Where the City Meets the Lake: Urban Encroachment into the Catchment of the Upper Lake (Bhoj Wetland), Bhopal

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ABSTRACT

Bhopal's Upper Lake (Bhojtal), the core of the Ramsar-listed Bhoj Wetland, has been the focus of conservation since 1989: buffer planting from that year, a catchment-protection project financed by the Japan Bank for International Cooperation from 1995 to 2004, and Ramsar designation in August 2002, midway through that project. This paper asks two separate questions: whether the lake's water surface has shrunk, and whether building growth on the land around its shore slowed as protection took hold. The lake's catchment (367.4 km²) was traced from the Bhadbhada dam using MERIT Hydro flow directions, and the land around the lake was divided into four shoreline distance bands (0–50 m, 50–300 m, 300 m–1 km and 1–3 km). Building growth in each band was measured from the Global Human Settlement Layer (1975–2020) and checked against Google's Open Buildings temporal data (2016–2023), calibrated against 102,937 building footprints from 50 cm imagery. Identical bands around eleven reservoirs within 40 km that lack comparable protection form the comparison set for a difference-in-differences test before and after 2000, and the lake's water extent was tracked with the JRC Global Surface Water record for 1990–2021. Building growth within 3 km of the Upper Lake slowed after 2000, from 0.197 to 0.127 percentage points a year, while growth around the pooled comparison reservoirs slowed only slightly. The slowdown is concentrated between 50 m and 1 km from the shore and fades by 1–3 km. A placebo test ranks the Upper Lake second of twelve sites; the one reservoir that slowed more, Hathaikheda, had largely run out of room to build. The lake's water surface shows no long-term decline. The pattern fits the sustained physical catchment works more closely than the Ramsar label itself.

Keywords: Bhoj Wetland, urban growth, difference-in-differences, Global Human Settlement Layer, Ramsar site

INTRODUCTION

The Upper Lake, known locally as Bhojtal, was created in the eleventh century by an earthen dam across the Kolans river and remains the largest of Bhopal's lakes and the principal source of drinking water for the city, together with the smaller Lower Lake immediately downstream (Wikipedia, n.d.-c, n.d.-f). The two lakes, and the wetland they form, were declared a site of international importance under the Ramsar Convention on 19 August 2002 (Site No. 1206), the first Ramsar site in Madhya Pradesh (Ramsar Sites Information Service, n.d.). The Ramsar tag is often treated, in passing references to the lake, as the moment its protection began. The documented history is less tidy: buffer-zone tree planting between the lake and the surrounding settlements started in 1989, and a comprehensive catchment-conservation project (desilting, sewage diversion and further buffer creation) ran from 1995 to 2004 with financing from the Japan Bank for International Cooperation (Global Water Partnership, n.d.; Jha, 2021; Madhya Pradesh State Wetland Authority, n.d.). Ramsar designation therefore falls roughly in the middle of a fifteen-year conservation programme, not at its outset, and a state Lake

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Conservation Authority was not constituted until 2004, two years after the designation itself (Madhya Pradesh State Wetland Authority, n.d.).

Whether any of this reduced building pressure on the lake's catchment is an open question, and one with a genuine caveat attached: Bhoj Wetland is the only wetland Madhya Pradesh claims to have notified under the national Wetland (Conservation and Management) Rules, 2017, and that notification, together with the demarcation of the wetland, has been challenged in the Jabalpur High Court (Afridi, 2023). A conservation history built substantially on physical works (planted buffers, desilting, diverted sewage) rather than on a settled legal boundary is a different thing to evaluate than a simple before/after policy change, and this paper tries to evaluate it on those terms rather than assuming 2002 was a clean switch.

The approach taken here is a spatial difference-in-differences: building growth is measured in four distance bands from the Upper Lake's shoreline, out to 3 km, and compared against the same bands drawn around eleven other reservoirs in the wider Bhopal region that carry no comparable conservation history. If the Upper Lake's catchment protection had a real effect on construction, growth in the bands nearest the lake should have slowed, after the mid-1990s to early 2000s, by more than growth slowed at reservoirs without that protection. The comparison set is deliberately not restricted to reservoirs that look similar to the Upper Lake in isolation; it also includes three reservoirs at Bhopal's urban fringe, which is important, because it lets the paper ask not just "did growth near the Upper Lake slow" but "did it slow more than growth near comparably placed, but unprotected, reservoirs".

Two separate questions, and what this paper can answer

It is easy to blur two different questions when talking about a lake under development pressure: has the lake itself got smaller, with water turning into dry land or built-up land, and has the land around the lake got more built up, whether or not the lake's own boundary has moved. This paper is almost entirely about the second question. The first four parts of the Results measure building growth in the land bands out to 3 km from the shoreline, using satellite-derived built-up area as the measure of that growth; they say nothing directly about the lake's own size. The final part of the Results addresses the first question separately, using the lake's own mapped water extent year by year rather than any building data, and finds no long-term decline over 1990–2021; if anything, the two most recent years on record show some of the highest water extent in the series. The two findings sit alongside each other rather than depending on one another: the lake has not measurably shrunk, and at the same time the land bordering it has grown far more built up since 1975, at a rate that slowed after roughly 2000 relative to comparable reservoirs.

It is also worth being explicit about what "built-up growth" does and does not establish. The satellite datasets used here (see Building growth) detect that a structure exists; they cannot tell whether it was legally sanctioned, and this paper does not have access to land records, ownership data, or notified buffer-zone boundaries that would be needed to identify unauthorised construction as such. Where the word "encroachment" appears in this paper, including in its title, it refers to the encroachment of built-up land into the lake's catchment and shoreline bands (a change in land cover), and not to a legal finding about any specific building or plot.

The remainder of the paper sets out the study area and the catchment actually traced for it, the data and the distance-band and control-selection methods, the resulting growth patterns and a placebo test across the individual comparison reservoirs, and a discussion of what those patterns can and cannot support, including two comparison reservoirs whose own histories complicate a simple reading of the placebo test, before closing with limitations and conclusions.

