Aspiring Towards a Surface- and Ground-Water Flow Model for Post-Fire Water-Repellent Soils in the Klamath

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1 Introduction

Each Summer and Fall fires blaze across the Western United States with effects ranging from smoke inhalation to tree mortality. Amidst a plethora of research into fire effects on ecosystems is a body of literature on the potential of fires to create water-repellent soil layers that began emerging in the 1960s. These water-repellent layers reduce infiltration leading to increased runoff and potentially decreased groundwater recharge.

Water-repellency has the potential for particularly devastating effects along the Klamath River Basin in California, the ancestral and present-day homelands of the Yurok, Karuk, Hoopa, Shasta, and Klamath peoples. The Klamath, once one of the largest Salmon runs in the continental United States, has seen a decline in Salmon with the construction of dams. Increased temperatures and reduced snowpack have compounded this problem leading to increased river temperatures threatening to exceed the threshold around 20° C above which Klamath Salmon species struggle to survive [38]. Tributaries such as the Scott, Shasta, Salmon, and Trinity rivers provide key cold water refugia and spawning grounds for Chinook and Coho salmon among other species.

A host of factors can reduce these late season flows including factors such as reduced summer rainfall, reduced snowpack, and agricultural groundwater extraction (which has been well-documented especially in the Scott Valley [37]). Additionally, fire can influence flows in a few ways including changing rainfall interception, faster snowmelt [24], and reduced evapotranspiration [36], and water-repellent soils. All these factors compound to threaten these vital salmon habitats.

The importance of salmon to Indigenous peoples of the Klamath goes beyond their pure nutritional value. A Karuk expression states that "if the Salmon quit running, the world will quit spinning" [41]. Addressing this topic of food sovereignty, of ecosystem sustainability, and cultural revitalization asks us to consider the role that post-fire water-repellent soils may be having on groundwater recharge and thereby their effect on late-season tributary flows that sustain Fall salmon spawning habitats.

The 2021 River Complex fire offers a perfect case study to build towards. Blazing from July 30 to

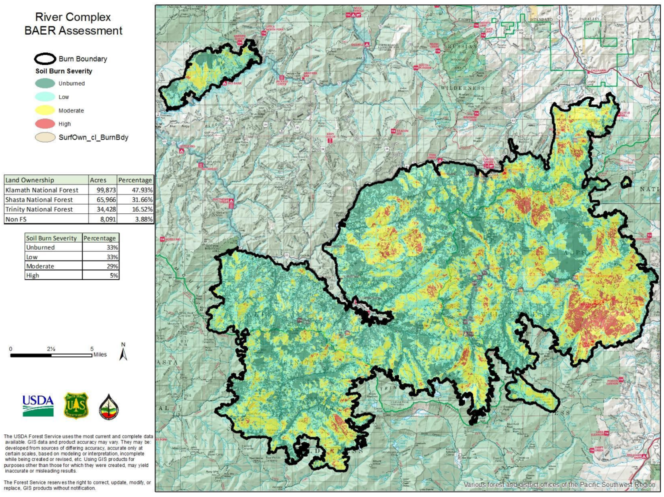

Figure 1: This figure shows the intensity of the 2021 River Complex Fire (CA) that spread across portions of the Salmon, Scott, and Trinity watersheds. See the NWCG website for more information: https://inciweb.nwcg.gov/incident/map/7868/1/127641

October 25, 2021 the River Complex fire burned through 200,000 acres in the mid-Klamath basin, affecting the Scott, Salmon, and Trinity watersheds, watersheds (see the fire intensity map in Figure 1) hosting three vital Klamath basin spawning grounds. The River Complex fire and other recent fires such as the 2021 McCash fire (95,000 acres in the Salmon Watershed) and the 2018 Slater fire (157,000 acres including a good portion of the Indian Creek watershed, another tributary of the Klamath) provide motivation and case studies to analyze if water-repellency layers are forming in mid-Klamath Basin fires and how extreme their effects may be in preparing for the next few years of potential changes in flow.

Motivated by these case studies, this paper will proceed with a literature review to build an understanding of what is needed to incorporate water-repellency into a fire-hydrology model on the Klamath. Section 2 will introduce the underlying chemistry behind water-repellency, and section 3 will discuss the mechanisms by which fire creates those chemical conditions. Then, section 4 will review literature on the processes and time needed for water-repellency to degrade. Section 5 will then look at the spacial patterns of formation of water-repellency. Combining all of this together I will look at existing hydrological models that account for runoff and subsurface flows with water-repellent soils in section 6. Then, section 7 will synthesize the previous material to propose a method for estimating changing flow patterns due to water-repellency from recent fires. Finally, I will conclude by discuss the potential for extending water-repellency modeling to understand likely flow patterns resulting from future wildfires and the return of cultural fire to the basin.

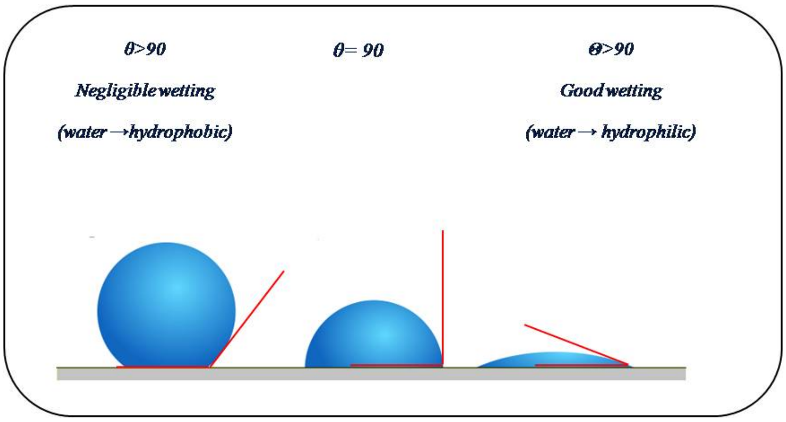

Figure 2: This figure shows how a water droplet will touch a surface of high, medium, and low contact angle. A contact angle above 90° means that droplet tends to repel from the surface (the surface is hydrophobic), whereas a contact angle below 90° means it is attracted to the surface (the surface is hydrophilic). Image source: https://fmps.fbk.eu/contact-angle-platform
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2 Chemistry of Water-Repellency

