The Witch Creek Fire: A Disaster Case Study Analysis Using System Dynamics Modelling

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I. Abstract

The present paper conducts an analysis on the Witch Creek fire to determine factors that contribute to wildfire spread and how to mitigate them. The Witch Creek Fire, one of the most destructive in California history, ignited due to human and policy error with power lines, and spread rapidly due to optimal weather conditions and lack of fire fighting resources. A causal analysis reveals influential factors that can mitigate growth including budget, fireproofing, brush maintenance, and power line regulation. Through system dynamic simulations, the disaster scenario is produced and modified to visualize how implementing new policies might reduce damages in future like situations. Implications from results prescribe introducing fireproofing campaigns, increasing department budgets for equipment and generators, and imposing/enforcing regulations for brush and power lines to diminish wildfire spread.

II. Introduction

The number of acres destroyed by wildfires has drastically increased over the past four decades. This growth is nearly tenfold, from one million acres annually in 1983 to ten million in 2020 (National Interagency Fire Center). These new levels of destruction are attributable to more frequent out-of-control wildfires, ones that span weeks and hundreds of thousands of acres.

This uptick is caused predominantly by global warming and human error. As temperatures grow hotter and conditions drier, fire seasons are extended with more brush than ever.[1] (Environmental Protection Agency). Likewise, human error is accountable due to our increased presence in the wilderness; this presence leads to ignition mistakes such as fireworks, campfires, power lines, and smoking (Barclay and Roberts). Frequent human mistake combined with optimal fire conditions drives this devastating trend.

The Witch Creek Fire is a prime example of such uncontained, damaging wildfires. The Witch Creek Fire was the most destructive fire of California's 2007 wildfire season, one of the most devastating to date. Officially classified as a firestorm,[2] the Witch Creek Fire burned for 198,000 acres and twenty-four days, destroyed 2,000 buildings, and resulted in over $1.3 billion in insured damages (Wikipedia).

The Witch Creek Fire was ignited on October 21, 2007 in Witch Creek Canyon. The fire began when unusually powerful winds knocked two power lines from San Diego Gas & Electric (SDG&E) together. Despite the faulting wires, power was not turned off for another six hours, giving time for electrical arcing and burning particles to catch fire on nearby brush in the hot weather (Murphy). The fire rapidly spread east, uninterrupted; firefighters were preoccupied with other wildfires and lacking resources to effectively combat the Witch Creek Fire in its early stages. By October 24, the Witch Creek Fire approached some of these neighboring fires (which

[1] Brush (bushes and shrubs) are naturally occurring foliage and common in grassland biomes. Brush is usually dry and flammable, making it one of the most common materials for wildfire spreading.

[2] A firestorm is generated when a wildfire builds to such a magnitude that it creates its own wind system, resulting in erratic wildfire patterns and long-range spotting

were younger and smaller). Firefighters should have been able to surround these smaller fires and prevent the merge, but due to overextended resources, the Witch Creek Fire merged into a gigantic complex fire by October 26th. The Witch Creek Fire was not fully contained until November 6th, the complex fire until November 13th (City of San Diego).

In the aftermath of the fires, a plethora of changes to the California fire response was recommended and implemented. These were frontlined by a demand for more resources and policies for fireproofing structures and removing brush (Ekhard et al.). SDG&E was found liable for breaking regulation on brush and wire distances from other wires (Nikelowski).

While wildfires are crucial players in an ecosystem's balance, the magnitude of wildfires like the Witch Creek Fire are more harmful than good. It is estimated that the total cost of wildfire suppression and damages is up to $120 billion dollars annually (Howard). As a result, it is imperative to understand how to (i) mitigate the spread and (ii) prevent the ignition of these wildfires as global climate conditions ever worsen going forward. The present paper will use the Witch Creek fire as a case study to analyze and propose policy interventions to this problem.