Study Area

The Upper Lake sits on the western edge of Bhopal city (23.21°–23.26° N, 77.28°–77.40° E), impounded by an earthen dam at Bhadbhada. Its catchment was traced for this study from the dam's coordinates using flow-direction data (see Catchment delineation) and came to 367.4 km², close to the 361 km² figure reported for the watershed (Wikipedia, n.d.-b, n.d.-c); the roughly two-percent difference is discussed under Limitations. The

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lake's maximum water extent over the Landsat record used here is 29.9 km², close to the commonly cited surface area of about 31 km² (Ramsar Sites Information Service, n.d.; Wikipedia, n.d.-c). The area classified as water in at least half of all cloud-free observations is smaller, 18.4 km², which reflects the lake's seasonal and inter-annual drawdown.

The catchment runs west and south-west of the lake, through largely rural and agricultural land toward Sehore, Narela and Bilkisganj, before the boundary turns north and closes along the built-up fringe of Bhopal itself; only the western edge of the city falls inside it. This asymmetry matters for how the results should be read: most of the catchment by area is not urban at all, and the building-growth question this paper asks (see Introduction) is specifically about the built fringe closest to the shoreline, not about the catchment as a whole (Figure 1a).

Figure 1a: The traced Upper Lake catchment, the lake's maximum water extent, the Bhadbhada dam, and the eleven comparison reservoirs (see Comparison reservoir selection), shown by whether they sit at Bhopal's urban fringe or in a more rural setting.

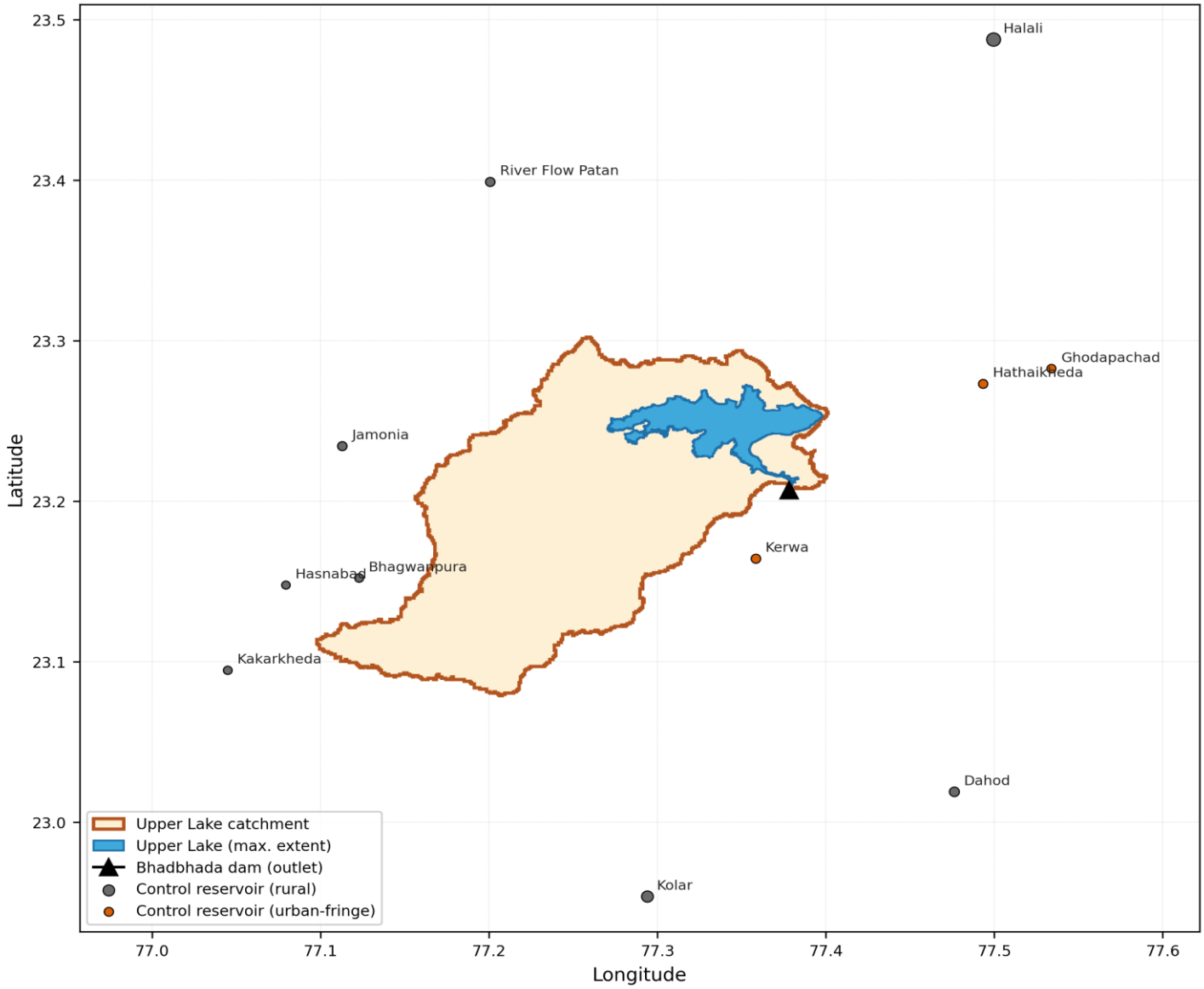
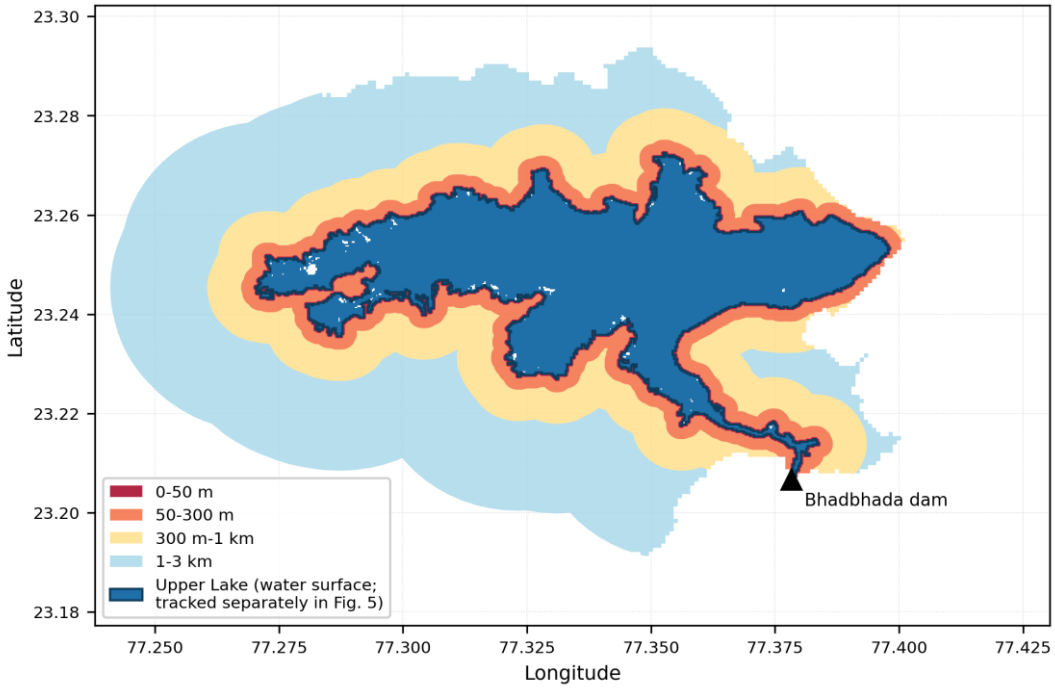


