Supplementary information

Shrinkage of Nepal's Second Largest Lake (Phewa Tal) Due to Watershed Degradation and Increased Sediment Influx

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Table 1. ASTER Thermal Infrared (TIR) and Landsat Thermal Infrared Sensor (TIRS) imagery used to derive lake temperature.

Sensor	Date	Time (NPT)	Mean temperature (ºC)	Standard deviation (ºC)
ASTER TIR	7-May-2018	10:57	26.4	0.3
	6-Oct-2015	10:57	28.1	0.2
	22-May-2012	10:56	26.9	0.3
	9-Apr-2008	10:56	23.6	0.2
	10-Feb-2004	10:57	17.7	0.2
	5-Oct-2003	10:56	27.3	0.2
	2-Oct-2002	10:57	29.0	0.2
	17-Feb-2001	11:08	19.0	0.2
	15-Dec-2000	11:09	19.3	0.2
	29-Nov-2000	11:09	21.8	0.2
Landsat 8 TIRS	17-May-2013	10:41	21.7	0.1
	8-Oct-2013	10:41	21.9	0.2
	24-Oct-2013	10:40	21.6	0.1
	24-Oct-2013	10:41	21.6	0.1
	9-Nov-2013	10:41	19.6	0.1
	25-Nov-2013	10:40	18.1	0.1
	25-Nov-2013	10:41	18.1	0.1
	11-Dec-2013	10:40	17.0	0.1
	11-Dec-2013	10:41	17.0	0.1
	27-Dec-2013	10:40	15.3	0.1
	12-Jan-2014	10:40	13.6	0.1
	28-Jan-2014	10:40	15.4	0.1
	13-Feb-2014	10:40	15.8	0.1
	17-Mar-2014	10:40	19.1	0.1
	2-Apr-2014	10:39	21.5	0.1

20-May-2014	10:39	23.6	0.1
11-Oct-2014	10:39	22.7	0.1
27-Oct-2014	10:39	20.1	0.1
12-Nov-2014	10:39	20.8	0.0
16-Feb-2015	10:39	15.2	0.1
23-May-2015	10:38	24.6	0.1
8-Jun-2015	10:38	25.8	0.1
14-Oct-2015	10:39	20.8	0.1
1-Dec-2015	10:39	18.2	0.1
17-Dec-2015	10:39	16.4	0.0
2-Jan-2016	10:39	15.2	0.1
2-Jan-2016	10:39	15.2	0.1
18-Jan-2016	10:39	15.1	0.1
18-Jan-2016	10:39	15.1	0.1
3-Feb-2016	10:39	14.9	0.1
3-Feb-2016	10:39	14.9	0.1
22-Mar-2016	10:39	20.2	0.1
23-Apr-2016	10:39	23.5	0.1
1-Nov-2016	10:39	21.5	0.1
1-Nov-2016	10:39	21.5	0.1
17-Nov-2016	10:39	19.8	0.1
17-Nov-2016	10:39	19.8	0.1
3-Dec-2016	10:39	17.4	0.1
19-Dec-2016	10:39	16.9	0.0
19-Dec-2016	10:39	16.9	0.1
4-Jan-2017	10:39	15.8	0.1
20-Jan-2017	10:39	15.6	0.1
21-Feb-2017	10:39	17.5	0.1
25-Mar-2017	10:39	19.8	0.1
10-Apr-2017	10:39	22.8	0.0
26-Apr-2017	10:38	23.7	0.1
17-Sep-2017	10:39	23.8	0.1
19-Oct-2017	10:39	23.3	0.1
19-Oct-2017	10:39	23.3	0.1
4-Nov-2017	10:39	20.7	0.1
20-Nov-2017	10:39	20.1	0.1
20-Nov-2017	10:39	20.1	0.1
22-Dec-2017	10:39	16.6	0.1
7-Jan-2018	10:39	14.7	0.0
23-Jan-2018	10:39	15.2	0.1
8-Feb-2018	10:39	15.8	0.1
24-Feb-2018	10:39	16.4	0.1
13-Apr-2018	10:38	21.7	0.1

Table S2. RapidEye imagery used to derive normalised difference vegetation indexes s.

