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Assessment of fuel related data in the Metropolitan District of Quito for modeling and simulation of wildfires, case study: Atacazo Hill wildfire

Evaluación de información relacionada con combustibles en el Distrito Metropolitano de Quito para el modelado y simulación de incendios forestales, caso de estudio: Incendio del cerro Atacazo

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Abstract

The Metropolitan District of Quito (DMQ) does not have all the information needed to design wildfire management strategies based on models and simulations. This work evaluated the use of information related to wildfires in the DMQ obtained from governmental and free sources, using the case study of the Atacazo Hill wildfire (09/29/2018). Topographic, meteorological and fuel data from different sources were processed. The topographic information was obtained from the topographic sheets of the Military Geographical Institute; the meteorological information was obtained from Guamaní station of the Metropolitan Network of Atmospheric Monitoring of Quito, and the fuel and vegetation cover information was estimated based on vegetation and alteration level categories of the coverage and land use map of the Thematic Cartography at Scale 1:25000 of Ecuador Project, executed by the Ministry of Agriculture, Livestock, Aquaculture, and Fisheries. The major paths and the fire arrival times were simulated on FlamMap for two different cases. In Case 1, the simulation included fire barriers based on OpenStreetMap data. Additional information gathered during field visits was included in Case 2. Satellite imagery was used to compare the real wildfire extent with the simulated extent using Sorensen and Cohen's kappa coefficients, obtaining 0.81 and 0.85 for Case 1, and 0.78 and 0.81 for Case 2, respectively. These results showed great similarity between the behavior of the model and the real wildfire. After the model was validated, it was applied to estimate the wildfire behavior in various scenarios of interest; it was found that the design of fire barriers based on simulations has great potential to reduce the affected area of a wildfire

Keywords: FlamMap, wildfires simulation, wildfires modeling, remote sensing.

Resumen

El Distrito Metropolitano de Quito (DMQ) no cuenta con toda la información necesaria para diseñar estrategias de gestión de incendios forestales basadas en modelos y simulaciones. Este trabajo evaluó el uso de información relacionada con incendios forestales del DMQ obtenida de fuentes gubernamentales y libres, tomando como caso de estudio el incendio del cerro Atacazo (29/09/2018). Se procesó información topográfica, meteorológica y de combustibles; las hojas topográficas se obtuvieron del portal del Instituto Geográfico Militar, la información meteorológica de la estación Guamaní de la Red Metropolitana de Monitoreo Atmosférico de Quito, y la información de combustibles y cobertura vegetal se estimó en base a las categorías de vegetación y nivel de alteración del mapa de cobertura y uso de la tierra del proyecto Cartografía Temática a Escala 1:25000 del Ecuador ejecutado por el Ministerio de Agricultura, Ganadería, Acuacultura y Pesca. Se realizaron simulaciones en FlamMap de los trayectos principales y tiempos de arribo del incendio para dos casos: el Caso 1 contempla barreras de fuego construidas con los datos de *OpenStreetMap*; y el Caso 2 complementa esta información con observaciones en campo. Se utilizó imágenes satelitales para comparar la extensión del incendio real con las simulaciones usando los coeficientes de Sorensen y kappa de Cohen; obteniendo 0,81 y 0,85 (Caso 1), y 0,78 y 0,81 (Caso 2), respectivamente. Estos resultados mostraron una gran similitud entre el comportamiento del modelo y el incendio real. Una vez validado el modelo, se lo aplicó para estimar el comportamiento del incendio en varios escenarios de interés; se comprobó que el diseño de barreras de fuego en base a simulaciones tiene gran potencial para disminuir el área de afectación de un incendio.

Palabras clave: FlamMap, simulación incendios forestales, modelado incendios forestales, sensores remotos.

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1 Introduction

Large wildfires have been reported in recent years in the Metropolitan District of Quito (DMQ). There were 285 wildfires during July 2019 – September 2019, which consumed almost 2500 ha of plant cover. Wildfires are one of the most recurring natural and anthropic threats in DMQ; they are considered catastrophic events due to their high environmental impact (Secretaría de Seguridad DMQ, 2015). Impacts of a wildfires that can affect ecosystems and nearby communities in the short or long term include loss of ecosystem services, threat to endangered species, simplification of forest structure and biological composition, entry of invasive species, and generation of dry climate conditions by greenhouse gas emissions (Moore et al., 2003; Barkhordarian et al., 2019).

The application of models and simulations for wildfire management, prevention and response covers various approaches (DeMagalhães et al., 2017; Srivastava et al., 2018; Botequim et al., 2019; Jahdi et al., 2019; Palaiologou et al., 2020; Xofis et al., 2020). For example, the Canadian Forest Service (CFS) develops various models and software applications for predicting a fire. These tools include the Canadian predicting fire spread Model (CanFIRE), used to predict short-term fire behavior, and the Probabilistic Fire Analysis System (PFAS), used to predict long-term effects. These tools assess the intervention need to suppress a fire when it is likely not to be extinguished naturally, saving hundreds of millions of dollars annually in fire suppression costs (Fitch et al., 2018; Government of Canada, 2020).

Traditionally, wildfire modeling includes prediction of fire spread, intensity, and length of flame. Part of easy-to-measure variables are related to fuel type, terrain topography and surface climatic conditions. Fuel types are often classified into different categories depending on their quantity, apparent density, heat content and extinction humidity. The characteristics of these fuel categories serve as inputs to semi-empirical fire behavior models implemented in software such as FlamMap and FIRESITE (Bakhshaii and Johnson, 2019; Zigner et al., 2020).

FlamMap is fire modeling and simulation software developed by the U.S. Fire, Fuel, and Smoke Science Program (FFS) widely applied today (Hernández et al., 2007; Jahdi et al., 2016; Botequim et al., 2017; Conver et al., 2018; Rios et al., 2019). This program implements several semi-empirical models to estimate the behavior, growth and spread of a fire. Simulations in each area using this software require meteorological, topographic and fuel information. This program can generate different outputs based on the results of fire behavior simulations, Minimum Travel Time (MTT) and Treatment Optimization Model (TOM) (Finney, 2006; Stratton, 2009).