III. Analysis of Contributing Errors

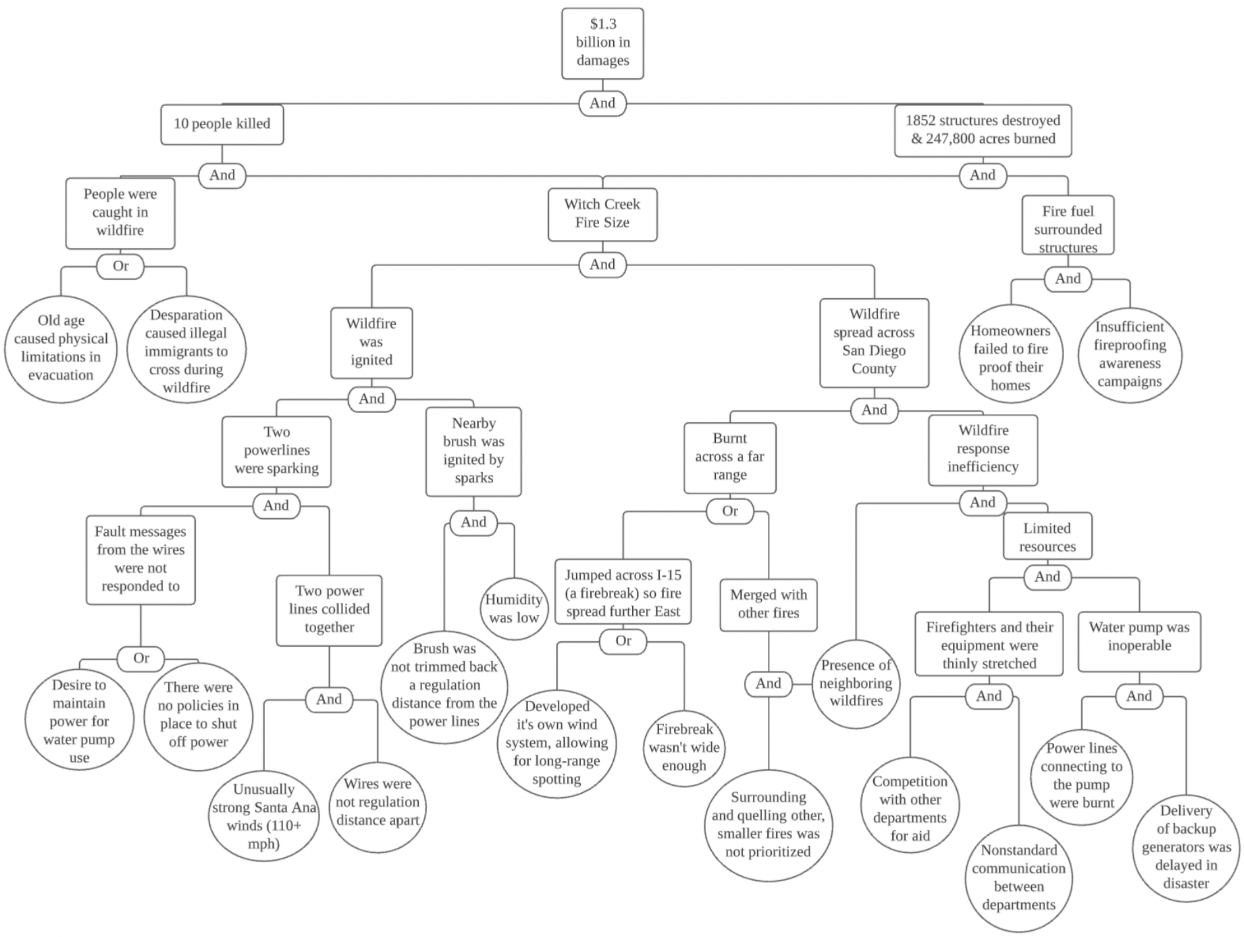
In order to mitigate factors that lead to fires like the Witch Creek Fire, we need to understand how these errors contribute to the spread of such large wildfires. A *fault tree diagram* is a method of visualizing the breakdown of a disaster into the base elements that caused it. In fault tree analysis, an undesired state is specified at the top (in this case the Witch Creek Fire outcome), and the system is then analyzed in the context of its environment and operation to determine all realistic ways in which the disaster event might have occured. (Stamatelatos et al.)

The following fault tree diagram decomposes the main outcome of the Witch Creek Fire, $1.2 billion in damages, into factors that led to that event, factors that led to those factors, and so on. Elements in circles are those which cannot be broken down further, representing the collection of errors that contributed to the magnitude of the disaster. Elements in squares are those which can be broken down further. Two elements are decomposed from one with "and" if both elements are required for that outcome, or "or" if only one is (Stamatelatos et al.).

The diagram (see following page) is composed in four main sections. The lower left section details how the Witch Creek Fire was ignited. The lower right section denotes how the firestorm spread so rapidly. The upper right section decomposes how structures came to be destroyed. Finally, the upper left section details how people died (there were 10 total deaths in the complex fire). The errors resulting from each of these sections are classified in the following categories based on their root cause: environmental, task, equipment, management, and human.

The environmental errors that contributed to the Witch Creek Fire relate to the temperature, wind, humidity, and landscape. The temperature was in the high 80s and dew point in the low 30s (half that of a "normal" humidity reading), which were conducive conditions for a wildfire to thrive (Weather Underground). Likewise, Santa Ana winds, otherwise known as "devil winds", were over 110 miles per hour, which caused the power lines to clash together that

Figure 1: Fault Tree Diagram



ended up sparking and starting the fire. Due to the natural climate of southern california, there is an excess of brush in the dry, hot conditions, which is highly flammable and led to the Witch Creek Fire's rapid spread (Barclay and Roberts).

Task errors, defined as mistakes in procedure execution, are shown to be largely attributable to SDG&E in the fault tree. First, the reason the power lines were able to clash together in high winds was because SDG&E did not install them a regulation distance apart (Murphy). Second, when the power lines snapped together and created sparking, they sent fault messages back to the company, however, these messages were not responded to (Jones). This could have been due to inattention, lack of policy, or a desire to maintain power for water pump use in the fire response. Third, when the power lines sparked, the sparks were able to ignite on nearby brush because SDG&E did not trim the brush a regulation distance back from their power lines (Nikelowski).

As for these reasons, many of the management errors are attributable to SDG&E for lack of oversight and policy on these task errors. The electric company should have (and implemented shortly after the disaster) a policy on mandating powerline shut off from fault messages. Likewise, fire departments had insufficient resources to fight the collection of fires, and did not place emphasis on preventing their merge into a complex fire (Ekhard et al.). These organizational errors allowed the fire to spread further, burning through land and homes. Furthermore, on behalf of the county government there was a lack of emphasis placed on fireproofing awareness campaigns, in which absence many homes had fire-fuel[3] and burned as a consequence (Ekhard et al.). It is estimated that if fire-fuel is properly removed from homes, they are 70-99% less likely to ignite in a wildfire (Municipality of Anchorage).

There was one main equipment error: a failure of the Ramona water pump, a central water pump that was needed for fire response. The water pump lost power due to damaged power lines in the fire, and due to the blaze, the delivery of back-up generators was delayed (Ekhard et al.).

Most human errors represented in this diagram come in the form of mistakes. Illegal immigrants crossing the border at the time of the wildfire and dying in the blaze was a mistake on their part (NBC San Diego). SDG&E employees made the mistake of choosing the wrong plan of action when not responding to the power line fault messages. Homeowners made the mistake of not removing fire-fuel from their homes during the fire season. All of these human errors contributed to damages from the blaze.

