Probability and consequence of post-fire contamination events in a water supply catchment

Peter Nyman[1], Peter Yeates[2], Christoph Langhans[3], Philip Noske[1], Shane Haydon[4] and Gary Sheridan[1]

1. University of Melbourne.
2. Netherlands Environmental Assessment Agency.
3. Hydronumerics Pty Ltd.
4. Melbourne Water Corporation.

Large cities around the world source their drinking water from forested catchments, which deliver water that is treatable at minimal costs.

Introduction

These forests are often prone to wildfire, which tend to increase surface runoff, destabilize soils and trigger increased sediment delivery into water supply systems (Emelko et al. 2011; Hohner et al., 2019; Smith et al. 2011). The consequences of wildfire for water supply are a significant concern, with the potential for extended periods of water supply disruption, increased water treatment cost, and a demand for catchment restoration and investment in expensive treatment infrastructure (Bladon et al. 2014; White et al. 2006; Writer et al. 2014). Moreover, with climate change, the likelihood of wildfire is increasing in many forest ecosystems making water supply systems increasingly exposed to post-wildfire contamination (Khan et al. 2015, Sankey et al. 2017).

There are numerous uses for models that predict water quality impacts. On an operational level, models that reveal spatial variation in the erosion susceptibility provide catchment managers with a means to prioritize risk mitigation through fuel reduction or post-wildfire response. In such cases, spatial mapping of erosion risk in a relative sense (e.g. Sheridan et al. 2009) may be sufficient to provide effective tools for allocating resources and mitigating risk in the areas of the catchment that are most likely to be producing sediment. When developing strategic plans and making decisions about the future management of a water resource, the demands on predictive models increase. For instance, a water supply agency may want to determine if there is a case for upgrading water treatment capability or adjusting the water supply network to reduce the likelihood of water supply interruptions due to wildfires. In this setting, a detailed understanding of risk is required for cost-benefit analysis to inform decisions about such investments.

In this study we are motivated by the need amongst water supply managers to know '*For how long is it likely that my reservoir will be offline due to contamination by post-wildfire erosion?*'. In addressing this question, we seek to provide the means for developing policy and investment strategies within environmental management frameworks that are underpinned by economics and risk (e.g. Investment Framework For Environmental Resources, INFFER: Pannell et al. 2009). The specific objective of the study is to model how frequency and magnitude of erosion in headwaters translates to probability and duration of water contamination exceeding treatability thresholds at the water offtake. In this study we only consider sediment in our risk model because treatment facilities are often highly vulnerable to turbidity caused by suspended sediment (Khan et al. 2017).

Our paper outlines a parameter-reduction approach whereby empirical transfer functions are used to link a probabilistic model of sediment delivery from burned headwaters and a reservoir hydrodynamic model. With these transfer functions we produce a direct measure of risk (i.e. probability of consequence) and discuss practical questions around potential cost of the wildfire threat to water supply agencies and the capacity for catchment managers to mitigate such costs. Furthermore, we use the model to evaluate how different model components contribute to uncertainty in risk.

Study area

The study was carried out in the Upper Yarra catchment, which is located ~100km east of Melbourne in SE Australia and flows into a 200 GL reservoir that is central to the potable water supply to more than 4 million people. The reservoir also receives transfers from the larger nearby Thomson Reservoir. Unfiltered water from the Upper Yarra reservoir is then transferred to smaller off-stream storages before treatment and supply into the metropolitan distribution network.

The 337 km^2 Upper Yarra catchment includes mixed species of dry Eucalyptus forests at lower elevations and on equatorial facing slopes, wet forests dominated by Mountain Ash at higher elevations, and damp mixed species forest in intermediate locations. The relief is 850 m and based on the Köppen classification the climate is temperate with no distinct dry season and mild to warm summers. Annual rainfall at the reservoir dam wall is ca 1100 mm yr^{-1}. At the catchment divide, the rainfall is 1700 mm yr^{-1}. The geology is predominantly sedimentary, and the soils are typically clay loams.

Modelling framework

The model is an implementation of the conceptual framework for assessing water contamination risk presented by Nunes et al. (2018). It includes three major components for predicting the probability and duration of water supply disruptions:

- Propagation of fine sediment within the reservoir, from entry point to the offtake
- Susceptibility of the landscape to extreme erosion events
- Stochastic spatial-temporal rain fields which cause erosion.

The models are coupled conceptually in a risk framework for predicting the probability and duration of water contamination events that exceed treatability thresholds (Figure 1).

In presenting the model and the results we take an asset-centric approach and begin with the processes that govern the transport of sediment between the reservoir boundary and the water offtake at the dam. With this we produce a reservoir transfer function, which is an empirical relation for linking magnitude of sediment delivery events at the reservoir boundary to sediment concentration at the water offtake (Figure 1). The link is realized by choosing four inflow locations that represent likely locations for post-fire sediment delivery events. Then we present the catchment response model, which predicts rainfall thresholds for erosion in contributing headwater catchments that have variable fire severities. Finally, we simulate the actual sediment delivery from headwaters to the reservoir boundary, using rainstorms from two types of stochastic rainfall generators. Together, the reservoir transfer function and simulated sediment delivery events are used to represent the probability and magnitude of water contamination events from post-fire erosion (Figure 1).