Semi-empirical wildfire models are the most used today, however, they have several limitations, such as their focus on the representation of fire behavior, but not on combustion and heat transfer mechanisms. In addition, they carry out several simplifications in order to provide methods of easy execution through statistical assumptions and geometric approximations in two dimensions of three-dimensional processes. On the other hand, the new generation of atmospheric wildfire models includes the application of Computational Fluid Dynamics (CFD) to numerically solve three-dimensional physical models of combustion, heat transfer, aerodynamics and turbulence. In addition, these models include Numerical Weather Prediction (NWP) methods that allow to simulate the interaction of the fire with the nearby atmosphere. In this way, the dynamics of complex three-dimensional processes that can occur during a fire can be represented, such as plume-driven fires, fire whirls, horizontal rolling vortices, fire combining with mountain winds, chimney fire, and fire storms. The main disadvantage of these models is the large number of computational resources required, so their applicability is focused on research (e.g., FIRETEC) (Bakhshaii and Johnson, 2019).

The main drawback for the simulation of wildfires with FlamMap in DMQ is that there is no database with fuel characteristics and vegetation percentages for wildfire management in DMQ. However, there are maps of vegetation type and land use generated by the Ministry of Agriculture, Livestock, Aquaculture and Fisheries (MAGAP) and the Ministry of Environment and Water of Ecuador (MAAE) with information that may be related to the type of fuel in an area. These data, in combination with OpenStreetMap maps and satellite imagery, may be potential sources of fuel information for fire simulation (MAAE, 2020; MAGAP, 2015). In addition, wildfire remote sensing tools such as the National Aeronautics and Space Administration (NASA) FIRMS system can be used to identify fires that serve as case studies in the DMQ; National Aeronautics and Space Administration) (NASA, 2021) or implement algorithms based on neural networks and multispectral satellite images (Govil et al., 2020; Mujtaba and Wani, 2018; Govil et al., 2020).

The aim of this paper is to evaluate the information available in the DMQ to model and simulate wildfires using FlamMap software and estimate the properties of fuels with free access information and government agencies, taking the fire of Atacazo Hill as a case study, which occurred in September 2018 (DMQ Fire Department, 2018). To validate the results of the simulations, the actual and simulated extent of fire will be compared using Sorensen and Cohen's kappa coefficients (Banko, 1998). Finally, the application of the model for the simulation of scenarios will be evaluated, these are: fire behavior in extreme weather conditions, fire behavior in the face of strategically designed fire barriers, and fire behavior in the face of a fire barrier failure.

2 Materials and Methods

The case study of this investigation is the wildfire of Atacazo Hill that occurred on September 29, 2018; four phases were considered to model and validate this fire: data collection, data processing, simulation and validation (Figure 1). In the first phase, meteorological information was collected from the Guamani weather station of the Metropolitan Atmospheric Monitoring Network of Quito (REMMAQ.), and topographic information was obtained from the topographic chart of Amaguaña parish of the DMQ created by the Military Geographic Institute (GGI), and an estimate of canopy cover and fuel type was made from the land coverage and use map of the MAGAP 1:25000 Thematic Mapping Project. This map has categories that classify the land according to the type of vegetation (herbaceous, shrub and forest) and alteration levels (low, medium and high). In addition, OpenStreetMap's natural road and cover data were used to supplement fuel information, because trails, secondary roads, water bodies and rocky areas may behave as barriers to natural or unintentional fires (Rigolot et al., 2004). In the second phase, an LCP file was created containing slope, elevation, aspect, fuel models and plant cover data; a WXS file with meteorological data; and two maps with fire barriers for case 1 and case 2. The extent of the fire on Atacazo Hill was estimated based on Sentinel-2 satellite images. In phase three, the fire extension simulation was performed using the calculation of the MTT in FlamMap. Finally, the precision of the simulation was calculated with the Sorensen coefficient and the Cohen's kappa coefficient.

2.1 Case Study

Atacazo Hill is in Ecuador, Pichincha province, on the southern border of the DMQ with Mejía canton (Figure 2). It is located at $0°21'15.8''$S $78°37'14.3''$W at a height of 4463 meters above sea level. Atacazo Hill is a stratovolcano that is part of the Western Cordillera, its average temperature is 11.9 °C, it has a humid tropical climate, and its vegetation is mainly paramo with herbaceous vegetation. The fire on Atacazo Hill began on September 29, 2018, lasted four days and consumed more than 1200 ha of DMQ and Canton Mejía (Figure 3). According to reports from the DMQ Fire Department, the fire was reported at 14h50 hours on September 29, 2018, was controlled at 7h06 on October 2, 2018, and was monitored for two more days. The duration of the fire, from its report to its control time, was 2 days, 16 hours and 16 minutes (3856 minutes in total). It is worth mentioning that there are telecommunication antenna installations on the top of Atacazo Hill. For this reason, there are second-order tracks that can be traveled in vehicles with dual transmissions that get very close to the rock cover of the top. This information is important because a road, wide enough to be traveled by a car, can behave as a fire barrier in a fire, as well as rocks and sand near the top of a volcano are surfaces where fire does not spread.

2.2 wildfire Modeling

Rothermel's semi-empirical surface fire propagation model is one of the most widely used models to describe the behavior of a wildfire. This model is generally applied in conjunction with other models of flame intensity, flame length, crown fire, fire attempts, fire propagation speed, fire front growth, among others, for fire and fuel handling. The final equation of Rothermel surface fire propagation model is detailed below (Andrews, 2018):

Equation 1

$$R = \frac{I_R \xi (1 + \phi_W + \phi_S)}{\rho_B \varepsilon Q_{ig}} \tag{1}$$

Where:

R is the propagation speed measured in $\frac{m}{min}$.
I_R is the reaction intensity measured in $\frac{J}{m^2 min}$.
ξ is the flow propagation reason.
ϕ_W is a factor related to the effect of wind on fire propagation.
ϕ_S is a factor related to the effect of the slope of the ground on the fire spread.
ρ_B is the apparent fuel density measured in $\frac{kg}{m^3}$.
ε is the effective heating number
Q_{ig} is the amount of heat needed to ignite a pound of fuel measured in $\frac{J}{kg}$.