IV. Cause and Effect Cycles

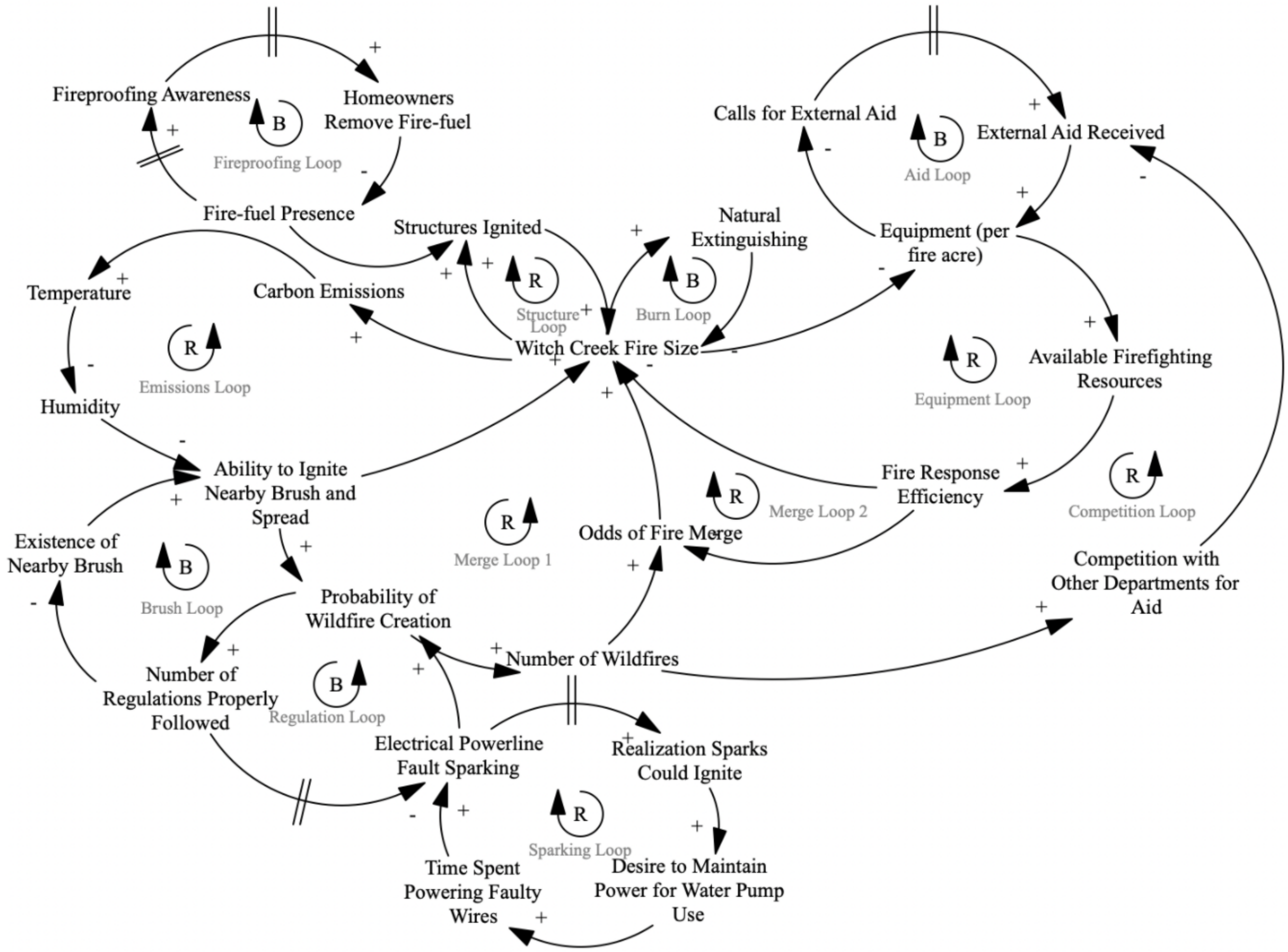
A *causal loop diagram* is a way of representing a system structure to determine the causes of the underlying patterns of behavior of the system. The diagram denotes all of the elements present in a system, in this case all of the factors contributing to the size of the Witch Creek Fire. In the causal loop diagram, an arrow between two elements indicates if a change in one influences a change in another element. That causal link is "positive" (denoted with a plus on the diagram) if a change in one variable produces the same direction of change in another. The causal link is "negative" (denoted with a minus symbol) if the change in one produces the opposite direction of change in another (Kirchwood 5-6).

As each of these loops are closed, whereby a change in one element eventually comes back to itself, they are known as *feedback loops* in the system, indicating that there is a control mechanism that creates consistent behavior over time. There are two kinds of feedback loops: balancing and reinforcing (denoted by a "B" or "R" in each loop respectively). A balancing loop is equilibrating; it keeps a component of a system stable or seeking a goal (Meadows 25-27). Investigating balancing loops can tell us in this analysis what factors we can use to mitigate the size of the fire spiraling out of control. Meanwhile, a reinforcing loop is exponential; it allows the growth of an element to build on itself even further (Meadows 30). Analyzing reinforcing loops will show us what factors we need to focus on mitigating to stop the wildfire spread.

The following diagram reveals how all of the elements that influence the accumulation "Witch Creek Fire Size" interact together, and from it we can determine their patterns of

[3] Fire-fuel refers to objects that are easily ignited and found nearby homes and structures. Fire-fuel includes items like trash, shrubbery, wooden decks, fabric awnings, and shake-wood roofs.