Throughout this paper I will follow the precedent from the 1968 proceeding Water-repellent soils: University of California, Riverside [1] of referring to a soil layer that doesn't allow infiltration as water-repellent rather than hydrophobic. I will reserve the term hydrophobic to describe compounds (or sides of compounds) that repel water. This choice can be understood by considering literature that finds water-repellent layers are typical brought about by compounds that have one side that is hydrophobic and one side that is hydrophilic (e.g. [10]).

A primary tool we will use to understand water-repellency and hydrophobic compounds is the concept of contact angles. [42] offers an in depth exposition on contact angles between a liquid (in our case water) and a surface (in our case soil). See Figure 2 for a visual description of contact angles as the angle formed between between a water droplet and the surface on which it lies. We define a substance as **hydrophobic** if its contact angle with water is above 90° and **hydrophilic** if the contact angle is less than 90°. The contact angle between a liquid and a surface affects the amount of capillary force a droplet experiences pulling it between or pushing it away from grains of soil. Approximating the soil as series of cylindrical tubes we can understand this force by Young-Laplace equation:

$$p_c = \frac{2\gamma_{SL}\cos(\theta)}{r} \tag{1}$$

where p_c is the capillary pressure pulling a water droplet into the tube of soil, γ_{SL} is the interfacial surface tension between the water and the soil, r is the radius of the pores between soil particles, and θ is the contact

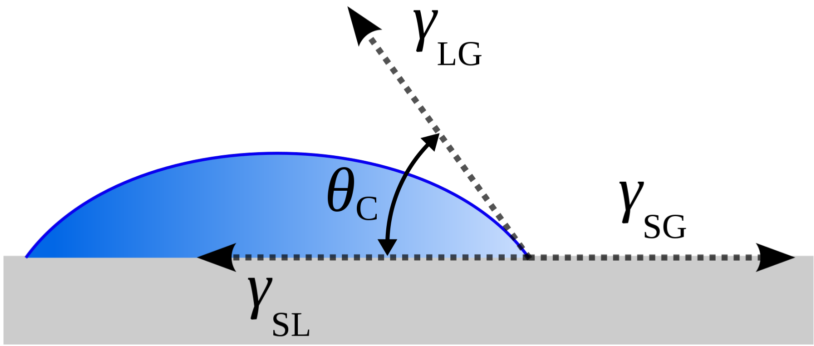

Figure 3: This figure shows the contact angle that forms and its relationship to the solid-gas interfacial energy γ_{SG}, the liquid-gas interfacial energy (surface tension) γ_{LG}, and the solid-liquid interfacial energy γ_{SL}. Imagine Source: https://upload.wikimedia.org/wikipedia/commons/thumb/e/e4/Contact_angle.svg/800px-Contact_angle.svg.png
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angle of between the water and soil. The contact angle θ can be further understood via its relationship with the liquid-soil surface tension, γ_{SL}, the solid-gas interfacial energy γ_{SG} and the liquid-solid interfacial energy γ_{SL} as shown visually in figure 3 and calculated via the Young equation:

$$\gamma_{SG} - \gamma_{SL} - \gamma_{LG}\cos(\theta) = 0. \tag{2}$$

From this equation we see that the contact angle will be above 90° (and thus the surface will by hydrophobic) if and only if the liquid-solid interfacial energy γ_{SL} exceeds the solid-gas interfacial energy γ_{SG} and figure 3

In a gravity-free environment, equation 1 dictates that we would see water flow into the soil pores when the capillary pressure is positive which happens if and only if $\theta < 90°$. Accounting for gravity one has to compare the pressure downward force from gravity with the force created by capillary action, and as the radius increases between soil particles, higher contact angle (above 90°) will be able to infiltrate. All this suggests the following molecule-scale definition of **soil-water repellency** as *the contact angle of a drop of water resting on the soil.* I will abbreviate this concept as water-repellency throughout this paper as we are talking exclusively about the context of water on top of soil.

I will now present several methods of measuring contact angles and water repellency. The first and arguably simplest is the Water Drop Penetration Time (WDPT) test, where a drop of water is placed on a soil surface and the time is measured for the drop to fully absorb. This test measures the persistence of water-repellency rather than the initial contact angle. Specifically, if the initial contact angle is above 90° the drop will not absorb immediately; over time the polar forces of the water will push on hydrophobic compounds in the soil to rearrange to reduce the water-soil contact angle until the contact angle reaches around 90° at which point the water will absorb.

A second method for measuring water repellency is the molarity of ethanol (MED) droplet test. This test utilizes the fact that adding ethanol to a water drop reduces it's polarity and thus it's liquid-gas surface tension γ_{LG} and its solid-liquid interfacial energy γ_{SL}; these have the combined effect of increasing the contact angle as calculated in equation 2. With enough ethanol added to the water drop we expect the contact angle of the drop to reduce below 90°, and thus enable quick infiltration into the soil. This test attempts to measure initial repellency rather than degrading repellency over time (as seen with the Water Drop Penetration test), and it is typically measured as the minimal ethanol content required to allow for absorption of the drop into the soil within 5 seconds. Results are typically recorded in the molarity of ethanol in the water, but occasionally may be reported in terms of the surface tension of the resulting mixture (also referred to as the critical surface tension test).