Although this model has existed since 1972, it is still implemented as part of more complex models and simulators widely used today such as FlamMap and FIRESITE. FlamMap is a wildfire simulator that implements different patterns of fire behavior, these are:

- Rothermel model (1972) for surface fire propagation.
- Van Wagner model (1977) for the initiation of crown fire.
- Rothermel model (1991) for the propagation of crown fire.
- Albini model (1979) for fire attempts.
- Finney's (1998) or Scott and Reinhardt's (2001) crown fire calculation method.
- Nelson's Dead Fuel Moisture Model (2000).

The input geospatial information for FlamMap is described by several raster combined into a Landscape file with LCP extension; weather information can be processed by the WindNinja tool and entered in WSX format. In addition, other data such as fire barriers and trigger points can be defined by maps with vector-type information.

2.3 Data processing

2.3.1 Landscape File

To generate the Landscape file for FlamMap, five rasters must be created: elevation or height, slope, aspect, plant coverage, and fuel models. For this, it is important that all rasters have the same cell or pixel size (in this case 20×20 m), that their pixels match exactly, and cover the same study area. In addition, it is necessary to indicate the projection used through a file with PRJ extension, in this case, WGS84 zone 17S.

2.3.2 Creating Height, Slope, and Aspect Rasters

Height, Slope, and Aspect Rasters are obtained from the level curves of the Amaguaña topographic sheet. This was done using the ArcGIS software and the procedure described in Figure 4. The result of this process is shown in Figure 5.

2.3.3 Creation of Fuel and Plant Cover Model Rasters

The MAGAP 1:25000 Thematic Mapping Project's land use and coverage map was used to generate the plant cover rasters and fuel models. This map is in vector format with attribute "coverage" that contains 25 categories of land coverage and use of Atacazo Hill area. The vegetation types indicated in these categories are related to Scott-Burgan fuel models for generating the FlamMap fuel raster (Scott and Burgan, 2005). On the other hand, ground alteration levels are related to ranges of plant coverage percentages to generate the coverage raster. In addition, guidelines from the National Wildfire Coordination Group (NWCG) fuel selection guide were considered. With this information, the database in Table 1 was created, where the attributes "fuel value" and "cc class" were used to create fuel model and plant cover rasters, respectively (Figure 6). In this table, each category of the "coverage" attribute is assigned a fuel model ("fuel type") with its respective numeric code ("fuel value") and a plant coverage class ("cc class"). In the plant coverage class, 0 corresponds to 0% coverage, 1 from 1 to 25% coverage, 2 from 26 to 50% coverage, 3 from 51 to 75%

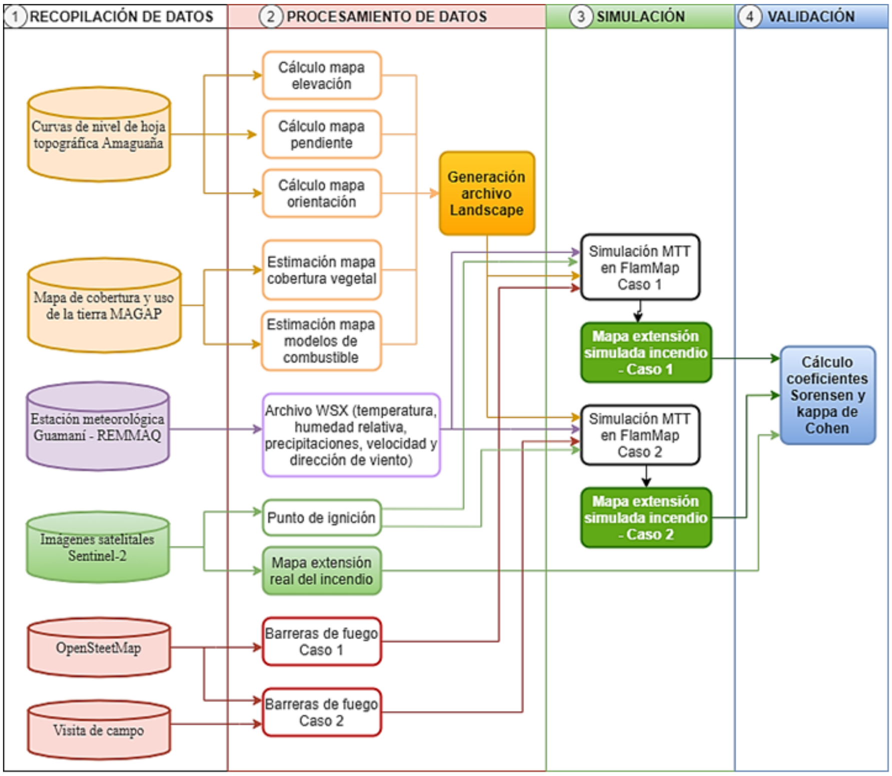

Figure 1. Methodology diagram (own elaboration)

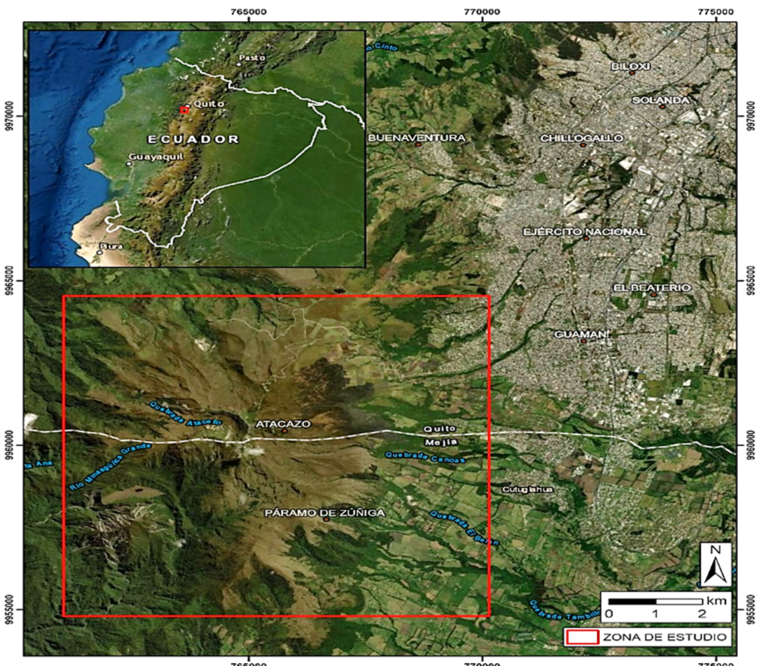

Figure 2. Location of Atacazo Hill (own elaboration)