Figure 1b zooms in on the lake itself to show the two things this paper keeps separate (see Introduction) side by side: the lake's own water surface in solid blue, tracked year by year for Figure 5, and the four shoreline distance bands in which building growth is measured for Figures 2–4, shown here as the coloured rings around it. The narrowest band, 0–50 m, is visually almost too thin to see at this scale, which is itself a useful illustration of why that band is the least reliable one in the results (see Limitations).

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Figure 1b: The Upper Lake's water surface (blue) and the four shoreline distance bands used to measure building growth in the Results (coloured rings), zoomed in from Figure 1a.



Eleven other water bodies within 40 km of the lake serve as comparison sites: Halali and Kolar, two large reservoirs that themselves supply water for drinking or irrigation to Bhopal or nearby towns (Sachdeva, 2009; Wikipedia, n.d.-e); Dahod, Jamonia, Bhagwanpura, Kakarkheda and Hasnabad, smaller reservoirs in a rural setting; an unnamed reservoir near Patan referred to here as River Flow/Patan; and three reservoirs at Bhopal's own urban edge (Kerwa, Hathaikheda and Ghodapachad; Wikipedia, n.d.-d), which form the subset most comparable to the Upper Lake in exposure to city growth and are treated separately in the results.

DATA AND METHODS

Catchment delineation

The catchment was delineated by tracing MERIT Hydro flow-direction data (Yamazaki et al., 2019; roughly 90 m resolution) upstream from a pour point snapped to the Bhadbhada dam's published coordinates (23.20833° N, 77.37889° E). An initial attempt at locating the dam's outlet from the lake's maximum water extent alone picked up a point on the Kaliasot river 3.3 km downstream of the actual dam; that wrong outlet gave a catchment of 382.6 km² using MERIT's own upstream-area estimate there, or as much as 422 km² using an alternative watershed-union method: 4% and 15% larger, respectively, than the corrected figure below. The corrected pour point, snapped to the pixel of highest upstream flow accumulation within 200 m of the published coordinates, sits 193 m from those coordinates and was traced upstream in stages until no further area was added, giving the 367.4 km² figure used throughout. The corrected trace was checked against MERIT's own upstream-area estimate at the dam (372.0 km², a 1.2% difference) and confirmed to exclude the earlier, erroneous Kaliasot outlet entirely.

Lake extent

The lake itself was redrawn, inside the corrected catchment only, from the JRC Global Surface Water dataset's maximum-extent and occurrence layers (Pekel et al., 2016), which excludes the downstream channel that had inflated the initial estimate (see Catchment delineation). The two measures used, maximum extent (29.9 km²) and the area classified as water at least half the time (18.4 km²), bracket normal seasonal variation; the first is close to the reservoir's commonly cited surface area, and the second is smaller because of drawdown (see Study area).

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Building growth

Two independent building datasets were used. The Global Human Settlement Layer's Built-up Surface product (release R2023A, Pesaresi & Politis, 2023; 100 m cells, a fraction of each cell's area classified as built) provides ten epochs from 1975 to 2020 and is the basis for the long-run, before/after comparison. Google's Open Buildings 2.5D Temporal dataset (Sirko et al., 2023; 4 m resolution, yearly 2016–2023, giving per-pixel building presence and height) provides a higher-resolution but shorter recent check; its building-presence probability was calibrated against 102,937 building footprints detected by Google from 50 cm imagery in the static Open Buildings v3 polygon dataset (Sirko et al., 2021). The calibration gave a central presence cut-off of 0.40, whose 2023 building area came within about one percent of the reference footprint area, with 0.35 and 0.45 used as a sensitivity range.

Distance bands

Both datasets were summarised in four concentric bands measured from the lake's shoreline (0–50 m, 50–300 m, 300 m–1 km and 1–3 km), computed on a common 10 m grid so that GHSL and Open Buildings count identical pixels in each band. These breakpoints were not chosen arbitrarily: 50 m and 300 m bracket documented buffer-zone widths at comparable Bhopal reservoirs (a 33 m buffer zone around the full-tank level of Kerwa and Kaliasot, enforced at least nominally [National Green Tribunal, 2024]; a wider regional-garden buffer reserved under the 2005 master plan), while 1 km and 3 km extend the comparison out to a scale at which any shoreline-specific effect should have faded if it is real (see Discussion for the enforcement context these figures come from). Land inside the traced catchment boundary but outside 3 km of the lake, and any area belonging to a comparison reservoir's own bands, is excluded from double counting. Reservoirs within 3 km of the Upper Lake were themselves excluded from the comparison set entirely (see Comparison reservoir selection); one comparison reservoir, Kerwa, sits only 3.4 km from the Upper Lake, close enough that its own outermost (1–3 km) band could in principle be clipped by this exclusion rule, a possibility examined directly under Limitations.