[20] discusses the WDPT and MED tests in greater detail. In particular Doerr finds a close relationship between the two methods for highly water-repellent soils but a poor relationship for moderately repellent soils. We will return to this question of measurement technique later when we discuss case-studies on the Klamath.

A host of factors can create and influence the development water-repellency including fire, fungi [6], low clay content [7], interstitial soil materials [5], and drought [11]. While initial intuition may suggest that hydrophobic compounds alone are the key for water repellency, [9] finds that water-repellent layers are often the result of compounds with both hydrophilic and hydrophobic ends. The hydrophilic ends bind to soil particles and the strength of that attraction determines the persistence of water-repellency and the strength of hydrophobicity of hydrophobic end of the compound determines how water repellent the soil will be. [8] determines that (real) contact angles of less than 90° may not be sufficient for infiltration and in fact many materials of (real) contact angles less than 60° have apparent contact angles greater than 120° due to porosity that allow the potential for water-repellency from a wider array of substances. In this case, real contact angles refer to the actual angle made between the edge of a droplet and a surface, whereas apparent contact angles are the angle we would see at a zoomed out scale ignoring local roughness of a surface as seen in figure 4

Having discussed the chemical sources of water-repellency, in the next section we will look at the mechanisms by which fire can produce these conditions.

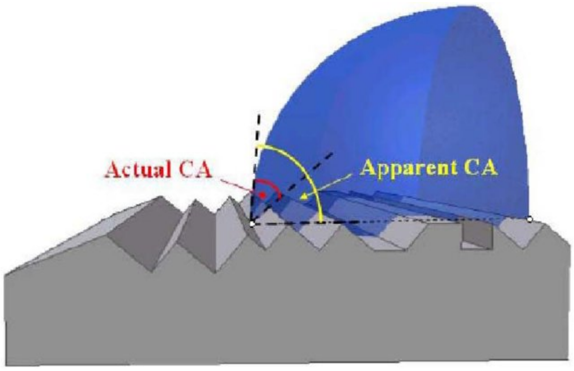

Figure 4: This figure illustrates the distinct concepts of apparent and real contact angles formed on rough. Imagine Source: https://www.researchgate.net/publication/259573845_Surface_phenomena_and_wetting_of_porous_solids/figures?lo=1
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3 Mechanisms of Post-Fire Water-Repellency

The simplest story for how fires create water-repellency is that chemicals are volatilized by higher temperatures, and heavier smoke particles will tend to move along the temperature gradient via thermophoresis. Thermophoresis is the process by which heavier compounds tend to move from hot to cold regions and lighter compounds tend to do the reverse. With high temperatures at and above the soil surface cooling along paths traveling down into the soil, heavier hydrophobic compounds volitalized from the surface litter layer will tend to move down into the soil until they reach a depth at which there is a cool enough temperature for them to condense onto soil particles. This will result in a water-repellent layer along that equipotential surface where condensation occurs [14]. The amount and type of litter (rather than properties of deeper soils) tends to be the source of these hydrophobic compounds [32], and one study argues that the effective soil-water contact angle after burning depends primarily on the proportion of surface area covered in organic material and the structure of it's hydrophobic group rather than soil chemical and physical properties [22]. However, this latter result is somewhat in contrast with Debano et. al.'s finding that litter on top of pure sand tends to create the most intense and thick repellency layers, suggesting that soil grain size does play a role as well [16].

Complicating this story is the role of pyrolysis, chemical reactions occuring during fire, in addition to vaporization in shaping the compounds that then condensate into water-repellent layers. In particular, [2] finds that a thermal loss of oxygen containing groups led to irreversible dehydration and decarboxylation of humus colloids, likely playing an important role in post-fire water-repellency.

A second complicating factor is that water-repellency is not linearly, or even monotonically, increasing with temperature or burn time. In fact, we typically see water-repellency begin to increase with as the temperature and duration of heat exposure allows the previously described volitalization-condensation process to occur, but as the temperatures or duration continue to increase eventual it will destroy all water-repellency (potentially making it lower than pre-burn levels). This can be understood as a combination of thermophoresis with random diffusion: while thermophoresis will move heavier smoke particles down along a thermal gradient into the soil random Fickian mixing processes from molecular diffusion and turbulent winds will move smoke particles along their concentration gradient. Therefore, the Fickian miixing process will over time move some hydrophobic compounds from the soil litter layer into low-concentration areas of the broader atmosphere. As the time of thermal exposure increases, more particles will be able to move move into the atmosphere in this way; this tends to lead to weaker water-repellent layers that are deeper in the soil (e.g. [13]). Similarly, an increase in temperature will increase the Fickian-diffusion constant accelerating this rate of movement of into the atmosphere. Therefore, to see a water-repellent layer form, there needs to be enough exposure to heat for the volatilization, pyrolysis, and thermophoresis processes to occur but not so much that the hydrophobic compounds move into the atmosphere and are unable to condensate back into the soil.

While modeling the physics of the combined thermophoresis and Fickian processes is challenging, we can luckily understand it empirically based on the temperature ranges at which water-repellency forms. [26] find in Mexican volcanic soils that water-repellency will form at around $200 - 250^\circ$ C and will be destroyed by temperatures around 300° C. [12] on the other hand finds that for granite soils water-repellency reaches its maximum when exposed to temperatures around 200° and that temperatures of 600° C are required to destroy water-repellency. Looking at the plethora of studies on this temperature range, we begin to understand a story of variability, suggesting a dependence on the local conditions of the studies and (as reviewed earlier) specifically the type and amount of soil litter present. This information will need to be calibrated to a location to develop a post-fire water-repellency model for its soils.