coverage, and 4 from 76 to 99 % coverage. It should be mentioned that the information corresponds to

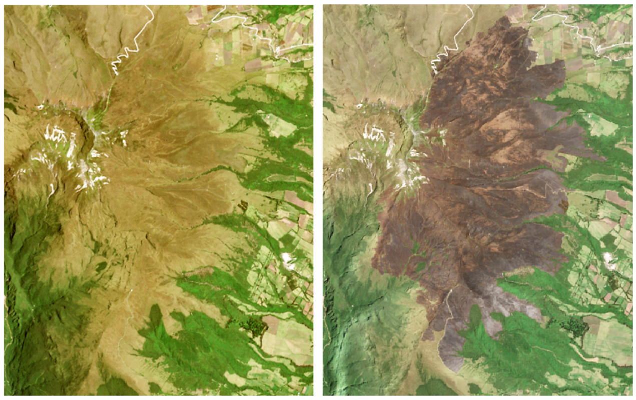

Figure 3. Sentinel-2 images, Atacazo Hill. Before the fire – 09/29/2018 (left) and after the fire – 10/24/2018 (right)

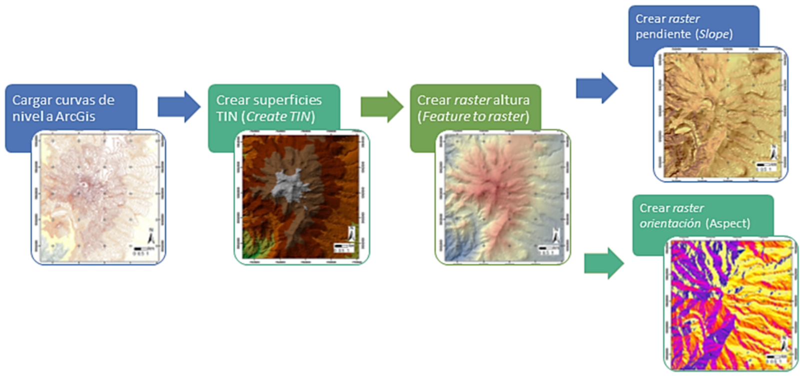

Figure 4. Steps for creating the height, slope and aspect rasters (own elaboration)

the year 2015 and is the most current and with the best resolution found.

2.3.4 Wxs file creation with weather conditions

The meteorological variables are temperature, relative humidity, cloud cover, precipitation, wind speed and wind direction. All these variables, except for cloud, are available at the REMMAQ's Guamani station between September 29 and October 5, 2018. With this data, a file with a WXS extension will be generated containing the input weather information for the dead fuel humidity calculations performed by FlamMap.

Table 2. WXS file meteorological variables and their mean value (own elaboration)

Variable	Units	Mean value
Temperature	Celsius Degrees	14
Relative humidity	Percentage	59
Precipitations	hundreths millimeters	0
Wind speed	Kilometers per hour	6
Wind direction	Grades	181
Nubosity	Percentage	0

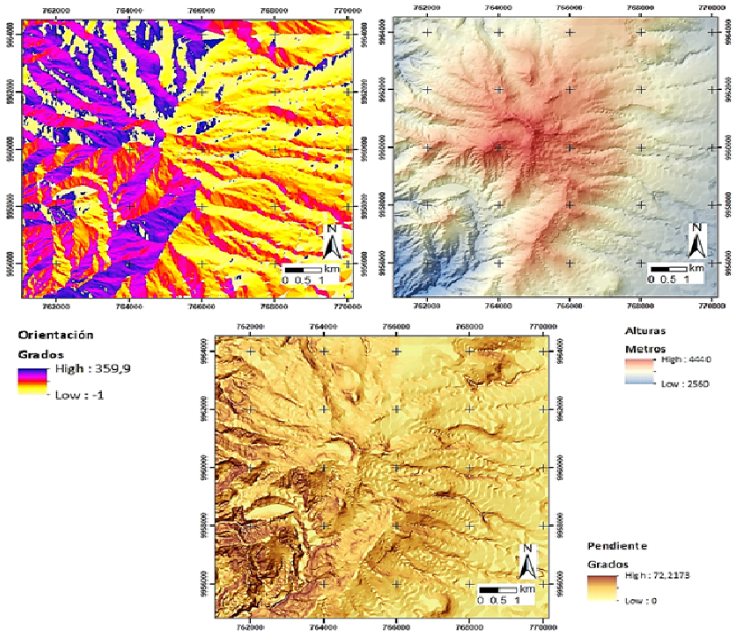

Figure 5. Rasters of height, slope and aspect of the study area (own elaboration)