Satellite	Date
RapidEye 1	14-Dec-2010
RapidEye 2	9-Nov-2011
RapidEye 4	16-Nov-2012
RapidEye 1	6-Nov-2013
RapidEye 3	17-Dec-2014
RapidEye 2	31-Oct-2015
RapidEye 1	5-Nov-2016
RapidEye 1	10-Nov-2017

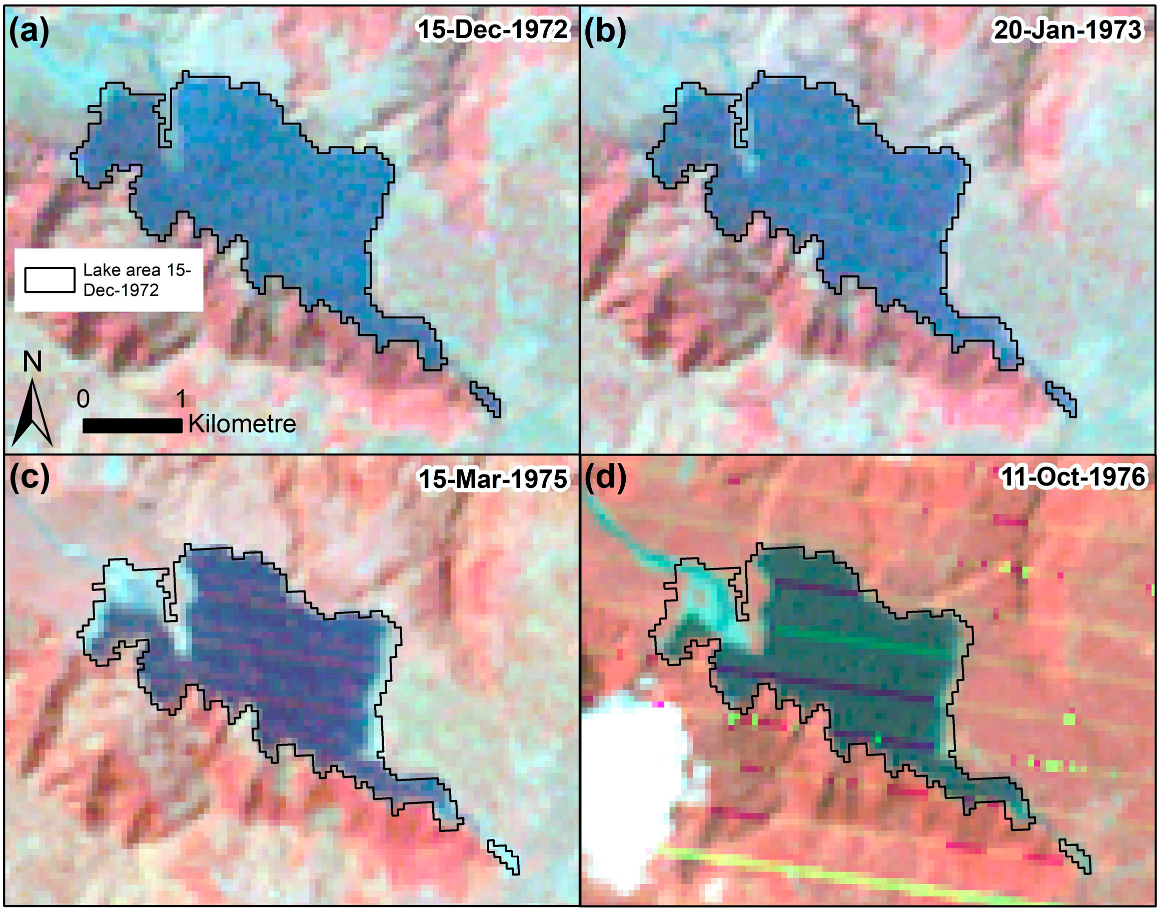
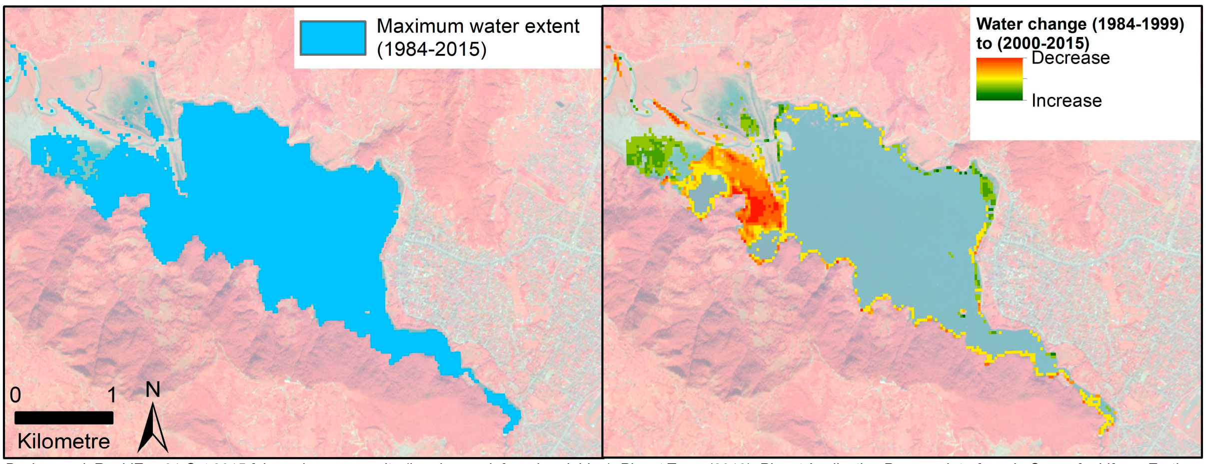