This story is further complicated by the role of soil moisture in dictating the formation of water-repellent layers. Soil moisture will delay the process of heat transfer from fires to soil particles as the surface layer of soil can shed heat via the vaporization of water for the first several minutes of exposure. Debano et. al. tested 5 minute and 25 minute burns over wet and dry sands, and found the thickest and most-intense water-repellent layers formed with 5-minute burns on dry sands, whereas the longer burn on dry sand destroyed water repellency in the upper cm of the soil [13]. The wetter burns on the other hand saw less intense water-repellency from 5-minute burns and an increase in water-repellency across the same time intervals. This suggests that it takes longer to reach the same extent of production and destruction of water-repellency for wet soils than dry soils. Debano et. al. therefore suggest that prescribed fire on wet soils may be a priority in areas where the formation of water-repellent layers is not desired. This conclusion is supported by Debyle's finding that broadcast burning does not seem to impact the water-repellency of soils [17]. This has implications for expanding and returning the use of Indigenous cultural fire as part of fire management in the Klamath and around the world, which will be discussed in section 8.

4 Persistence of Water Repellency

As mentioned in section 2, the persistence of water-repellency may be caused by the strength of the bond between the hydrophilic sides of compounds with soil molecules. Given that water-repellency can be the typical state of ecosystems even when outside of the influence of disturbances like fire (see section 2), it is not necessarily to be expected that soils return to zero (or negative repellency in the case of hydrophilic compounds in the soil). [4] uses the water drop penetration test and finds that post-fire water-repellent soils tend to persist in their water-repellency for a long time (i.e. the polarity of water droplets is not quickly able to rearrange soil particles to reduce the contact angle below 90°). That is to say, it is unlikely that water-repellency will simply degrade with its first exposure to water during the first post-fire rain event.

However, increased water-repellency from fires does not seem to be a permanent condition of soil. [21] finds that in the Oregon Cascades, water-repellency can be measured for the first five years after a fire but is negligible by the sixth year. [29] on the other hand finds that water-repellency degrades and is no longer detectible by the end of the first year after fire Colorado ponderosa and lodgepole pine soils; additionally they determine that water-repellency typically disappears once soil moisture exceeds a threshold (after which soil particles become hydrophilic). For unburnt soil, this threshold was found to be 12% increasing to up to 25%; however this process can be reversed when the soil dries out again. It should be noted that they do not claim that this increased threshold will return to the lower threshold after its first wetting cycle and that return of soil moisture threshold is what they find to take a year to reduce.

Rakhmatulina et. al. adds to the story by proposing a mechanism for this degredation of water-repellency. They find that freeze-thaw cycles on wet (but not dry) soils seem to be a key factor in the degradation of water-repellency over time [33]. It is likely that local data is needed to calibrate a model of water-repellency degradation over time in a given soil system.

In addition to naturally-occuring processes that degrade the water-repellency of soils, there are a variety of wetting agents that can be used. While they have been shown to be effective at reducing water-repellency, [28] recommends reserving them for cases of highly erodible soils due to their high costs and potential ecological effects. Given this paper's motivating question of changing watershed scale flow patterns, it is unlikely that wetting-agents can be applied on the scale to have a significant impact.

5 Spacial Heterogeneity in Infiltration through Water-Repellent Soil

Even with water-repellent soils (contact angles above 90°), infiltration is still possible if sufficient pressure is applied to overcome the capillary pressure resisting water's infiltration into soil pores. This can occur if ponds form above the soil, which can be modeled by

$$h_p = -2\gamma_{SL}\cos(\theta)/\rho g r \tag{3}$$

where h_p is the depth of pooling required to begin infiltration, ρ is the density of water, g is gravitational acceleration constant, r is radius of soil pores, and θ is the soil-water contact angle (see [4]). Of course, with variable pore size and potentially varying contact angles across heterogenous soil, there will not be a single critical value and instead we expect to see an increase of infiltration across the ranges of depths implied by the the distribution of parameters in the soil. Therefore, rather than modeling post-fire water-repellent soils as a binary of allowing infiltration or not, we should attempt to quantify this small-scale heterogeneity by estimating its reduction of infiltration rate. In this vain, one study by Debano finds that infiltration rates to decrease by a factor of 25 when soils contain hydrophobic substances [15].

However, in addition to this micro-scale variability in infiltration through water-repellent soil layers, we also tend to see substantial macro-scale variation. One fire-experiment with Spanish soils found that runoff coefficients were high at a small spatial scale on burnt samples, but that the increased runoff is eventually able to seep through macro-pores leading to no measurable effect as they zoomed out [25]. While in this experiment there a significant change in runoff coefficients was not found at a large scale, this is likely dependent on the size and frequency at which macro-pores form and the quantity of water that can infiltrate through them; this will likely depend on the local soil conditions. This is illustrated by a contrasting result by [23], which finds a similar story of intense concentrated infiltration through water-repellent soils via burrow holes, tension cracks, and root channels, but in this case they note the potential for downstream flooding even with these concentrated infiltration channels.

These fit in with a broader literature of **finger flows**, the preferential flow of water in more wettable areas that tends to follow finger-like patterns. This has been documented in water-repellent layers of a variety of soil types including dune sands [18] and loam soils [19]. [34] clarifies that finger formations tend to recur along the same pathways due to hysteresis (where previously wetted soils are more wettable in the future), and over time hydrophobic substances leach along fingers further increasing the infiltration rates of water through these fingers.

In order to predict runoff and infiltration through water-repellent soils from data such as contact angles, we will need to build a model that accounts for these spatially variable infiltration patterns. The next section lays begins to build the conceptual roots of such a model by reviewing existing literature on post-fire runoff and proposing how to fill in gaps in existing models.

