Recently constructed hydropower dams were associated with reduced economic production, population, and greenness in nearby areas

Peilei Fan[a,b,1], **Myung Sik Cho**[b,c], **Zihan Lin**[b,c], **Zutao Ouyang**[d], **Jiaguo Qi**[b,c], **Jiquan Chen**[b,c], and **Emilio F. Moran**[b,c]

[a]School of Planning, Design and Construction, Michigan State University, East Lansing, MI 48824; [b]Center for Global Change and Earth Observations, Michigan State University, East Lansing, MI 48824; [c]Department of Geography, Environment, and Spatial Sciences, Michigan State University, East Lansing, MI 48824; and [d]Department of Earth System Science, Stanford University, Stanford, CA 94305

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Hydropower dams produce huge impacts on renewable energy production, water resources, and economic development, particularly in the Global South, where accelerated dam construction has made it a global hotspot. We do not fully understand the multiple impacts that dams have in the nearby areas from a global perspective, including the spatial differentiations. In this study, we examined the impacts of hydropower dam construction in nearby areas. We first found that more than one-third of global gross domestic production (GDP) and almost one-third of global population fall within 50 km of the world's 7,155 hydropower dams (<10% of the global land area sans the Antarctic). We further analyzed impacts of 631 hydropower dams (≥1-megawatt capacity) constructed since 2001 and commissioned before 2015 for their effects on economy, population, and environment in nearby areas and examined the results in five regions (i.e., Africa, Asia, Europe, North America, and South America) and by different dam sizes. We found that recently constructed dams were associated with increased GDP in North America and urban areas in Europe but with decreased GDP, urban land, and population in the Global South and greenness in Africa in nearby areas. Globally, these dams were linked with reduced economic production, population, and greenness of areas within 50 km of the dams. While large dams were related with reduced GDP and greenness significantly, small and medium dams were coupled with lowered population and urban land substantially, and large and medium dams were connected to diminished nighttime light noticeably in nearby areas.

hydropower dams | impacts | economy | population | environment

As one of the most-significant infrastructures for promoting economic development, hydropower dams have received renewed interest in recent decades, particularly in emerging countries in Asia and South America. According to the Global Georeferenced Database of Dams (GOODD)—the largest open-source, global, georeferenced database of dams—more than 38,000 dams are visible on satellite imagery (1). Most dams were constructed in the 20th century, when dam construction was intensified and flourished on the continents of North America, Europe, and Australia, where both social and economic development progressed faster than they did in other regions of the world (2). Most hydropower dams in North America and Europe were built before 1975 (3); since then, new construction has shifted to Asia and South America, especially over the past two decades. Of the 7,155 hydropower dams in the database of the World Resources Institute (WRI), 6,200 were built before 2001, with about two-thirds located in North America (2,063) and Europe (1,922). Of the 955 hydropower dams built after 2001, 81% were built in Asia (342) and South America (427) (4) (Fig. 1). This trend likely will continue into the future, as at least 3,700 hydropower dams with a capacity of more than 1 Megawatt (MW) are currently either planned or under construction, primarily in three emerging countries (Brazil, China, and India), where an extremely high number of hydropower projects have been carried out (2) (*SI Appendix*).

Dams have been constructed for irrigation, flood control, water supply, navigation, aquaculture, and recreation for over 3,000 y, with hydroelectric power generation emerging later, after the first hydropower dam that was built in Wisconsin in 1882 (5, 6). Hydropower dams are seen as an approach to alleviate the negative impacts of severe drought and flooding that are likely to increase in the coming decades as well (7). Despite these benefits, dams also have been criticized for their negative impacts on people, local ecosystems, and the environment. Their profound impacts on economies, people, and local communities include energy generation, job creation, livelihood change, resident relocation, and others (2, 8–12). The biophysical impacts include alteration of the hydrological processes (13–17), changes in the ecological system (8, 9, 18, 19) (particularly on biodiversity) (20–23), and transformations in land cover and land use (24, 25). For example, in evaluating 12 proposed hydropower dams for the main stream in the Lower Mekong Basin, where many large-capacity dams have been constructed,

Significance

This research provides a global-scale evaluation of the impact of dam construction by using a variety of global spatial databases. In particular, it provides insight into the impacts on economy, population, and greenness of 631 recently built hydropower dams by region and dam size. We discovered that 631 recently built hydropower dams were associated with reduced local economy, population, and greenness in areas within 50 km of the dam sites, particularly in the Global South. This is contrary to claims that dams improve the livelihoods of people as well as ecosystem services. The research highlights that policy interventions are needed to address impacts on populations and urban land near small and medium dams.

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[1] To whom correspondence may be addressed. Email: fanpeile@msu.edu.

[2] Deceased December 25, 2021.

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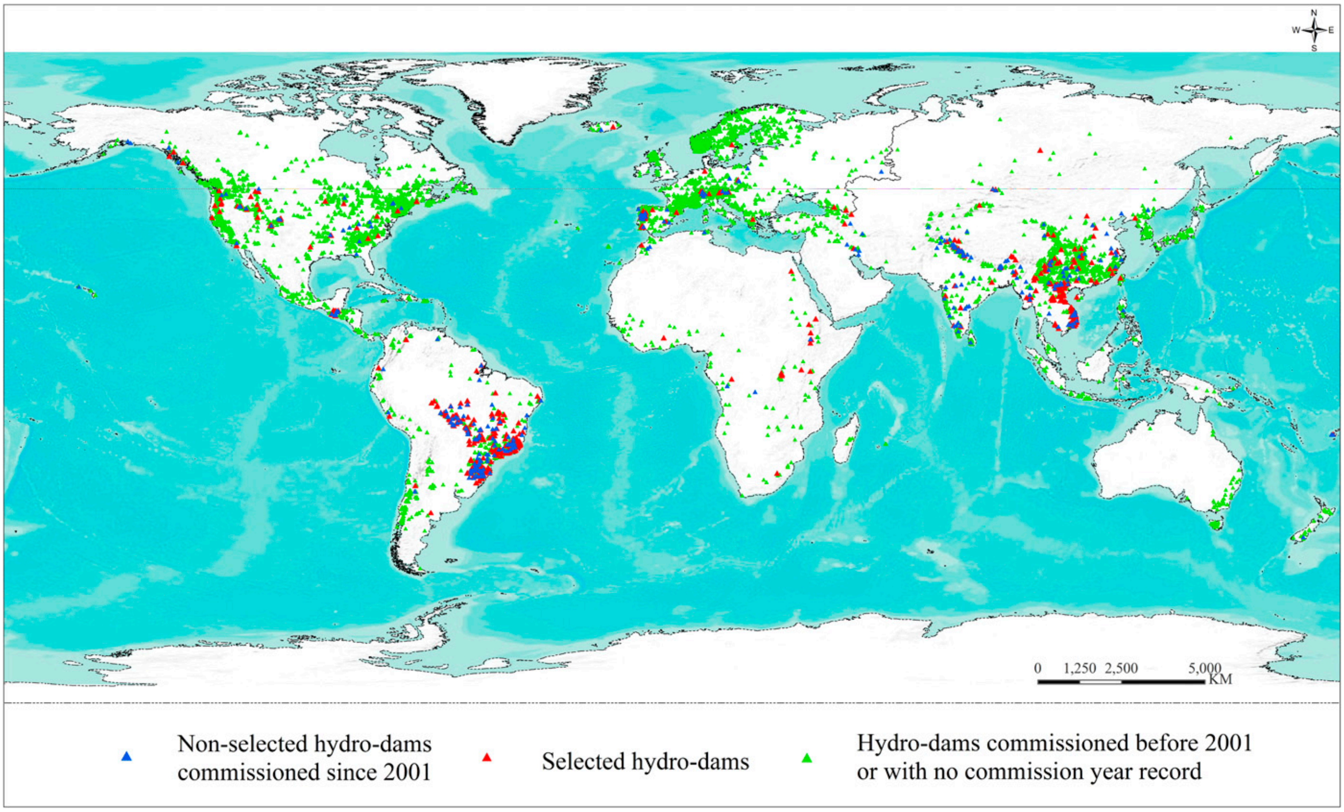


