



Supplement of

Seasonal influence on post-fire debris flow likelihood after the 2020 Lake Fire

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This supplementary material consists of 4 text sections, 7 figures, and 7 tables.

1. Additional basin properties and tests

We used ASTM E11 test sieves with mesh sizes 2 mm, 1 mm, 0.5 mm, 0.25 mm, 0.125 mm, and 0.063 mm. Sieves were stacked and shaken on a RO-TAP sieve shaker.

We performed a Water Droplet Penetration Test (WDPT) during the first field survey at the basin outlets and recorded unchanged droplets after 5 and 10 minutes. This led us to assume a significantly low hydraulic conductivity value despite the unavailability of a mini disk infiltrometer.

Using the National Land Cover Dataset, both the 2020 Lake Fire and 2016 Fish Fire have similar categories of Shrubs/Scrub. The entire Fish Fire is dominated by California mesic and dry-mesic chaparral, mixed evergreen woodland and mixed conifer and woodland, and montane grasslands (Staley et al., 2018). This is similar to the Lake Fire sites within the Los Angeles National Forest area where Chaparral also dominates (Paysen et al., 1980).

See **Table S6** for summarized basin properties.

2. Test for dNDVI calibration and validation

We validated our dNDVI values with field observations using a consistent resolution from the satellite (3 x 3 meters). We identified and validated using the road and three other locations (1 unburned campsite & 2 by the river in the burned perimeter). We created another set of calibration sites on roads only to have more consistent dNDVI values than the other locations due to the absence of vegetation and greater exposure to sunlight.

We found that on some dNDVI dates, the road values either showed a similar reduction/increase in dNDVI or varied across the five points. On the few dates where dNDVI values fluctuate across location pixels, we can use the mean values to subtract across the image to calibrate. However, on the other dates, the different dNDVI values across the five points can be attributed to local effects (e.g., shadows, water, dust) or other processes. In this study, we were not successful in creating a standardized dNDVI calibration due to the inconsistent orbits and acquisition times from the satellite imagery and the lack of consistent field validation over long periods at the different locations. Future work should perform calibration at specific sites and closely separated time to better understand the values in dNDVI and consider the effects of seasons and weather.

3. Other satellite imagery processing

To determine the effectiveness of other vegetation index methods, we tested with relative NDVI (rdNDVI) in our study site. The rdNDVI method has been used to detect landslides and show the severity of debris flow changes using the relative percent change (equation 2 in Scheip and Wegmann 2021). However, in our study, there were no clear differences between rdNDVI and dNDVI. A possible reason for the lack of clear differences is the lack of the greenest-pixel composite that is needed for the reference-NDVI image in our study, which requires extensive computational power and time to acquire. Moreover, our rdNDVI has values greater than -100%

or 100%, which could be caused by the different imaging sensors on PlanetScope as compared to Sentinel-2 or Landsat-7/8 (Scheip and Wegmann 2021). However, further analysis is also needed to understand the product of calibrating different satellite sensors with inconsistent orbits.

4. Numerical modeling parameters

We use a numerical model, KWAVE from the Community Surface Dynamics Modeling System (CSDMS) (<https://csdms.colorado.edu/wiki/Model:KWAVE>), as described in Rengers et al. (2016) and Rengers et al. (2019), to simulate runoff and debris flow initiation. KWAVE uses the kinematic wave approximation for overland flow and the Green-Ampt equation to represent infiltration and canopy interception (Rutter et al., 1975).

We modified only the input parameters that correspond to our field and satellite measurements as described in Section 3.4. All remaining parameters have been kept at the default values as measured from the Fish Fire (e.g., Hoch et al., 2021): the hydraulic roughness parameter ($n_0 = 0.1$), canopy interception parameters ($S_i = 0.00044$, $g_i = 525$, $K_i = 0.000012$), and Manning's roughness = 0.1, exponent in roughness model ($\epsilon = -0.33$) and the critical depth in roughness model ($h_0 = 0.003$).

We also used a suction head ($h_f = 0.01$ m) and initial volumetric soil moisture content, $\theta_i = 0.1$, and soil moisture at saturation ($\theta_s = 0.41$) derived from Carsel & Parrish (1988) when assuming loamy sand, which is used for our hydraulic conductivity measurements (K_s). However, we assigned a $\theta_s = 0.30$ to represent an extreme lower-bound case for this study. Similarly, we set a constant Manning's roughness to better understand the specific changes from the parameters described in the main text; however, we propose that our assumption here is the lower bound and that Manning's roughness could increase in subsequent years.

