Supplementary Material to *Brief Communication: The Khurdopin surge revisited – extreme surge velocities and formation of a dammed lake in 2017*

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# 1 Data

Table S1: LANDSAT/Planet Data for Velocity Datasets and Animation. All scenes were acquired and visually pre-selected for cloud cover, snow cover and image quality over the glacier outline. The numbers in the first column refer to the actual pairing to derive velocities in Table S3.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **COSI-Corr pair (Table S3)** | **Satellite / Scene** | **Band** | **Resolution** | **Acquisition Date** |
| 1 | L7 LE07\_L1TP\_149035\_20000911\_20170210\_01\_T1 | 8 (Panchr.) | 15 m | 11/09/2000 |
| 1 / 2 / 3 / 4 | L7 LE07\_L1TP\_149035\_20030531\_20170125\_01\_T2 | 8 (Panchr.) | 15 m | 31/05/2003 |
| 2 / 6 | 2008\_0925\_20161029\_01\_T1LT05\_L1TP\_149035\_ | 7 (SWIR) | 30 m | 25/09/2008 |
| 3 / 5 | 2010\_1017\_20161012\_01\_T1LT05\_L1TP\_149035\_ | 7 (SWIR) | 30 m | 12/10/2010 |
| 4 | 2011\_0918\_20161006\_01\_T1LT05\_L1TP\_149035\_ | 7 (SWIR) | 30 m | 18/09/2011 |
| 5 | 2009\_0928\_20161025\_01\_T1LT05\_L1TP\_149035\_ | 7 (SWIR) | 30 m | 28/09/2009 |
| 6 / 7 | 2010\_1017\_20161012\_01\_T1LT05\_L1TP\_149035\_ | 7 (SWIR) | 30 m | 17/10/2010 |
| 7 | 2011\_0918\_20161006\_01\_T1LT05\_L1TP\_149035\_ | 7 (SWIR) | 30 m | 18/09/2011 |
| 8 | LC08\_L1TP\_149035\_20130518\_20170504\_01\_T1 | 8 (Panchr.) | 15 m | 18/05/2013 |
| 8 / 9 | LC08\_L1TP\_149035\_20140910\_20170419\_01\_T1 | 8 (Panchr.) | 15 m | 10/09/2014 |
| 9 / 10 | LC08\_L1TP\_149035\_20150828\_20170405\_01\_T1 | 8 (Panchr.) | 15 m | 28/08/2015 |
| 10 / 11 | LC08\_L1TP\_149035\_20160510\_20170325\_01\_T1 | 8 (Panchr.) | 15 m | 10/05/2016 |
| 11 / 12 | LC08\_L1TP\_149035\_20161001\_20170320\_01\_T1 | 8 (Panchr.) | 15 m | 01/10/2016 |
| 12 / 13 | LC08\_L1TP\_149035\_20161220\_20170315\_01\_T1 | 8 (Panchr.) | 15 m | 20/12/2016 |
| 13 / 16 | LC08\_L1TP\_149035\_20170427\_20170515\_01\_T1 | 8 (Panchr.) | 15 m | 27/04/2017 |
| 14 | Planet Mosaic | Optical | 3 m | 30/12/2016 |
| 14 / 15 | Planet Mosaic | Optical | 3 m | 16/04/2017 |
| 15 | Planet Mosaic | Optical | 3 m | 27/04/2017 |
| 16 / 18 | LC08\_L1TP\_149035\_20170513\_20170525\_01\_T1 | 8 (Panchr.) | 15 m | 13/05/2017 |
| 17 | Planet Mosaic | Optical | 3 m | 10/05/2017 |
| 17 / 19 | Planet Mosaic | Optical | 3 m | 25/05/2017 |
| 18 / 21 | LC08\_L1TP\_149035\_20170529\_20170615\_01\_T1 | 8 (Panchr.) | 15 m | 29/05/2017 |
| 19 / 20 | Planet Mosaic | Optical | 3 m | 29/05/2017 |
| 20 / 22 | Planet Mosaic | Optical | 3 m | 03/06/2017 |
| 21 / 30 | LC08\_L1TP\_149035\_20170801\_20170811\_01\_T1 | 8 (Panchr.) | 15 m | 01/08/2017 |
| 22 / 23 | Planet Mosaic | Optical | 3 m | 12/06/2017 |
| 23 / 24 | Planet Mosaic | Optical | 3 m | 19/06/2017 |
| 24 / 25 | Planet Mosaic | Optical | 3 m | 24/06/2017 |
| 25 / 26 | Planet Mosaic | Optical | 3 m | 27/06/2017 |
| 26 / 27 | Planet Mosaic | Optical | 3 m | 08/07/2017 |
| 27 / 28 | Planet Mosaic | Optical | 3 m | 21/07/2017 |
| 28 / 29 | Planet Mosaic | Optical | 3 m | 26/07/2017 |
| 29 / 31 | Planet Mosaic | Optical | 3 m | 01/08/2017 |
| 30 / 32 | LC08\_L1TP\_149035\_20170817\_20170825\_01\_T1 | 8 (Panchr.) | 15 m | 17/08/2017 |
| 31 / 33 | Planet Mosaic | Optical | 3 m | 19/08/2017 |
| 32 | LC08\_L1TP\_149035\_20170918\_20170929\_01\_T1 | 8 (Panchr.) | 15 m | 18/09/2017 |
| 33 | Planet Mosaic | Optical | 3 m | 12/09/2017 |