Fig. 1. Distribution of global hydropower dams. Data are based on WRI's Global Database of Power Plants (4). Note that the geographic focus of hydropower dam construction has shifted from North America and Europe to Asia and South America over the past two decades. Out of 7,155 global hydropower dams, 87% (6,200 green triangles) were built before 2001 (or without the commission year recorded), with 64% of these built in North America and Europe; 13% (955 blue and red triangles) were built since 2001, with 81% of these built in Asia and South America. We selected 631 dams constructed after 2001 and commissioned no later than 2015 for our current study (red triangles).

the International Centre for Environmental Management estimated that these projects, if implemented, would increase power security, navigation conditions for large vessels, and foreign investment and economic development for certain sectors; at the same time, they would produce adverse impacts on ecosystem functions, hydrological dynamics, fisheries, agricultural land, and social systems (26).

While hydropower dams are a global phenomenon and will continue to produce fundamental and widespread impacts on energy and economy, there remains a major knowledge gap regarding their benefits and damages to nearby areas of dams around the globe. Three major limitations exist. First, despite the plethora of literature that has evaluated the impacts of individual hydropower dams, there is no comprehensive evaluation of these impacts at a global scale, which is hindered partially by a lack of practical measurements for socioeconomic impacts (11, 27). The lack of global-scale analysis of dams' impacts also prevents us from understanding overall impacts in different global regions and why they have been adopted enthusiastically in certain countries. Second, previous assessments have mostly focused on specific areas, with different definitions of geographical scope, such as fisheries and livelihoods of adjacent rural communities or land cover and land use change and ecological impacts at the watershed scales, thus making cross comparison of impacts difficult. Third, despite the overall benefits or tradeoffs at country/regional levels, there is a lack of analysis on the spatial differences in the benefits and losses to the local economy, population, and environment in nearby areas of dams.

Attempting to fill abovementioned knowledge gaps, we examined the impacts of hydropower dams in the nearby areas of the dams on economy, population, and greenness at multiple spatial scales, both in five regions (i.e., Africa, Asia, Europe, North America, and South America) and by dam sizes. This was made possible due to the availability of multiple open-access, global, spatial databases of land cover and land use, population density, and economy (*Data* and *SI Appendix*). In this paper, we endeavored to answer the research question: What have been the impacts of hydropower dams on economy, population, and environment by region and dam size? Specifically, 1) What is the economy generated and population located within the nearby areas of hydropower dams (NAHDs) in different global regions? and 2) How did economy, population, and environment change for the nearby area as well as along the gradient from the construction site to the edge of the nearby areas among global regions and by dam size?

We hypothesize that the economy generated and population located in the nearby areas of dams are disproportionally higher than those of the land area at the global level and for all regions (H1). This hypothesis is derived based on the facts that population and gross domestic production (GDP) tend to concentrate and cluster according to a variety of factors, with geography of water exerting an influence (rivers, ports, and dams) despite the changed dependence of human's dependence on freshwater bodies (28–30). We further hypothesize that the nearby areas of the dams may experience reductions in economy, population, and greenness (i.e., an indicator of ecosystem function) related to dam construction (H2). This hypothesis is derived based on case studies and consideration that dam construction can cause relocation of economic activity and population and construction of related facilities such as operating rooms or roads that further reduce greenness (31–38). Substantial spatial differences may exist in terms of impact magnitude of dams along the gradient from the construction site to the edge of the nearby areas.

In this paper, we define the NAHDs as a circular boundary within 50 km of a dam. We first calculated total GDP and population in 2015 within the NAHDs of 7,155 hydropower dams. These dams, including information about installed capacity (MW) and years of commission, were listed in the Global Database of Power Plants (4)—one of the most comprehensive and updated databases on global hydropower dams. We then built a database of 631 recently constructed hydropower dams (i.e., dams with installed capacity ≥1 MW constructed after 2001 and commissioned before 2015), for Africa, Asia, Europe, North America, and South America. Our selection of the study period 2001 through 2015 was based on the availability of global databases on the impacts that we were interested in examining. We categorized the dams as large-, medium-, and small-sized by their installed capacity of >300 MW, 10 MW to 300 MW (i.e., >10 MW and ≤300 MW), and 1 MW to 10 MW (i.e., ≥1 MW and ≤10 MW), respectively. We then analyzed the impacts of these 631 dams on economy, population, and vegetation using five quantitative measures from several global spatial databases: economy, nighttime light (visible near-infrared emission) (NTL), population density, and two measures of land cover (*SI Appendix*, Table S1). For changes in economy, we used GDP, urban and built-up land (Urban), and the intensity of NTL (the degree of brightness of NTL). Their differences (i.e., ΔGDP, ΔUrban, and ΔNTL) were calculated by comparing the values 1 y before dam construction and 3 y after being commissioned. Population change (ΔPopulation) was calculated as the change in population density over the same period. We evaluated environmental impact through the change in total greenness by using the Normalized Difference Vegetation Index (NDVI), a measure of vegetation greenness. We acknowledge that NDVI is an extremely simplified measure for environmental impact, as it does not consider other important dimensions, such as biodiversity. To assess impacts of dam construction along a spatial gradient from the construction site, we identified four zones based on distance from the dam. Zone 1 (<5 km), Zone 2 (5 to 20 km), and Zone 3 (20 to 50 km) are in NAHDs, whereas the fourth, the reference zone (50 to 60 km), is outside the NAHDs (*Materials and Methods*).