Figure S1. Lake area shrinkage due to the 1975 dam failure. The lake outline from 15 December 1972 is shown on all panels. **(a–d)** Landsat Multispectral Scanner background false colour composite (near-infrared, red, green).



Background: RapidEye 31 Oct 2015 false colour composite (bands near infrared, red, blue). Planet Team (2018). Planet Application Program Interface: In Space for Life on Earth. San Francisco, CA. https://api.planet.com

Figure S2. Surface water extent and change from Landsat image classification by Pekel et al. (2016).

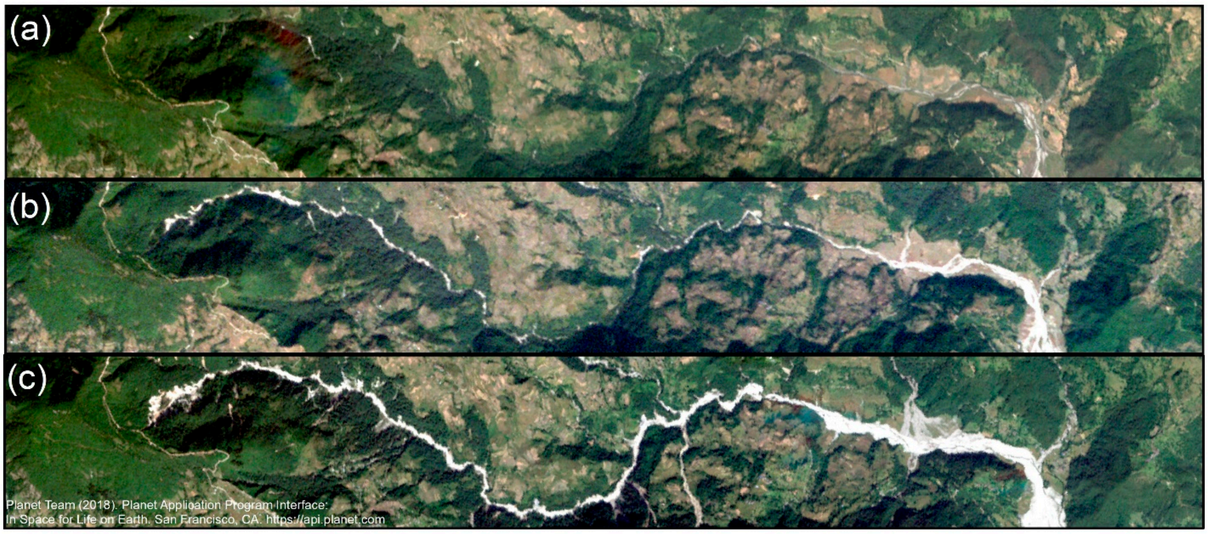


Figure S3. Landslide activity in the upper Phewa catchment (Figure 7) revealed by RapidEye true colour imagery from: **(a)** 6 November 2013; **(b)** 17 December 2014; **(c)** 31 October 2015.

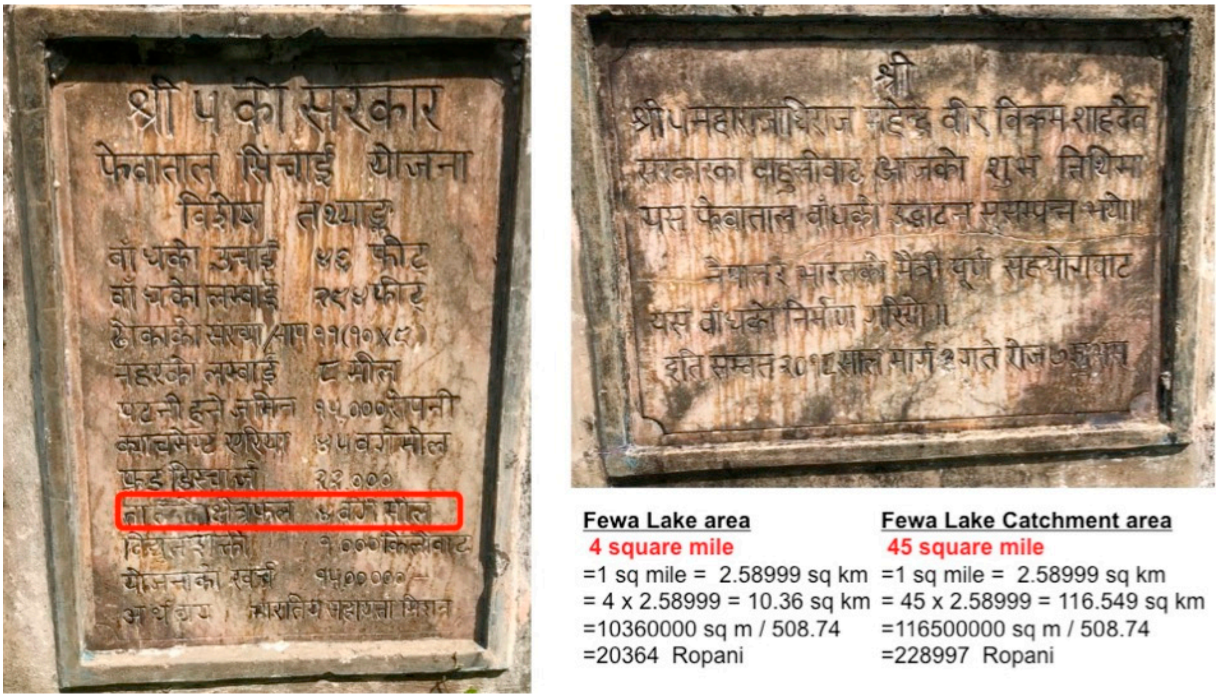


Figure S4. Stone inscription used at the time of the inauguration of a dam on 16 January 1962.