Table S2: DEM Data

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Satellite / Product ID | Resolution | Acquisition Date | Reference |
| 1 | ASTER / AST\_L1A.003:2253120815 | 30 m | 21/05/2017 | (NASA LP DAAC, 2017) |
| 2 | TanDEM-X / TDM1\_DEM\_\_04\_N36E075\_DEM | 12 m | Multiple during 2011 | DLR |
| 3 | SRTM | 1 arc second (~30 m) | 02/2000 |  |

Table S3: Velocity values [m a-1] from all data products for the period between 2000 and 2017. Rows are km along the glacier tongue starting at the terminus. Columns are time steps and associated satellite products as described in Table S1. Color code corresponds to quiescence (green), build up (yellow) and surge (red).

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **1 L7** | **2 L7/L5** | **3 L7/L5** | **4 L7/L5** | **5 L5** | **6 L5** | **7 L5** | **8 L8** | **9 L8** | **10 L8** | **11 L8** | **12 L8** |
| **1** | 4 | 2 | 2 | 2 | 3 | 3 | 3 | 2 | 1 | 3 | 2 | 19 |
| **2** | 5 | 2 | 3 | 2 | 2 | 2 | 3 | 2 | 1 | 3 | 3 | 17 |
| **3** | 8 | 2 | 2 | 2 | 2 | 4 | 6 | 2 | 2 | 5 | 4 | 19 |
| **4** | 12 | 2 | 2 | 2 | 3 | 6 | 9 | 9 | 6 | 7 | 6 | 16 |
| **5** | 6 | 2 | 2 | 1 | 1 | 4 | 7 | 6 | 4 | 7 | 9 | 10 |
| **6** | 5 | 2 | 3 | 2 | 1 | 3 | 6 | 5 | 10 | 16 | 35 | 82 |
| **7** | 9 | 2 | 2 | 1 | 2 | 5 | 9 | 19 | 28 | 41 | 129 | 286 |
| **8** | 7 | 3 | 3 | 2 | 3 | 9 | 12 | 42 | 53 | 68 | 216 | 401 |
| **9** | 6 | 3 | 4 | 4 | 5 | 12 | 15 | 54 | 62 | 77 | 250 | 430 |
| **10** | 11 | 2 | 27 | 11 | 14 | 16 | 18 | 83 | 89 | 92 | 297 | 435 |
| **11** | 13 | 2 | 11 | 21 | 14 | 11 | 29 | 96 | 96 | 102 | 296 | 417 |
| **12** | 13 | 1 | 3 | 18 | 17 | 6 | 25 | 96 | 105 | 107 | 298 | 384 |
| **13** | 28 | 1 | 2 | 12 | 6 | 6 | 15 | 120 | 125 | 121 | 314 | 359 |
| **14** | 41 | 1 | 4 | 11 | 6 | 8 | 9 | 140 | 139 | 133 | 305 | 330 |
| **15** | 52 | 1 | 13 | 12 | 5 | 5 | 6 | 147 | 152 | 148 | 306 | 297 |
| **16** | 61 | 2 | 60 | 38 | 5 | 2 | 4 | 162 | 167 | 162 | 308 | 272 |
| **17** | 70 | 2 | 29 | 51 | 4 | 5 | 9 | 164 | 185 | 166 | 332 | 254 |
| **18** | 79 | 2 | 73 | 43 | 2 | 5 | 6 | 76 | 197 | 206 | 331 | 232 |
| **19** | 111 | 2 | 65 | 75 | 21 | 7 | 6 | 198 | 204 | 199 | 296 | 240 |
| **20** | 111 | 1 | 26 | 33 | NA | 7 | 5 | 201 | 210 | 202 | 273 | 239 |
| **21** | 53 | 1 | 19 | 25 | NA | 12 | 5 | 144 | 224 | 213 | 275 | 240 |
| **22** | 57 | 1 | 2 | 10 | NA | 13 | 5 | 146 | 254 | 239 | 292 | 254 |
| **23** | 47 | 1 | 3 | 2 | NA | 6 | 4 | 193 | 246 | 232 | 279 | 255 |
| **24** | 22 | 1 | 3 | 2 | NA | 7 | 4 | 126 | 211 | 173 | 217 | 258 |
| **25** | 38 | 1 | 3 | 2 | NA | 9 | 3 | 41 | 193 | 197 | 274 | 292 |
