Modeling post wildfire hydrology in the Western US

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Abstract

Post-wildfire hydrology research and development efforts within the US Army Corps of Engineer (USACE) Engineer Research and Development Center (ERDC) include research on post-wildfire runoff generation mechanisms for enhancing the post-fire flood simulation capability of USACE hydrological models. This study developed wildfire-induced soil hydraulic factors to account for the dynamic, hydrophobic intensity as a function of soil moisture content and burn severity, both identified at a 30 m grid scale. This method is implemented in the Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model. The coupled model has been applied in several Western US watersheds to develop, test, and verify post-wildfire hydrologic and flood risk assessments. The study watersheds include: (a) Upper Arroyo Seco and Haines Canyon watersheds after the 2009 Station Fire in CA, (b) Tule River watershed after the 2021 Windy Fire in CA, (c) San Ysidro watershed after the 2017 Thomas Fire in CA, (d) Trapper Creek after the 2020 Badger Fire in ID, (e) Weiser watershed after the 2020 Wood Head Fire in ID, and (f) Detroit Lake watershed in OR after several wildfire events in the last two years. This approach improved post-fire hydrologic simulations by increasing simulated flood peaks and volumes as well as the flooding extents, resulting in a closer correlation to observed values in the Upper Arroyo Seco watershed and the San Ysidro Creek watershed in Southern California. The Nash–Sutcliffe Efficiency (NSE) of simulated hydrograph results in the Upper Arroyo Seco watershed was 82% and the coefficient of determination (R^2) of the predicted flooding depths in San Ysidro Creek watershed was 0.79. This method was also applied in the modeling of post-fire flooding scenarios for emergency assessments in the Tule River watershed, Trapper Creek watershed, Weiser watershed, and the Detroit Lake watershed.

Introduction

Hydrological changes in a watershed after a fire primarily arise from decreases in infiltration due to an increase in soil water repellency (DeBano 2000). Although the soil water repellency effect diminishes with increasing soil moisture content (MacDonald and Huffman, 2004), there are few observations to suggest a soil moisture threshold of the transition from hydrophobic to hydrophilic conditions at a watershed scale. Changes to hydrodynamic and geophysical processes and associated parameter behavior in post-wildfire conditions result in increased runoff magnitude, erosion potential, and pollutant delivery. Therefore, it is critical to integrate post-wildfire hydrological understanding into a physics-based distributed hydrologic model to facilitate improved predictions for post-fire land and water management decisions.

In this post-wildfire runoff modeling, the following points are taken into consideration: (a) a realistic initial soil moisture distribution, (b) wildfire-induced changes to infiltration formulation that includes a hydraulic conductivity reduction factor, burn severity factor (Pradhan and Floyd, 2021), and soil moisture threshold, and (c) runoff routing parameterization under burned conditions. This method is integrated into the Green and Ampt (Green and Ampt, 1911) infiltration process used in the U.S. Army Corps of Engineers (USACE) Gridded Surface/Subsurface Hydrologic Analysis (GSSHA) model (Downer and Ogden, 2006, Pradhan and Floyd, 2021). The post-fire integrated hydrological model has been applied in several burned watersheds in the Western US to develop, test, and verify post-wildfire flooding assessments. The study watersheds include: (a) Upper Arroyo Seco and Haines Canyon watersheds after the 2009 Station Fire in CA, (b) Tule River watershed after the 2021 Windy Fire in CA, (c) San Ysidro watershed after the 2017 Thomas Fire in CA, (d) Trapper Creek after the 2020 Badger Fire in ID, (e) Weiser watershed after the 2020 Wood Head Fire in ID, and (f) Detroit Lake watershed OR after several wildfire events in the last two years. Results indicate improved post-wildfire flooding extent and hydrograph simulations using this new approach.

Wildfire-Induced Soil Hydraulic Factors

Vegetated soils that have recently been burned experience a reduction in soil hydraulic conductivity by up to 90% (Blake et al., 2009; Pradhan and Floyd, 2021) due to an increase in combustion of organic matter and the sealing of soil matrix macro pores (Blake et al., 2009). In order to relate burn severity (Parson et al., 2010) to the corresponding reduction in soil hydraulic conductivity, Pradhan and Floyd (2021) developed a formulation that applies multiplying factors to pre-fire soil hydraulic conductivity in order to estimate the reduction in hydraulic conductivity in post-fire conditions. These factors are multiplied to the vadose zone unburned soil hydraulic conductivity (a function of the soil water characteristic curve) to obtain the burned soil hydraulic conductivity as:

$$K_{burned} = RF_k \cdot BDF \cdot K_{unburned} \tag{1}$$

where, K_{burned} = the hydraulic conductivity of the soil for burned conditions, $K_{unburned}$ = the soil hydraulic conductivity for unburned conditions, BDF = the burn degree factor, and RF_k = the reduction factor of hydraulic conductivity under high burn severity locations.