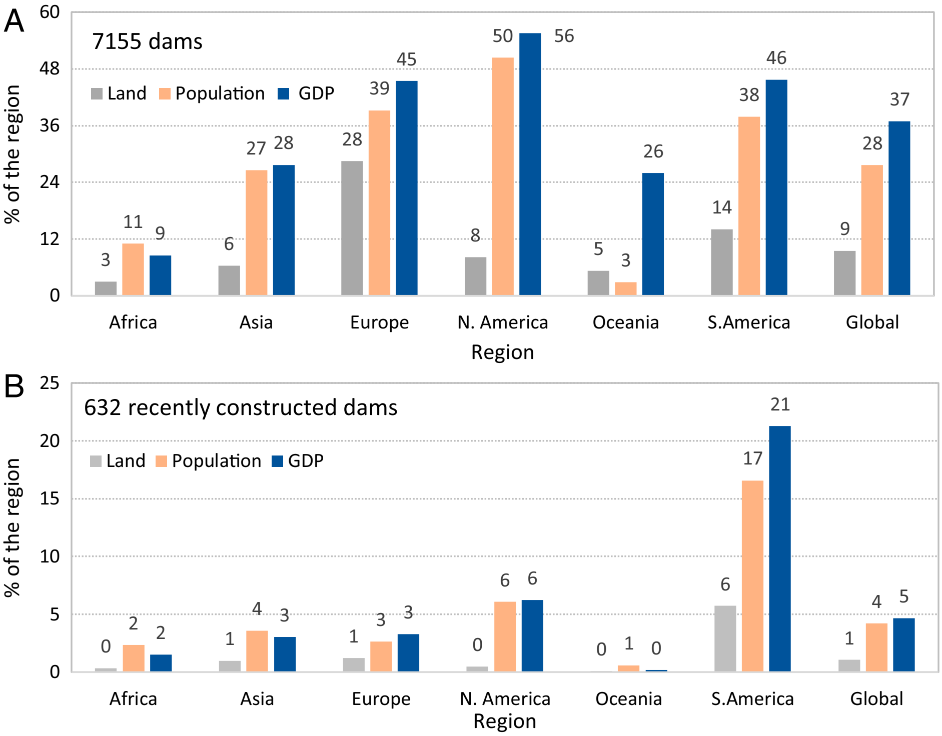
Results

Economy and Population in NAHDs. Globally, a significant proportion of economic value and population fall within NAHDs, especially in North America, Europe, and South America. In total, 37% of global GDP was generated, and 28% of the global population resided in the NAHDs of 7,155 hydropower dams in 2015, which amounted to 9.5% of the land area of these six continents (Fig. 2*A*). NAHDs accounted for 56%, 46%, and 45% of the regional GDP of North America, South America, and Europe, respectively. NAHDs hosted more than half of the population of North America, trailed by European and South American NAHDs, which hosted one-third of their populations. Europe leads in proportion of land areas in the NAHDs, followed by South America and North America.

According to the database of WRI (4), a total of 632 hydropower dams with ≥1-MW capacity were constructed since 2001 and commissioned before 2015, with 333 (53%) being medium sized (*SI Appendix*, Table S2). While only accounting for a small portion (8%) of the global total, these 632 dams nevertheless show a sizable influence on GDP and population within their NAHDs: ∼5% of global GDP and ∼4% of global population in 2015, which occupied 1% of the land area of the continents (Fig. 2*B*). South America distinguishes itself from other regions, where NAHDs, 6% of its land area, amounted to 21% of GDP and 17% of population of the region. In contrast, 3% of GDP, 4% of population, and 1% of land area in Asia and 3% of both GDP and population and 1% of land area in Europe were from NAHDs. Cautiously, our findings are significantly correlative between population and GDP, especially for recently constructed dams, with Pearson correlation coefficients of 0.876 and 0.996, for 7,155 dams and 632 newly constructed dams, respectively (Fig. 2*C*), implying the colocations of economic activities and population. It should be noted that we excluded one dam in Oceania in the analysis for impact of recently constructed hydropower dams (i.e., a total of 631 hydropower dams were analyzed for impact of hydro power construction) (*Study Area*).

Impact of Recently Constructed Hydropower Dams in Global Regions. While our reference area experienced increased economic development, NAHDs showed either a decrease in economic development or a smaller increase than their respective reference areas at the global scale, particularly in the Global South, measured by ΔGDP, ΔUrban, and ΔNTL (Table 1 and Fig. 3). Furthermore, when compared with reference zones, urban land decreased for all zones in NAHDs (−49%, −40%, and −33% for Zones 1, 2, and 3, respectively). NTL seems particularly high in Zone 1 (∼1.0) when compared with Zones 2 and 3 (∼0.2 and ∼0.1). All zones in NAHDs experienced lower GDP, leading to a change of GDP −19%, −27%, and −23% for Zones 1, 2, and 3, respectively, when compared with reference zones. For Asia, South America, and Africa, the average GDP and urban land cover decreased (ΔGDP < 0 and ΔUrban < 0) in Zones 1, 2, and 3 but increased in their reference areas (ΔGDP > 0 and ΔUrban > 0), except in Zones 1 and 2 for Africa (ΔGDP > 0). In contrast, in the Global North (i.e., North America and Europe), the average GDP and urban land cover increased in NAHDs and reference areas (ΔGDP > 0 and ΔUrban > 0). In particular, GDP of NAHDs and each of the Zones 1, 2, and 3 in North America showed three to seven times the increase compared with that of the reference areas; urban land of NAHDs in Europe had five to nine times the increase compared with that of the reference areas. The results indicated that dams were associated with increased GDP in North America and urban land in Europe but decreased GDP and urban land on other continents. NTL, which suggests the economic vitality of a place, increased (ΔNTL > 0) for both NAHDs and reference areas globally, although less increase was observed in NAHDs than in the respective reference areas. Furthermore, NTL decreased (ΔNTL < 0) in North America (all zones), Asia (Zones 2 and 3), and Africa (Zone 3), whereas the NTL values increased in their respective reference areas. The negative ΔGDP, ΔUrban, and ΔNTL of NAHDs, in contrast to their positive values in respective reference areas or smaller increased values of NAHDs than those in reference areas, imply that dam construction was linked with reduced economic production in NAHDs worldwide, except in North America (measured by GDP) and Europe (measured by urban land).

NAHDs showed decreased population across the globe (ΔPopulation ∼ −6.6), which is in contrast to the increased population in the reference zone (ΔPopulation ∼14.8). Population decreased more with increased distance from the construction site within the NAHD, illustrated by the proportion of population change to that of the reference zone (i.e., −16%, −35%, and −46% for Zones 1, 2, and 3, respectively). Asia and South America followed the global trend of decreased population in all zones in NAHDs. While population increased in some zones in North America, Africa, and Europe (ΔPopulation > 0), these increases are much smaller than their respective reference areas, with the highest being 77% of the reference zone level in Zone 2 in Europe. The decrease or the smaller increase of the population indices in NAHDs compared to the positive values of the reference areas implies significant



C

Correlation Coefficient (r) (bolded number indicate the significant correlation)

Global dams 2015	**Land**	**Population**	**GDP**
Land	1.000	0.527	0.557
Population		1.000	**0.876**
GDP			1.000
Newly constructed dams 2015	Land	Population	GDP
Land	1.000	**0.950**	**0.967**
Population		1.000	**0.996**
GDP			1.000

Significance (P value)

Global dams 2015	**Land**	**Population**	**GDP**
Land		0.224	0.194
Population			**0.010**
GDP			
Newly constructed dams 2015	Land	Population	GDP
Land		**0.001**	**0.000**
Population			**0.000**
GDP			

Fig. 2. GDP and population in the nearby areas (50-km radius buffer zones) of dams as a percentage of their respective regions in 2015. (*A*) 7,155 dams. (*B*) 632 recently constructed dams. (*C*) Correlation matrix of the results of *A* and *B*. Note that in 2015, the nearby areas of the 7,155 hydropower dams generated more than 1/3 (37%) of global GDP and hosted almost 1/3 (28%) global population, though they occupied only 10% of land area of the six continents. The 632 recently constructed dams generated 5% of global GDP, hosted 4% of the population, and occupied 1% of land area. North America and Europe led in economy and population hosted in NAHD for all dams, and South America tops others substantially in economy and population in NAHD for recently constructed dams.

negative impacts on population in nearby areas associated with dam construction.