| **26** | 51 | 1 | 3 | 2 | NA | 7 | 4 | 81 | 287 | 461 | 400 | 320 |

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **13 L8** | **14 P** | **15 P** | **16 L8** | **17 P** | **18 L8** | **19 P** | **20 P** | **21 L8** | **22 P** | **23 P** | **24 P** |
| **1** | 15 | 12 | NA | 12 | 39 | 45 | 166 | 55 | NA | NA | NA | NA |
| **2** | 13 | 16 | NA | 10 | 54 | 28 | 185 | 80 | 5 | 880 | 495 | 1510 |
| **3** | 17 | 27 | 85 | 38 | 729 | 273 | 1523 | 1487 | 125 | 2452 | 1788 | 1768 |
| **4** | 151 | 86 | 805 | 890 | 2892 | 1649 | 3192 | 2765 | 406 | 2502 | 2013 | 1879 |
| **5** | 538 | 308 | 2486 | 2681 | 3701 | 2856 | 4000 | 3432 | 1188 | 2936 | 2454 | 2211 |
| **6** | 527 | 304 | 2943 | 2719 | 3643 | 3145 | 4161 | 3591 | 1269 | 3124 | 2549 | 2392 |
| **7** | 1319 | 331 | 3732 | 4466 | 5034 | 4732 | 5242 | 4469 | 2145 | 3825 | 3138 | 3000 |
| **8** | 1002 | 275 | 3715 | 4642 | 4836 | 4756 | 5167 | 4417 | 2392 | 4056 | 3284 | 2979 |
| **9** | 1543 | 282 | 3581 | 4607 | 4837 | 5105 | 4930 | 4280 | 2149 | 3721 | 3138 | 2832 |
| **10** | 1842 | 300 | 3390 | 4375 | 4435 | 4665 | 4883 | 4159 | 1766 | 3595 | 3095 | 2805 |
| **11** | 684 | 273 | 3317 | 3980 | 4633 | 4809 | 5011 | 4288 | 2193 | 3759 | 3162 | 2887 |
| **12** | 991 | 333 | 2860 | 3747 | 4366 | 4611 | 4526 | 3948 | 2317 | 3521 | 2937 | 2665 |
| **13** | 1395 | 314 | 2924 | 2663 | 4018 | 3814 | 4247 | 3682 | 1774 | 3361 | 2792 | 2540 |
| **14** | 947 | 318 | 2664 | 2696 | 3508 | 3350 | 3954 | 3506 | 1830 | 3157 | 2643 | 2604 |
| **15** | 1067 | 310 | 2487 | 2426 | 3065 | 3400 | 3321 | 3147 | 1917 | 2819 | 2309 | 2220 |
| **16** | 1083 | 336 | 2860 | 2193 | NA | 3199 | 3257 | 3107 | 1772 | 2865 | 2370 | 2244 |
| **17** | 1029 | 386 | 2389 | 1816 | NA | 2684 | 2983 | 2844 | 1628 | 2659 | 2258 | 2092 |
| **18** | 611 | 346 | NA | 1320 | NA | 1998 | 2368 | 2281 | 1209 | 2142 | 1851 | 1817 |
| **19** | 929 | 379 | NA | 1403 | NA | 1938 | 2059 | 2072 | 1447 | 1982 | 1738 | 1778 |
| **20** | 875 | 422 | NA | 1083 | NA | 1729 | NA | 1807 | 1523 | 1920 | 1852 | 1856 |
| **21** | 571 | 374 | NA | 891 | 2227 | 1334 | NA | NA | 1324 | 1633 | 1753 | 1340 |
| **22** | 565 | 328 | 871 | 784 | 1881 | 1076 | NA | NA | 1424 | 1453 | 1509 | 1247 |
| **23** | 413 | 305 | 657 | 626 | 1674 | 1029 | NA | NA | 1457 | 1173 | 1190 | 987 |
| **24** | 279 | 321 | 654 | 532 | 1388 | 603 | NA | NA | 740 | 962 | 1019 | 813 |
| **25** | 336 | 327 | 1004 | 378 | 947 | 315 | NA | NA | NA | 823 | 905 | 756 |
| **26** | 296 | 350 | 1155 | 296 | NA | 318 | NA | NA | NA | NA | NA | NA |

