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# A framework for modelling suspended sediment flux following wildfire in forested water supply catchments, south-eastern Australia

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**Abstract:** Wildfire represents a potentially important threat to the security of water storage reservoirs situated in fire-prone forest catchments. From a water treatment perspective, managers are interested in exceedence probabilities for event suspended sediment loads rather than estimates of average annual loads. To address this, we aim to develop a stochastic model of wildfire and storm event probabilities that are linked to erosion response and suspended sediment loads entering reservoirs. In this paper we present a conceptual catchment-scale model framework that will form the basis for the development of this model. The study focuses on the two main forested water supply catchments that provide potable water to Melbourne, Victoria.

Determining probabilities of wildfire occurrence for the study catchments presents a significant challenge, given the limited historic data available. An approach to modelling wildfire involves the use of expert opinion to quantify probabilities of either wildfire entering the catchments from different directions, internal ignition at one or more points, or no fire occurring on days with high fire risk weather. With each annual simulation a wildfire may occur based on random sampling of the wildfire occurrence probabilities. The fire front direction (or internal ignition point), combined with random sampling of fire weather data, form inputs to a deterministic fire behaviour model, which is used to generate burn area and severity spatial data for a range of scenarios.

The post-fire storm event component is based on distributions for the maximum annual storm and flow event (for two rainfall event types) that may occur during the recovery period (three years). The two event types are localised, high intensity, short duration summer storms and widespread, high magnitude rainfall events that may occur over 1-3 day periods during winter and/or spring. Erosion response to the contrasting rainfall and associated flow characteristics of the event types is represented using various sub-models for key post-fire erosion processes, namely, hillslope surface erosion and delivery to streams, debris flow (runoff and mass failure-generated), and flood-driven channel erosion.

Hillslopes and small tributary sub-catchments within the study catchments are divided into spatially-defined erosion response units based on modelled fire severities and forest-soil categories. Erosion process sub-models are run for response units depending on unit properties, fire severity, and rainfall event type. Sediment outputs from these response units are delivered to adjacent channels, with the extent of delivery to reservoirs dependent on in-channel/floodplain storage losses. Erosion associated with post-fire channel change along the main trunk streams is also modelled and included in the estimated total suspended load entering the reservoirs. The effect of post-fire recovery is captured through functions that represent temporal changes in response units (e.g. vegetation regrowth). Data on post-fire hillslope erosion, debris flow scour, and catchment sediment yields (1-100 km$^2$) has been collected from areas similar to the water supply catchments for sub-model development and validation.

Linking all model components within the catchment-scale framework will enable production of outputs in the form of distributions of the maximum annual event suspended load (for the two event types) in tributary streams entering the reservoirs. This will provide managers with the capacity to evaluate the risk to water supplies associated with post-fire suspended sediment loads and to develop appropriate strategies to mitigate the threat posed by wildfire and storm events.

***Keywords:*** *stochastic models, wildfire, forests, erosion, water quality, model frameworks, Australia*

## 1. INTRODUCTION

Wildfire presents a potentially important threat to the quality of water supplies in forested catchment reservoirs. Post-fire erosion can generate large amounts of sediment, nutrients and other constituents (e.g. ash, trace metals) that may be delivered to streams and reservoirs (Shakesby & Doerr, 2006). This may result in water supplies that are unfit for consumption. Such water quality issues are of immediate concern during the post-fire recovery period during which vegetation cover is low and changes to soil hydrological properties continue to persist (Sheridan et al., 2007). In this paper we seek to develop a catchment-scale conceptual model framework to be utilised in quantifying the risk to water supply from wildfire, subsequent storm events, and the associated erosion response which generates and delivers suspended sediment and other constituents to reservoir tributary streams. This framework will provide the basis for subsequent development and parameterization of a set of linked models (or adaptation of existing models) that will be used to generate probabilistic estimates of different constituent loads entering reservoirs. The overall objective of this research program is to determine the probabilities of key constituents exceeding a defined threshold load or delivery rate in tributary streams at the reservoir boundary in the study catchments for a given duration in a) any given year and b) during the post-fire recovery period. The scope of this work is limited to catchment-scale processes and does not extend to modelling the transport and transformation of constituents from tributary streams at the reservoir boundary to the reservoir outlet, which will be undertaken in a separate project. In this paper we focus on fine suspended sediment (<20 μm), with additional constituents for modelling to be included subsequently based on the literature on post-fire water quality in conjunction with drinking water standards, available data, and model constraints.