Comparison reservoir selection

Every water body of at least 0.5 km² in the JRC maximum-extent layer within 40 km of the Upper Lake's centroid, and more than 3 km from the Upper Lake itself, was treated as a candidate; each was matched to a named reservoir by comparing its mapped area against reservoirs of similar size visible on satellite imagery, and every match was independently confirmed against Google Maps satellite imagery and, where available, secondary sources. Eleven candidates were confirmed as genuine, largely permanent reservoirs; two very low-compactness water bodies that turned out to be river channels, rather than lakes, were excluded, as were several small, partly seasonal ponds under 1 km². The eleven form the comparison set used throughout; three of them (Kerwa, Hathaikheda and Ghodapachad) sit at Bhopal's own urban fringe and are also reported as a separate subset, since they face development pressure more directly comparable to the Upper Lake's than the more rural reservoirs do.

Difference-in-differences design

For the Upper Lake and, separately, for each comparison reservoir, the annualised growth rate in the share of land built up (bands 1–4 pooled, and each band individually) was computed for 1990–2000 and for 2000–2020, using GHSL's epochs nearest the conservation period. The difference between the two (the post-2000 rate minus the pre-2000 rate) is the slope-change statistic reported in the Results; a negative slope-change means growth decelerated after 2000. This same statistic, computed identically for each of the eleven comparison reservoirs on their own, forms a placebo test: it shows where the Upper Lake's slope-change falls within the range that ordinary urban growth around any of these reservoirs produced over the same period, rather than relying on a single pooled comparison number.

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Water-surface time series

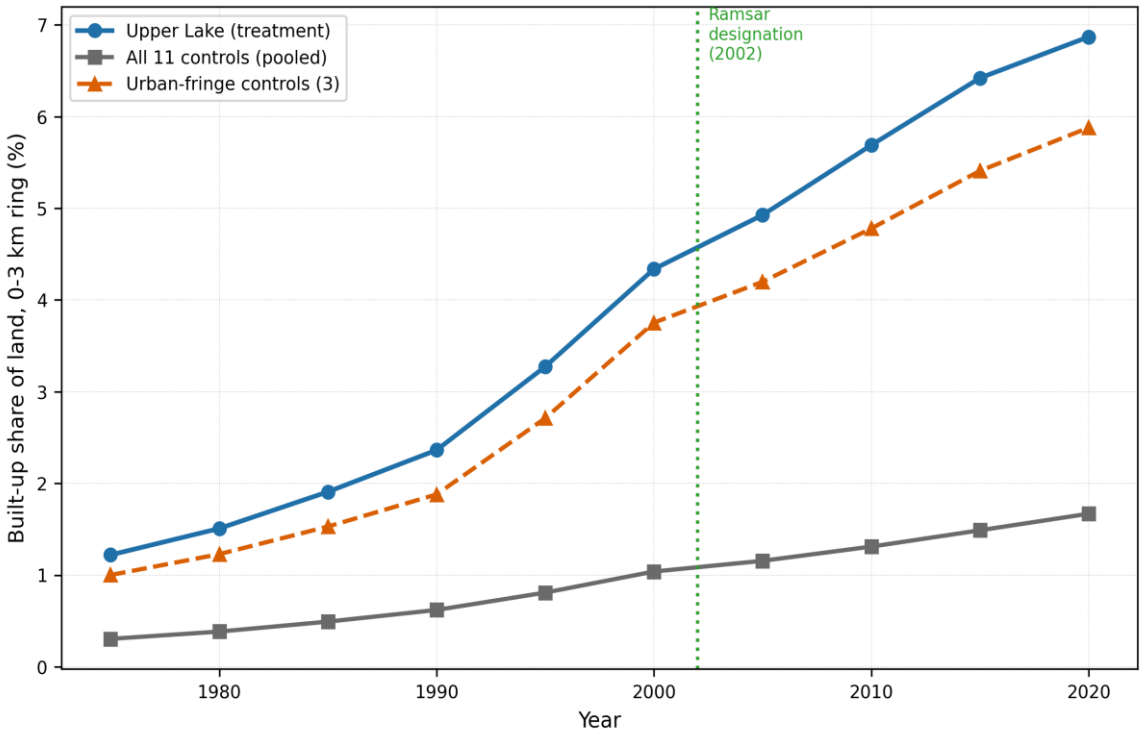
An independent check comes from the JRC dataset's monthly and annual water classifications (Pekel et al., 2016), 1984–2021, alongside annual rainfall. The years 1984–1989 show no classified water at all in most months despite non-zero rainfall, which is a satellite-coverage artefact of the earlier Landsat record rather than a real absence of water, so the water-extent series reported in the Results begins in 1990.

RESULTS

Overall growth trajectory

Figure 2 plots the share of land built up within 3 km of the lake, pooled across bands 1–4, for the Upper Lake, for the pooled eleven comparison reservoirs, and for the three urban-fringe reservoirs alone. All three rise steadily from 1975 to 2020, as expected of any Indian urban region over this period, but after roughly 2000 the Upper Lake's curve flattens far more than the pooled comparison line: its built-up share rose at about 0.197 percentage points a year between 1990 and 2000 (reaching 4.34% of the 0–3 km ring in 2000), but at only 0.127 points a year between 2000 and 2020 (to 6.87%). Over the longer span from 1975 (1.22%) the contrast is hidden, because growth before 1990 was slow, which is why the comparison in this paper is anchored at 1990–2000 against 2000–2020 (see Difference-in-differences design). Read from Figure 2, the pooled comparison line slows by only about 0.01 percentage points a year after 2000 (from about 0.042 to 0.032), against 0.071 for the Upper Lake. The urban-fringe line also bends after 2000, by about 0.08 points a year, but that bend comes almost entirely from one reservoir, Hathaikheda; the other two urban-fringe reservoirs accelerated (see the placebo test below).

Figure 2: Built-up share of land within 3 km of the Upper Lake, compared against the pooled eleven comparison reservoirs and the urban-fringe subset of three, 1975–2020.