Figure 2: Causal Loop Diagram



behavior. Namely, there are three critical trends that this causal loop diagram reveals that are important to the coming model: the equipment and aid loops, the structure and fireproofing loops, and the regulation, brush, and sparking loops.

In the equipment loop we observe exponentially growing behavior for the Witch Creek Fire size that is balanced by the aid loop. In the equipment loop, as the fire size increases, the amount of equipment available per fire acre declines. As the equipment declines, the available firefighting resources declines, which in turn influences the fire response efficiency to decline. As the fire response efficiency declines, the Witch Creek Fire size grows even further. However, by introducing the aid loop, we impose stability on equipment, preventing the fire size from spiraling out of control. This is because as the equipment available per fire acre declines, fire departments send out more calls for aid, which in turn increases the amount of aid received (after a delay), which ultimately increases the amount of equipment. Following the equipment loop then, this results in eventual increase in response and decrease in fire size. These loops emphasize the importance of having sufficient equipment and resources in extinguishing fires.

In a similar fashion, in the structure loop we observe reinforcing behavior that is mitigated by the stabilizing nature of the fireproofing loop. In the structure loop, as Witch Creek Fire size increases, that increases the number of structures that are reached and burned, which in turn increases the fire size more. However, this exponential behavior is dampened by the fireproofing loop, whereby the fire-fuel presence can decrease the number of structures ignited. This is because as fire-fuel presence increases, fireproofing campaigns increase which in turn increases the fire-fuel removed by homeowners (with a delay), which decreases the fire-fuel presence, and thus the structure ignition rate. These loops highlight the importance of fire-proofing structures in order to prevent their ignition, which is responsible for many of the billion dollar damages from fires like these.

Finally, we see how regulation compliance can impact the ignition and spread of wildfires. As we see in the regulation loop, as the probability of wildfire creation increases, adherence to these regulations is more enforced. In the balancing brush loop, as these regulations regarding brush trimming are followed, the existence of nearby brush is decreased (due to controlled burns and removal), which reduces the ability for wildfires to ignite and spread. Similarly, in the sparking loop, as these regulations are followed, instances of power line failure and sparking decrease. These trends highlight the need for implementing and following regulations for power line safety and brush reduction, which can prevent the ignition and mitigate the spread of a wildfire.

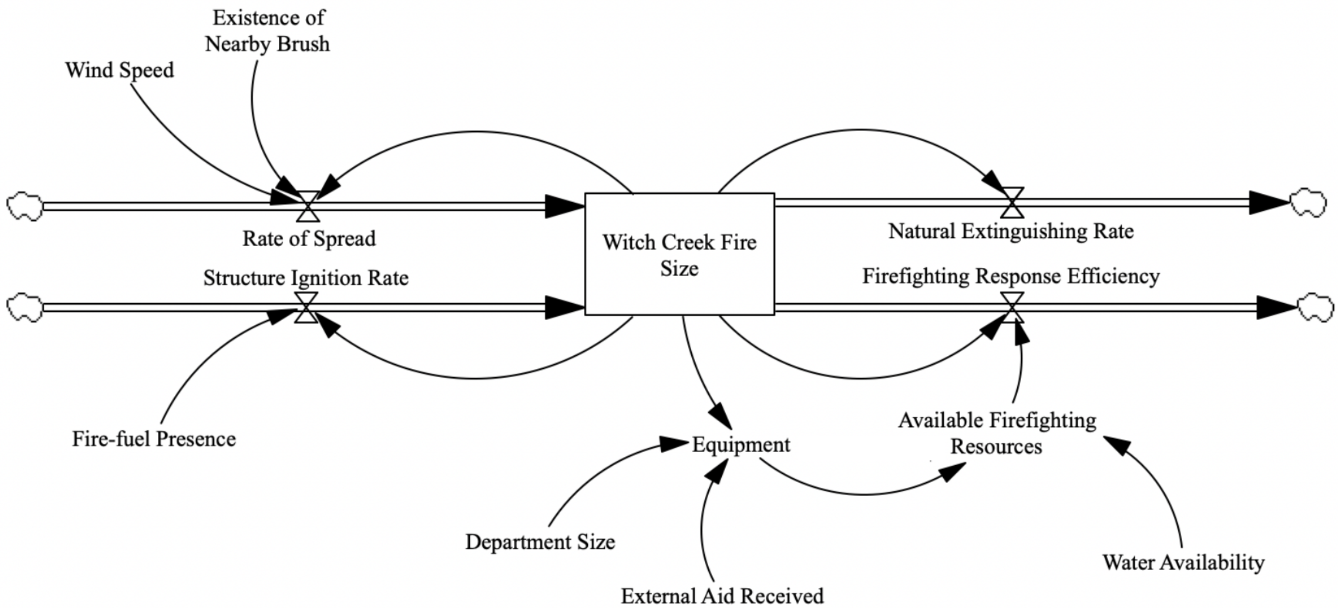
V. Wildfire Accumulation Diagram

Another way of representing this information is with a *stock and flow diagram.* Like the causal loop diagram, the stock and flow diagram shows the relationship between variables; however, the stock and flow diagram distinguishes itself by making distinctions between variables. Using the information gained from the causal loop diagram, we can use the stock and flow diagram to organize the most critical elements in a way that can be modeled numerically. In this diagram, *stocks* (or *levels*) refer to variables that can accumulate such that if you froze time, you could measure their amount. *Flows* represent the movement from one stock to another, and usually cannot be measured if time was frozen (Kirchwood 19). An inflow adds to the stock accumulation, whereas an outflow subtracts from it.