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **25 P** | **26 P** | **27 P** | **28 P** | **29 P** | **30 L8** | **31 P** | **32 L8** | **33 P** |
| **1** | NA | 31 | 19 | 61 | 61 | NA | 40 | NA | 5 |
| **2** | 968 | 196 | 320 | 380 | 229 | 89 | 190 | 46 | 115 |
| **3** | 2391 | 1036 | 1047 | 874 | 643 | 172 | 373 | 96 | 215 |
| **4** | 2727 | 1510 | 1358 | 901 | 773 | 333 | 392 | 154 | 206 |
| **5** | 3089 | 1616 | 1451 | 992 | 936 | 381 | 405 | 147 | 189 |
| **6** | 3236 | 1723 | 1509 | 1003 | 943 | 357 | 355 | 111 | 140 |
| **7** | 4018 | 2132 | 1902 | 1276 | 1200 | 409 | 421 | 120 | 153 |
| **8** | 3972 | 2200 | 1943 | 1230 | 1203 | 351 | 361 | 84 | 120 |
| **9** | 3903 | 2096 | 1864 | 1174 | 1113 | 286 | 304 | 54 | 81 |
| **10** | 3943 | 2125 | 1811 | 1200 | 1139 | 281 | 285 | 51 | 68 |
| **11** | 4073 | 2172 | 1845 | 1235 | 1159 | 302 | 306 | 51 | 80 |
| **12** | 3830 | 2049 | 1703 | 1094 | 1135 | 285 | 274 | 44 | 80 |
| **13** | 3604 | 1998 | 1628 | 1039 | 1105 | 281 | 281 | 48 | 77 |
| **14** | 3472 | 1952 | 1556 | 1001 | 1058 | 284 | 284 | 68 | 110 |
| **15** | 3193 | 1753 | 1403 | 924 | 1006 | 288 | 299 | 76 | 129 |
| **16** | 3160 | 1774 | 1473 | 948 | 1024 | 331 | 333 | 115 | 168 |
| **17** | 2971 | 1682 | 1403 | 944 | 1012 | 378 | 403 | 194 | 247 |
| **18** | 2553 | 1419 | 1202 | 886 | 873 | 493 | 404 | NA | NA |
| **19** | 2452 | 1393 | 1196 | 923 | 891 | NA | 453 | NA | NA |
| **20** | 2459 | 1383 | 1171 | 887 | 933 | 492 | 480 | NA | NA |
| **21** | 2085 | 1194 | 1001 | 751 | 852 | 363 | 431 | NA | NA |
| **22** | 1935 | 1101 | 940 | 718 | 817 | 348 | 462 | NA | NA |
| **23** | 1487 | 928 | 781 | 616 | 715 | 330 | 411 | NA | NA |
| **24** | 1219 | 793 | 671 | 570 | 651 | 332 | 364 | NA | NA |
| **25** | 1058 | 722 | 638 | 537 | 642 | NA | 355 | NA | NA |
| **26** | NA | NA | NA | NA | NA | NA | NA | NA | NA |