Results: probability of consequence

Applying the modelling framework in Figure 1 to the Upper Yarra catchment gives a distribution of probabilities for days of interrupted supply (Figure 2). The distributions are different depending on where in the catchment the storm cells are centered. However, all distributions are equally likely. Thus, the maximum impact shown in solid black line in Figure 2 is the most relevant one because that represents the highest risk to reservoir water quality. The duration of undeliverable water for exceedance probabilities of 0.5, 0.4, 0.3, 0.2 and 0.1, marked with arrows in Figure 2, are 15, 130, 320 and 450 and 900 days, respectively. When centered on an erosion hotspot, a storm with an AEP of 0.3 will produce about 2000 Mg of clay from debris flows. This equates to 30 times the median clay load (i.e. 62 Mg) from debris-flow producing headwaters.

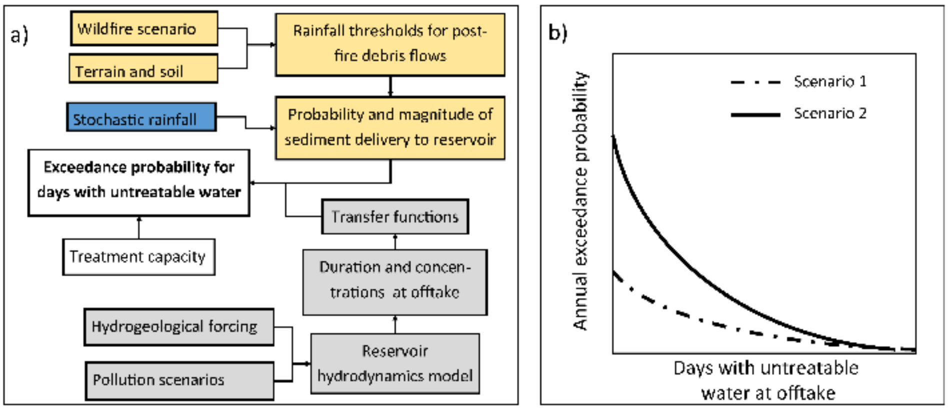

Figure 1: a) Model framework showing the workflow for producing a risk metric from transfer functions that couple an erosion model with a reservoir hydrodynamics model. b) Example of the final risk metrics which is the probability of consequence.

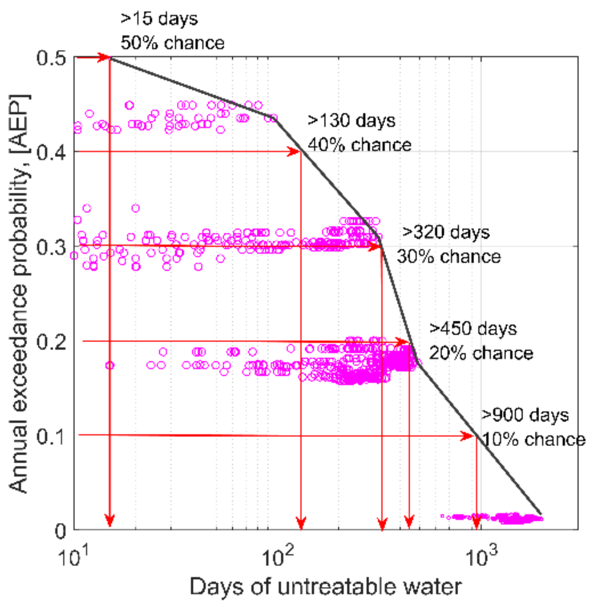

Figure 2: Annual exceedance probabilities (AEPs) for days of undeliverable water. Produced from the modelling framework presented in Figure 1. The scatter plot is the number of days that water exceeds treatability threshold for storms cells with different exceedance probabilities. The variation stems from storm cells being centered on different locations in the catchment. The solid black line is the AEP when storms are centered at a location most susceptible to debris flows.

Discussion

We present a comprehensive approach to water quality risk assessment in flammable water supply catchments. The research draws on the best available models of reservoir hydrodynamics, a stochastic rainfall generator and a validated post-fire erosion model to predict the probability and magnitude of impact on treatability. This is the first time that the threat of catchment erosion after wildfire is linked to actual impacts on water supply by accounting for sediment propagation in a reservoir. Ultimately, we use the output from our modelling to estimate the potential cost associated with post-fire erosion in the Upper Yarra catchment that directly delivers water to 4 million residents of Melbourne in SE Australia. The novelty of the work lies in how the different models are linked and the risk metrics that we can produce with our approach. It is a template approach for future studies that aim to derive information from post-fire hydrological models that can be used to directly guide cost-benefit analysis, investment and policy in the water resources sector.

We estimate that a high severity wildfire in the Upper Yarra catchment can lead to water supply interruptions lasting for periods of months to years. The debris-flow susceptibility is spatially variable within the catchment, with hotspots on the eastern flank of the northern reservoir arm representing highest risk. These areas receive lower annual rainfall and have soil properties that are more likely to produce runoff than the those in high rainfall areas at higher elevation. This pattern stems from the way in which infiltration is parametrized in the debris-flow response model, where aridity and fire severity are both causing variation in infiltration (Langhans et al. 2016, Van der Sant et al. 2018). Much of the risk in Upper Yarra catchment can be attributed to a very small area. Thus,

mitigation efforts can be highly targeted at specific areas of the water supply catchment.

The model was developed using the Upper Yarra catchment (and reservoir) as a case study. However, the approach of linking reservoir hydrodynamics with an event-based erosion model to quantify risk is generally applicable and could be applied to debris-flow prone water supply catchments elsewhere. The approach can be easily adapted to operate with debris-flow models that have been developed for other hydro-geomorphic settings (e.g. Gartner et al. 2014).

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