In this diagram, there is one main stock studied: the accumulation of the Witch Creek Fire size. This includes all land that is actively on fire. This stock has inflows of “rate of spread”, which is the amount the fire increases in size from spreading each day, and “structure ignition rate”, which adds in the fize expansion due to structure destruction. The stock has two outflows: the “firefighting response efficiency” which represents the rate of fire extinguishing from fire fighting efforts, and “natural extinguishing” which measures the rate at which the fire naturally moves on from completely burnt land.

These flows are all influenced by other levels, which are determined by the key relationships that were observed in the causal loop diagram. Fire-fuel presence influences the structure ignition rate as decreasing the presence decreases the likelihood a structure is ignited.

Figure 3: Stock and Flow Diagram



The existence of nearby brush due to regulation compliance influences the rate of spread as decreasing brush availability decreases the fire's ability to spread. Department size and external aid are variables that influence the amount of available equipment, and water availability influences the amount of available resources, which as these increase, the firefighting response efficiency increases in turn.

VI. System Dynamics Model

The above stock and flow diagram can be adapted into a system dynamics model. Using Vensim PLE software, each level, variable, and flow is given a value or equation based on the variables that influence it. These equations are based on real numerical data along with reasonable assumptions to their values and impacts in this simulation (Vensim).

Starting out with the basic model, the Witch Creek Fire size is given by the accumulation of the inflows minus the outflows, which is given mathematically by:

$$\int_{0}^{50} (rate\ of\ spread\ +\ structure\ ignition\ rate\ -\ natural\ extinguishing\ rate\ -\ fire\ response\ efficie$$

The model runs from time 0 to time 50 in days, however, we only expect the wildfire to last for three weeks at maximum.

The rate of spread is impacted by the wind speed and the existence of brush. Wind speed is given in miles per hour, and represents the average wind speed each day in San Diego County. The "existence of nearby brush" variable is measured on a 0 to 1 scale and represents the percentage of brush, from none to full, in the fire's path at a given time. Both of these variables use PULSE functions[4] to achieve different values at different times in the wildfire simulation. The rate of spread equation is given by the following command:

```
IF THEN ELSE(Witch Creek Fire Size > 0 , 15360 * IF THEN ELSE( Wind
Speed > 100, 4 , IF THEN ELSE(Wind Speed > 85, 2, 1)) * (0.2 +
Existence of Nearby Brush) , 0)
```

Walking through the equation, there is the condition on the fire size because if there is no fire, it has no ability to grow. If there is fire, then it spreads at a base rate of 15360 acres per day, which is the equivalent of 1 mile per hour in converted units. This rate is magnified by the wind speed and scaled by the presence of brush. Extensive research has been conducted on wind propulsion for wildfires, so the following factors are approximations of this research and the southern california biome: for high winds (>110mph) the fire simulation will spread at 4 mph, medium (>90mph) 2mph, and low 1mph (Seigel) (Beer).

The structure ignition rate takes into account the section of the fire that is on the edge of and encountering new structures, the density of homes in the land about to be burned, and the percentage of those structures that will ignite (informed by the fire-fuel presence). This is given by the formula:

```
("Fire-fuel Presence" + (1 - "Fire-fuel Presence")*0.2) * SQRT(
Witch Creek Fire Size / 3) * 0.5
```

Here the first term approximates the percentage of homes that will burn (all of those not fireproofed and 20% of those fireproofed) (Municipality of Anchorage), multiplied by the number of homes that the fire will encounter that day. This is given by a third of the circumference of the wildfire (the portion that is burning into new territory) times the home density, which is 0.5 per acre.

The natural extinguishing rate measures the rate at which the fire will naturally put itself out and leave an area due to lack of remaining fuel to burn on. This is approximated with a flat rate of `0.25*Witch Creek Fire Size`, or a quarter of the wildfire having burned through everything and moving on from that region each day.

Finally, "firefighting response efficiency" depends on numerous variables, including department size, external aid, water availability, equipment, and available resources. The department size is a fixed quantity based on the number of San Diego Fire Department trucks and helicopters. The external aid doesn't begin until the fire grows extensively, at which point it increases with nested RAMP[5] functions. The combination of these equipment units composes the "equipment" variable; "available firefighting resources" is the multiplication of the equipment times the water availability (measured on a 0 to 1 scale as a percentage using a PULSE function for when availability disappears). Altogether this gives the firefighting response efficiency:

```
IF THEN ELSE(Witch Creek Fire Size > 0 , Available Firefighting
Resources*2000*5/50 , 0 )
```

For nonzero fire size, the efficiency is given by the total number of firefighting resources (given in units like trucks and helicopters), times their capacity in carrying water (around 2800 gallons in helicopters and 1200 in trucks averaged to 2000) (McLoon), multiplied