The burn severity map, or the BARC severity classification (Parson et al., 2010), is used to define BDF in Equation 1. BDF is a calibration parameter, which is found to be 1, 2 and 3, respectively, for high burn, medium burn and low burn severity cases (Pradhan and Floyd, 2021). RF_k refers to the maximum reduction of the soil hydraulic conductivity under high burn BARC classification. Pradhan and Floyd (2021) found this value to be 0.1. RF_k = 0.1 means a maximum of 90% reduction in the soil hydraulic conductivity value under high burn severity condition which is in agreement with the findings by Blake et al. (2009). The unsaturated soil hydraulic conductivity $K_{unsaturated}$ in Equation 1 is defined as (Brooks and Corey, 1964):

$$K_{unsaturated} = K_{burned} \left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)^{3+2/\lambda} \tag{2}$$

where, θ = water content of the soil, θ_s = saturated water content of the soil, θ_r = residual water content of the soil, and λ = soil distribution index.The watershed soil and burn severity maps are combined to show the spatial location of burned soil.

Hydrophobic to hydrophilic soil moisture threshold identification

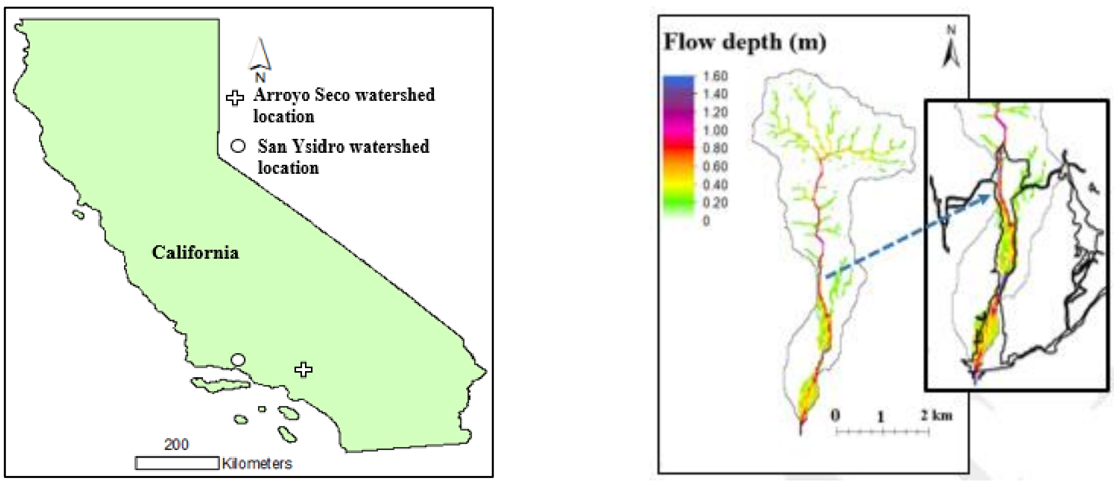
The reduction of infiltration and the water repellent soil property in a post-wildfire scenario is diminished at higher initial soil moisture content (Rengers et al., 2019). SERVES-estimated (Pradhan, 2019) fine resolution distributed soil moisture is used as the initial soil moisture condition. Soil moisture threshold formulation is developed to limit the wildfire effects on hydrology during the model run as:

$$\begin{aligned} K_{burned} &= RF_k \cdot BDF \cdot K_{unburned} \quad \text{if } \theta_i < \theta_t \\ K_{burned} &= K_{unburned} \text{ if } \theta_i > \theta_t \end{aligned} \tag{3}$$

where, θ_t = the soil moisture threshold value. To identify a consistent value of θ_t at watershed scales, model runs are performed with increasing θ_t values from wilting point. For each model simulation, runoff volume error, peak flow error and Nash-Sutcliffe efficiency are estimated.

Post-fire watershed hydrological modeling

The soil hydraulic factors and moisture threshold formulation are explicitly linked to wildfire soil burn severity. They are implemented in the post-fire GSSHA hydrological model to reduce unburned soil hydraulic conductivity (see equation 3) in the Green and Ampt infiltration process. K_{burned} from equation 3 is used in equation 1 to obtain the unsaturated soil water characteristic curve . SERVES estimated initial soil moisture was used In the post-wildfire routing process, Manning's roughness was changed according to the land cover and the soil burn severity condition (Pradhan and Floyd, 2021). Figures 1-3 show the application of this post-wildfire hydrological modeling in the Western US watersheds. The NSE of the predicted post-fire hydrograph in the Upper Arroyo Seco watershed was 82% (Pradhan and Floyd 2021). The approach improved post-fire hydrologic simulation results by increasing the post-fire flooding extent, and therefore more closely matching the observed floods in the San Ysidro Creek watershed in Southern California (Figure 1). The simulated post-fire flooding depths in Figure 1 (b) resulted in an R^2 of 0.79 (Olmos de Aguilera, 2022).