# 2 Model Settings and Uncertainties

**2.1 Velocities**

COSI-Corr is sensitive to chosen initial window sizes as well as window steps (Leprince et al., 2007). In this study we work with different satellite products in respect to resolution and band quality – from the 30 m bands of the initial LANDSAT MSS Satellite to the 3 m optical product of Planet – which made different setups necessary. For the 30 m bands of Landsat MSS and Landsat-5 we used an initial window (W) of 128 pixels, a final window (F) of 16 pixels and a step size of 2 pixels (d) (W128-F16-d2). For Landsat 7 and Landsat 8 as well as Planet imagery we used a W128-F16-d4 setting while for surge events, when displacement is substantial or imagery is far apart in time, W256-F16-d8 is used. We used the Non-Local Means Filter of COSI-Corr (Ayoub et al., 2009) to smooth the gridded data. Velocities measured on stable off-glacier terrain were used to assess the validity of the on-glacier data. The Landsat-MSS off-glacier velocities are in the same range as on-glacier velocities, which makes the COSI-Corr approach not suitable for this data. Off-glacier displacement based on Landsat 5 data was between 2 – 5 m a-1, and this is sufficiently accurate to investigate the build-up and surge phase where velocities are generally one order of magnitude higher. Landsat 7 and 8 as well as Planet data used in the analysis from 2013 onwards generally show off-glacier displacements of 2 - 3 m a-1 for imagery multiple days to weeks apart, which corresponds to the likely error identified by (Luckman et al., 2007). To make sure that noise, resulting from errors in the co-registration process, is not included in the data analysis, we discard all pixel values with a signal-to-noise ratio smaller than 0.75, following (Kraaijenbrink et al., 2016). As large displacements during a surge are picked up as noise by the algorithm in many cases, this constraint had to be loosened for surge peaks. In these cases patches on the surface that showed erratic behaviour (no uniform direction, large variability in velocities on a small area) were discarded visually.

**2.2 DEMs**

We compare the offset between the respective DEMs in relatively flat valley areas where all 3 DEM products are available (Figure S1a). Both TanDEM-X and the ASTER DEM are of less quality in steep terrain, however the 90th percentile of slope values on the investigated glacier surface is 10°, below which the quality is generally acceptable. We therefore exclude all values from the test areas with a slope above 10°. This results in a median offset between the TanDEM-X and the SRTM in the test areas of -24.8 m (σ = 8.5 m, Figure S1b), which is caused by the different geoids of the datasets, WGS84 and EGM96 respectively. Between the ASTER and the TanDEM-X an offset of -12.4 m (σ = 2.3 m) is found and used for correction on the ASTER (Figure S1c).