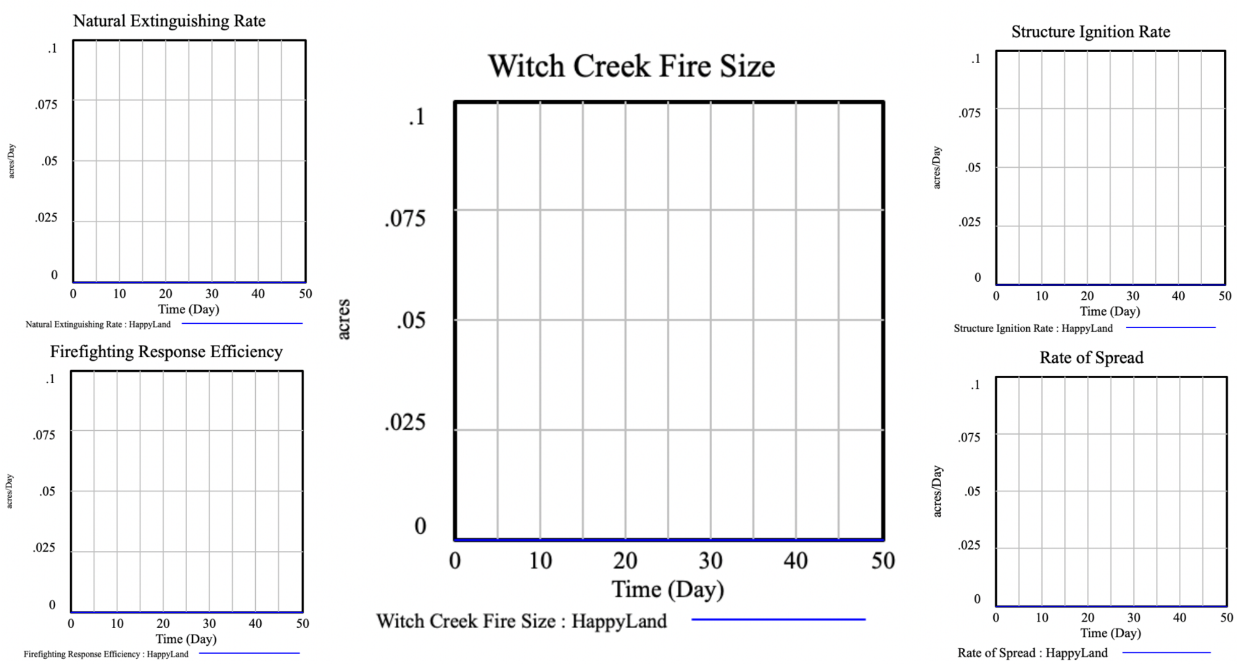
[4] PULSE(start, width) is a function that returns 1 from time start to time start+width, and 0 otherwise
[5] RAMP(slope, start, end) is a function that increases at rate slop from start to end.

by the number of trips each unit can make a day, divided by the approximate number of gallons needed to put out an acre, which is fifty (Meiners).

VII. Results

The first simulation run is the "happy land" scenario, which models the fire progression in the instance that the fire was never ignited as a baseline scenario. In this case, the only adjustment to the model described in the previous section is that the initial value given to the Witch Creek Fire Size is 0. The following graphs show the values over time for the main accumulation, Witch Creek Fire Size in acres, and each of the inflows (right) and outflows (left) in acres/day.

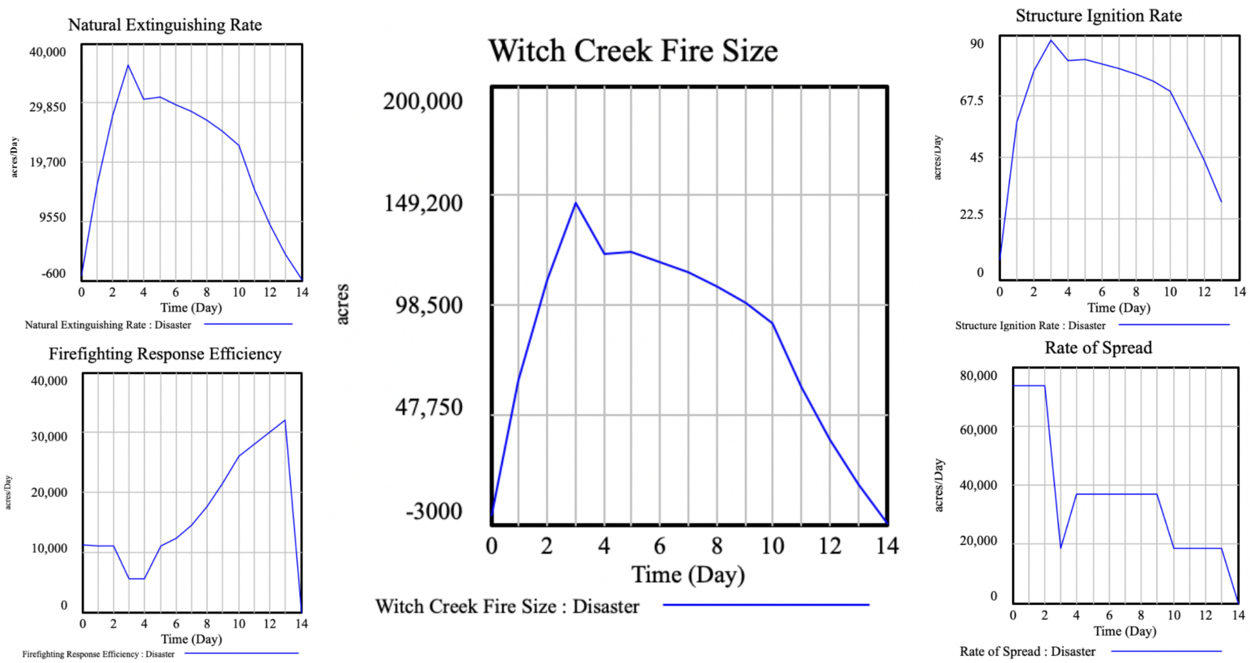
Figure 4a: "Happy Land" Simulation Graphs



These results show that in the instance the wildfire is never ignited, it experiences no growth, and as a result all of the inflows and outflows remain at 0 throughout the time horizon.

More interestingly, the second simulation is a model of the actual disaster scenario. Mirroring the actual weather patterns, the wind speed variable maintains a value of 110 mph for the first three days, declining to 90 over the following three and 60 for the remainder of the period (Weather Underground). The fire-fuel presence is approximated at 75% of all structures. The department size of the San Diego Fire Department is given at 56 trucks (San Diego Fire Authority), and external help begins on the fifth day with 5 units and increases by 2 in slope each day until the wildfire is manageable. On days 3 and 4, there is a water shortage, which results in a 50% reduction in resources.