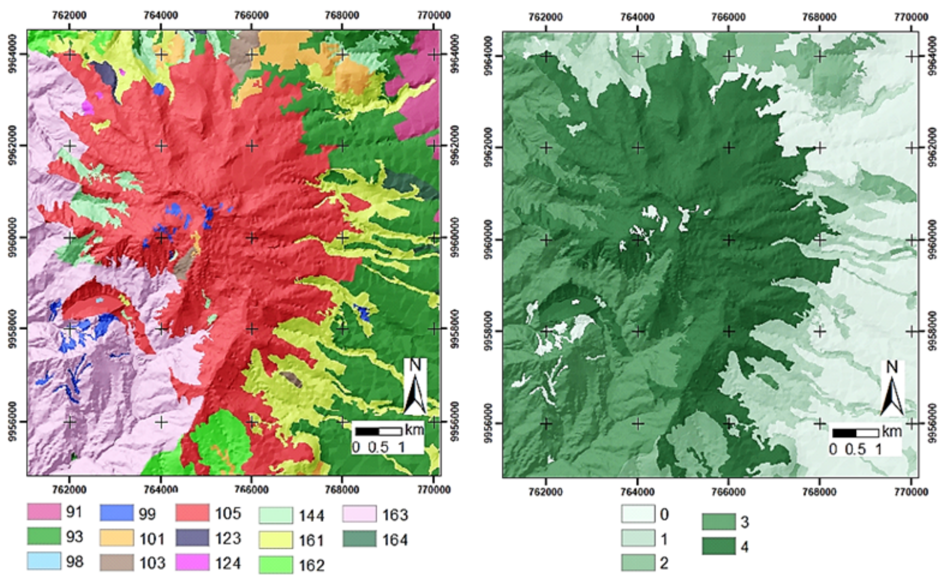

Figure 6. Raster of fuel models and plant cover of the study area (own elaboration)

2.3.5 Point of ignition

One of the advantages of the case study is that a satellite image Sentinel-2 is available with little cloud shortly after its first report. The fire developed on the south of Hill Atacazo and was reported at 14h50 on September 29, 2018. In addition, one of the theories of its creation is that it was caused by an uncontrolled agricultural burning. For these reasons, the black area near the planting shown in Figure 7 was considered as an ignition point. A shapefile interpreted on the satellite image was created in the shape of this area to be used for MTT simulations in FlamMap.

Table 1. Coverage database, fuel models, numerical code of fuel models, and vegetation cover (own elaboration)

Cover	fuel_type	fuel_value	cc_class
AREA IN THE PROCESS OF URBANIZATION	NB1	91	0
POPULATED AREA	NB1	91	0
URBAN	NB1	91	0
MISCELANEO SHORT CYCLE	NB3	93	0
MISCELANEO FORESTRY	NB3	93	0
POTATO	NB3	93	0
CULTIVATED GRASS	NB3	93	0
LAKE/LAGOON	NB8	98	0
EROSION PROCESS AREA	NB9	99	0
QUARRY	NB9	99	0
MINE	NB9	99	0
VERY DISTURBED HUMID HERBACEOUS VEGETATION	GR1	101	4
DISTURBED HUMID HERBACEOUS VEGETATION	GR5	105	4
MEDIANLY DISTURBED HERBACEOUS PARAMO	GR3	103	3
MEDIANLY DISTURBED SHRUBBY PARAMO	GS4	124	2
LITTLE DISTURBED HERBACEOUS PARAMO	GR5	105	4
VERY DISTURBED HUMID SHRUB	TU1	161	1
VERY DISTURBED HERBACEOUS PARAMO	GR1	101	2
POORLY DISTURBED WET SCRUB	GH4	144	3
DIRTURBED SHRUBBY PARAMO	GS3	123	1
MODERATELY DISTURBED WET SCRUB	SH4	144	2
MODERATELY DISTURBED HUMID FOREST	TU2	162	2
PINE	TU2	162	2
SLIGHTLY DISTURBED HUMID FOREST	TU3	163	3
EUCALIPTUS	TU4	164	2

2.3.6 Fire Barriers According to OpenStreetMap Map

Vehicle walkways could be identified by means of an area recognition. The width of these roads and the low height of the surrounding herbaceous vegetation make it possible for them to behave like fire barriers. On the other hand, water bodies and rocky areas on the top are surfaces where fire does not spread. With these observations and information from the OpenStreetMap platform, two sets of fire barriers were generated. Case 1 includes fire barriers built only with OpenStreetMap data, while case 2 complements this information with field observations (Figure 8).

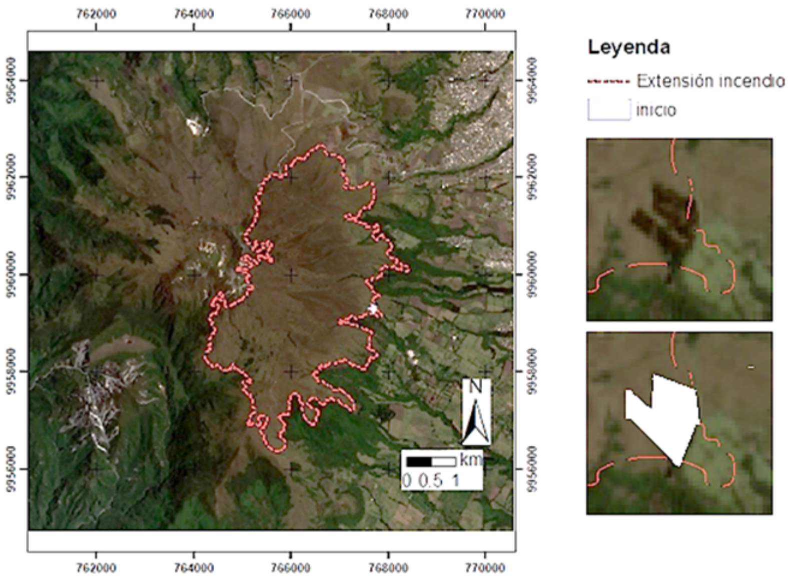

Figure 7. Probable ignition point of the fire at Atacazo Hill (own elaboration).