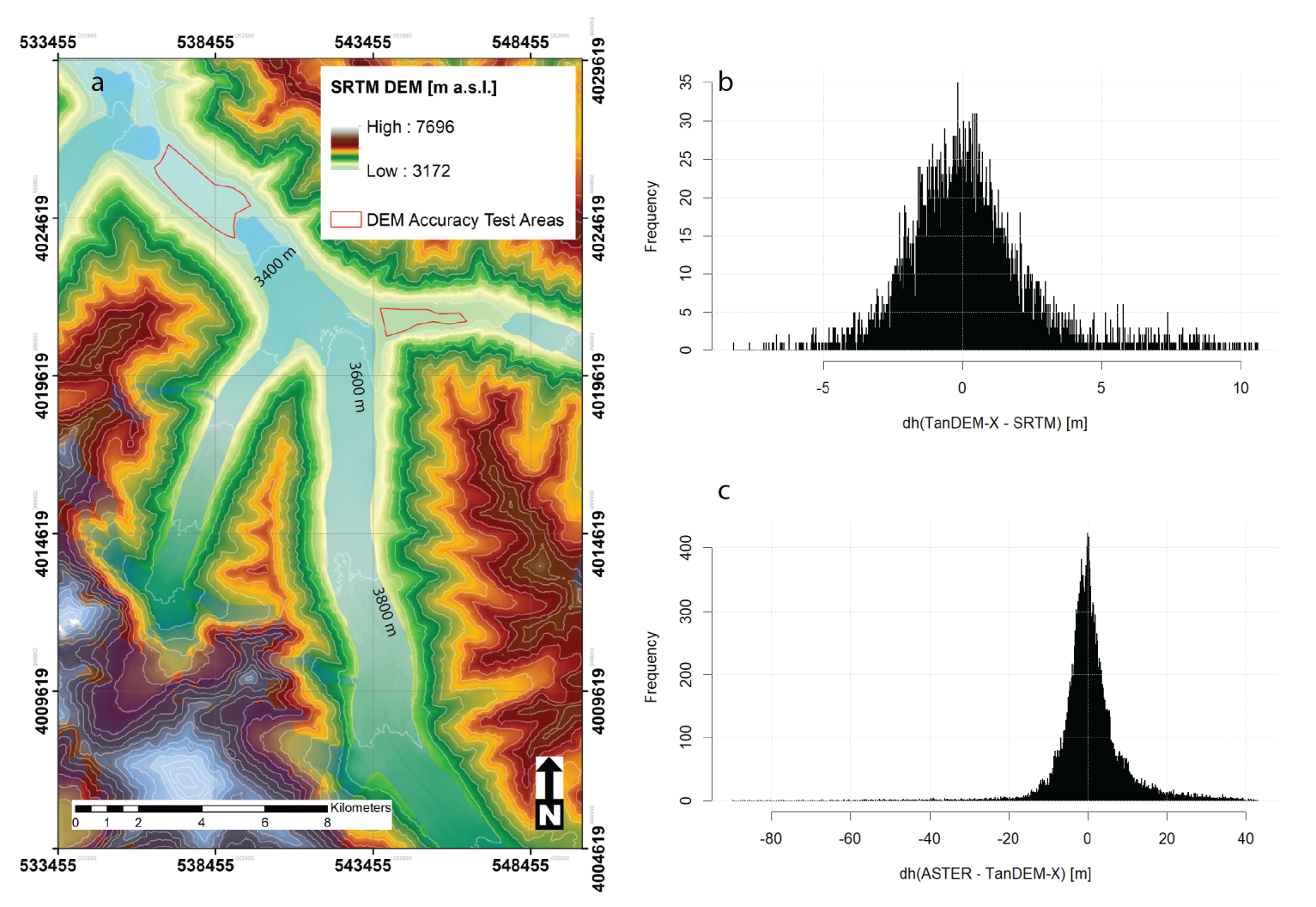
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Figure S1: (a) Flat stable areas chosen in the catchment used for comparison of the DEM. Blue shaded areas are glacier tongues. (b) Difference between TanDEM-X and adjusted SRTM. (c) Difference between corrected ASTER and TanDEM-X. Coordinates are in UTM WGS84 Zone 43.