## 2. STUDY CATCHMENTS

This study focuses on the two main water supply catchments that provide potable water to Melbourne (population 3.8 million), Victoria. These reservoirs are situated in the Thomson and Upper Yarra River catchments, located east of Melbourne, and have catchment areas of 487 km$^2$ and 337 km$^2$, respectively (Figure 1). The reservoir catchments were selected for modelling because they contain large areas of fire-prone Eucalyptus forest and currently supply most of Melbourne's water, with the Thomson and Upper Yarra reservoirs accounting for 60% and 11% of the total water storage capacity (1,787,500 ML), respectively. Melbourne's water generally only undergoes limited treatment, which includes disinfection, fluoridation and pH correction. Development of additional treatment capacity is one possible response to the potential risk posed by wildfire to reservoir water quality. However, in order to justify the large capital investment associated with the expansion of treatment facilities, there is a need for some measure of the level of risk to water quality from wildfire and subsequent storm events.

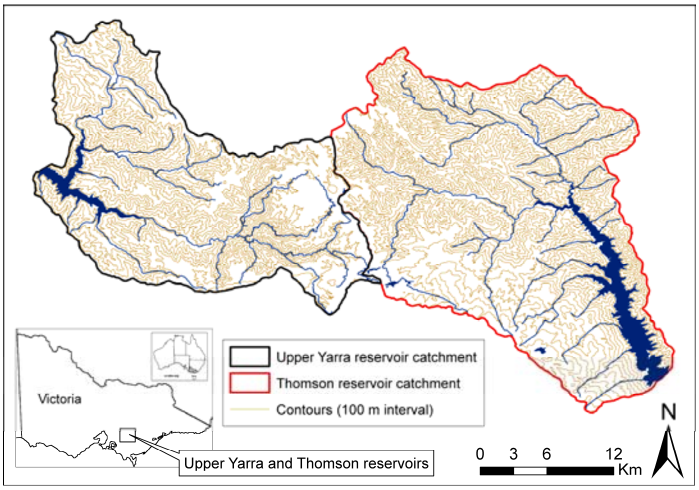


**Figure 1.** Location of the Upper Yarra and Thomson reservoir catchments

## 3. MODEL FRAMEWORK

From a water supply and treatment perspective, managers are interested in exceedence probabilities for event suspended sediment (and other constituent) loads. However, many existing erosion and sediment flux models only generate average annual estimates of erosion rates and sediment yields. These models also fail to capture the effect of large, infrequent, events that tend to dominate sediment flux in forested catchments (e.g. Lane et al., 2006). The catchment-scale conceptual model framework proposed in this paper consists of a linked stochastic-deterministic wildfire model component used to generate repeated simulations of burn area and severity, which, when coupled with the stochastic storm and flow event component, may be used to run post-fire erosion process sub-models (Figure 2). This enables the probabilities of wildfire and storm event occurrence for various wildfire and storm event scenarios to be linked to erosion response and suspended sediment input to reservoir tributary streams. The main components of the model framework are outlined in the following sections. The purpose of this is not to provide a detailed description of model functionality but rather to give an overview of the components and the basis for their inclusion in the framework.