6 Surface-Groundwater Models over Water-Repellent Soil

The simplest model to calculate runoff Q involves a runoff coefficient C, rainfall intensity I, and a catchment area A and models runoff as

$$Q = CIA. \tag{4}$$

Unfortunately this fails to capture the heterogeneity of runoff on burned areas. Therefore, [31] expands this runoff model by replacing a homogenous runoff coefficient with a hydraulic functional connectivity coefficient that measures the repellency along flow paths and sums the calculated runoff coefficients along all flow paths. While this model allows for spatial heterogeneity it does not account for the range of infiltration rates through repellent soils.

Expanding from there, we could consider a host of modeling techniques in literature ranging from using runoff curve numbers to empirically measurement of post-fire, which have been used most primarily for the prediction of flooding during peak runoff events. However, I will focus on PFHydro [40], a model that both accounts for spatial variability and predicts runoff at a variety of intensities of rainfall events. The PFHydro model combines two conceptual models for runoff generation: the infiltration-excess and saturation-excess overland flow models. The infiltration-excess overland flow model treats infiltration through a water-repellent layer as the limiting factor on infiltration, whereas the saturation-excess overland flow model treats soil saturation (and thus groundwater flow speed) as the limiting factor. When there is a significant water-repellent layer (for example the first year after a fire in a severely-burned area), the flow is determined by the infiltration-excess model whereas with longer after a burn or in an unburned area water-repellency is determined by the saturation-excess model.

The biggest drawback of the PFHydro is its rather course calculation of changing infiltration with water-repellency. For a given soil system, they calibrate a parameter μ (between .1 and .7) and define post-fire hydraulic conductivity as μK, $1.2\mu K$ and $1.4\mu K$ after high-, medium-, and low-severity fires where K is the pre-fire hydraulic conductivity. While the model does therefore allow for spatial heterogeneity of water-repellency, this assumption seems severely limiting in its ability to model the full heterogeneity of water repellency.

A second weakening assumption of PFHydro is its treatment of the persistency of water-repellency. It treats water repellency as having two constants states, one for the first year after a fire and another for the second, after which it is assumed to have fully dissipated. This fails to account for its gradual degradation and seasonal variability with freeze-thaw cycles, and creates a dependency on when calibration takes place during the first and second years.

To address this first drawback, the ideal solution would be to collect water-repellency data with high spatial resolution; unfortunately, this would require an impractical amount of field work to compile for the hundreds of thousands of acres we will often see with burn scares. The next best approach may be to use utilize satellite imaging or other remote sensing data on temperature over at points along the fire's burn path. We could then calibrate a model for temperature-dependent water-repellency from a smaller set of soil samples (assuming homogenous soil moisture at the time of burn). Baring access to suitable data, minor improvements may still be found by calibrating post-fire hydraulic conductivity for low-, medium-, and high-severity fires individually (rather than assuming a reduction factor of 1.4μ, 1.2μ, and μ accurately characterizes the effects of intensities across ecosystems).

To address the second weakness, I propose regular sampling of a group of sites in each burn-severity. While measuring several times per year would be ideal, it is especially important to measure repellency before and after winter to re-calibrate flow dynamics to the degradation of water-repellency from freeze-thaw cycles. [27] details procedures to follow with air-drying and light sieving to account for small-scale heterogeneity of infiltration rate

7 Project Proposal: Co-producing a model for water-repellency induced Groundwater Changes after recent Klamath fires

The goal of this section is to propose how to apply the literature review of the previous sections down to questions on the Klamath. Research in the Klamath Basin is inextricably linked with the past and present stewards of the land: the Karuk, Yoruk, Hoopa, Shasta, and Klamath Peoples. Therefore, given my positionality as a non-Indigenous settler on (Duwamish and Coast Salish Indigenous lands), my research in the Klamath must be in collaboration and co-production with Indigenous holders and co-creaters of knowledge place-based knowledge.

The Karuk Department of Natural Resources centers pikyav as the guiding principle for research Collaborations with the Karuk Tribe [39]. Pikyav means "to fix" or "to repair." Practicing Pikyav means practicing community engagement, informed consent, doing work that benefits the Tribal community, youth education, data and intellectual sovereignty, and reciprocity, among a host of other values. It entails building a Karuk review committee who will review each stage of the research process.

Therefore, this section and the ensuing concluding section should be seen as a project proposal in the early stages of collaboration based on interest from potential Karuk collaborators in returning cultural fire back to the basin and allowing spring lightning fires to burn unsuppressed, healing tributary ecosystems and their salmon habitats, and in predicting erosion and flooding that will result from future Klamath flows. This paper may help serve as an early iteration in building a collaboration as we figure out if and how questions around post-fire water-repellency might be built with and for The Karuk Tribe and other Indigenous people in the Klamath.

A first task in building this project is determining the extent to which water-repellency has occurred or might occur with future fires and what impact it has for Indigenous-cultural resources such as river flows and salmon. Essentially this hopes to answer the series of questions: is water-repellency occurring after Klamath wildfires, is it creating increased runoff, and is it reducing groundwater recharge. From there we can predict the effect that reduced groundwater recharge will have on late-season tributary flows to understand its implication for salmon.

While data is limited as to the water-repellency resulting from Klamath basin fires, research has found post-fire water repellency to form in similar Oregon and California ecosystems (e.g. [32]). Therefore, we may a-priori enter with a hypothesis that water-repellent layers are possible on the Klamath and look to see if the fire conditions to create this repellency occurs. To begin answering this question, I propose starting by skipping over direct measurement water-repellency and instead look for measurable changes in runoff patterns resulting from fires.

Specifically we could analyze fire boundary and intensity data and river flow data from recent Klamath fires including the 2021 River Complex Fire, the 2021 McCash Fire, and the 2018 Slater Fire. The River Complex fire lies at the intersection of the Salmon, Scott, and Trinity watersheds; the McCash fire lies in the Salmon watershed, and the Slater fire covers large swaths of the Indian Creek watershed (among other watersheds North of the Klamath basin).