Greenness, reflected by NDVI, decreased within the NAHDs, with the highest reduction found in Zone 1 (ΔNDVI ~ −0.004), a smaller change in Zone 2 (ΔNDVI ~ −0.002), and a minor change in Zone 3 (ΔNDVI ~ −0.001). This contrasts to the increase in reference areas (ΔNDVI ~ 0.013) at the global level. Among the five regions, Africa had the most-significant relative loss in greenness of the NAHDs in comparison with the reference zone (−40%), which is substantially larger than the global average of −6%. Europe and Asia experienced the most-significant decrease in greenness for

Table 1. Impacts of hydropower dam construction illustrated by average changed values of five indices of the buffer zones for different global regions

Region	Global		Africa		Asia		Europe		North America		South America	
$\triangle$GDP (Million dollars)												
Zone 1 (<5 km)	−6,021,947	−19%	19,063,010	78%	−10,991,470	−28%	48,748,587	303%	37,872,421	659%	−18,183,144	−53%
Zone 2 (5 to 20 km)	−8,731,524	−27%	5,705,802	23%	−9,250,586	−24%	12,032,548	75%	30,547,340	532%	−18,622,539	−54%
Zone 3 (20 to 50 km)	−7,381,805	−23%	−7,673,398	−31%	−9,356,665	−24%	8,488,121	53%	15,990,569	278%	−12,002,126	−35%
NAHD (0 to 50 km)	−7,570,664	−23%	−5,399,154	−22%	−9,357,101	−24%	9,422,390	59%	18,392,903	320%	−13,056,998	−38%
Reference Zone (50 to 60 km)	32,326,438		24,433,029		38,767,215		16,102,404		5,746,072		34,614,073	
$\triangle$Urban (km^2)												
Zone 1 (<5 km)	-2.52×10^{-08}	−49%	-3.78×10^{-08}	−64%	-4.38×10^{-08}	−52%	3.12×10^{-08}	941%	4.96×10^{-08}	87%	-3.06×10^{-08}	−97%
Zone 2 (5 to 20 km)	-2.05×10^{-08}	−40%	1.17×10^{-08}	20%	-3.16×10^{-08}	−38%	1.55×10^{-08}	467%	1.97×10^{-08}	35%	-2.54×10^{-08}	−80%
Zone 3 (20 to 50 km)	-1.68×10^{-08}	−33%	-2.83×10^{-08}	−48%	-1.69×10^{-08}	−20%	1.55×10^{-08}	468%	9.15×10^{-09}	16%	-2.49×10^{-08}	−79%
NAHD (0 to 50 km)	-1.74×10^{-08}	−34%	-2.24×10^{-08}	−38%	-1.94×10^{-08}	−23%	1.57×10^{-08}	472%	1.11×10^{-08}	20%	-2.50×10^{-08}	−79%
Reference Zone (50 to 60km)	5.14×10^{-08}		5.93×10^{-08}		8.34×10^{-08}		3.32×10^{-09}		5.68×10^{-08}		3.17×10^{-08}	
$\triangle$NTL (DN)												
Zone 1 (<5 km)	1.0	54%	1.3	65%	0.6	26%	0.5	61%	−0.4	−47%	1.6	87%
Zone 2 (5 to 20 km)	0.2	9%	0.1	4%	−0.2	−8%	0.4	45%	−0.5	−58%	0.5	28%
Zone 3 (20 to 50 km)	0.1	7%	−0.1	−3%	−0.2	−10%	0.4	51%	−0.2	−20%	0.5	24%
NAHD (0 to 50 km)	0.2	8%	0.0	−1%	−0.2	−10%	0.4	50%	−0.2	−26%	0.5	26%
Reference Zone (50 to 60 km)	1.9		2.0		2.4		0.9		0.9		1.9	
$\triangle$Pop (Person/km^2)												
Zone 1 (<5 km)	−2.4	−16%	27.5	49%	−3.2	−15%	−5.2	−210%	4.1	32%	−4.1	−43%
Zone 2 (5 to 20 km)	−5.2	−35%	4.1	7%	−5.8	−27%	0.5	21%	2.3	18%	−7.4	−77%
Zone 3 (20 to 50 km)	−6.9	−46%	−25.2	−45%	−9.0	−42%	1.9	77%	−2.5	−19%	−6.2	−65%
NAHD (0 to 50 km)	−6.6	−45%	−20.3	−36%	−8.5	−40%	1.6	66%	−1.7	−13%	−6.4	−66%
Reference Zone (50 to 60 km)	14.8		56.1		21.4		2.5		13.1		9.6	
$\triangle$NDVI (index number)												
Zone 1 (<5 km)	−0.004	−34%	−0.003	−53%	−0.005	−35%	−0.006	−47%	−0.002	−11%	−0.004	−38%
Zone 2 (5 to 20 km)	−0.002	−15%	−0.004	−73%	−0.003	−26%	−0.003	−22%	0.001	4%	−0.001	−9%
Zone 3 (20 to 50 km)	−0.001	−4%	−0.002	−35%	−0.001	−8%	−0.001	−9%	0.000	−1%	0.000	0%
NAHD (0 to 50 km)	−0.001	−6%	−0.002	−40%	−0.001	−11%	−0.002	−12%	0.000	0%	0.000	−1%
Reference Zone (50 to 60 km)	0.013		0.005		0.013		0.014		0.021		0.011	

Note that the table indicates the average changed values of five indices in different sizes of buffer zones (Zones 1 through 3) in NAHDs and a reference zone in five global regions. It also shows their relative proportions to the changes in the respective reference zones. Globally, these recently constructed dams were linked with reduced economic production, population, and greenness of areas within 50 km of the dams. While recently constructed dams were associated with increased GDP in North America and urban areas in Europe, they were related with decreased economy (reflected by GDP and urban land) and population for the Global South (Africa, Asia, and South America) and greenness for Africa. Furthermore, as distance increases from the construction site to 50 km (from Zone 1 to Zones 2 and 3), while population decreased more, NTL increased less and urban land and greenness decreased less, with GDP declining the most in the area of 5- to 20-km distance to the construction site.

Zone 1 (ΔNDVI ~ -0.006 and -0.005, respectively). Africa and Asia experienced the most-significant decrease in greenness for Zone 2 (ΔNDVI ~ -0.004), followed by Europe (ΔNDVI ~ -0.003). Africa also had the highest decrease in greenness for Zone 3 (ΔNDVI ~ -0.002), followed by Europe and Asia (ΔNDVI ~ -0.001). All regions experienced increased greenness in reference areas, with ΔNDVI of ~0.005, 0.013, 0.014, 0.021, and 0.011) for Africa, Asia, Europe, North America, and South America, respectively. In North America, Zone 3 experienced increased NDVI, but the increase is much smaller than that of the respective reference areas (4%).