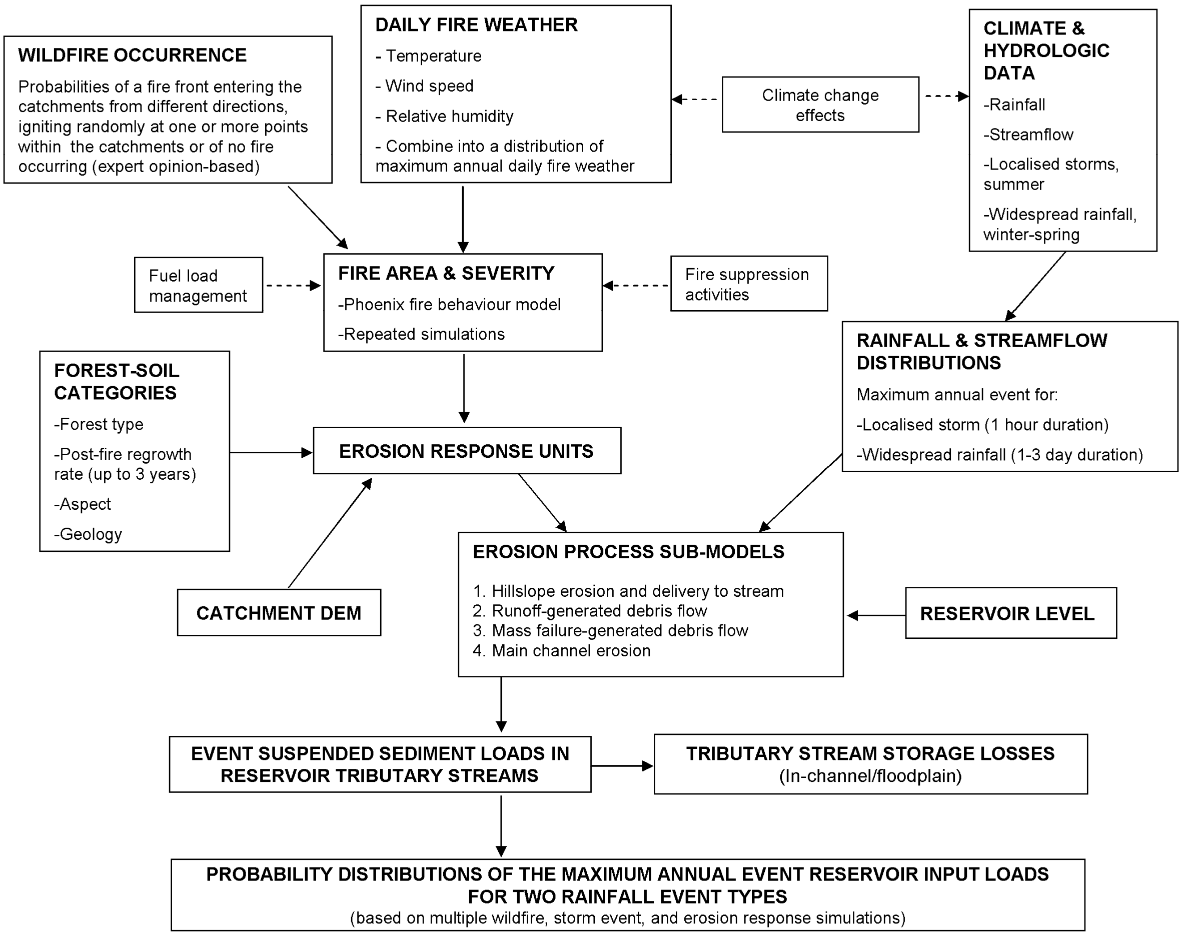


**Figure 2.** Conceptual model framework for deriving the probabilities of suspended sediment loads associated with different wildfire and storm event scenarios entering the study catchment reservoirs

Development of the conceptual model framework has been based on landscape attributes (defined forest-soil categories, steep slopes, high energy streams, confined floodplains) and post-fire erosion processes likely to be important for the erosion and delivery of fine suspended material in the Thomson and Upper Yarra reservoir catchments. This has been guided by previous research in comparable forest environments to those present within these catchments (e.g. Lane et al., 2006; Sheridan et al., 2007). However, the model framework may be more broadly applicable to the fire-prone, steep, upland, forest areas in south-eastern Australia, particularly given that the framework allows incorporation of regionally varying landscape controls (as spatially defined erosion response units) and different post-fire erosion processes (as sub-models).

### 3.1. Wildfire component

Determining probabilities of wildfire occurrence, burn extent and severity for the study catchments presents a significant challenge, given that historic records are short. Alternative, longer-term techniques for estimating fire regimes (e.g. dendrochronological analysis of fire scars, sedimentation records) provide only partial insight into catchment-wide fire frequency and extent, being necessarily constrained in space and applicable to varying timescales. This lack of data on wildfire frequency limits the extent to which wildfire component of the model framework may be developed. Therefore, a preliminary approach to determining probabilities of wildfire occurrence and the resulting burn area and extent is presented here.