As a first pass estimate, we can analyze tributary flow increases after high-precipitation events[1]. If water-repellent layers are substantially affecting runoff we would expect to see a more significant flow response to high rainfall events after the fires than before; that is to say if a 1 cm rainfall led to a 1 cfs increase in flow before the fire and a 2 cfs increase in flow during a rain event after the fire, it likely indicates that a higher fraction of the rain is running off.

[1] We can use tributary flow data for the Scott River, Salmon River, Trinity River, and Indian Creek found on the USGS water data website: waterdata.usgs.gov

While a finding of increased runoff might indicate the presence of post-fire water-repellency of soils, it could also be attributable to other ecosystem effects such as reduced rainfall interception (with burnt tree canopy and understory) or reduced evapotranspiration. To distinguish between reduced interception and increased water-repellency, we could utilize the duration of rainfall events as a differentiating metric; whereas maximum interception is limited by the time it takes for evaporation and absorption into plants to occur, infiltration rates through water-repellent soils will be fairly constant throughout the time of water exposure. Therefore, for a fixed total amount of rainfall, different durations of precipitation will likely yield similar total interception whether it occurs over the course of an hour or a day, whereas longer exposure of water-repellent soils to pooling and flows will lead to more water infiltrating into the soils (at the soils infiltration rate). That is to say, runoff resulting from reduced interception is likely driven primarily by total precipitation whereas runoff due to water-repellent soils is likely driven more by precipitation rate. Therefore, we may be able to distinguish between these two sources by determining if precipitation rate or total precipitation is driving runoff quantities.

There may be an additional story of reduced post-fire evapotranspiration leading to more saturated soils and therefore a greater amount of saturation-excess flow that is flowing as runoff. To distinguish this from water-repellency we could take soil samples below the depth of potential water-repellency both within the burned areas and within unburned control sites and compare soil moisture contents. [3] finds that low-intensity fires tend to lead to net-wetter soils with evapotranspiration changes outweighing changes in water-repellency whereas high-intensity fires tend to do the reverse and lead to net dryer soils. Determining whether increased or decreased soil moisture is occurring in soil samples between burned and control sites will likely distinguish if increased runoff is driven by increased saturation-excess flow (from reduced evapotranspiration) or from water-repellency.

Applying these results to fires on the Klamath would allow us to determine if the primary source of hydrological change is resulting from changing water-repellency, changing evapotranspiration, or changing interception. While the source of runoff may seem like a moot point, it has implications in using runoff changes to predict changes in groundwater recharge. If reduced evapotranspiration creating increased soil saturation is the primary driver of increased runoff, then we can expect an increase in groundwater recharge from wetter soils. If reduced interception is the primary driver of increased runoff, then the extra runoff is likely to have evaporated directly off or have been absorbed by plants and trees to eventually be transpired, either way having minimal impact on groundwater. If water-repellent soils, on the other hand, are the primary driver of increased runoff, we are seeing water flow as runoff that would otherwise be absorbed by unburned soils with higher infiltration rates, thereby reducing groundwater recharge.

Suppose that after running the previous analysis we find that there is an increase in runoff caused by water-repellency. How do we translate that into predicting late-season tributary flows? We could begin with a water budget of the ecosystem. Summing all the increased flow events after rainfalls, we could calculate the increase in runoff expected from a range of precipitation events. Aggregating this over the regions rainfall regime we could then calculate the expected annual increase in runoff. This increase has to come from somewhere. Even if repellency seems to be the primary driver of increased runoff, a water budget will need to account for decreased evapotranspiration which can be calculated following the work of [35]. We would similarly wish to include changing interception if it appears to be of a sufficient order of magnitude to affect the water budget. Subtracting the reduction of evapotranspiration (and interception) from the increase in runoff we could calculate the decrease in groundwater recharge (assuming the precipitation regime remains constant across years and that these are the only mechanisms of water flowing out of the system that are experiencing significant change after fire).

We could then divide this total changes in groundwater flow by the area affected by fire (perhaps weighting by the intensity of fire in the area using soil samples to calibrate water-repellency with fire intensity). These numbers could then be inputted into a model such as ModFlow [30] to estimate changing groundwater flow and late-season tributary flow patterns resulting from our selected fires. The outputs of ModFlow could be calibrated to and verified against US Geological Survey groundwater data and potentially against private well data[2].

How does this proposed analysis fit in with the PFHydro model discussed in section 6? Whereas the modeling approach described in section 6 builds upward from the chemical and physical processes creating water-repellency, this section proposes an empirical analysis from actual flow data. Whereas the previous section starts at the micro-scale and builds outward to a macro-flow model, this section starts with macro-flow data to understand what is happening at the micro-scale. These two approaches should not be seen as in conflict with each other and instead should be viewed in tandem, validating and calibrating each other. The more readily available flow data entail a smaller initial cost for this sections empirical approach suggesting that this post-rain-event flow analysis may be a good starting place for determining if water-repellency appears to be a real issue in the region worth devoting further field work. If it does, then applying PFHydro or a similar model may be the next step to further understand the post-fire water repellency of Klamath soils.

[2]Private wells are common like in the Scott Valley.

8 Conclusion: Aspiring towards a Water-Repellency Model for Future Wildfire and Cultural Fire in the Klamath

This paper began with a literature review of post-fire water-repellent soils. In doing so, it discussed the chemistry of water-repellency, the mechanisms by which fire produce water-repellency, the persistence of water-repellency, it's spatial distribution, infiltration patterns through water-repellent soils, and existing models for flow through and over water-repellent soils. We then synthesized this literature review into a project proposal to understand the effects of water-repellency on later-season flows after fires in the Klamath, a question that is important for predicting the health of salmon populations.