It should be noted that there are significant and positive correlations between ΔGDP, Δurban, ΔNTL, and Δpopulation for Zones 1, 2, and 3 and the reference zone, except for Δurban and Δpopulation for Zone 1 (*SI Appendix*, Table S3). The positive correlations imply the possible synergistic effect between economic activities (reflected by GDP, urban land, and NTL) and population.

Impact of Different Sizes of Recently Constructed Hydropower Dams. Overall, NAHDs of all sizes of dams experienced less economic development, indicated by negative or smaller changes in GDP, NTL, and urban land compared to their respective reference areas of −23%, −34%, and 8% (Table 2 and Fig. 4). However, dam size is a factor for quantifying the impacts. First, GDP of the NAHDs decreased ($\Delta\mathrm{GDP} < 0$), while those of the reference zones of all sized dams increased; NAHDs of large dams had the largest GDP decrease when compared with reference zones (−39%), in comparison to −10% and −27% of NAHDs of small and medium dams, respectively. Second, urban land cover decreased ($\Delta\mathrm{Urban} < 0$) for NAHDs but increased for reference zones of all sizes of dams; NAHDs of medium and small dams had a substantially larger decrease compared with the reference zones (−49% and −40%) than large dams (−12%). Third, NTL increased ($\Delta\mathrm{NTL} > 0$) for NAHDs and reference zones of all sizes of dams; however, the increases of NAHDs were much smaller than the increases of their respective reference zones, with the maximum increase of 19% of the reference zone for NAHDs of the small dams.

Population decreased within the NAHD zones of dams of all sizes, but it increased in their reference areas. Population declined more in NAHDs of medium and small dams (ΔPopulation ~ -7.1 to ~ -6.6) than around large dams (ΔPopulation ~ -4). When compared with the reference zones, medium and small dams also showed a larger relative decline (−45% and −49%) than that of the large dams (−28%). While population declined similarly in all NAHD zones for small dams (ΔPopulation ~ -5 to ~ -6), it declined more as distance

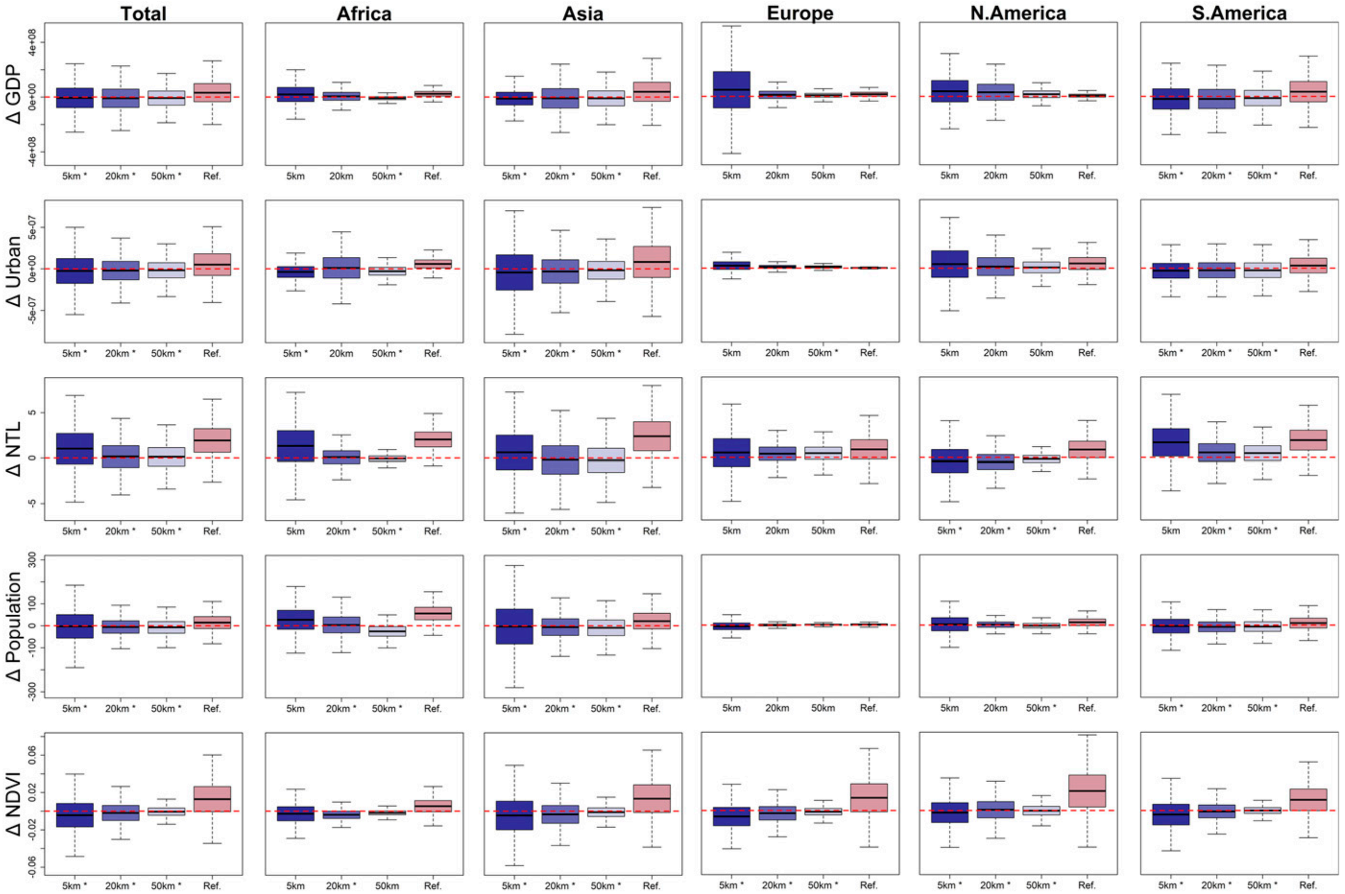


Fig. 3. Impacts of hydropower dam construction on economy, population, and greenness in five global regions. Note that the dashed red lines refer to the average value within the NAHD zones and reference zone. The boxes indicate one SD, and the whisker indicates two SDs. The outliers are defined as observations outside two SDs and are not included for better presentation of the distribution. Hydropower dam construction was associated with less economic development in NAHD zones than their reference areas at the global level, especially for the Global South, as indicated by the negative values of ΔGDP, ΔUrban, and ΔNTL of NAHDs, in contrast to their positive values in the respective reference areas or small increased values in NAHDs over those in reference areas. The decrease or smaller increase of the population indices in NAHDs is in contrast to the positive values of the reference areas. Greenness, measured by NDVI, decreased within NAHDs, with the highest reduction within 5-km distance of the dams. While recently constructed dams were associated with increased GDP in North America and urban areas in Europe in nearby areas, they were related with decreased GDP, urban land, and population in the Global South and greenness in Africa. * at the label means the change for that buffer zone is significant ($P < 0.001$).

increased from medium and large dams (i.e., a significant decrease in Zones 2 and 3 for medium dams [ΔPopulation ∼ −0, −6, and −7 for Zones 1, 2, and 3] and Zone 3 for large dams [ΔPopulation ∼ −1, −1, and −5 for Zones 1, 2, and 3]).