Where the deceleration is concentrated

Table 1 and Figure 3 break the same comparison down by distance band. The pattern is not one of growth being pushed further from the lake; it decelerates at every distance, and does so far more than the comparison reservoirs' pooled bands at 50–300 m and 300 m–1 km, weakly at 0–50 m, and not at all by 1–3 km, where the Upper Lake's slowdown is practically the same as the comparison reservoirs' own.

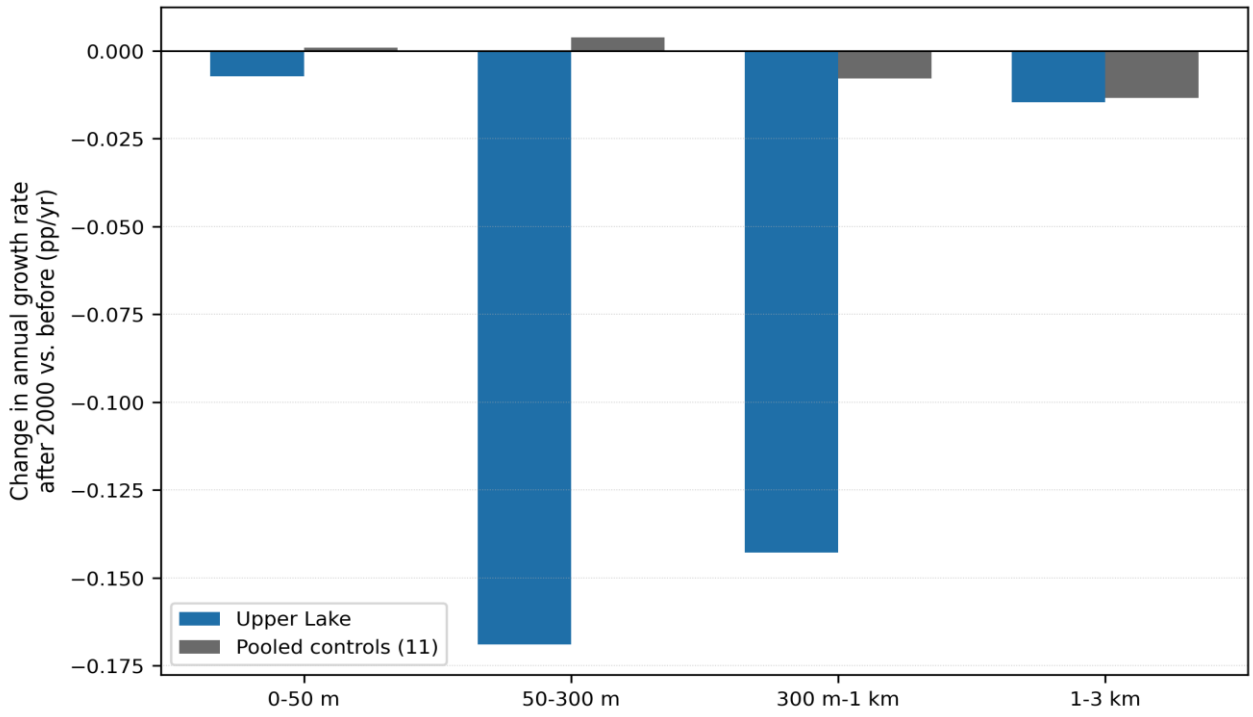
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Table 1: Change in the annualised growth rate of built-up land after 2000 versus before, by distance band. A negative value is a deceleration; the final column is the Upper Lake's deceleration minus the pooled comparison reservoirs'.

Band	Upper Lake Δ (pp/yr)	Controls Δ (pp/yr)	Difference (DiD)
0–50 m	−0.007	+0.001	−0.008
50–300 m	−0.169	+0.004	−0.173
300 m–1 km	−0.143	−0.008	−0.135
1–3 km	−0.015	−0.013	−0.001

Read together with Figure 3, the effect is best described as a shoreline band of reduced growth: strongest one to three hundred metres out and within a kilometre, negligible in the narrow strip immediately at the water's edge (where GHSL's 100 m cells are also least reliable, see Limitations), and undetectable by the time the ring reaches one to three kilometres from the shoreline.

Figure 3: Change in the annualised growth rate after 2000, by distance band, Upper Lake versus the pooled comparison reservoirs.