Planning for the future also asks us to models to future rainfall and fire conditions. With climate change, we can expect a drier and hotter climate in the Klamath, intensifying fires, reducing summer precipitation, and reducing snowpacks (thereby reducing late-season flows). The goal of returning historic levels of cultural fire to the Klamath basin offers a mitigation strategy preventing the build up of fuels that lead to severe fires that produce water-repellent layers. Likewise, a reversal of the National Forest Service policy of suppressing the less-threatening spring-lightning fires would on its own play a substantial role towards the same end.

We (a collaboration of FRESH Lab researchers at the University of Washington and researchers at the National Center for Atmospheric Research) are in the early stages of building a Klamath basin scale model to predict the future fire-hydrology on the Klamath. The project combines research into the historical ecology of traditional land-cover in the basin with hydrological modeling for a future changing climate and return of traditional landcover and cultural fire. We plan to use the NCAR Community Terrestrial Systems Model, to understand how water will flow under predicted future fire regimes. While the model is able to evaluate evapotranspiration, it currently ignores the potentially critical effects of water-repellent layers.

In one sense incorporating post-fire water repellency into future modeling adds complexity to an already complex problem of modeling post-fire water repellency; it requires us to predict the hydrological effects of a whole range of fire events that is already quite challenging to understand for a single fire event. On the same token, it may also simplify by requiring only an understanding of the distribution of water-repellent conditions and spatial correlations created by fire, potentially reducing the necessity for a vast set of field data one would need capture the full spatial distribution of water-repellency across a single fire.

With an understanding of the water-repellency responses of Klamath basin soils (likely varying between the volcanic soils of the upper klamath and the silty loam soils of the mid-Klamath) to fires across a range of temperature and moisture ranges we could estimate the water-repellency response to the range of temperatures, times of exposure, and spatial variability that we expect from future fires.

With Indigenous cultural fire having been developed over millennia, it embodies the needs of the healthy landscapes and cultural resources that have sustained its people; practices that created widespread water-repellent layers that threatened salmon habitats would not have persisted over millennia; on the other hand, the minimal impacts of prescribed fire on water-repellency has only recently become understood by western science (as well as discussed in section 3). Of course with climate change and changing ecosystems, new regimes are being navigated at the intersection of traditional and modern Indigenous ecological knowledge; if Indigenous cultural-fire-practitioners want support in targeting cultural-burn methods and temperatures to minimize the formation of water-repellency from cultural fire, this modeling approach may be of service. On the other hand, the development of Klamath water-repellency models may provide further justification to government agencies on the benefits of returning of cultural fire to the Klamath as we learn more about the risks posed by high-fuel-induced future severe wildfires to late-season river flows. In doing so, can we heal for the future of salmon by healing the past and present exclusion of cultural fire from the Klamath?

References

[1] Water-repellent soils: University of california, riverside. *Proceedings*, 1968.

[2] G. Almendros, F.J. Gonzalez-Vila, and F. Martin. Fire-induced transformation of soil organic matter from an oak forest - an experimental approach to the effects of fire on humic substances. *Soil Science*, 149(3):158–168, 1990.

[3] Adam L. Atchley, Alicia M. Kinoshita, Sonya R. Lopez, Laura Trader, and Richard Middleton. Simulating surface and subsurface water balance changes due to burn severity. *Vadose Zone Journal*, 17(1), 10 2018.

[4] Gary Barrett and Olav Slaymaker. Identification, characterization, and hydrological implications of water repellency in mountain soils. *Catena*, 16:477–489, 1989.

[5] E.B.A. Bisdom, L.W. Dekker, and J.F.Th. Schoute. Water repellency of sieve fractions from sandy soils and relationships with organic material and soil structure. *Geoderma*, 56(1):105–118, 1993. International Workshop on Methods of Research on Soil Structure/Soil Biota Interrelationships.

[6] R.D. Bond. Factors responsible for water repellence of soils. *Water-repellent soils: University of California, Riverside, May 6-10, 1968, Proceedings*, pages 259–264, 1968.

[7] R.D. Bond. The occurrence of water-repellent soils in australia. *Water-repellent soils: University of California, Riverside, May 6-10, 1968, Proceedings*, pages 1–6, 1968.

[8] R.D. Bond and L.C. Hammond. Effect of surface roughness and pore shape on water repellence of sandy soils. *Soil and Crop Science Society of Florida Proceedings*, 30:308–315, 1970.

[9] K.B. Bozer and G.H. Brandt. Chemistry of materials that make soils hydrophobic. *Water-repellent soils: University of California, Riverside, May 6-10, 1968, Proceedings*, pages 189–204, 1968.

[10] K.B. Bozer, G.H. Brandt, and J.B. Hemwall. Chemistry of materials that make soils hydrophobic in debano, l.f., and letey, john, eds., water-repellent soils: University of california, riverside, may 6-10, 1968. *Proceedings*, pages 189–204, 1968.

[11] G.J. Burch, I.D Moore, , and J Burns. Soil hydrophobic effects on infiltration and catchment runoff. *Hydrological Processes*, 3:211–222, 1989.

[12] J.T. Cory and R.J. Morris. Factors restricting infiltration rates on decomposed granitic soils. *Water-repellent soils: University of California, Riverside, May 6-10, 1968, Proceedings*, pages 149–161, 1968.

[13] L. F. Debano, S. M. Savage, and D. A. Hamilton. The transfer of heat and hydrophobic substances during burning. *Soil Science Society of America Journal*, 40(5):779–782, 1976.

[14] L.F. DeBano. The relationship between heat treatment and water repellency in soils. *Water-repellent soils: University of California, Riverside, May 6-10, 1968, Proceedings*, pages 265–279, 1968.