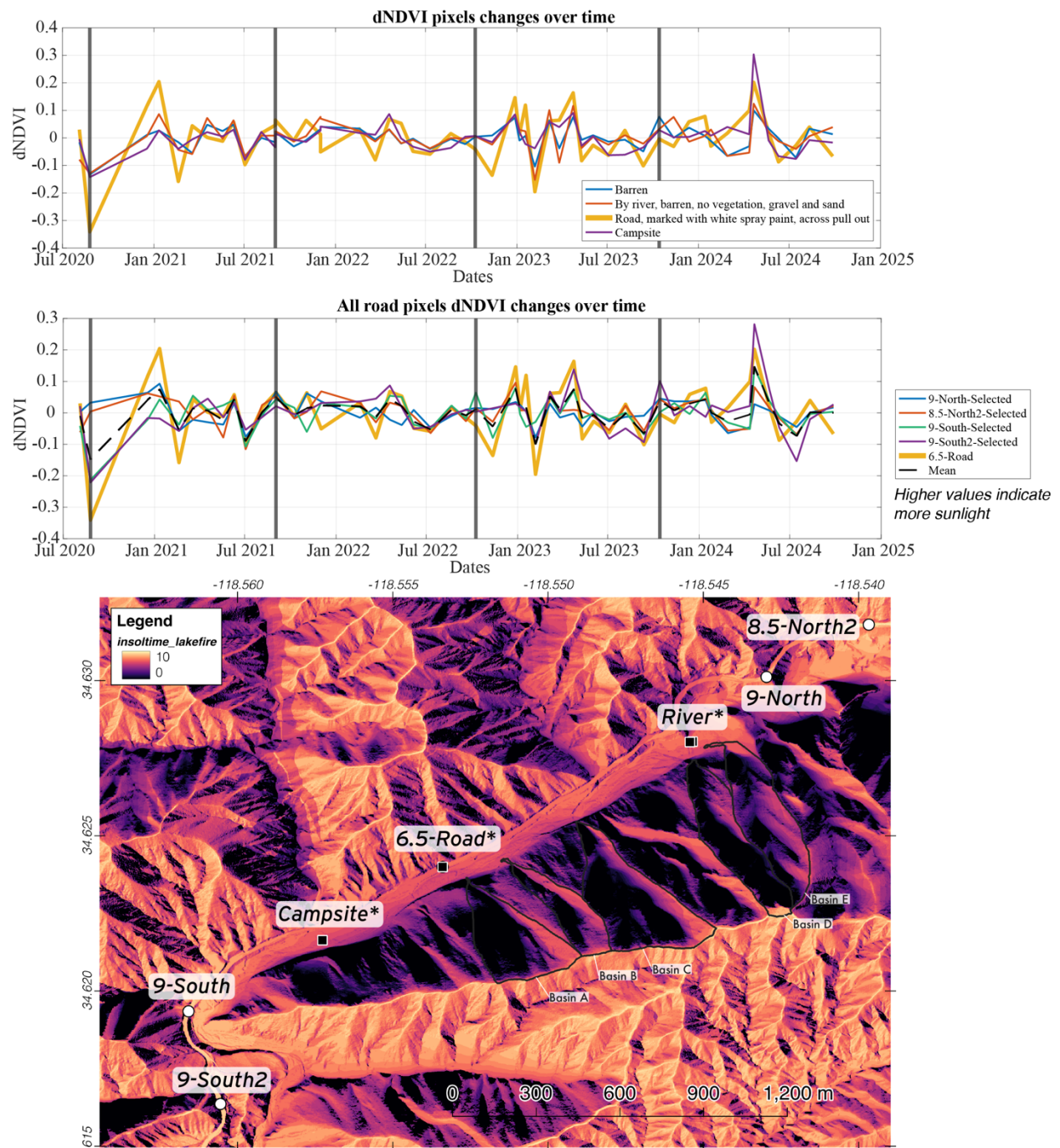


Figure S1: Top panels show the dNDVI pixel changes across four points with field validation. The middle panel shows the dNDVI pixel changes across pixels on the road; the value before the name is the insolation time (hours). The bottom map panel shows the location of the road pixels from field-validated and unvalidated road pixels in a solar insolation map (hours). Values before the name (e.g., 9-North) are the insolation time for each pixel on the road. * indicate field-validated points to check the pixel coverage.