Greenness decreased in all NAHD zones, whereas it increased in all reference areas, with ΔNDVI of 0.000, −0.001, and −0.002 for small, medium, and large dams and 0.012, 0.012, and 0.019 for their reference zones, respectively. Compared with reference zones, large dams showed the highest decline (−11%), followed by medium and small dams (−8% and 0%). Small dams show similar changes as the distance from the dam site increases (ΔNDVI ∼ −0.002, −0.000, and −0.000 for Zones 1, 2, and 3, respectively), whereas large dams illustrate the most-dramatic decreases in greenness (ΔNDVI ∼ 0.008, −0.004, and −0.002, respectively). It appeared that dam construction was coupled with a decrease in greenness, with the largest decline within 5 km, a minor decline within 20 km, and an insignificant change within 50-km radius perimeters, notably for medium and large dams, whereas for small dams, the greenness only changed noticeably within 5 km.

Discussion

Our results support our first hypothesis that NAHDs are important locations for economy and population, despite occupying a small proportion of the land area. This finding is not entirely surprising, as human beings have long inhabited places with easy access to water. Fang and Jawitz studied human population distance to water in the United States from 1790 to 2010 and revealed that water became more important for human settlement locations after industrialization (29). Kummu et al. showed that more than half of the world's population lives within a 3-km distance of a freshwater body, whereas only 10% of the population lives farther than 10-km away (30). The distinction among regions is noteworthy, with North America and Europe leading in economy produced and population hosted in NAHDs for all dams and South America topping others substantially in economy and population in NAHDs for recently constructed dams. This finding is highly associated with the intensified construction of dams in North America and Europe in the 20th century and corresponds well with the industrial development of these nations vis-à-vis the developing world, which only started to industrialize in recent decades.

Our second hypothesis regarding the different impacts in NAHDs compared to the reference zones, distinct patterns for the Global South compared to the North and for dams of different sizes, and spatial differences in the impacts within NAHD were also confirmed. Dam construction was associated with reduced economic production, population, and greenness in NAHDs at the global level. While recently constructed dams

Table 2. Impacts of hydropower dam constructions illustrated by average changed values of five indices of the buffer zones for different sized dams

Dam size	All		Small		Medium		Large	
△GDP (Million dollars)								
Zone 1 (<5 km)	−6,021,947	−19%	9,139,494	29%	−13,273,861	−49%	−20,071,921	−34%
Zone 2 (5 to 20 km)	−8,731,524	−27%	327,899	1%	−10,439,957	−38%	−29,266,543	−50%
Zone 3 (20 to 50 km)	−7,381,805	−23%	−3,825,735	−12%	−6,749,536	−25%	−21,468,156	−37%
NAHD (0 to 50 km)	−7,570,664	−23%	−3,073,038	−10%	−7,368,342	−27%	−22,623,952	−39%
Reference Zone (50 to 60 km)	32,326,438		31,593,303		27,226,239		58,216,089	
△Urban (km^2)								
Zone 1 (<5 km)	-2.52×10^{-08}	−49%	-2×10^{-08}	−47%	-2×10^{-08}	−51%	-7×10^{-08}	−49%
Zone 2 (5 to 20 km)	-2.05×10^{-08}	−40%	-2×10^{-08}	−44%	-2×10^{-08}	−49%	-4×10^{-08}	−26%
Zone 3 (20 to 50 km)	-1.68×10^{-08}	−33%	-2×10^{-08}	−39%	-2×10^{-08}	−49%	-1×10^{-08}	−9%
NAHD (0 to 50 km)	-1.74×10^{-08}	−34%	-2×10^{-08}	−40%	-2×10^{-08}	−49%	-2×10^{-08}	−12%
Reference Zone (50 to 60 km)	5.14×10^{-08}		5×10^{-08}		3×10^{-08}		1×10^{-07}	
△NTL (DN)								
Zone 1 (<5 km)	1.0	54%	0.8	38%	1.2	68%	0.9	44%
Zone 2 (5 to 20 km)	0.2	9%	0.3	16%	0.1	3%	0.2	10%
Zone 3 (20 to 50 km)	0.1	7%	0.4	20%	0.0	−1%	0.1	3%
NAHD (0 to 50 km)	0.2	8%	0.4	19%	0.0	0%	0.1	4%
Reference Zone (50 to 60 km)	1.9		2.0		1.8		2.1	
△Pop (Person/km^2)								
Zone 1 (<5 km)	−2.4	−16%	−6.1	−45%	−0.2	−1%	−1.3	−9%
Zone 2 (5 to 20 km)	−5.2	−35%	−5.2	−38%	−6.3	−40%	−0.7	−5%
Zone 3 (20 to 50 km)	−6.9	−46%	−6.8	−50%	−7.4	−47%	−4.7	−32%
NAHD (0 to 50 km)	−6.6	−45%	−6.6	−49%	−7.1	−45%	−4.0	−28%
Reference Zone (50 to 60 km)	14.8		13.6		15.7		14.4	
△NDVI (index number)								
Zone 1 (<5 km)	−0.004	−34%	−0.002	−15%	−0.005	−44%	−0.008	−40%
Zone 2 (5 to 20 km)	−0.002	−15%	0.000	0%	−0.003	−23%	−0.004	−20%
Zone 3 (20 to 50 km)	−0.001	−4%	0.000	0%	−0.001	−5%	−0.002	−9%
NAHD (0 to 50 km)	−0.001	−6%	0.000	0%	−0.001	−8%	−0.002	−11%
Reference Zone (50 to 60 km)	0.013		0.012		0.012		0.019	

Note that this table indicates the average changed values of five indices in different sizes of buffer zones (Zones 1 through 3) in NAHDs and reference zones for different sizes of dams (small, medium, and large). It also shows their relative proportions to the changes in the respective reference zones. While large dams were associated with significantly reduced GDP and greenness, small and medium dams were linked with more decrease in population and urban land, whereas large and medium dams had noticeably less NTL in nearby areas.

were linked to some positive impacts for the Global North (e.g., increased GDP in North America and urban land in Europe), they were related to reduced economic development (reflected by GDP and urban land) and population in the Global South (Africa, Asia, and South America) and greenness in Africa. While NAHDs of large dams experienced reduced GDP and greenness significantly, NAHDs of small and medium dams witnessed more decrease in population and urban land, whereas NAHDs of large and medium dams had noticeably lower NTL in NAHDs. Furthermore, as distance increases from the construction site to 50 km, while population decreased more, NTL increased less, and urban land and greenness decreased less, with GDP declining the most in the area of 5- to 20-km distance from the construction site. These global-scale findings by region, dam size, and along the gradient from dam sites to the edge of NAHDs together with case-based literature advance our understanding of impacts of dam constructions, and they have important policy implications, as detailed below.