(a) Location of watersheds (b) Post-fire simulated flood

Figure 1. Pictured: (a) location of San Ysidro Creek watershed and Arroyo Seco watershed (b) San Ysidro Creek watershed post-Thomas Fire simulated flood with transferred Upper Arroyo Seco post-Station Fire parameter information.

The method was also applied in the modeling of post-fire flood scenarios for emergency assessments in the Trapper Creek watershed and the Weiser River watershed. The simulated spatial extent and level of flooding in Figure 2 inform locations where evacuations are necessary.

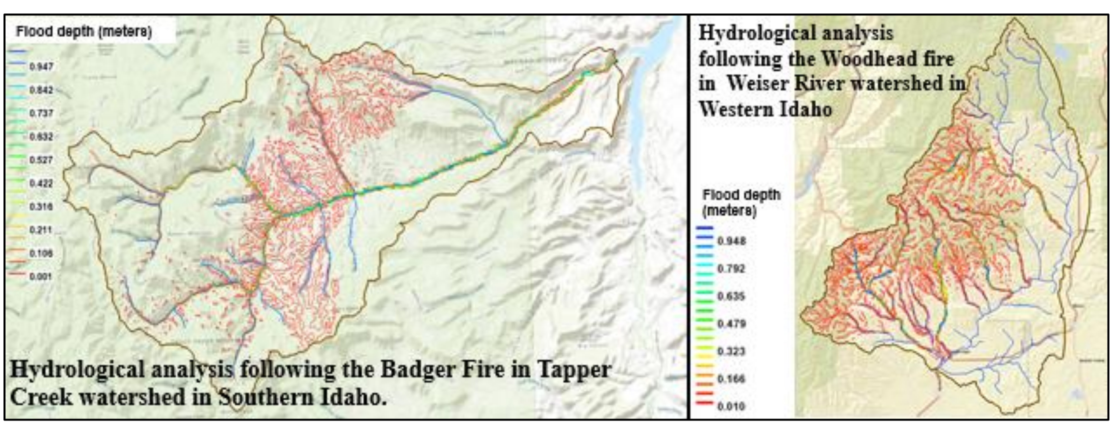


Figure 2. Shown here are results from the post-fire flood simulation for the Tapper Creek catchment after the Badger Fire (left panel) and the Weiser River catchment after the Woodhead Fire in Idaho (right panel). The flood depth scale on the left figure ranges from 0.001 m (red) to 0.947 m (blue). The flood depth scale on the right figure ranges from 0.010 m (red) to 0.948 (blue).

Simulation results as well as the comparison of pre- and post-fire flood peaks and volumes of the Tule River watershed and the Detroit Lake watershed can be seen in Figure 3. These results show a significant increase in runoff after a post-fire rainfall event compared to that of a pre-fire rainfall event.

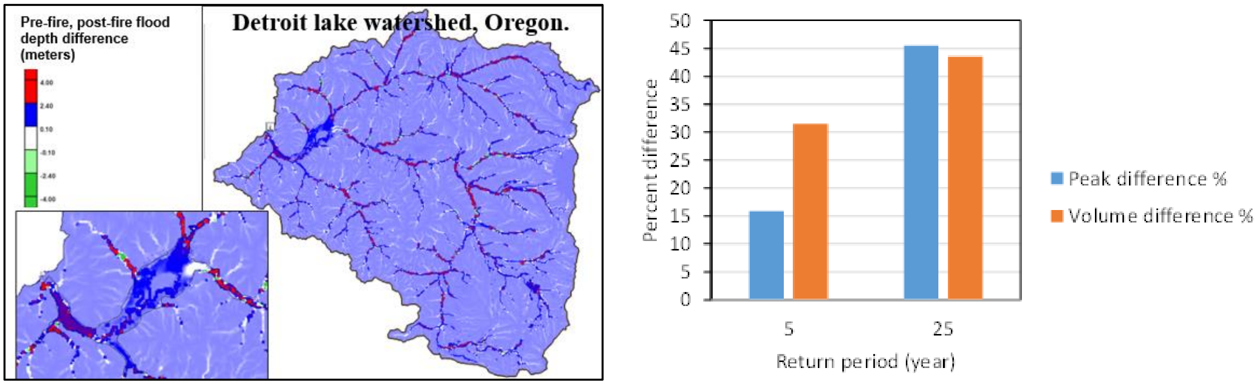


Figure 3. Post-fire flood inundation simulation in the Detroit Lake watershed, located in Oregon (left panel), and the percent difference between pre-fire and post-fire hydrologic simulations in the Tule River watershed, located in California (right panel). The flood depth scale on the left figure ranges from -4.00 m (green) to 4.00 m (red).

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