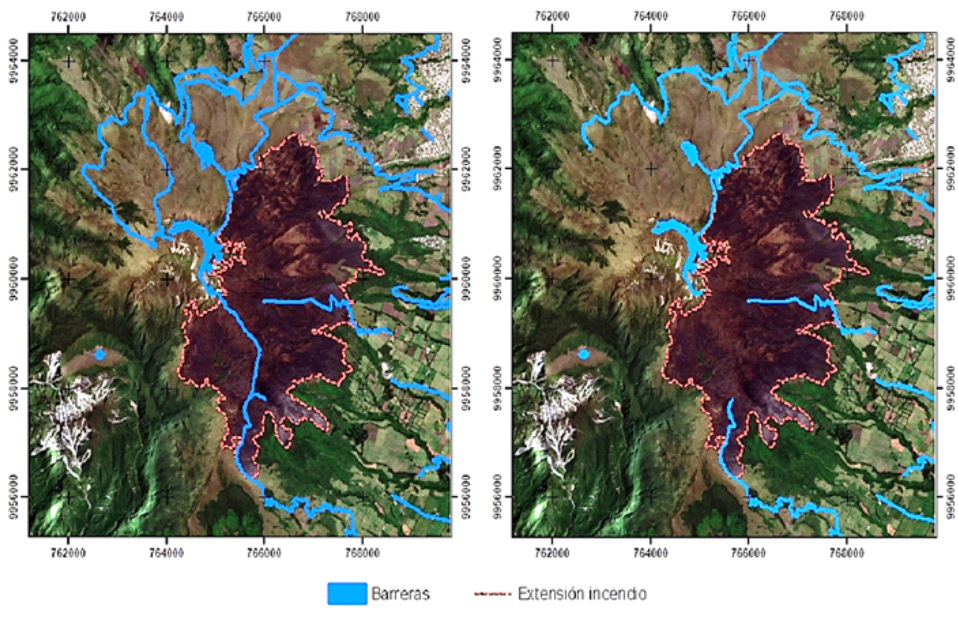

Figure 8. Fire barriers: Case 1 (left), case 2 (right) (own elaboration).

2.4 Error measures

2.4.1 Sorensen's coefficient

This coefficient aims to compare the similarity of two samples with information on the existence or non-existence of a finished characteristic. In the context of wildfire simulation, the burned or unburned areas of the real fire can be compared with the simulations. The formula for calculating this coefficient is as follows:

Equation 2

$$SC = \frac{2a}{2a+b+c} \tag{2}$$

Where:

SC is the Sorensen coefficient.
a is the number of cells burned in the simulation and actual fire.
b is the number of cells burned in the simulation and not burned in the actual fire.
c is the number of cells not burned in the simulation and burned in the real fire.

2.4.2 Cohen's kappa coefficient

Cohen kappa coefficient is a measure of error that can be derived from an error matrix or confusion matrix. This coefficient evaluates the overall adjustment of the error matrix, considering the elements outside its diagonal. In the context of a wildfire, it can be calculated using the following formula:

Equation 3

$$KC = \frac{N\sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r}(x_{i+}x_{+i})}{N^2 - \sum_{i=1}^{r}(x_{i+}x_{+i})} \tag{3}$$

Where:

KC is Cohen's kappa coefficient.
r is the number of rows in the error array.
N is the total number of observations.
x_{ii} is the number of observations in row i and column i of the error matrix
x_{i+} is the marginal total of row i.
x_{+i} is the marginal total of column i.

3 Results

3.1 Simulation of major paths and arrival time

MTT-based simulations were run in both cases to obtain the major paths and arrival time map (Figure 9). The main routes make it easy to identify fuel treatment areas, while the arrival time map allows to visualize the extent of the fire. In case 1, the extent of the fire is limited to the north, south and west by the fire barriers considered, while the change in vegetation type is limited to the east. This type of vegetation is classified as highly altered wet scrub and corresponds to fuel model TU1 (mixture of forest and understory of grass and shrubs) with a plant coverage percentage between 1 and 25%. In case 2, the extent of the fire is limited to the north and northwest by the fire barriers considered, while the change in vegetation type is limited to the southwest, east and south. Vegetation to the east is classified as highly altered wet scrub and corresponds to fuel model TU1 (forest with low grass and shrub load) with a plant coverage percentage between 1 and 25%. Vegetation to the south is classified as a moderately altered humid forest and corresponds to fuel model TU2 (forest with moderate load of grass and shrubs) with a plant coverage percentage between 25 and 50%. Vegetation to the southwest is classified as poorly altered wet forest and corresponds to fuel model TU3 (forest with moderate load of grass and shrubs) with a plant coverage percentage between 51 and 75%. It is worth mentioning that the fire begins to spread through this last type of vegetation at the end of the simulation.

3.2 Model Validation

To compare the simulated and actual extent of the fire, Sorensen and Cohen kappa coefficients are calculated. For this, it is necessary to create rasters that classify each pixel into "burned" and "unburned" cells to calculate the a, b, and c parameters of equation 2 (Figure 10) and generate the error matrices of equation 3 (Table 3 and table 4). Sorensen's coefficient values obtained are 0.81 and 0.85 for case 1 and 2, respectively. Cohen's kappa coefficient values are 0.78 and 0.81 for case 1 and case 2, respectively. Hence, the simulation where OpenStreetMap information was supplemented with field observations has better results.

3.3 Simulation of scenarios

Different simulations of scenes of interest can be generated with the validated model; in this research three scenarios were used. The first scenario considers extreme weather conditions with zero rainfall. It can be observed that the fire spreads to the southwest through vegetation categorized as little disturbed wet forest, reaching an area of high slopes (Figure 11); causing the fire to spread over a large area beyond the study area. The second scenario simulates the fire's behavior in the event of a fire barrier to the north. It can be seen how the fire spreads to a large area to the west of Atacazo Hill (Figure 11). The third scenario considers two fuel treatments; the first treatment is to place a fire barrier that cuts off the major paths leading the fire to the southwest in the first scenario; the second treatment extends a road near the top, creating a barrier that begins at the agrarian border, at the bottom of the hill, and ends at its top (Figure 12).