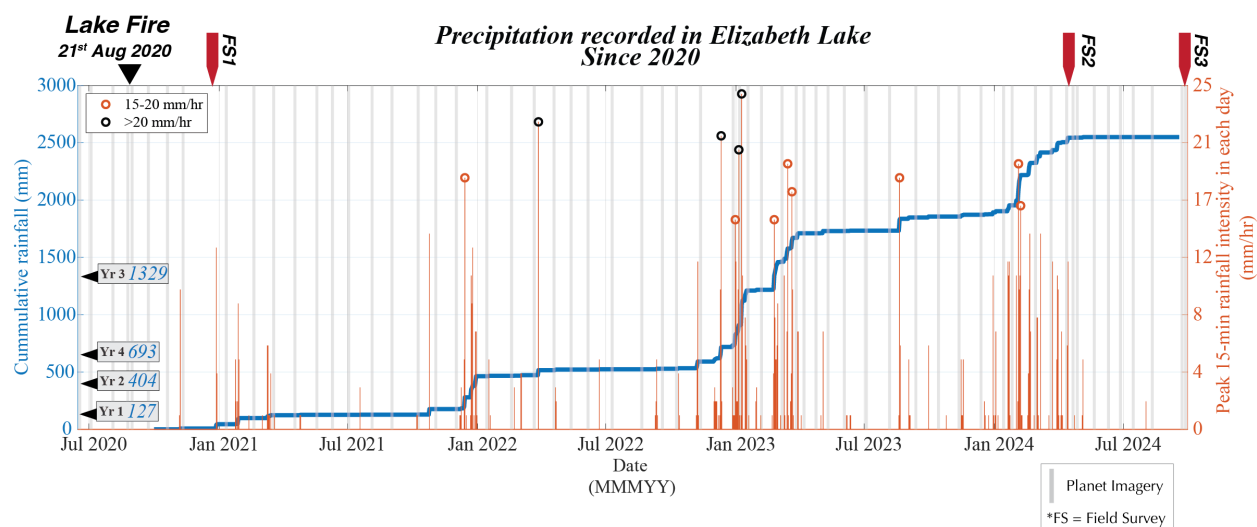
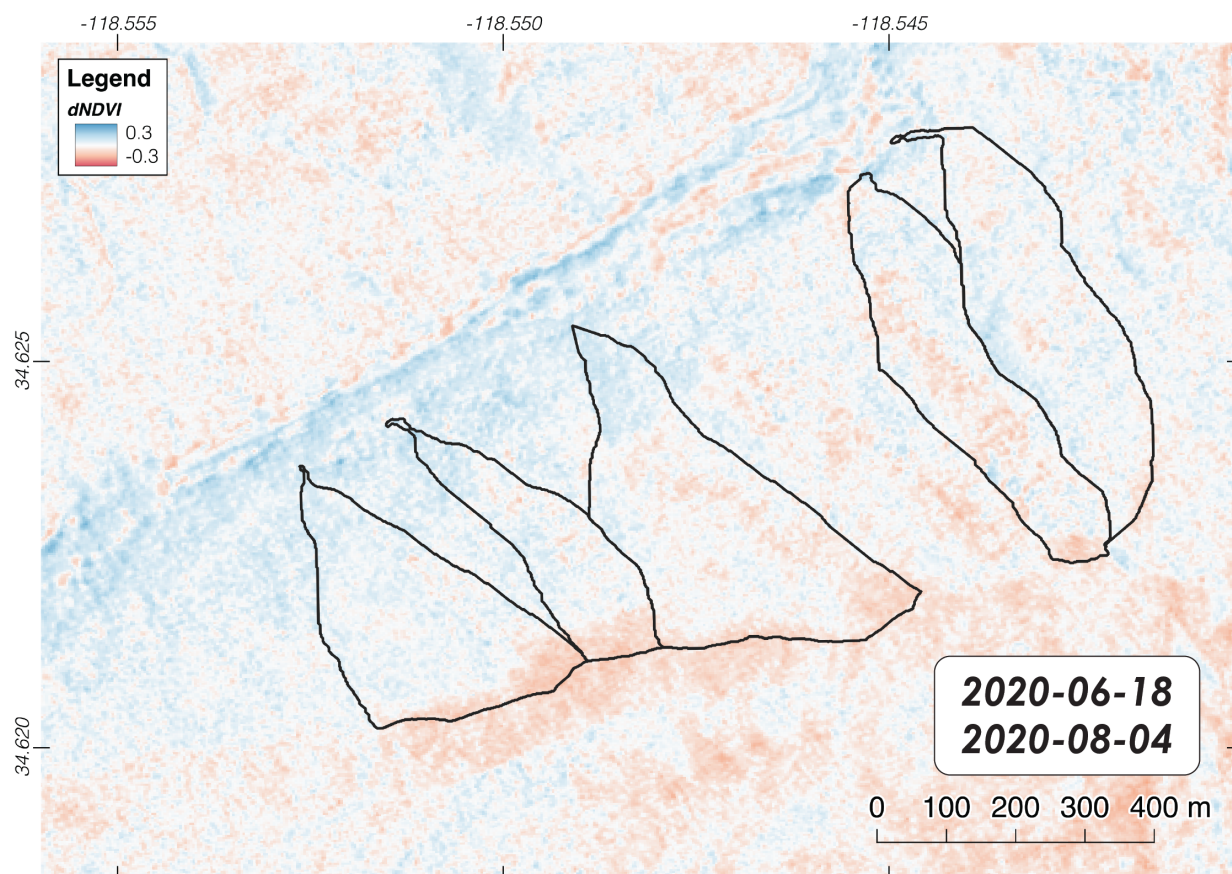