Wildfire ignition may occur outside the catchments or within at one or more points (such as by lightning strike). Fires that start outside the catchments may travel large distances on an extreme fire weather day and approach each catchment from various directions. We require the probabilities of either fire fronts entering the catchments from different directions, fires being ignited internally, or of no fire occurring on days with high fire risk weather (high temperatures, strong winds, low humidity). Given the limited historic data available, expert opinion will be used to quantify these probabilities. With each annual simulation a wildfire may occur based on random sampling of the expert-based wildfire occurrence probabilities. When a fire does occur, the selected direction from which the fire front enters the catchments or the internal ignition point(s) (randomly assigned, excluding areas such as riparian zones) are combined with a randomly sampled input from a distribution of maximum annual daily fire weather risk (based on historic data for daily temperature, wind speed, and relative humidity), which is sub-divided into a limited set of categories to reduce the number of possible fire weather values sampled. The combination of fire type (external from different directions or internal) with a fire weather risk category is used to select a catchment burn area and severity scenario. These burn scenarios are generated using Phoenix, a deterministic fire behaviour model (Tolhurst et al., 2008). Phoenix models the rate and direction of fire spread and generates burn spatial data (using a grid cell resolution of 100 m). Approximately 5-10 burn scenarios will be generated for each fire front direction and for internal ignition (using historic fire weather time-series data for model runs which are linked to the fire weather risk categories). Each burn scenario will have a probability value linked to it which is derived from combining the probabilities attached to wildfire occurrence and the fire weather risk categories.

### 3.2. Rainfall-runoff event component

The stochastic rainfall-runoff event component will be based on random sampling of distributions for the maximum annual storm (using available historic rainfall data) and associated flow event (using historic data from gauged streams entering the reservoirs) for two rainfall event types that are considered to most likely produce large post-fire suspended sediment inputs to reservoirs. The two event types are localised, high intensity, short duration summer storms and widespread, high magnitude rainfall events that occur over 1-3 day periods during winter and/or spring. The localised summer storms are randomly placed within the study catchments, with the area impacted by the storm based on observations of average storm area from weather radars. The widespread, high magnitude winter-spring event is assumed to cover the whole catchment. An assumption of the model is that the two event types would account for most of the post-fire inputs of suspended sediment to reservoirs in a year. The dominance of sediment flux through catchments by a few large events has been widely reported in south-eastern Australia (e.g. Lane et al., 2006). Notably, a similar focus on maximum annual events was also adopted by Robichaud et al. (2007) in a probabilistic model of post-fire hillslope erosion, given the importance of these events for erosion and the need for model efficiency. Also potential short-term post-fire increases in event rainfall-runoff relationships relative to pre-fire levels may occur during the recovery period, making use of pre-fire flow data problematic. However, in contrast to small catchments (e.g. Lane et al., 2006), this is difficult to evaluate for large catchments (>100 $km^2$) due to increased variation in rainfall across larger areas (and the generally sparse rain-gauge coverage in remote forest catchments), and there are few studies at this scale. An exception to this is Tomkins et al. (2008) who found no detectable increase in post-fire event rainfall-runoff relationships from two large dry forest catchments (104 and 446 $km^2$) near Sydney.

### 3.3. Spatially distributed erosion response units

For the purpose of modelling erosion processes, hillslopes and small tributary sub-catchments within the study catchments are divided into Erosion Response Units (ERU). ERUs are based on the spatial extent of burn severities resulting from Phoenix fire behaviour modelling and forest-soil categories derived from spatial data for forest type, aspect, and geology (in the absence of soil spatial data). ERUs represent areas for which key environmental controls and burn severity are treated as uniform and will be used in conjunction with Digital Elevation Models (DEM) for the study catchments as the basic spatial template for erosion process modelling. In addition, channel erosion is modelled separately for the main floodplain streams within the two study catchments. Selection of the erosion process modelled at each ERU is dependent upon the rainfall event type and critical ERU properties (fire severity, slope, forest and soil type), with the selection criteria based on field observations, data, and available literature for each process.

### 3.4. Erosion process sub-models

The erosion response to the contrasting rainfall characteristics of the two event types are represented using various sub-models for key post-fire erosion processes, namely, hillslope surface erosion (e.g. Smith & Dragovich, 2008), runoff and mass failure-generated debris flows (e.g. Cannon et al., 2008), and flood-driven channel erosion (e.g. Moody & Martin, 2001). In addition, erosion sub-model outputs will be required for unburnt conditions, in order to estimate suspended sediment load inputs to reservoirs in the years when no fire occurs. Previous research suggests that in unburnt forest catchments erosion may largely be from channel change and possibly mass failure-generated debris flows in response to high magnitude rainfall events (Rutherfurd et al., 1994). Unburnt forest hillslope erosion rates are very low and the catchments are managed to minimize impacts on water quality from roads and other disturbances. Burnt conditions appear to be a necessary factor for runoff-generated debris flows to occur. The modelled post-fire recovery period is limited to three years on the basis of previous research which suggests that hillslope runoff and erosion rates in upland forest environments comparable to those present in the reservoir catchments will probably decline to near pre-fire levels within this period (Sheridan et al., 2007).