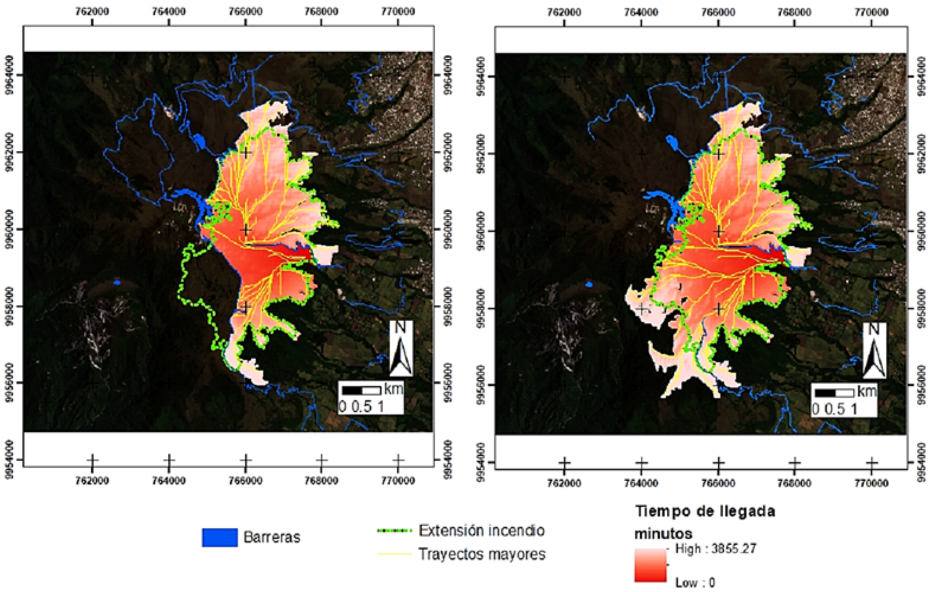

Figure 9. Simulation of major paths and arrival time for case 1 (left) and case 2 (right) (self-elaboration).

Table 3. Error matrix simulation case 1 (own elaboration).

	Burned Cell (Simulation)	Unburned Cell (Simulation)	Total
Burned Cell (Real)	25920	6732	32652
Unburned Cell (Real)	5190	183743	188933
Total	31110	190475	221585

4 Discussion

Although Cohen's Sorensen and kappa coefficients show great similarity between simulations and the

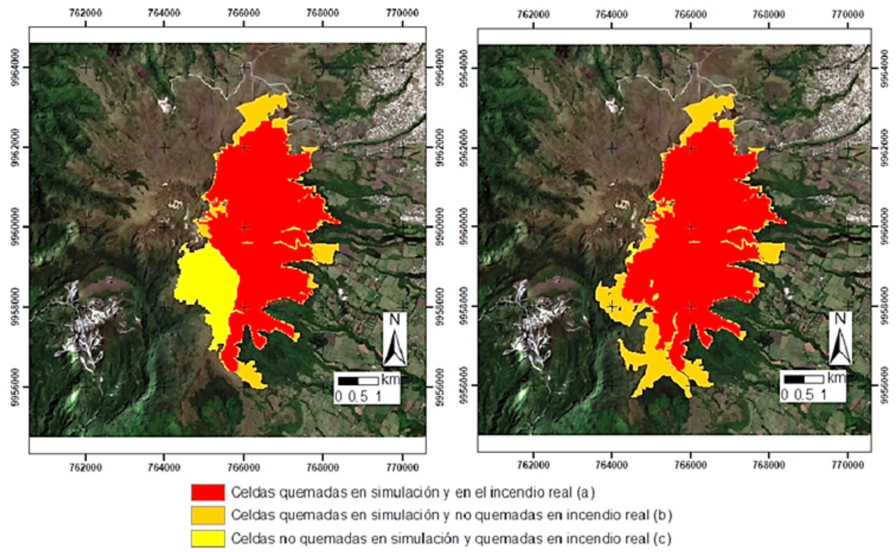

Figure 10. Parameters for calculating Sorensen and Cohen kappa coefficients for case 1 (left) and case 2 (right) (own elaboration).

Table 4. Simulation error matrix Case 2 (own elaboration).

	Burned Cell (Simulation)	Unburned Cell (Simulation)	Total
Burned Cell (Real)	31771	881	32652
Unburned Cell (Real)	10772	178161	188933
Total	42543	179042	221585

real fire, and their values are consistent with similar studies (Jahdi et al., 2016), it should be mentioned that this is due to the homogeneity of the vegetation in the area, among other reasons. The reliability of the proposed methodology can be increased by calibrating the model with several fires before applying it for simulation scenarios, and it is recommended to do so with at least three fires (Stratton, 2009). It is recommended to calibrate fuel model humidity and fire barriers; this can be done by combining simulations with field observations, experimental measurements or satellite images.

On the other hand, there are several sources of error that were not considered because of the difficulty in estimating or because of lack of information, for example: the effect of firefighting actions by fire fighters is not considered (nor is there any information available); the fuel models used correspond to ecosystem vegetation present in the United States, which excludes ecosystems typical of the Andes. Therefore, it is important to develop fuel models belonging to the study area (Elia et al., 2015); much information used was not raised for the purpose of simulating fires, for this it is possible to raise from scratch the data of fuels and vegetation using laser object detection and measurement techniques (LIDAR; Laser Imaging Detection and Ranging) (Jakubowksi et al., 2013; Stefanidou et al., 2020), Stratified random sampling, multispectral satellite images, supervised classification, or some combination of these techniques. On the other hand, the weather conditions were taken from a station located more than one kilometer away from Atacazo hill and the calculation of Cohen's Sorensen and kappa coefficients was carried out with the final ex-