Decrease in economy, population, and greenness is detected within NAHDs, vis-à-vis the locations beyond, especially in the Global South. This implies the need to pay attention to the livelihoods of people who live in NAHDs. In particular, more economic development was generated in some zones of NAHDs in the Global North but not in any zones of NAHDs in the Global South. We suspect that population relocation from NAHDs to reference areas in the Global South is highly associated with the decreased GDP and urban land cover. Furthermore, local communities in NAHDs in the Global South may have been inexperienced in negotiating the benefits of dam construction that can lead to increased GDP or urban land. For example, Lee et al. pointed out the inadequate compensation provided to relocate indigenous communities to accommodate dam construction in Malaysia and the need for greater participation of indigenous communities in the compensation process for large development projects (39). In another case, to construct the Chixoy hydroelectric dam in Guatemala, local communities were forcefully displaced through violence and massacres under the military dictatorship, and people in the communities were left in extreme poverty in the following decades (40). The finding that NAHDs of large dams suffered the biggest declines in GDP seems to support the conclusion that larger dams tend to benefit distant locations rather than nearby areas, as noted in Fearnside and other studies (9). We also speculate that small- and medium-sized dams may tend to bring irrigation benefits to locals, resulting in less decreased GDP than that around large-sized dams. It is interesting that some research has shown positive impacts on economic development illustrated by GDP growth. For example, De Faria et al. found that countries that built hydropower plants had greater GDP and tax revenues than countries that did not build dams (32). Furthermore, irrigated lands can benefit from dam construction, as they have shown smaller GDP decreases during droughts in the whole region of the Lower Mekong River Basin (38). However, case studies in other research have found that dam construction has led to huge social and environmental costs for people living close to dams, such as the review of the construction of dams

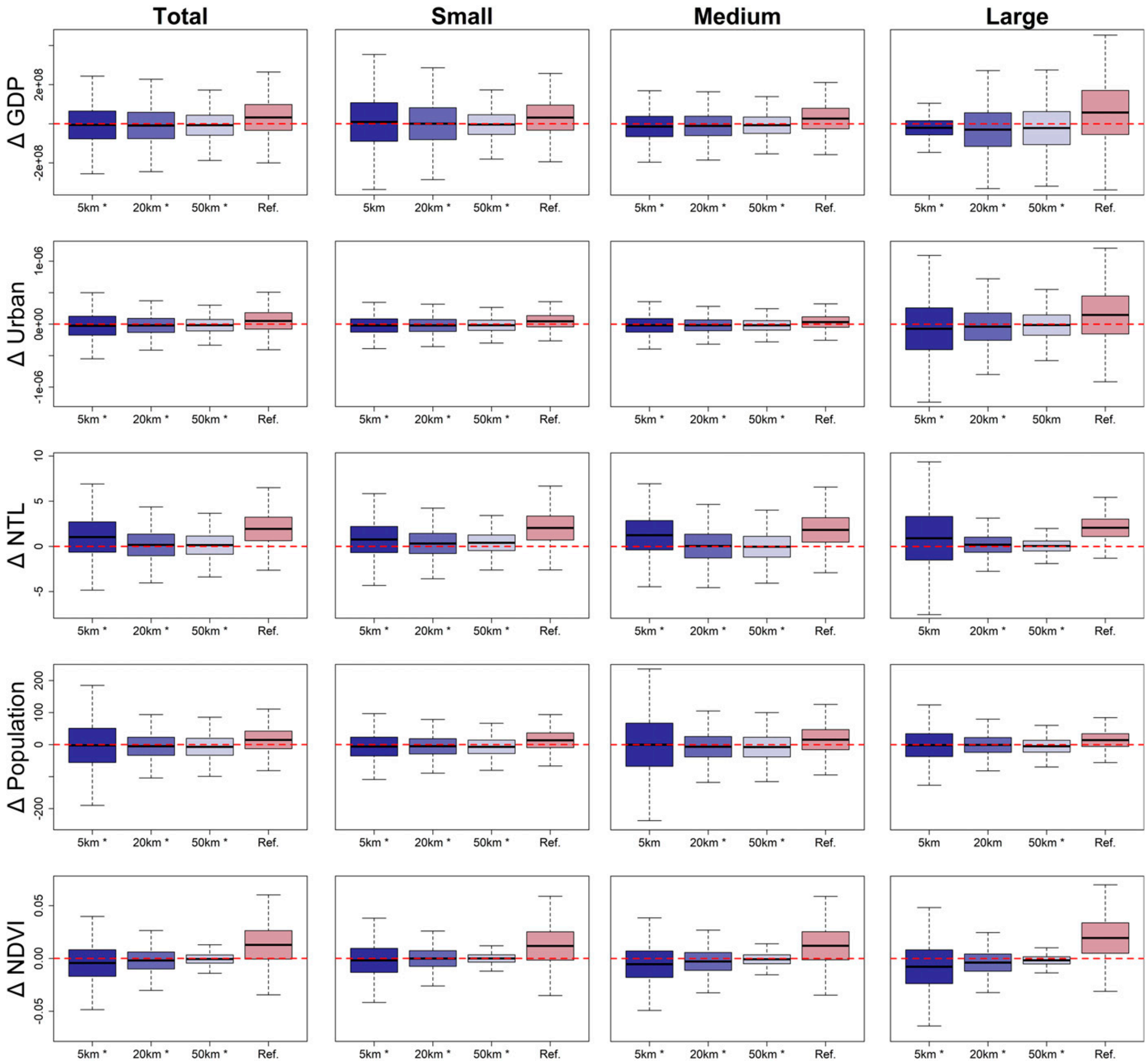


Fig. 4. Impacts of dam construction on economy, population, and environment by dam size. Note that NAHD zones of all sized dams experienced less economic development when compared with their respective reference areas, as indicated by changes in GDP, NTL, and urban land. Population and greenness decreased in all NAHD zones of all sized dams, whereas they all increased in the reference areas.

for aluminum-smelting factories in Brazil; while the dam may have increased the electricity supply for the whole country, the people who were directly affected have received little economic benefit (9). Our findings caution us to consider the spatial differentiation of the benefits and losses of local environment and population, despite the possible overall benefits of dam construction at the country level. Additionally, we note that the different impacts brought to an area may depend on the original landscape (e.g., population density). The Global South has more croplands (45%) than the Global North (24%) but less forest, grassland/shrubland, and built-up areas (34%, 18%, and 0%) than the Global North (46%, 24%, and 1%) in the NAHDs of the 631 dams (*SI Appendix*, Table S4). The differences in original landscape settings may contribute to the difference in the five impacts. For example, the impacts of dams of the same size commissioned in the Amazon, where population density is low, are different from those in heavily populated areas in the Mekong River Basin. It is possible that even corrected internally, the impact would be different.

NAHDs also experienced decreased population density, especially in Asia and South America and particularly around small and medium dams. This implies significant negative impacts on population around dam construction, highlighting the need to assist the relocated residents who are affected by dam construction. There is a wealth of literature studying population relocation, including forced relocation, to accommodate construction of mega and large dams, including the important historical works on Kariba in Zambia by Scudder and Colson (31, 35), the more-recent research surrounding the Three Gorges Dam in China (33, 37), and a study that evaluated the long-term (over 30 y) response of people relocated to make way for the Kinzua Dam in the United States (550 people)

(41). Dam construction often necessitates population relocation away from the NAHD due to water inundation. Our research revealed that relocation is prevalent at global scale, and it is even more distinguished for small and medium dams. This could be because the areas around smaller dams may have a more-habitable environment and thus originally host a larger population very close to the dam construction site. Therefore, construction of smaller dams may lead to more population relocation. Our findings highlight the need to study the population impacts of small- and medium-size dam construction. Furthermore, in addition to the numbers of people relocated, researchers and policy makers should be sensitive to the extremely stressful and emotional experiences of the relocated population. Heming et al. highlighted the misery and hardship caused by involuntary relocation and the discrimination that the resettled population encountered related to the construction of China's Three Gorges Dam (1994 through 2009) (33). Scudder and Colson argued that people and communities respond to the stress of relocations in predictable ways, and policies can be formed to alleviate their distress (36). Furthermore, to deal with relocation stress, Xi and Hwang noted that relocated residents have employed a variety of coping strategies, with the most-effective one being emotion-focused coping strategies (37). While our research does not provide further analysis of coping strategies, we echo the sentiment in these studies that it is necessary to guide public policies to assist relocated populations given the negative impacts on these populations.