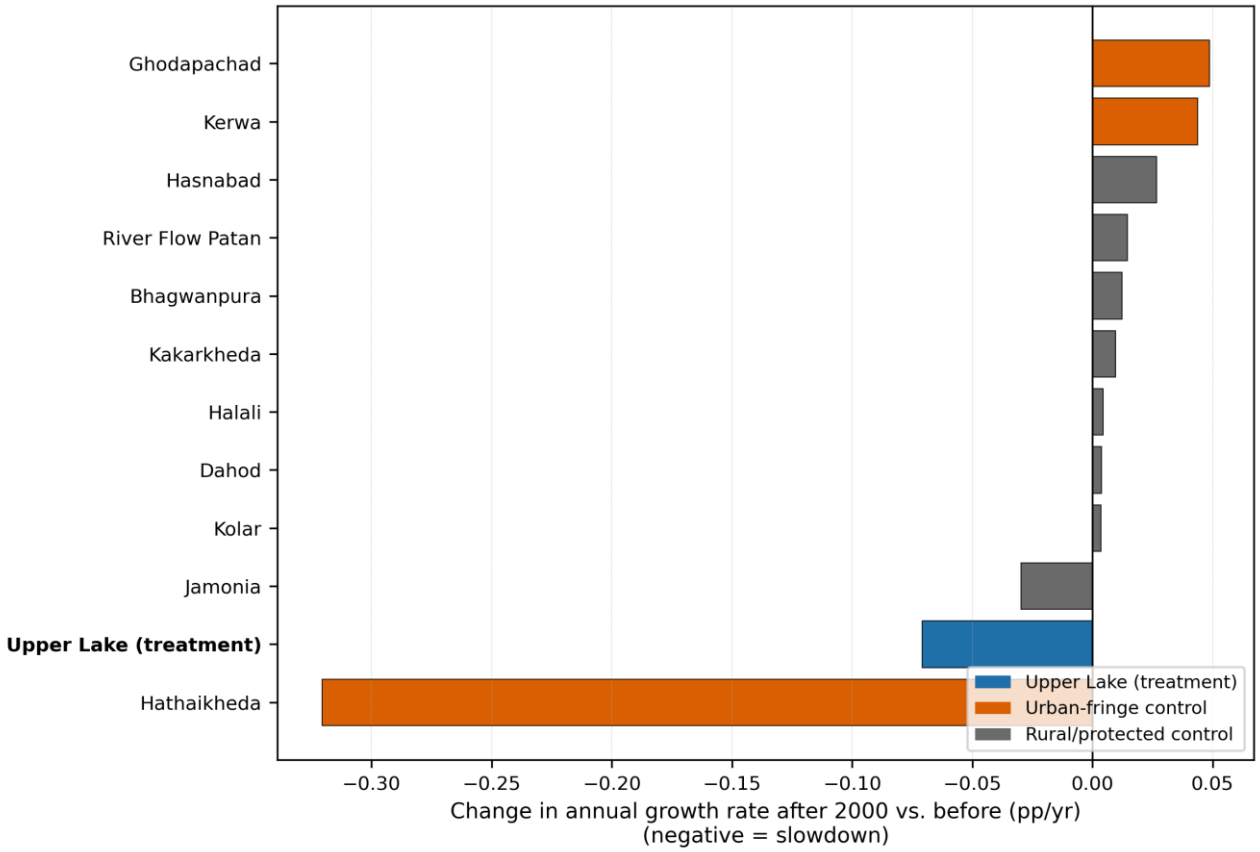


A placebo test across the comparison reservoirs

Pooling the eleven comparison reservoirs into a single number risks hiding as much as it shows, so the same pooled-band slope-change statistic was computed for each comparison reservoir individually. Figure 4 ranks all twelve sites (the Upper Lake and its eleven comparisons) by this statistic. The Upper Lake's deceleration (−0.071 percentage points per year) ranks second-largest of the twelve; only Hathaikheda, one of the three urban-fringe comparisons, decelerated more (−0.321 pp/yr). Read as an informal, randomisation-style test, this rank corresponds to a one-sided placebo probability of about 2/12, or 0.17: suggestive, and larger than all but one of eleven genuine comparison sites, but not a result that would clear a conventional significance threshold on the ranking alone; the qualitative pattern across the individual reservoirs (see Discussion) is what does the remaining evidential work. The other two urban-fringe reservoirs, Kerwa and Ghodapachad, did not decelerate at all; both accelerated after 2000 (+0.044 and +0.049 pp/yr respectively). The eight more rural or already-protected reservoirs averaged a slope-change of essentially zero (+0.006 pp/yr), meaning ordinary urban growth around a typical reservoir in this region did not slow down after 2000 on its own.

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Figure 4: The same slope-change statistic computed individually for the Upper Lake and each of the eleven comparison reservoirs, ranked from largest deceleration to largest acceleration.



A recent, higher-resolution check

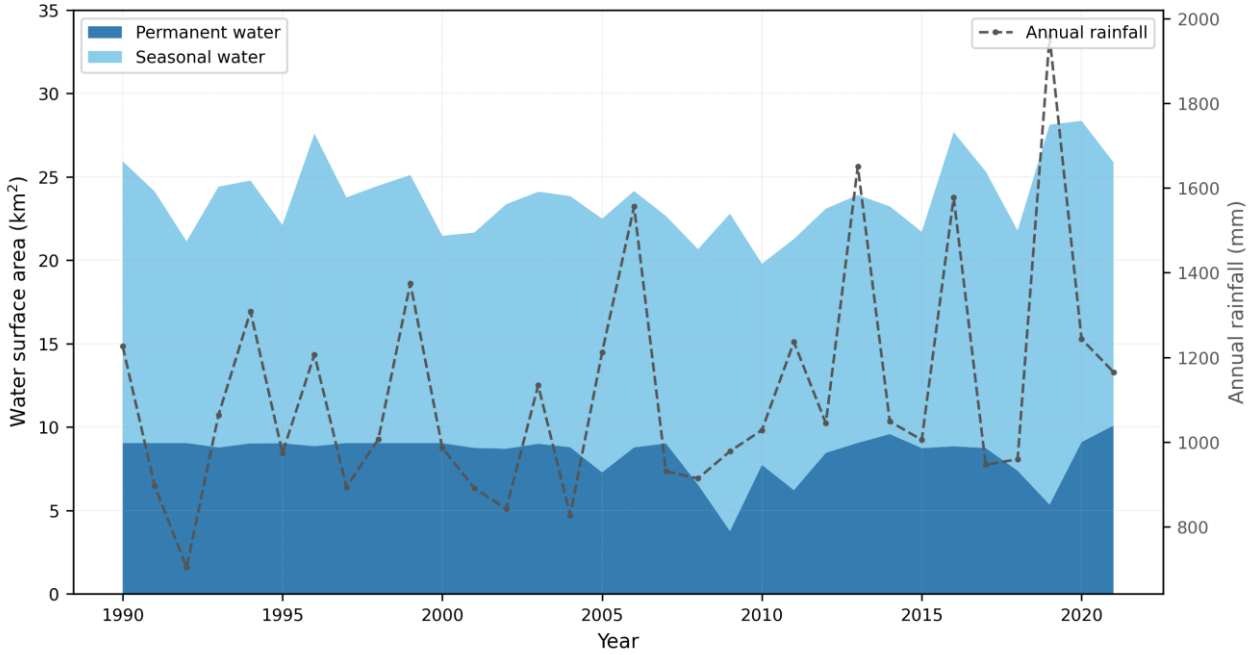
Because Open Buildings only runs from 2016, it cannot test the pre/post-2000 break, but it offers an independent, much higher-resolution (4 m) check on whether the Upper Lake's slower growth persisted into the recent past. Between 2016 and 2023, built-up area within 3 km of the Upper Lake (at the calibrated 0.40 presence cut-off) grew by 22.0%, against 27.7% for the pooled comparison reservoirs and 27.4% for the urban-fringe subset, consistent with the GHSL-based finding that the Upper Lake's ring has grown more slowly than comparable reservoirs', using a wholly different dataset and a much finer resolution.