**Table 1** Available datasets for parameterisation and testing of erosion process sub-models

| Process | Method | Location | Data |
|---|---|---|---|
| Hillslope sheet & rill erosion | • Experimental burns (low to high fire severity plots) and monitoring of hillslopes burnt by wildfire<br>• Rainfall simulation<br>• Soil measurements | - Upper Yarra reservoir catchment<br>- NE Victoria | • Plot scale runoff & erosion rates<br>• Post-fire surface vegetation recovery<br>• Pre & post-fire soil properties: water repellence, $K_{SAT}$, ash depth, water content, organic carbon content, nutrients |
| Hillslope-to-stream connectivity | • Experimental & wildfire burnt areas (hillslope-scale)<br>• Near-channel runoff & erosion measurements | - Upper Yarra reservoir catchment,<br>- NE Victoria | • Runoff and sediment delivery rates to stream edge from burnt hillslopes |
| Runoff generated debris flow | • Survey of known debris flow sites<br>• Channel deposit sampling | Surveyed sites:<br>- Licola (x2)<br>- Germantown<br>- Yarrarabula<br>- Rose River | • Hillslope erosion<br>• Channel scour (n = 42)<br>• Soil bulk densities and particle size<br>• Peak channel flow estimates |
| Mass failure generated debris flow | Literature review | Upper Yarra and Thompson reservoir catchments | • Literature-based risk assessment<br>• Catchment DEM |
| Main channel erosion | • Channel mapping using historic aerial photographs<br>• Contemporary channel locations from LiDAR<br>• Floodplain deposit sampling | Floodplain areas in Upper Yarra and Thompson reservoir catchments | • Historical rates of channel change<br>• Contemporary channel locations<br>• Floodplain sediment bulk densities |
| Catchment sediment and nutrient yields (1-100 km$^2$) | • Monitoring of discharge and sediment flux from catchments burnt by both wildfire and prescribed fire | NE Victoria (wet and dry forests):<br>- East Kiewa<br>- West Kiewa<br>- Long Corner Creek<br>- Cropper Creek | • Pre and post-fire discharge, sediment and nutrient yields |

The erosion process sub-models will be developed and/or adapted from existing models for application in burnt forest environments using various datasets to parameterise and test the sub-models (Table 1). This includes data collected from experimental burns at different fire severities and from wildfire burnt areas (plot to catchment scale), surveys of existing post-fire runoff-generated debris flow sites (Central Highlands, Victoria), previous post-fire studies in comparable forest-soil environments, and remote sensing techniques (LiDAR survey, aerial photographs). A summary of the likely modelling approaches adopted for each erosion process is outlined below.

#### 3.4.1. Hillslope erosion and delivery to stream sub-model

After fire, soil water repellence and ash blockage of soil pores may reduce infiltration capacities and enable generation of infiltration-excess overland flow, which is otherwise rare in unburnt forests and likely to dominate runoff during summer-autumn months when soils are most water repellent and intense rainfall may occur during localised storms (Sheridan et al., 2007). In contrast, saturation-excess overland flow is more likely to dominate burnt hillslope runoff generation during winter-spring months (in response to the widespread rainfall event type) when soil water repellence is generally low due to increased antecedent soil moisture. We propose to use the hillslope-scale Stochastic Runoff Connectivity (SRC) model developed by Sheridan et al. (in prep.), in conjunction with WEPP soil erosion parameters, to model burnt hillslope infiltration-excess overland flow and suspended sediment exports from hillslopes to adjacent streams. Modelling of saturation-excess overland flow and hillslope sediment delivery will require estimation of saturated source areas contributing runoff and sediment to streams. This may be achieved using a variable source area model (e.g. TOPMODEL) in conjunction with soil erosion parameters. The effect of post-fire recovery in subsequent years will be incorporated through functions that represent ERU changes (e.g. vegetation regrowth rate, declining soil water repellence) that influence key parameters (namely soil infiltration, soil erodibility). Suspended sediment inputs to streams from unburnt hillslopes are considered negligible.