[15] L.F. DeBano. The effect of hydrophobic substances on water movement in soil during infiltration. *Soil Science Society of America Proceedings*, 35(2):340–343, 1971.

[16] L.F. DeBano, L.D. Mann, and D.A. Hamilton. Translocation of hydrophobic substances into soil by burning organic litter. *Soil Science Society of America Proceedings*, 34:130–133, 1970.

[17] N.V. DeByle. Broadcast burning of logging residues and the water repellency of soils. *Northwest Science*, 47(2):77–87, 1973.

[18] L.W. Dekker and C.J. Ritsema. How water moves in a water repellent sandy soil-1. potential and actual water repellency. *Water Resources Research*, 30(9):2507–2517, 1994.

[19] L.W. Dekker and C.J. Ritsema. Fingerlike wetting patterns in two water- repellent loam soils. *Journal of Environmental Quality*, 24:324–333, 1995.

[20] Stefan Doerr. On standardizing the 'water drop penetration time' and the 'molarity of an ethanol droplet' techniques to classify soil hydrophobicity - a case study using medium textured soils. *Earth Surface Process and Landforms*, 23:663–668, 1998.

[21] C.T. Dyrness. Effect of soil wettability in the high cascades of oregon:. *U.S.D.A. Forest Service Research Paper*, PNW-202:18 p., 1976.

[22] D.H. Fink. Water repellency and infiltration resistance of organic-film-coated soils. *Soil Science Society of America Proceedings*, 34:189–194, 1970.

[23] G.T. Foggin and L.F. DeBano. Some geographic implications of water-repellent soils. *Professional Geographer*, 23:347–350, 1971.

[24] Kelly Gleason, Joseph McConnell, Monica Arienzo, Nathan Chellman, and Wendy Calvin. Four-fold increase in solar forcing on snow in western u.s. burned forests since 1999. *Nature Communications*, 10, 2019.

[25] A.C. Imeson, J.M. Verstraten, E.J. van Mulligen, and J. Sevink. The effects of fire and water repellency on infiltration and runoff under mediterranean type forest. *CATENA*, 19(3):345–361, 1992. Selected papers of the 2. ICG Symposium on Mediterranean Erosion.

[26] Antonio Jordn, Lorena M. Zavala, Jorge Mataix-Solera, Alejandra L. Nava, and Nancy Alans. Effect of fire severity on water repellency and aggregate stability on mexican volcanic soils. *Catena*, 84(3):136–147, 2011.

[27] P. M. King. Comparison of methods for measuring severity of water repellence of sandy soils and assessment of some factors that affect its measurement. *Soil Research*, 19:275–285, 1981.

[28] J.S. Krammes and J. Osborn. Water-repellent soils and wetting agents as factors influencing erosion. *Water- repellent soils: University of California, Riverside, May 6-10, 1968, Proceedings*, pages 177–187, 1968.

[29] Lee MacDonald and Edward Huffman. Post-fire soil water repellency: Persistence and soil moisture thresholds. *Soil Science Society of America Journal*, 68(5):1729–1734, 2004.

[30] Michael G. McDonald, Arlen W. Harbaugh, and the original authors of MODFLOW. The history of modflow. *Groundwater*, 41(2):280–283, 2003.

[31] John A. Moody, Richard A. Shakesby, Peter R. Robichaud, Susan H. Cannon, and Deborah A. Martin. Current research issues related to post-wildfire runoff and erosion processes. *Earth-Science Reviews*, 122:10–37, 2013.

[32] R.J. Poff. Distribution and persistence of hydrophobic soil layers on the indian burn. *Symposium on Fire and Watershed Management: Pacific Southwest Forest and Range Experiment Station, Sacramento, Calif., October 26-28, 1988, Proceedings, General Technical Report PSW-109*, page 153, 1988.

[33] E Rakhmatulina and S. Thompson. Freeze?thaw processes degrade post-fire water repellency in wet soils. *Hydrological Processes*, 34:5229–5241, 2020.

[34] Coen J. Ritsema, Louis W. Dekker, John L. Nieber, and Tammo S. Steenhuis. Modeling and field evidence of finger formation and finger recurrence in a water repellent sandy soil. *Water Resources Research*, 34(4):555–567, 1998.

[35] James Roche, Qin Ma, Joseph Rungee, and Roger Bales. Evapotranspiration mapping for forest management in california's sierra nevada. *Frontiers for Global Change*, 30, 2020.

[36] James W. Roche, Qin Ma, Joseph Rungee, and Roger C. Bales. Evapotranspiration mapping for forest management in california's sierra nevada. *Frontiers in Forests and Global Change*, 3:69, 2020.

[37] Daniel Sarna. *Scales of Sovereignty: the Search for Watershed Democracy in the Klamath Basin.* UC Berkeley, 2015.

[38] Steven Stenhouse, Caitlin Bean, William Chesney, and Mark Pisano. Water temperature thresholds for coho salmon in a spring-fed river, siskiyou county, california. *California Fish and Game*, 98(1):19–37, 2012.

[39] Karuk Tribe. Practicing pikyav: A guiding policy for collaborative projects and research initiatives with the karuk tribe.

[40] Jun Wang, Michelle A. Stern, Vanessa M. King, Charles N. Alpers, Nigel W.T. Quinn, Alan L. Flint, and Lorraine E. Flint. Pfhydro: A new watershed-scale model for post-fire runoff simulation. *Environmental Modeling & Software*, 123:104555, 2020.

[41] Kyle Whyte. Food sovereignty, justice and indigenous peoples: An essay on settler colonialism and collective continuance. *Oxford University Press*, 2017.

[42] Yuehua Yuan and Lee Randall. *Contact Angle and Wetting Properties. In: Bracco G., Holst B. (eds) Surface Science Techniques.* Springer, 2013.