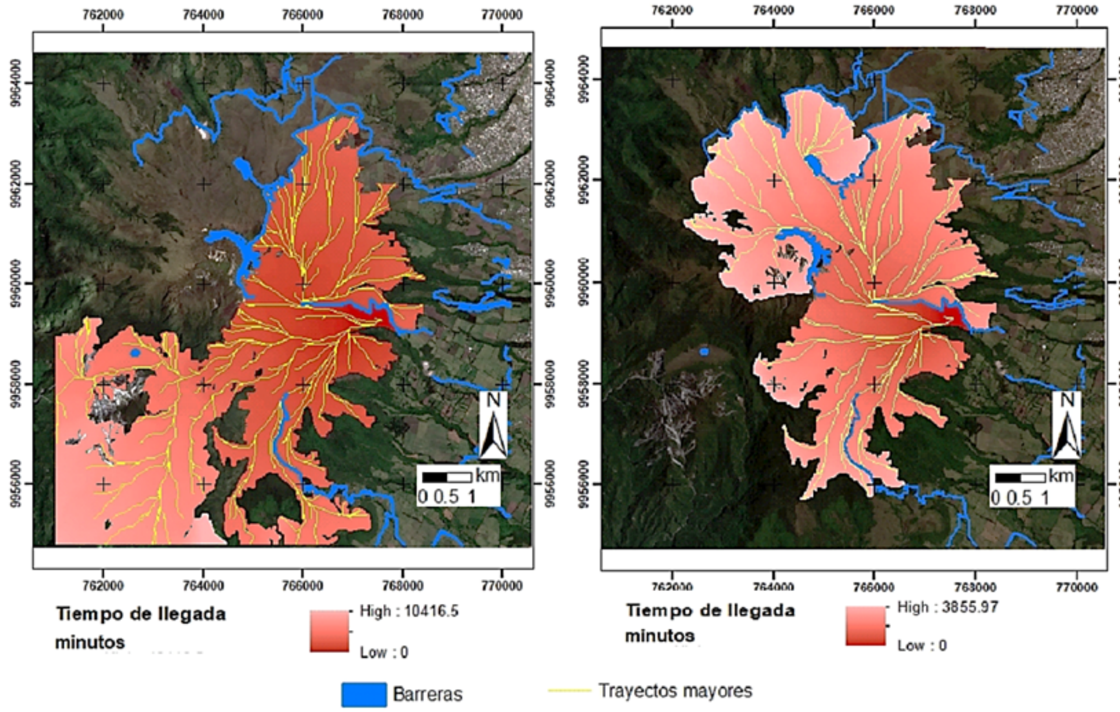

Figure 11. Simulation of major paths and arrival time for the first (left) and second (right) scenario (own elaboration).

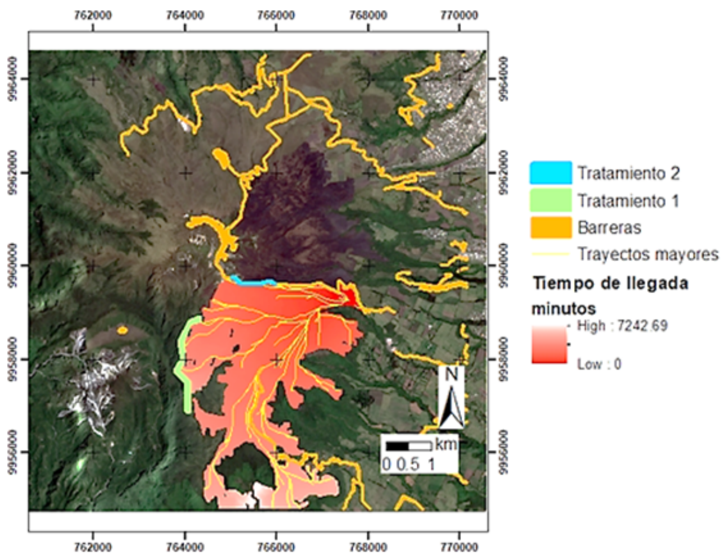

Figure 12. Simulation of major paths and arrival time for the third scenario (own elaboration).

tension of the fire, therefore, there is no information on the accuracy of the model to represent its time evolution (Stratton, 2009).

It can be seen, both in the simulations and in the real fire, that the areas classified as a poorly disturbed herbaceous paramo possess high fire propagation; the fire barriers and the change of vegetation are the limits in the final extension of the fire. The identification of these limitations is important because Atacazo hill has a large amount of vegetation of this type to the west of its top, through which a fire can spread if the fire barriers fail to contain it.

On the other hand, simulation by calculating fuel moisture based on the changing weather conditions of the WSX file allows the results to be much closer to the actual fire behavior (Finney, 2006). A simulation with fixed weather conditions would mean skipping the increase in humidity and the decrease in temperature in the evenings and early mornings; it may cause fire to spread through areas with poorly disturbed humid forest or very disturbed humid scrub. In a real scenario, this would correspond to a fire that takes place in an unusual dry summer and extremely unfavorable weather conditions (little rain and strong winds).

It is important to mention the effectiveness in controlling a fire showed by the implementation of strategically located fire barriers (Figure 12), becoming decisive elements in the expansion of a fire in large areas. Moreover, its implementation is common in other countries (Rigolot et al., 2004) and is quite convenient because of the existence of several paths and roads commonly used by tourists and workers. However, the ecological impact of its implementation is still under discussion (Shinneman et al., 2019). It should be mentioned that a properly designed fire barrier can serve a dual purpose, first, it will prevent the spread of fire, and then it will facilitate access by fire personnel to the site.

5 Conclusions

This paper studied Atacazo Hill, which began to evaluate on September 29, 2018, the use of the information available in the DMQ in the modeling and simulation of wildfires using FlamMap software. In the DMQ, there is no raised information specifically aimed at modeling and simulating these emergencies. Data are needed on the type of fuel and percentage of plant cover in the territory. As mentioned before, the data used to estimate fuel models and plant cover percentages were not collected for the purpose of being used in the modeling and simulation of wildfires. For this reason, there are many ways to improve the reliability of simulation results based on improved generation of fuel model rasters and vegetation percentages. Some options are:

- Generate DMQ-specific fuel models: Scott-Burgan models are developed for the types of vegetation present in the United States; so, using them in DMQ implies an approach that can be improved by generating own models for the high mountain ecosystems of the Andean Mountain range of DMQ (Elia et al., 2015).
- Generate fuel and plant cover maps from scratch: the approximations made by collecting the data from the plant cover and land maps used in this work may involve major changes in the simulation of a fire. For example, a small, poorly classified area can cause the fire to expand into very large areas in a simulation. In addition, an area with a certain type of fuel may contain areas with a different percentage of coverage, which implies the fire to spread differently.

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