Geological Controls on Landsliding and Silt Production

Geology— along with slope and precipitation factors considered by Dhakal (2016)— is an underpinning of both the suspended sediment load of the Phewa watershed and of the landslide and debris flow production and delivery of sediment to the watershed's rivers, such as Harpan Khola. Bedrock formation nomenclature, stratigraphic positions, and tectonics are inconsistently mapped in Nepal's Lesser Himalaya, including Pokhara Valley. Older mapping—though still in use—consider the whole area of the Pokhara Valley's bedrock to be in the Seti formation (gray to greenish gray phyllites, gritty phyllites, quartzites with minor conglomeratic layers and basic intrusions; Hada 1982). Newer mapping considers the Phewa watershed bedrock to be divided between the Kuncha formation (meta-sandstone, phyllite, and conglomerate; also termed the "Ranimata formation") and Fagfog Quartzite (quartzite-phyllite-amphibolite) (Koirala et al. 1998, Paudel and Arita 2000, DeCelles et al. 2004, Martin et al. 2011, Cross 2014). Our observations indicate that phyllite, psammitic (sand-derived) and pelitic (mud/silt-derived) mica schist, meta-conglomerate, and quartzite dominate the Harpan Valley and its main tributary, the Andheri Khola valley. Examples from a 2015 landslide in the Harpan Valley, derived from the Kuncha formation, are highlighted in Figure S5. Though conglomerate and coarse-grained quartzite is present, the mineralogical content of most rocks observed in the area include a preponderance of silt-size quartz, as well as mica minerals, muscovite and biotite. The preserved bedding and metamorphic schistosity may lend itself to rock failure along those micro- and meso-structural contacts; furthermore, high-energy landslides may tend to break down along the contacts and grain boundaries of the micaceous rocks to produce large amounts of silt composed mainly of the minerals seen in Figure S5. That fine material is then carried in suspension by the Harpan/Andheri River system to Phewa Lake.

Koirala et al. (1998) mapped a large number of active and old landslides; most are within the Kuncha formation. Disproportionately far fewer landslides are developed in the Fagfog Quartzite—though these include the largest 2015 landslide—and most of those are located very near the contact with the Kuncha formation. Many other large landslides in Nepal are also developed in the Kuncha formation, such as the giant Jure landslide. The Harpan watershed's largest 2015 landslide (detailed in Figure S3) occurs on the axis of an anticlinal fold. The anticline and other folds extend up the Harpan Valley from Phewa Lake to that landslide. Newer geological mapping indicates that a major tectonic thrust—the Ramgarh Thrust—cuts through the area. The major tectonic features may have weakened the rocks and juxtaposed contrasting lithologies, which can contribute to landslide development. The fact that the same landslides are repeatedly reactivated in the Harpan-Andheri valley indicates that the weakness vulnerabilities extend deep into the bedrock, as, of course, the main tectonic structures do. Conditioning and triggering of landslides by earthquakes, road building, and monsoon precipitation are expected to be frequent reoccurrences and to affect the Kuncha formation disproportionately and mainly spare the Fagfog Quartzite, except near its stratigraphic contact with the Kuncha formation. Larger landslides than those of 2015 are possible and could cause big spikes in the siltation of Phewa Lake.