### 3.4.2. Runoff-generated debris flow sub-model

Development of a post-fire runoff-generated debris flow model is challenging, given the limited data available from forest environments in south-eastern Australia (Nyman et al., in prep.). Based on surveys of the extent of hillslope stripping and channel scour at five debris flow locations (in small, steep, burnt forest sub-catchments), as well as data on source material particle size and nearby rainfall event intensities, a simple empirical model of fine sediment exports by debris flows in small catchments (1-5 $km^2$) could be developed. However, this would provide no insight into processes and controls contributing to post-fire runoff-generated debris flow occurrence, such as downslope runoff bulking of ash and sediment and fire-induced changes to soil hydrological properties (Gabet & Sternberg, 2008). Preferably, development of a linked stochastic-deterministic model will be possible, with testing against estimated fine sediment exports determined from survey data. Model development will be supported by collection of soil hydrological data and hillslope-scale runoff measurements from high severity burn sites similar to those locations where debris flows have occurred. The criteria for sub-model activation will be based on the characteristics of surveyed sites and available information on the rainfall events which have generated debris flows (Nyman et al., in prep.). For example, when a dry forest sub-catchment (<5 $km^2$) comprised of a single ERU with high fire severity, steep slopes (>25°) and shallow soils is impacted by a high intensity (>40 mm $h^{-1}$), short duration (<30 min) summer storm event, a runoff-generated debris flow sub-model may be triggered.

### 3.4.3. Mass failure-generated debris flow sub-model

Few mass failure-generated debris flows have been reported in native forests catchments in south-eastern Australia and these did not occur after fire (Rutherfurd et al., 1994). Occurrence of these events after fire has been examined in forest areas in north-western USA, with modelling efforts focusing on the loss of tree root cohesion associated with stand-replacing fires and soil saturation from extended rainfall periods and/or snowmelt (e.g. Istanbulluoglu et al. 2004). In south-eastern Australia such stand-replacing fires tend only to occur in higher elevation wet forest areas comprised of fire-sensitive species, with dry forest Eucalypts generally surviving wildfires. Given the lack of data, the modelling approach adopted for this sub-model is yet to be determined.

### 3.4.4. Channel erosion sub-model

An event-based sub-model of bank erosion and channel change along the main tributary streams within the study catchments is required to estimate the likely amount of fine sediment eroded from floodplains and delivered to the reservoirs. Given that the magnitude of event discharge (and associated stream power) is likely to be a key driver of the extent of floodplain channel change, historic discharge and channel change data may be utilised in sub-model development. Reservoir level, which determines the extent of exposed channel and valley floor for the lower part of the main tributary streams, may be pre-set or randomly sampled from a distribution of levels based on historic data.

### 3.5. Main tributary stream suspended sediment loads and delivery to reservoirs

The extent of connectivity between suspended sediment sources (hillslopes, channels and small sub-catchments), the main tributary streams, and reservoirs will need to be accounted for in order to determine event loads entering the reservoirs. In some circumstances it may be possible to assume that eroded fine material (<20 μm) will remain in suspension once delivered to the high energy mountain streams during flow events (only the maximum annual rainfall-runoff events are modelled). Given that travel distances may be considered short (maximum stream lengths are <25 km), this assumption may be reasonable for the large, widespread rainfall-runoff event type. An exception to this may be when overbank flow and deposition occurs on confined floodplains of the main tributary streams. In contrast, connectivity between sediment sources and the reservoirs for the localised storm event will largely depend on the random placement of the storms in the study catchments. For example, if a storm is located over sub-catchments on the reservoir flank the level of connectivity may be close to 100%, alternatively, if located upstream of the reservoir a large proportion of the suspended sediment load may be deposited in-channel.

To generate probabilities for a particular wildfire (or no fire) and storm event sequence which is linked to a reservoir input load, the individual randomly sampled probabilities for wildfire occurrence, fire weather, and the maximum annual rainfall events (and associated flows) are combined. Depending on the fire and storm scenario, different erosion process sub-models may be activated, delivering suspended sediment to the main tributary streams, with the reservoir input load the sum of total tributary stream inputs less in-channel/floodplain storage losses. Using repeated simulations, probability distributions of the maximum annual event suspended sediment loads entering the reservoirs will be generated for the two rainfall-runoff event types.

## 4. SUMMARY

The conceptual model framework presented in this paper offers a potential catchment-scale approach for assessing the risk to water quality from wildfire and subsequent storm events that may generate large inputs of suspended sediment and other constituents to reservoirs. It is anticipated these linked models will provide managers with a tool that may contribute to decisions on future water treatment options based on the level of risk identified and enable development of appropriate strategies to mitigate the threat posed by different wildfire and storm event scenarios.

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