Figure 4b: Disaster Simulation Graphs



The resulting graphs are approximations to the events that occurred during the Witch Creek Fire; using assumptions grounded in factual basis, they slightly underestimate the duration and overestimate the size. That said, they are sufficiently accurate to the overall trends and behavior for the purposes of this analysis. The simulation shows that the fire size increases relatively linearly until the fifth day, upon which a combination of decrease in spread due to changing wind and increased aid from external forces begin taking over control. These trends are observed as the rate of spread decreases over time in jumps based on these external factors. Likewise, firefighting response efficiency increases after the fifth day due to external help, but dips in the beginning due to lack of water. Ultimately, while at the beginning the fire might observe what is closest to exponential behavior from the reinforcing loops, the balancing loops cause it to dip back down due the goal seeking nature (best seen in rate of spread approaching 0 and firefighting response efficiency increases near exponentially).

The following two figures simulate two different scenarios if certain changes are made to fire response protocols. The first of these two "what if" simulations is an approximation of the results if the fire departments are fully funded, and have all of the equipment they would desire. It is estimated that ideally these departments would have 2.13x the number of trucks they currently have, so the department size is increased to 119, outside help increases by thirty percent, and there is never a water shortage as they have money for backup generators. The second "what if" scenario models if regulations are implemented and followed to prevent the spread of fire. These include fire-fuel being removed from homes to only 10% present and controlled burns removing brush from certain areas prior to fire start, so it encounters two periods of less brush (one 75% less at day 3 and the other 50% less at day five for three days).

Figure 4c: Fully Funded Simulation Graphs

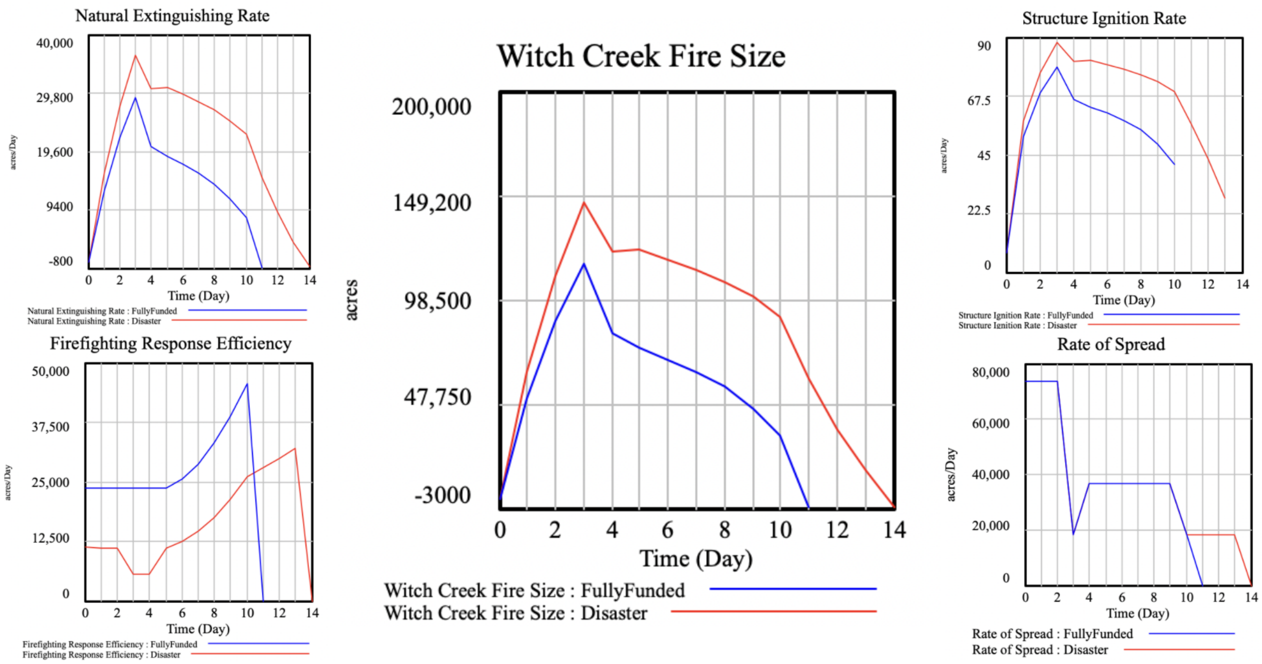
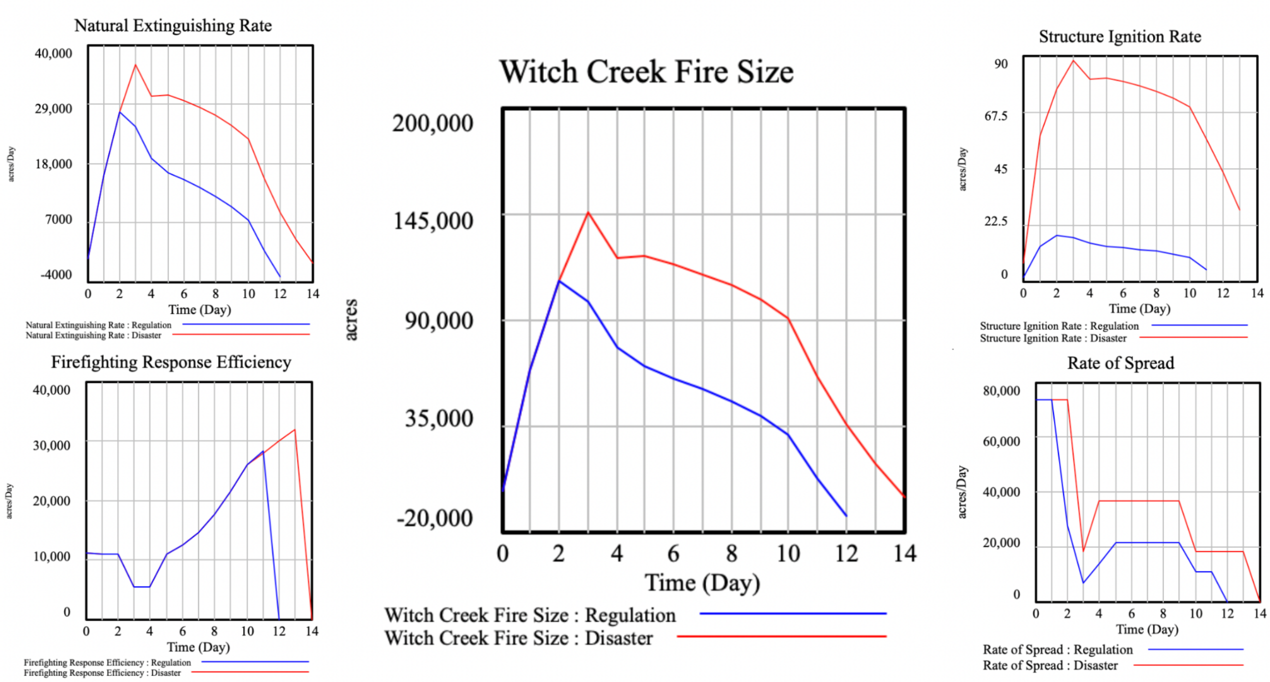