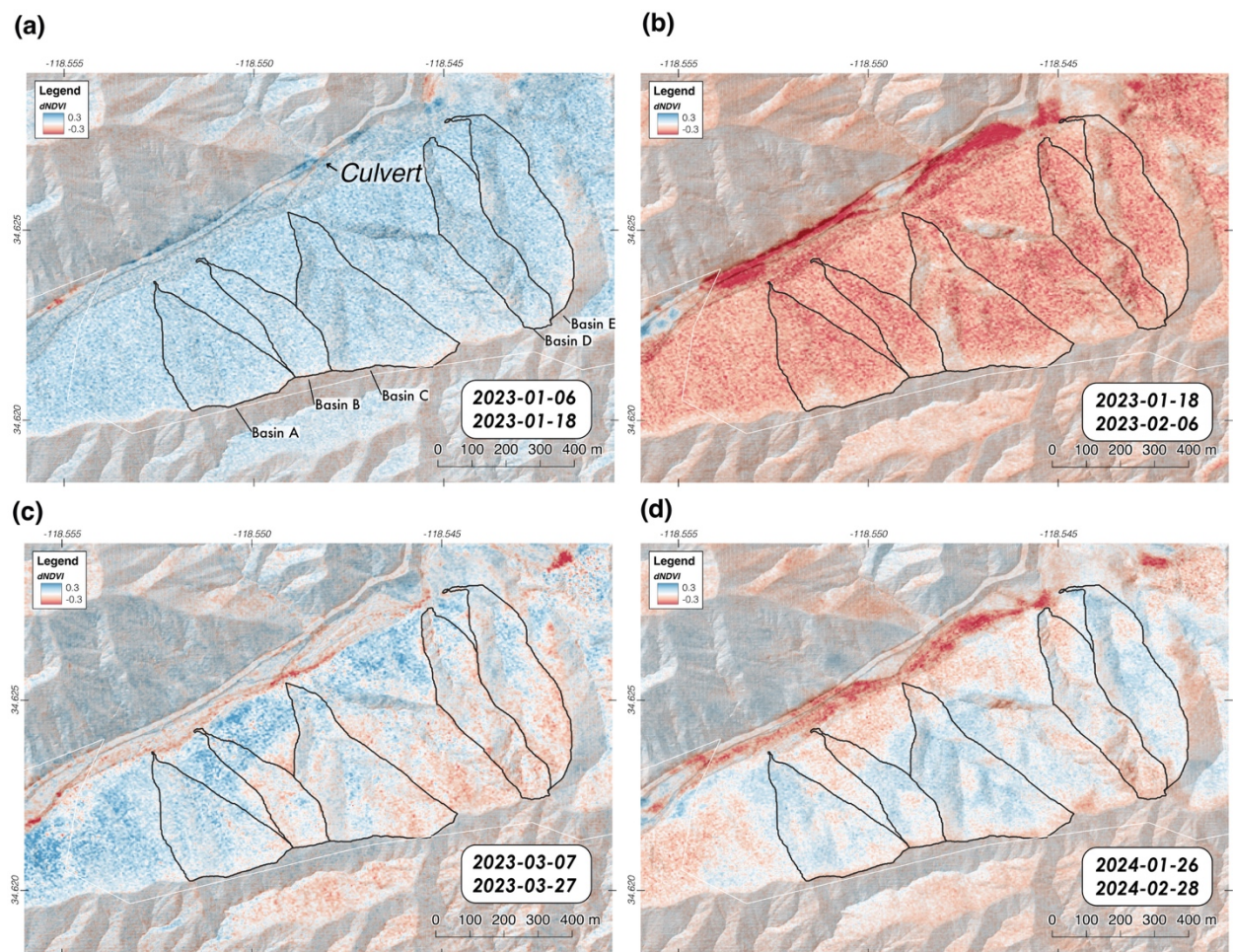