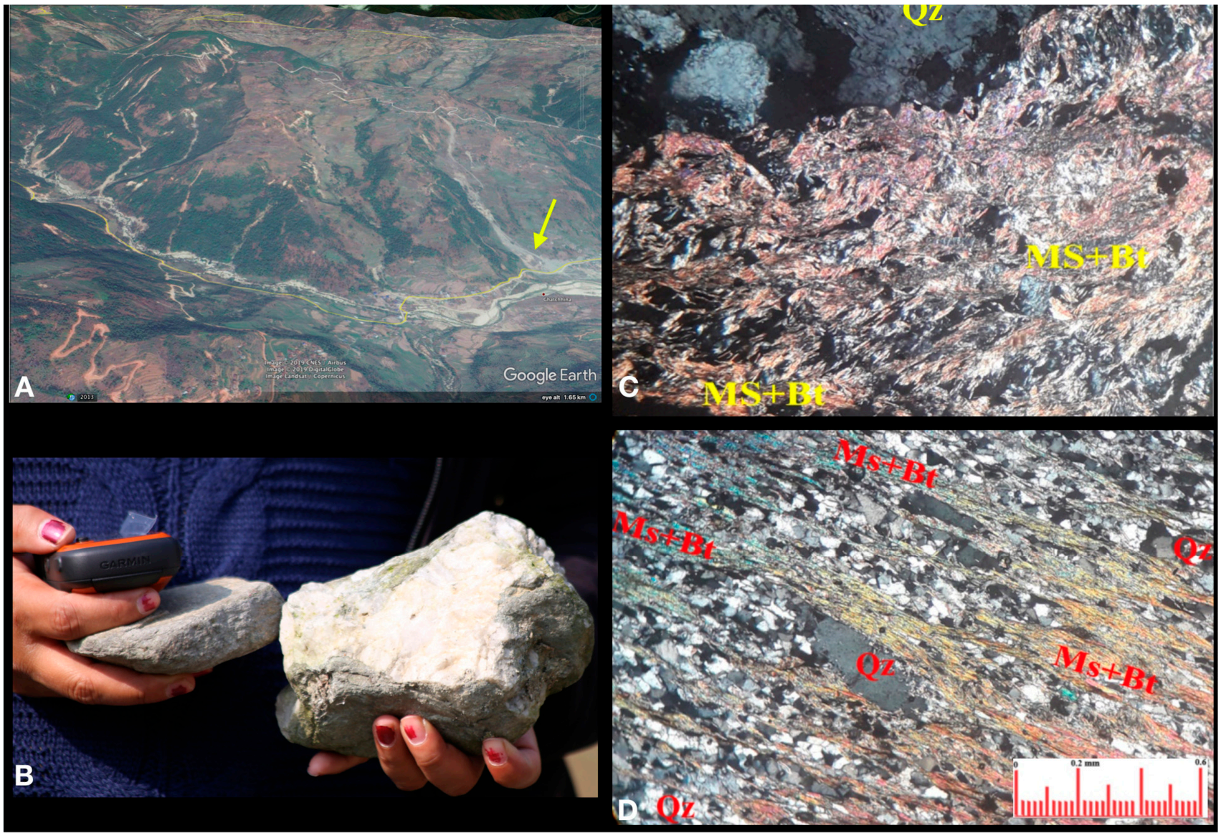


Figure S5. (a) A 2015 landslide sourced in the Kuncha formation and nearly reaching Harpan Khola, composed of rocks such as these **(b)** shown in the thin section (crossed polarizers): **(c)** the pelitic schist and **(d)** psammitic schist, commonly forming meta-conglomerate (**(b)**, right). In **(c)** and **(d)**, Qz = quartz, Ms = muscovite, and Bt = Biotite, and the scale bar is 0.6 mm. Panel **(a)** is a DigitalGlobe scene projected in Google Earth (acquisition date 10 March 2016).

Figure S6. Environmental water quality and ecological problems of Phewa Lake. (**a**) Outlet pipe emits wastewater into the lake, where fishermen extract fish. (**b**) Evidence of the wastewater effects on water quality. (**c**) Water hyacinth, an aggressive invasive species from the Amazon Basin has invaded Phewa Lake. (**d**) Plastic pollution and water hyacinth.

The rampant growth of water hyacinth is maximised by high aqueous organic content, such as in sewage-contaminated sites (Rezania et al, 2015), and by water temperatures in the 25-30°C range (Kasselmannn 1995), thus suggesting that urban growth of Pokhara, poorly treated effluent discharges into Phewa Lake, and climate warming (cf. Figure 3e) could act to increase the water hyacinth problem.

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