Figure 4d: Regulation Compliance Simulation Graphs



For the fully funded scenario, the Witch Creek Fire accumulation is of a lesser magnitude and ends sooner. This is fully attributable to the increased fire response efficiency in the lower left-hand corner, as it notably no longer has a dip due to water shortage, has a higher magnitude and exhibits more exponential behavior. As all other figures and numbers remain the same, this difference highlights that with complete budgets, wildfire response efficiency is more powerful and decreases the fire damages and duration.

In the regulation compliance scenario, the fire size is lesser and ends sooner due to a decrease in its rate of spread from lack of ignitable material. This is visualized as the rate of spread is lower in magnitude, and in the structures ignited figure, as the number of homes destroyed is a fraction of before. Thus, not only do these regulations help mitigate the overall spread of the wildfire over the land, but they significantly decrease the structures destroyed and consequently the primary source of insured damages.

VIII. Implications

Based on the system dynamic modeling results, there are three main takeaways about what fire departments and government officials can do going forward to mitigate damages from future wildfires. First, county officials partnered with local fire departments should hold fire-fuel awareness campaigns to encourage homeowners to fireproof their homes. The leading source of insured damages after a wildfire are from destroyed building claims. Given that fireproofing homes leads to a 70+% decrease in change of ignition in a wildfire, removing fire-fuel would have a major impact (Municipality of Anchorage). Fireproofing would decrease damages, decrease the amount the wildfire spreads, and give residents a secure feeling in their homes.

Second, having and following strict regulations regarding brush and power lines can both prevent ignition and hamper the spread. After the Witch Creek Fire, trials were held against SDG&E for liability for damages for starting the blaze. Taking nearly a decade and appealing up the Supreme Court, SDG&E was found responsible for ignition due to their out-of-regulation power lines (Nikelowski). Investigators found that it is likely that had the power lines been further apart, they never would have collided and sparked even in irregular winds. Consequently, following these power line protocols can prevent wildfires from ever beginning (over 85% are started by human error like improper powerline installation) (Barclay and Roberts). Likewise, as demonstrated in the simulation, reducing the amount of brush through regulated trimmings and controlled burns can both prevent the sparks from igniting on flammable material and reduce the rate of spread. Thus, enforcing both power line and brush policies strictly could reduce the number of wildfires and their severity.

Third, it is imperative that fire departments have the equipment that they need. Wildfires can only be fought on the perimeter or from above. This requires trucks to hose water from (there are no hydrants in the woods) or helicopters. Having a shortage of these vehicles prevents firefighters combatting the wildfires effectively, which allows the wildfire to grow out of hand. This was especially the case with the Witch Creek Fire, which grew uncontained due to other wildfires taking up resources nearby, and then merged with other wildfires because firefighters were unable to surround and prevent it due to lack of resources. Similarly and as observed in the simulations, water is one of the most critical fire resources, and a loss of water access can have detrimental impacts on response. As with the Witch Creek Fire, the water pump lost power as the power lines were down due to the fire, and the back-up generators were delayed in delivery due to the fire (City of San Diego). As power lines can get burned, having the budget to have back-up generators at all important water pumps would allow fire response teams to be as efficient as possible with their efforts and equipment. Therefore, governments allocating greater budgets to fire departments for added equipment and water pump generators could improve response efficiency and thus decrease fire severity.

IX. Conclusion

The Witch Creek Fire caused extensive damages, and wildfires like it are only becoming more frequent. The present paper sought to analyze the errors contributing to the wildfire and understand them in order to prevent such devastation in future wildfires. Error analysis revealed that the main contributing errors were weather, unfollowed regulations, and overstretched resources. Cause and effect cycles highlighted how with these errors, the wildfire would grow exponentially if it was not checked by balancing variables. These included calling in for external aid, strictly enforcing regulations, and raising fireproofing awareness. Simulating the wildfire with these key variables, a disaster scenario was reproduced and adjustments to these key variables were made to investigate their impact on the fire. Results revealed that fully funding the department with equipment and backup generators increased the response efficiency and decreased the wildfire size and duration. Similarly, imposing regulations on brush, power lines, and fire-proofing awareness drastically decreased homes that were burned and also diminished the wildfire size and duration.

X. References

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