Figure S2: Record of cumulative precipitation in the blue graph (blue axis) and the daily peak rain intensity (orange axis). Orange circles represent rain intensity between I_{15} of 15-20 mm/hr, and dark circles are I_{15} greater than 20 mm/hr. FS represents field survey. Grey lines represent the dates with PlanetScope images. See **Table S6** for the dates exceeding the $I_{15} = 15$ mm/hr. The overall rainfall recorded for the first, second, third, and fourth years was 127.5 mm, 404.1 mm, 1329 mm, and 693.7 mm, respectively

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90 **Figure S3:** Pre-fire dNDVI from June 2020 to August 2020 (Lake Fire started on August 12, 2020). Basins are extracted from QGIS’s Channel Network and Drainage toolbox.



95 **Figure S4:** Additional date pairs showing dNDVI in 2023 and 2024 that overlapped with rain events (**Table S6**). Warmer colors are negative dNDVI (loss of green band) and cooler colors are positive dNDVI (gain of green band, vegetation growth)

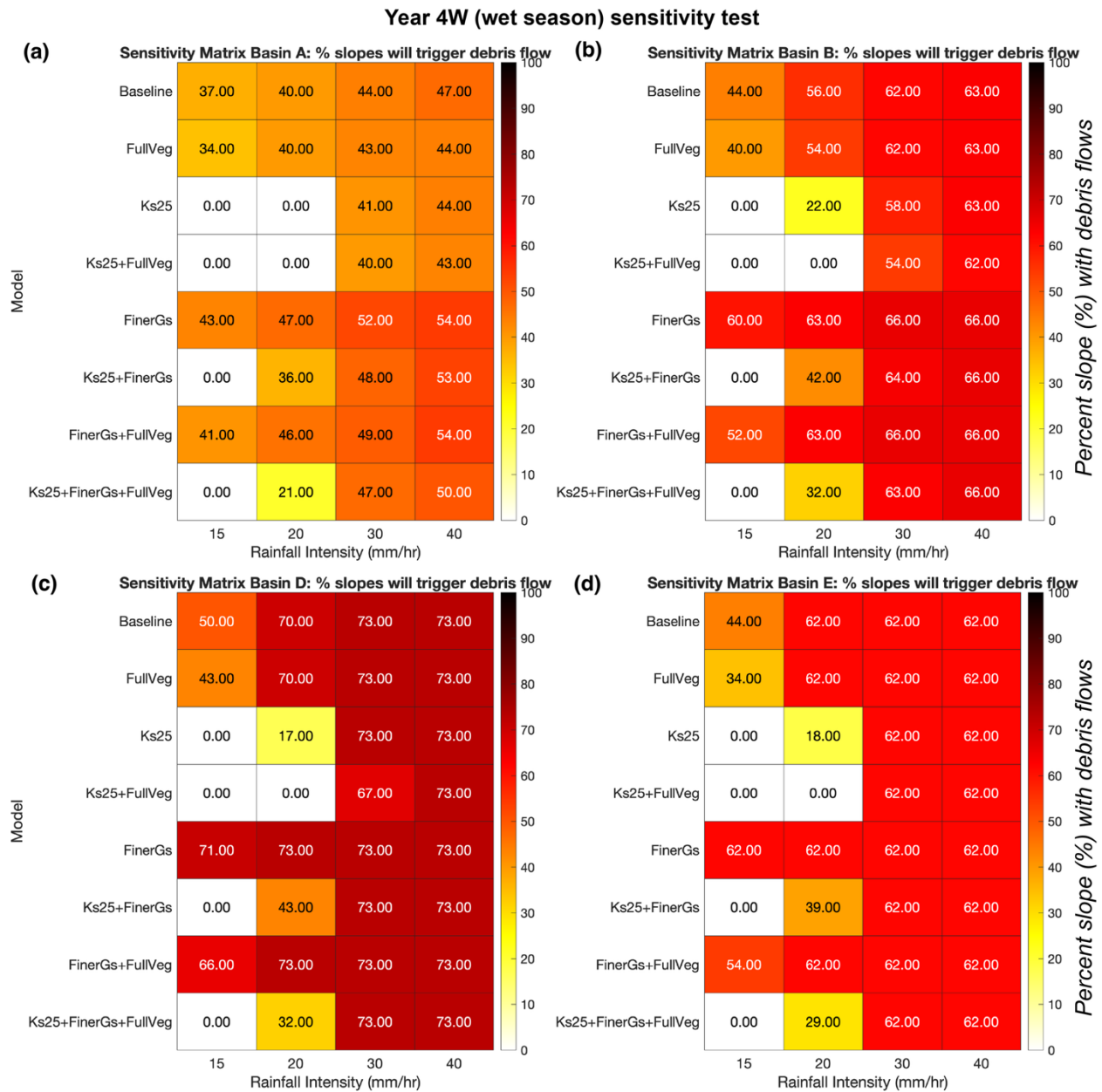


Figure S5: Sensitivity test using grain size from the 2nd field sampling (April 2024). Plotted from **Table S4**. Greater percentage values indicate a higher number of slope angles (0–90°) exceeding the threshold. Percentages do not reach 100% because the maximum slope in each basin is less than 90°.

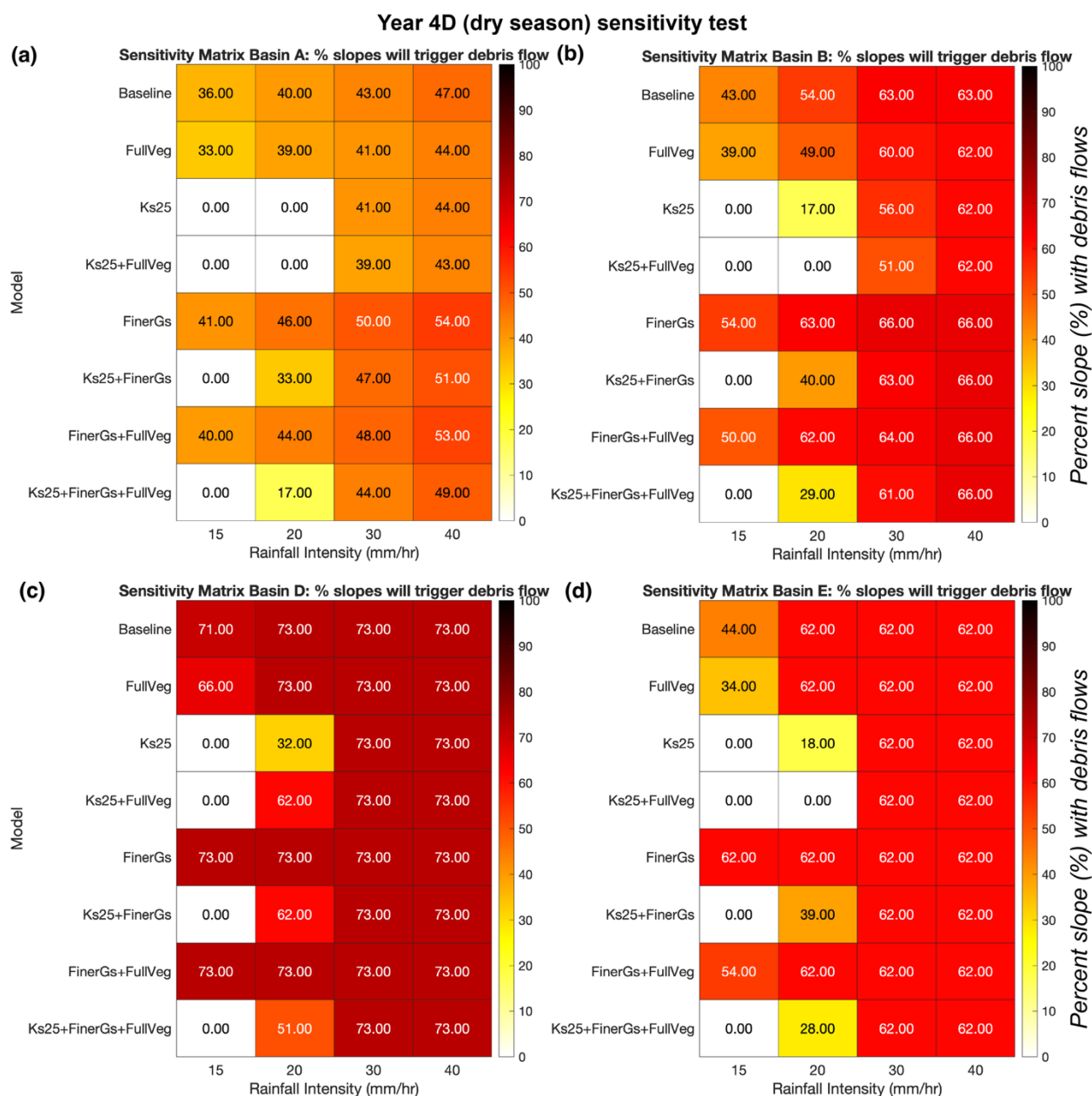


Figure S6: Sensitivity test using grain size from the 3rd field sampling (September 2024). Plotted from **Table S5**. Greater percentage values indicate a higher number of slope angles (0–90°) exceeding the threshold. Percentages do not reach 100% because the maximum slope in each basin is less than 90°.