Water-surface extent, 1990–2021

Figure 5 shows the lake's permanent and seasonal water-surface area alongside annual rainfall. Permanent water cover has stayed mostly in a 6–10 km² range across the record, with two years falling clearly below it: 3.8 km² in 2009, with an uneven, partial recovery through the following two years (7.7 km² in 2010, 6.2 km² in 2011), and 5.4 km² in 2019, after 7.4 km² in 2018. In both cases the lake recovered within a year or two. The two most recent years on record, 2020 and 2021, stand at 9.1 and 10.1 km² respectively; 2021 is the highest permanent-water value in the whole series. Total water extent (permanent plus seasonal) tracks rainfall loosely rather than tightly, which is unsurprising given that the lake's level also reflects deliberate management (the Bhoj Wetland Project's desilting work in particular) rather than rainfall alone. There is no evidence in this record of a long-term shrinkage of the lake.

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Figure 5: Upper Lake permanent and seasonal water-surface extent (left axis, stacked) and annual rainfall (right axis), 1990–2021. 1984–1989 are omitted; see Water-surface time series.



DISCUSSION

A shoreline effect, not an outward displacement

One possible reading of a shoreline slowdown is that construction was simply pushed further out, so that growth near the water was displaced rather than reduced. The data do not support this. With both periods annualised on a consistent basis (ten years before 2000, twenty after), the difference-in-differences value for the 1–3 km ring is effectively zero (Table 1): growth slowed in a band roughly fifty metres to a kilometre from the shoreline, and the slowdown fades rather than reappearing further out. That is the pattern a shoreline buffer policy would be expected to produce, not an outward displacement.

What the individual comparison reservoirs add

The placebo test in the Results puts the Upper Lake's deceleration in context rather than treating it in isolation. Against the eight more rural or state-managed reservoirs, which as a group show no deceleration at all after 2000, the Upper Lake's slowdown looks genuinely distinctive. Against the two other urban-fringe reservoirs specifically comparable in their exposure to city growth, it looks similarly distinctive: Kerwa and Ghodapachad kept accelerating through the same period. The one reservoir whose own deceleration exceeds the Upper Lake's, Hathaikheda, complicates a simple reading of "urban-fringe reservoirs slow down" and is worth examining directly, because its history points to a different mechanism.

Hathaikheda sits immediately beside Bhopal's BHEL industrial township at Piplani and Anand Nagar, a state-owned engineering complex founded in August 1956 and dedicated to the nation in November 1960, whose residential township is described by the company itself as spread over roughly 20 km² (Bharat Heavy Electricals Limited, Bhopal, n.d.; Wikipedia, n.d.-a), developed across the decades before this study's 1990 starting point. A study of urban flooding in Bhopal further notes that irrigation reservoirs such as Hathaikheda, once on the outskirts of the city, had become an integral part of it as the city expanded in all directions (Sachdeva, 2009), reinforcing that its shoreline lay within the built-up city rather than on its rural fringe. Consistent with this, Hathaikheda's own pre-2000 growth rate (+0.503 percentage points per year) was more than double the Upper Lake's (+0.197), the highest pre-2000 rate of any reservoir in the comparison set; its subsequent deceleration reads far more plausibly as a ceiling effect (a shoreline running out of room to build) than as evidence of a rival conservation programme with no documented buffer, notification or management authority of its own.

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Kerwa and its neighbouring Kaliasot reservoir, by contrast, are not without a nominal legal buffer: the National Green Tribunal has repeatedly ordered the removal of encroachments from a 33-metre buffer zone around the full-tank level of both (Free Press Journal, 2023, August 23; National Green Tribunal, 2024), and Madhya Pradesh's 2005 master plan reserves a wider area around them for botanical and regional gardens with only limited construction permitted (Free Press Journal, 2024). Yet a 2024 report on the same sites describes construction continuing in defiance of that order, including villas built under the guise of permitted farmhouses (Free Press Journal, 2024), and an earlier report names specific commercial operators (restaurants and a dairy business) running inside the supposedly protected catchment (Free Press Journal, 2023, August 19). A legal buffer that is repeatedly and openly violated is, in practical terms, closer to no buffer at all, and Kerwa's continued acceleration after 2000 is consistent with that reading.

Put together, the placebo test rules out the two most obvious alternative explanations for the Upper Lake's slowdown rather than leaving it unexplained: it is not simply what happens at any large, ageing reservoir near a city (Hathaikheda's deceleration has a different, saturation-driven cause), and it is not simply what a legal designation alone can produce without enforcement (Kerwa carries a court-ordered buffer of its own and shows no slowdown). It should be said plainly that both of these explanations were constructed after Hathaikheda and Kerwa stood out as the two individual reservoirs most relevant to the Upper Lake's result, rather than predicted in advance of looking at the data; the documentary evidence behind each (Hathaikheda's pre-1990 township growth, Kerwa's repeatedly violated buffer) is independent of the remote-sensing analysis itself, which limits but does not eliminate the risk of a post-hoc account fitted to whichever comparisons happened to be outliers. What is left, by elimination rather than by direct proof, is the Upper Lake's own, more sustained history of physical catchment works.

A fuzzy treatment date, and an unresolved legal question

This paper has anchored its before/after comparison at the year 2000, the closest GHSL epoch to the 2002 Ramsar designation, for want of a sharper alternative. The actual conservation history is spread across a decade and a half: buffer planting from 1989, the JBIC-financed project from 1995 to 2004, Ramsar designation falling in the middle of that project in 2002, and a state Lake Conservation Authority created only in 2004 (Global Water Partnership, n.d.; Madhya Pradesh State Wetland Authority, n.d.). The 1990/2000/2020 epochs used here therefore bracket this period only approximately, and some of the pre-2000 growth already reflects the early years of the same conservation programme rather than an untreated baseline. This paper's finding is better read as evidence that the sustained 1989–2004 catchment-protection effort coincided with a real, spatially concentrated deceleration, not as evidence that the 2002 Ramsar designation itself was the operative cause. It is also worth recording, since it bears directly on how durable that protection is, that the notification of Bhoj Wetland under the national Wetland Rules, and the wetland's demarcation, were under legal challenge in the Jabalpur High Court as of 2023 (Afridi, 2023); the mechanism this paper detects looks more like physical works on the ground than a settled legal designation.

