-the art" review on the topic of fire and hydrological impact and can be considered a *qualitative systematic review* that is widely referred to by the research community.

Meta-Analysis

Meta-analysis is the *quantitative* component of a systematic review. It is a set of techniques where the results of several independent studies can be statistically combined for an overall answer to the question of interest. Meta-analysis can give more objectivity to a review than a conventional literature review, and it is often more generalizable than any single study.

Meta-analysis is generally used in control-treatment situations, i.e., experimental research. For example, it is widely accepted and used in the field of medicine to evaluate the efficacy of certain treatment options over a large number of trials. Its use in the field of ecology is limited but increasing. Examples of meta-analysis in forest management are emerging as a result of large experimental programs, such as the Fire and Fire Surrogates Study (FFS), and other monitoring programs, such as the Long-Term Ecological Research (LTER) network. In forestry, meta-analysis has been used to evaluate impacts of forest management on soil nutrients (Johnson and Curtis, 2001; Boerner, Huang, and Hart, 2009) and biodiversity (Kalies, Chambers, and Covington, 2010; Verschuyl et al., 2011). Meta-analyses is very limited in the hydrological literature (e.g., Locatelli and Vignola, 2009); we have found no meta-analyses conducted on the particular linkage between forest treatment and water resources.

A key requirement for conducting a meta-analysis is a sufficient number of eligible studies from the research area in question. Although this is certainly not true of the EID/ENF study area that was the focus of the current study, the literature review (*Literature and Data Review* above), the individual studies mentioned in Neary, Ryan, and DeBano (2005), and recent conversations with DWR, CAL FIRE, and USDA Forest Service staff (M. Rayej, K. Larvey, B. Hill; personal communication, November 2011) about long-term monitoring sites in California suggest that a meta-analysis should be possible. Its utility can be gauged with the example of Johnson and Curtis (2001), who used meta-analysis to analyze 73 observations from 26 publications across several countries to determine mean responses of forest soil carbon and nitrogen to different management techniques and to place confidence limits around those means. The authors were able to determine whether particular experimental conditions or forest types elicited quantitatively different responses to management. To provide the analog to our own research question, we can test whether there are significant differences in mean hydrological response among categorical groups (e.g., hardwoods or conifers, or time since treatment, or type of fires) across the available studies.

Incorporating Expert Knowledge in Bayesian Networks

Bayesian networks are a type of decision support tool in which variables are related to one another using conditional probabilities via Bayes' rule (Bayes, 1763). Several features make them useful for the type of ecological management decision making of interest here (Cain, 2001). In the context of integrated water resources management, Bromley (2005) describes in detail the application of Bayesian networks through case studies from the United Kingdom, Denmark, Spain, and Italy. Bayesian networks can cover a broad range of topics and are more generic than most modeling tools and can be represented graphically (particularly through directed graphs linking cause and effect). Most importantly, they can capture qualitative and incomplete information, offer a coherent way to treat uncertainty, and can be sequentially updated over time as more information (e.g., from more experimental evidence from LTER) becomes available.

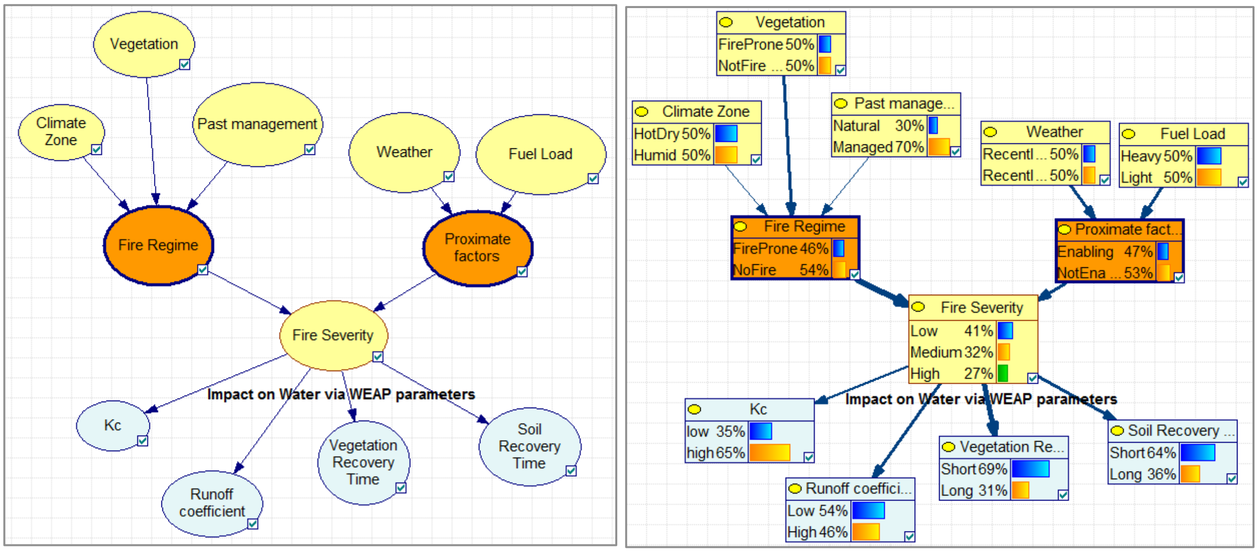
A Bayesian network has three elements: a set of variables (called "nodes") relevant to the problem, the links between these variables that describe cause and effect, and the conditional probability tables for each node that are used to calculate the state of the node given the states of its parents. The first two form the network diagram, and the third makes it a fully functioning Bayesian network. Nodes can be of any type (physical, environmental, social, etc.). Each is assigned a series of (descriptive or numerical) "states" that the node might occupy under different conditions. For nodes without parent nodes, an unconditional distribution is defined: It is the operator who decides the state of that node—this can be on the basis of existing evidence or this can represent a scenario or potential action that may take place.