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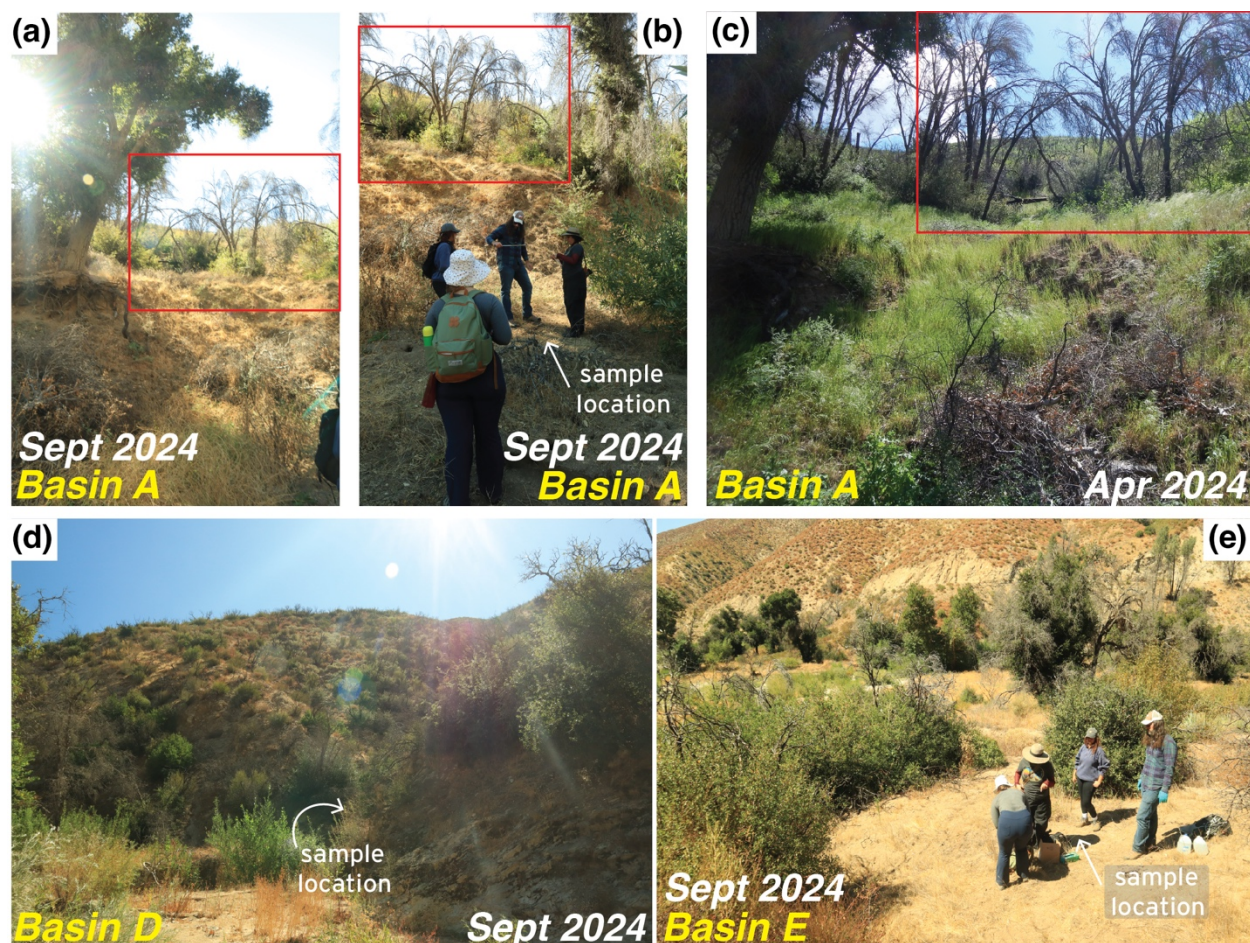


Figure S7: Additional field photos from the 2024 field surveys. At Basin A, the second and third survey sampling locations were approximately 1 meter below the first survey's sampling location, where a flat surface allowed for mini disk infiltrometer measurements. See Figure 2a for the corresponding 2020 (first) survey location, which did not include hydraulic conductivity measurements.