The water-surface record

The water-extent series in the Results speaks to a related but distinct question (whether the lake itself has been shrinking) rather than to catchment land use directly, and the answer it gives is reassuring on its own terms: no long-term decline is visible across three decades, and the two most recent years show some of the highest permanent-water extent in the record, following the wettest year in the record, 2019 (1,957 mm), and plausibly also reflecting the desilting work carried out under the Bhoj Wetland Project (Global Water Partnership, n.d.; Jha, 2021). It does not, by itself, confirm or rule out anything about building growth in the surrounding bands, but it is consistent with an active, ongoing management effort rather than one that lapsed after the initial 1995–2004 project window.

Limitations

Several limits bear on how far these findings should be pushed. GHSL's 100 m cells smooth the narrowest, 0–50 m band considerably, which is very likely why that band shows the smallest and least reliable deceleration in

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Table 1; the 4 m Open Buildings data are better suited to that band but only cover 2016–2023 and so cannot speak to the pre/post-2000 comparison. GHSL's built-up surface fraction also has no independent accuracy check across its full 1975–2020 record comparable to the one performed for Open Buildings against 50 cm reference footprints (see Building growth); the long-run trend therefore carries some unquantified measurement error beyond what the calibration exercise covers.

Kerwa sits only 3.4 km from the Upper Lake, close enough that its own outermost (1–3 km) band could in principle be clipped by the study's 3 km exclusion rule around the Upper Lake (see Distance bands), which would matter because Kerwa carries real weight in the argument of the Discussion. As a direct check, Kerwa's own 1–3 km band covers 33.2 km² of land, larger than the same band at Bhagwanpura (26.1 km²) or Hasnabad (25.6 km²), both more than four times farther from the Upper Lake and clearly unaffected by any clipping, and comparable to Hathaikheda's (35.1 km²). This is evidence against severe truncation, but it is not a substitute for re-running the analysis with the exclusion buffer relaxed around Kerwa specifically, which a future revision of this work should do.

The eleven comparison reservoirs vary greatly in size, setting and their own institutional history. Kolar is a documented drinking-water source for Bhopal city itself, supplying roughly 60% of the city's treated water (Wikipedia, n.d.-e); Several of the rural reservoirs may also carry some institutional protection as irrigation or water-supply sources (Sachdeva, 2009, lists Halali and Kerwa among Bhopal's irrigation reservoirs), which this study did not investigate further. Eleven is, in any case, a modest sample for a placebo test, though the qualitative pattern (the Upper Lake distinctive against rural reservoirs, and comparable only to one urban-fringe reservoir with a documented and unrelated cause) does not depend on precise sample size, and the Results report the associated informal placebo probability (about 0.17) rather than treating the ranking alone as conclusive.

The traced catchment (367.4 km²) differs from the commonly cited 361 km² figure by about two percent, some of which likely reflects the boundary of the working region used during tracing rather than a real difference in the underlying watershed. GHSL's built-up surface fraction and Open Buildings' presence probability are both proxies for building footprint, not measures of population, floor area or the intensity of encroachment, and neither dataset can distinguish authorised construction from encroachment as defined in the enforcement literature cited in the Discussion. The explanations offered in the Discussion for why Hathaikheda and Kerwa behave as they do were constructed after those two reservoirs stood out in the results, not predicted beforehand, which the Discussion already flags explicitly. Finally, the water-surface record in the Results is descriptive; it was not designed to, and does not, establish a causal link between catchment protection and lake condition.

CONCLUSION

Building growth in the ring immediately around Bhopal's Upper Lake decelerated after 2000, and did so by more than at ten of the eleven comparison reservoirs in the wider region (two of which accelerated); only one, Hathaikheda, decelerated more, for a documented and unrelated reason examined in the Discussion. The deceleration is concentrated in a band roughly fifty metres to a kilometre from the shoreline and is not detectable further out, which is consistent with a shoreline buffer policy working as such policies are meant to, rather than with growth being displaced outward. Placed against the individual comparison reservoirs rather than a single pooled average, the Upper Lake's slowdown is real but not unique (an informal placebo probability of about 0.17 on the ranking alone, treated here as suggestive rather than conclusive), while two reservoirs with a comparable urban-fringe exposure and a nominally similar legal buffer kept growing throughout, consistent with well-documented, ongoing non-enforcement at those sites. Taken together, the most defensible reading is that the Upper Lake's sustained, largely physical catchment-protection effort between 1989 and 2004, rather than the 2002 Ramsar designation as a discrete legal event, coincided with a measurable, spatially bounded slowdown in shoreline development, at a lake whose open-water extent has itself shown no long-term decline over the same three decades. Given that the wetland's notification under the national Wetland Rules has been challenged in court, and given how much enforcement appears to matter at comparable sites nearby, continued protection of the Upper Lake's shoreline looks more dependent on maintaining active catchment works than on the durability of any one legal label.

Ethical Considerations

This study is based entirely on publicly available satellite data and published sources. It did not involve human participants or animals, and ethical approval was therefore not required.

Conflict Of Interest

The authors declare no conflict of interest.

Data Availability

All input datasets are publicly available in Google Earth Engine: MERIT Hydro (MERIT/Hydro/v1_0_1), JRC Global Surface Water (JRC/GSW1_4), GHS-BUILT-S R2023A (JRC/GHSL/P2023A/GHS_BUILT_S), Google Open Buildings 2.5D Temporal (GOOGLE/Research/open-buildings-temporal/v1) and Open Buildings v3 polygons (GOOGLE/Research/open-buildings/v3/polygons). The derived tables and the Earth Engine scripts used in this study are available from the corresponding author on reasonable request.

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