By way of illustration, Figure A-6 conceptualizes a simple Bayesian network that links fire (treatment) characteristics to hydrologic impacts through the framework developed in the sections of this report. The Bayesian network was constructed using GeNIe (Graphical Network Interface) (Decision Systems Laboratory Wiki, 2010), a development environment for building graphical decision-theoretic models developed at the Decision Systems Laboratory, University of Pittsburgh, that is made available to the research community at no charge. Although simplified, Figure A-6 illustrates three important aspects of the proposed research that significantly extend the current research output. Both aspects involve elicitation of expert opinion as well as data collection from experimental forests.

1. Linking the occurrence of a fire to its effects.
   Recall that the current research output did not address *when* or *how* a wildfire of given severity occurs—it instead built a framework for how hydrologic impacts can be modeled, *if* a fire of given severity occurs. Figure A-6 is a Bayesian network that shows how a graphical model can be built that *links* the likelihood of a fire of certain severity in a sub-network of driving forces, to its impact on the hydrologic parameters.
2. The elicitation of the probability distributions of the hydrologic parameters that had been assumed in Figure A-4.
3. The possibility of constructing an alternative Bayesian network, depending on expert consensus.

Expert opinion can be elicited in a variety of formal ways (see O'Hagan, 2006). SEI has developed an extension that can be used to link a Bayesian network with WEAP. The extension is a dynamic-link library that allows passing values from WEAP to a GeNIe model as evidence, running the model, and collecting the values from the Bayesian network nodes back into WEAP.

Figure A-6: Hypothetical Bayesian Network for Fire Severity Linked to Water Resource Impacts



NOTES: The left graphic shows the basic Bayesian Network. The right graph shows a Bayesian Network with an assumed conditional probability table linking the nodes, and the relative influence thereof is shown by the thickness of the arrows.

Modeling of LTER Sites

As noted earlier, a key challenge for the study was the lack of pre- and post-fire *hydrologic* information that could inform the modeling framework that we developed. The most direct approach for the next phase of research was to apply the modeling framework presented in this report to a site that *has* hydrologic observations on pre- and post-fire (treatment). The most likely candidate watersheds would be from LTER sites. Possible candidates from experimental forests are presented below along with links to more information on each, based on interactions with staff from CAL FIRE, DWR, and the USDA Forest Service. A final list of sites would emerge from further investigation with the assistance of forest personnel at these sites.

Experimental Forests

1. Caspar Creek Experimental Watershed Study (Mendocino—North Coast)
   http://www.fs.fed.us/psw/topics/water/caspar/
2. Kings River Experimental Watershed (Southern Sierra)
   http://www.fs.fed.us/psw/topics/water/kingsriver/stream_discharge.shtml
3. Sagehen Experimental Forest (near Truckee)
   http://www.fs.fed.us/psw/ef/sagehen/
   http://sagehen.berkeley.edu/resources.htm
4. Teakettle Ecosystem Experiment (Southern Sierra)
   http://teakettle.ucdavis.edu/index.htm
5. Blacks Mountain Experimental Forest (Cascade—Lassen)
   http://www.fs.fed.us/psw/ef/blacks_mountain/

6. Redwood Experimental Forest (Humboldt—North Coast)
   http://www.fs.fed.us/psw/ef/redwood/
7. San Dimas Experimental Forest (Southern California)
   http://www.fs.fed.us/psw/ef/san_dimas/
8. University of California Natural Reserve System
   http://www.ucnrs.org

This research component would integrate well and indeed benefit enormously with the *Knowledge Synthesis* component section, especially given the complex nature of the problem. Long-term experimentation in Caspar Creek (Redwood Sciences Laboratory, 1993) illustrates the importance of both the accumulated knowledge of the expert community, as well as the inherent complexity of the problem, especially when one attempts to scale up experiments on forest plots, or very small catchments, to a larger watershed scale. As a Caspar Creek research hydrologist concludes in one report, the data alone do not always show clearly the impact of road building and selective logging on watershed scale streamflows (Redwood Sciences Laboratory, 1993). Another publication out of Caspar Creek (Anonymous, 1993) reported changes in summer flows as a result of logging, changes that diminished over time after logging ceased and as the vegetation recovered.

There is an opportunity that these nuanced interactions could be discerned from a combination of knowledge synthesis and long-term data feeding into a WEAP modeling approach.

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