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Date	Time (UTC)	Satellite code 4- digit	ID	Notes
6/18/20	17:52:52	2304	20200618_175152_97_2304	PreFire
7/4/20	17:52:57	2277	20200704_175257_02_2277	PreFire
8/4/20	17:50:10	220b	20200804_175010_87_220b	PreFire
8/25/20	17:53:50	2304	20200825_175350_53_2304	PostFire; dNDVI yearly
8/31/20	17:49:04	2206	20200831_174904_51_2206	PostFire
9/23/20	17:57:35	2259	20200923_175735_97_2259	PostFire
10/20/20	17:54:37	2257	20201020_175437_23_2257	PostFire
11/11/20	17:50:50	220b	20201111_175050_48_220b	PostFire
12/18/20	17:52:20	222b	20201218_175220_11_222b	Post; sample collection on 23rd Dec 2020
1/11/21	17:56:58	225a	20210111_175658_38_225a	PostFire
2/19/21	17:56:17	2233	20210219_175617_31_2233	PostFire
3/19/21	17:51:51	2428	20210319_175151_40_2428	PostFire
4/18/21	17:52:41	222b	20210418_175241_02_222b	PostFire
5/19/21	17:50:42	2445	20210519_175042_85_2445	PostFire
6/10/21	17:48:25	2444	20210610_174825_69_2444	PostFire
7/3/21	17:49:22	222b	20210703_174922_92_222b	PostFire
8/5/21	17:45:50	241b	20210805_174550_13_241b	PostFire
9/2/21	17:58:06	2251	20210902_175806_40_2251	PostFire; dNDVI yearly
10/9/21	17:47:22	2423	20211009_174722_95_2423	PostFire
11/3/21	17:46:34	242b	20211103_174634_39_242b	PostFire
12/2/21	17:44:06	2442	20211202_174406_76_2442	PostFire
1/14/22	17:48:06	2432	20220114_174806_76_2432	PostFire
2/18/22	17:45:41	2431	20220218_174541_32_2431	PostFire
3/22/22	17:43:48	245a	20220322_174348_57_245a	PostFire
4/19/22	17:43:18	2439	20220419_174318_02_2439	PostFire
5/13/22	17:40:35	2449	20220513_174035_23_2449	PostFire
6/6/22	17:42:09	241d	20220606_174209_43_241d	PostFire
7/10/22	17:39:16	2436	20220710_173916_95_2436	PostFire

8/21/22	17:40:53	2455	20220821_174053_41_2455	PostFire
9/19/22	17:41:03	2432	20220919_174103_42_2432	PostFire; dNDVI yearly
10/9/22	17:37:58	2459	20221009_173758_96_2459	PostFire
11/12/22	17:38:42	2429	20221112_173842_34_2429	PostFire
12/28/22	18:14:27	24a5	20221228_181427_50_24a5	No other 17:00UTC scenes
1/6/23	17:58:52	225a	20230106_175852_17_225a	PostFire
1/18/23	17:39	2458	20230118_173959_26_2458	PostFire
2/6/23	17:43	24b3	20230206_174355_36_24b3	PostFire
3/7/23	17:47:15	24be	20230307_174715_25_24be	Cloud present within the image
3/27/23	17:43:56	24a1	20230327_174356_21_24a1	PostFire
4/7/23	17:42:57	24b2	20230407_174257_70_24b2	PostFire
4/24/23	17:42:04	2465	20230424_174204_61_2465	PostFire
5/11/23	17:40:11	241d	20230511_174011_35_241d	PostFire
6/3/23	17:45:38	24c4	20230603_174538_06_24c4	PostFire
7/4/23	17:48:06	24bb	20230704_174806_23_24bb	PostFire
8/6/23	17:45:37	24b4	20230806_174537_35_24b4	PostFire
9/12/23	17:39:57	2451	20230912_173957_55_2451	PostFire; dNDVI yearly
10/14/23	17:50:06	24bb	20231014_175006_68_24bb	PostFire
11/12/23	17:45:49	24bf	20231112_174549_76_24bf	PostFire
12/13/23	17:50:52	24b9	20231213_175052_25_24b9	PostFire
1/14/24	17:51:21	24b0	20240114_175121_05_24b0	PostFire
1/26/24	17:51:41	24c2	20240126_175141_62_24c2	Checking after heavy January rain
2/28/24	17:51:21	2423	20240228_175123_37_2423	Checking before heavy February rain
3/21/24	17:54:15	24ca	20240321_175415_38_24ca	Month-long rain since March
4/12/24	17:55:26	24ba	20240412_175526_58_24ba	Month-long rain since March
4/21/24	17:57:54	2455	20240421_175754_47_2455	(2nd survey) Day of sampling: PostFire
4/27/24	17:55:27	24c9	20240427_175527_48_24c9	PostFire
5/21/24	17:54:01	24b5	20240521_175401_39_24b5	PostFire
6/10/24	17:57:06	24af	20240610_175706_05_24af	PostFire

6/27/24	17:56:59	24a1	20240627_175659_40_24a1	PostFire
7/15/24	17:55:00	24bf	20240715_175500_33_24bf	PostFire
8/11/24	17:59:27	24ce	20240811_175927_64_24ce	PostFire
9/27/24	18:03:16	24ce	20240927_180316_48_24ce	(3rd survey) Day of sampling, PostFire; dNDVI yearly

Table S1: Descriptions of the 61 Planet images downloaded for analysis.

Symbol	Definition	Unit	Value
n0	Hydraulic roughness coefficient	$\text{s m}^{-1/3}$	0.1
h0	Critical depth in roughness model	m	0.003
ε	Exponent in roughness model	—	−0.33
hf	Wetting front suction head	m	0.01
θ_i	Initial soil moisture	—	0.1
θ_s	Soil moisture at saturation	—	0.30
gi	Decay parameter	m^{-1}	525
Si	Canopy storage capacity	mm	0.44
Ki	Drainage rate coefficient	m s^{-1}	1.2×10^{-5}

Table S2: Summary table of the parameters that are fixed across all the basins and years. See Section 4 text for detailed descriptions.