**3 Lake Volume Calculation**

The volume of the lake was calculated by (1) deriving lake perimeters from the orthophotos, (2) draping them over the TanDEM-X digital elevation model, (3) taking the lake level as the 90th percentile of all elevation values (as the polygon of the perimeter does not have a continuous value due to the inaccuracies of the DEM), and (4) deriving the difference between this plane and the DEM (Figure S2). The lake volumes fit well with the exponential function derived by (Cook and Quincey, 2015) for lower volumes. As (Cook and Quincey, 2015) describe for ice-dammed lakes (Fig.4 therein), the curve steepens, i.e. volume increases faster than area, for larger areas, which is true for this lake as well. However for much greater extents (as observed in 2000) the relation does not hold anymore as areas increase faster due to the lake flooding a very shallow alluvial fan at the confluence of the Vijerab and the Khurdopin valley (see green and red markers in Figure S2b).

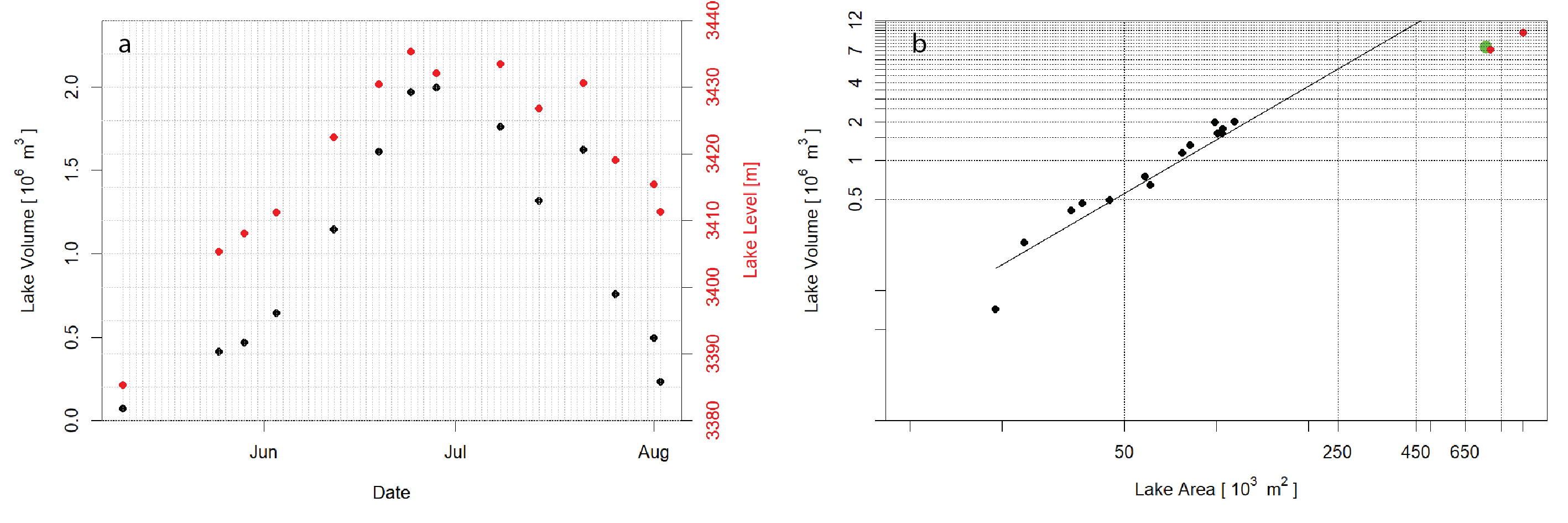


Figure S2: (a) Lake areas derived from orthophotos and associated lake levels (red) as well as volumes (black). (b) Relating lake area to lake volume. The black dots are values from 2017, the green marker is the lake in May 2000 and the red markers are projected areas and volumes with possible increase in lake level height 10 m above the value measured in 2000. The solid line is a relation for Volume-Area scaling found by Cook and Quincey, 2015 which fits well for the observations in 2017, but overestimates for larger lake areas.

**4 Supplementary Animation of all Landsat Scenes**

Using all available Landsat imagery, we compiled an animation over all scenes with suitable image quality. The images were not enhanced but comprise the raw rasters used for the velocity analysis.

# References

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