Bas ins	Intensity	Base line	Model 1Veg	Model 2Ks25	Model3K s25Veg	Model 4Gs	Model5 KsGs	Model6 GsVeg	Model7K sGsVeg
A	15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A	20	0.00	0.00	0.00	0.00	0.19	0.00	0.17	0.00
A	30	0.17	0.14	0.01	0.00	0.71	0.68	0.70	0.16
A	40	0.71	0.69	0.68	0.14	0.72	0.70	0.71	0.71
B	15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B	20	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00
B	30	0.01	0.01	0.00	0.00	0.63	0.01	0.63	0.00
B	40	0.01	0.01	0.01	0.01	0.68	0.26	0.67	0.23
D	15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D	20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D	30	0.00	0.00	0.00	0.00	0.63	0.00	0.19	0.00
D	40	0.00	0.00	0.00	0.00	0.63	0.61	0.63	0.21
E	15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E	20	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00
E	30	0.01	0.00	0.00	0.00	0.24	0.13	0.21	0.01
E	40	0.19	0.17	0.01	0.00	0.69	0.26	0.68	0.22

Table S3: Sensitivity test using grain sizes from first field sampling. Values in tables show the percentage change with slopes exceeding the threshold to cause runoff-generated debris flows. The matrix plot is shown in **Figure 6**.

Bas ins	Intensity	Base line	Model 1Veg	Model 2Ks25	Model3K s25Veg	Model 4Gs	Model5 KsGs	Model6 GsVeg	Model7K sGsVeg
A	15	0.37	0.34	0.00	0.00	0.43	0.00	0.41	0.00
A	20	0.40	0.40	0.00	0.00	0.47	0.36	0.46	0.21
A	30	0.44	0.43	0.41	0.40	0.52	0.48	0.49	0.47
A	40	0.47	0.44	0.44	0.43	0.54	0.53	0.54	0.50
B	15	0.44	0.40	0.00	0.00	0.60	0.00	0.52	0.00
B	20	0.56	0.54	0.22	0.00	0.63	0.42	0.63	0.32
B	30	0.62	0.62	0.58	0.54	0.66	0.64	0.66	0.63
B	40	0.63	0.63	0.63	0.62	0.66	0.66	0.66	0.66
D	15	0.50	0.43	0.00	0.00	0.71	0.00	0.66	0.00
D	20	0.70	0.70	0.17	0.00	0.73	0.43	0.73	0.32
D	30	0.73	0.73	0.71	0.67	0.73	0.73	0.73	0.73
D	40	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73
E	15	0.44	0.34	0.00	0.00	0.62	0.00	0.54	0.00
E	20	0.62	0.62	0.18	0.00	0.62	0.39	0.62	0.29
E	30	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62
E	40	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62

Table S4: Sensitivity test using grain sizes from the 2nd field sampling (45 months post fire, April 2024). Values in the table show the percentage change with slopes exceeding the threshold to cause runoff-generated debris flows. The matrix plot is shown in **Figure S5**.

Bas ins	Intensity	Base line	Model 1Veg	Model 2Ks25	Model3K s25Veg	Model 4Gs	Model5 KsGs	Model6 GsVeg	Model7K sGsVeg
A	15	0.36	0.33	0.00	0.00	0.41	0.00	0.40	0.00
A	20	0.40	0.39	0.00	0.00	0.46	0.33	0.44	0.17
A	30	0.43	0.41	0.40	0.39	0.50	0.47	0.48	0.44
A	40	0.47	0.44	0.44	0.43	0.54	0.51	0.53	0.49
B	15	0.43	0.39	0.00	0.00	0.54	0.00	0.50	0.00
B	20	0.54	0.49	0.17	0.00	0.63	0.40	0.62	0.29
B	30	0.63	0.60	0.56	0.51	0.66	0.63	0.64	0.61
B	40	0.63	0.62	0.62	0.62	0.66	0.66	0.66	0.66
D	15	0.71	0.66	0.00	0.00	0.73	0.00	0.73	0.00
D	20	0.73	0.73	0.43	0.32	0.73	0.62	0.73	0.51
D	30	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73
D	40	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73
E	15	0.44	0.34	0.00	0.00	0.62	0.00	0.54	0.00
E	20	0.62	0.62	0.18	0.00	0.62	0.39	0.62	0.28
E	30	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62
E	40	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62

Table S5: Sensitivity test using grain sizes from the 3rd field sampling (50 months post fire, September 2024). Values in the table show the percentage change with slope exceeding the threshold to cause runoff-generated debris flows. The matrix plot is shown in **Figure S6**.

Dates	Peak 15-min duration rain intensity (I_{15}) (mm/hr)
14 th December 2021	18.28
28 th March 2022	22.35
11 th December 2022	21.36
31 st December 2022	15.24
5 th January 2023	20.32
9 th January 2023	24.38
24 th February 2023	15.24
15 th March 2023	19.30
21 st March 2023	17.27
20 th August 2023	18.28
4 th February 2024	19.03
7 th February 2024	16.26

Table S6: Days with rainfall intensity exceeding $I_{15} = 15$ mm/hr. The table also shows the dates of the respective peak I_{15} .

Basins	Mean basin slope [degrees]	Mean basin aspect [degrees]	Mean channel slope [degrees]	Mean channel aspect [degrees]
A	34.5	276	32.8	306
B	34.7	306	33.76	315
C	34.5	227	28.18	264
D	37.2	196	32.0	214
E	33.1	220	30.78	237

Table S7: Summary of the basin properties, including the channel and basin slope and aspect.

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