Dam construction appeared correlated with decreased greenness, particularly around medium and large dams, with the largest decrease within 5 km. This is consistent with many case studies in the literature, confirmed again with this global study. The findings on the decreased greenness and population in the nearby areas also echo studies that demonstrate impacts of dams on land cover change and population due to water inundation within the 5-km buffer and population relocation (34, 42, 43). The decrease of NDVI may be attributed to deforestation during construction activities, which diminishes as the distance from the dam site increases and at the end of the construction. If so, NDVI may experience a decrease during dam construction and then gradually increase after the dam begins to operate. This pattern is mainly caused by the neighboring land-cover and land-use transition. Specifically, nearby lands may be converted from grassland/woodland to agricultural land due to the hydropower dam support for irrigation. In this case, the NDVI trajectory increases but may not reach the original magnitude before the construction starts. We did not conduct a trend analysis for the annual NDVI change over the period from T1 to T2; that is beyond the scope of current study but important to address in future research.

There are some limitations of this study due to data availability, methodology constraints, and the scope of the paper that suggest possible future research directions. While we were able to examine the economies and populations in NAHDs for all of the 7,155 hydropower dams listed in the Global Database of Power Plants (4), our second research question was limited to dams constructed since 2001 due to the availability of spatially gridded data. Nevertheless, our detailed analysis of five quantitative measures includes all of the 631 hydropower dams (>1 MW) that were constructed since 2001 and were commissioned by 2015. Therefore, our findings present a general and comprehensive picture for all dams over 1-MW capacity. Moreover, our current analyses are performed over two discrete periods instead of as a consecutive time series and thus fail to detect any trend. Furthermore, our analysis did not consider the influence of two or more dams located in a distance smaller than 120 km. Our data shows that one-third of the 631 dams are within a 5-km distance from another dam, and 83% of these dams are within a 50-km distance from another dam. Thus, we may have overestimated the changed values of the indices associated with dam construction for buffer zones/reference areas when linked with multiple dams. Furthermore, using a circular radius around a dam for a buffer zone ignores the anisotropic footprint of dams, as rivers are inherently directional and linear and partially responsible for the directional impacts on surrounding land use and land cover change by dam construction (34). There is also possibility that the influenced area may be extended beyond the 50-km radius. While there is a trade-off between "on-the-ground" realities and the tractability of assessing impacts for a global-scale study, we acknowledge that this is one of the limitations of our analysis. Future research may also examine population dynamics comprehensively at the global scale if data are available. Population in areas around dam construction sites is a result of three combined forces: 1) relocation of the original population, 2) temporary migration of workers who come to work on construction and then leave when it is completed, and 3) migration of residents from other areas to dam areas before and after dams are completed, usually for job opportunities in the area. As our study period covered 1 y before construction and 3 y after completion, we captured the relocation of the original population and people who came to live in areas of the dams after their completion in the population change. We did not capture the temporary construction migrant population in our analysis. In future research, we can consider the use of annual data to fully illustrate the population dynamic before, during, and after the dam construction. Our analytical approach and the global spatial datasets in this paper can also be used to evaluate the impacts of other large infrastructures, such as ports, highways, railroad station, etc. Future research thus can be conducted to compare the differences of impacts of dams from other infrastructures at global and continental scales.

Materials and Methods

Study Area. Globally, the Asian and South American continents have become hot spots for dam construction (Fig. 1), contributing to 80% of the new hydropower dams of medium and large sizes constructed since 2000 (4). A total of 632 dams with an installed capacity of ≥1 MW were constructed after 2001 and commissioned by 2015. Oceania had only one qualifying dam, with an installed capacity of 40 MW, built during our study period. Therefore, we excluded this one dam from our analysis for the second research question, because the statistical analysis that we would perform on Oceania would be meaningless, as it would only reflect the actual value of that particular dam (*SI Appendix*, Fig. S1 and Table S2).

Because we are interested in dams' impacts on areas close to the dams, we define a nearby area as a circular area of 50-km radius around the dam location, following Hossain et al., who called the same area a "dam region." In their study of the impacts of 92 large dams in the US, Hossain et al. found a zone larger than 50-km radius overlapped extensively with neighboring dams (44); therefore, 50 km offered the best approach for identifying a statistically significant stand-alone mesoscale effect with minimal overlap from neighboring dams (42).

Our second research question is to explore the impact of dam construction along the spatial gradient from the construction site to the edge of the nearby area; thus, we use a range of proximity distances that have been widely used in buffer zone analysis for evaluating the human and ecological impacts (e.g., ref. 45). As mentioned in the introduction, Zones 1, 2, and 3 refer to the areas of distance <5 km, 5 to 20 km, and 20 to 50 km from the dam construction site, respectively. We chose 5 km as the smallest buffer radius, based on the influencing distance of land use and land cover impact identified by others as 5 km or smaller (42, 43). We further set the areas beyond 50 km (radius 50 to 60 km) from the dam sites as reference areas, so we can use them to compare the impacts of dams in Zones 1, 2, and 3. We do acknowledge that if a reference zone partly falls into the NAHD of another dam, there is a limitation of it serving as a reference zone due to the impact of another dam.

Data. There exist several popular and widely used global dam databases, such as the aforementioned GOODD, Global Reservoir and Dam Database (GRanD), Future Hydropower Reservoir and Dams Database (FHReD), and WRI Global Database of Power Plants. Among these databases, the georeferenced GOODD contains the highest number of identified and recorded dams, up to

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38,667 by 2020 (1). Yet, GOODD does not provide any information about the dam other than its geolocation (30). In the original GRanD database, a total of 6,862 reservoirs/dams were manually inspected and verified with critical reservoir/dam properties included (e.g., storage capacity [m^3]) (46). An additional 458 reservoirs/dams were added into the GRanD database in 2016 (47). In 2015, the FHReD database was released, and it contains 3,700 dams with associated information (2). WRI's Global Database of Power Plants includes 7,155 global hydropower plants with detailed information on dams, such as installed capacity, geolocation, purpose, status, commission year, and river basin (4). We chose to use WRI data as we used installed capacity (MW) and years of commission to select the dams for our analysis, and the database is relatively up to date compared to others, as it was updated in 2018.

To extract data for our five indices—GDP, urban land, population, NTL, and NDVI—we used several global databases (*SI Appendix*, Table S2). GDP by purchasing power parity data were obtained from the annual GDP dataset derived from national and subnational reported data with temporal interpolation and extrapolation (48). These GDP data were based on subnational data for 85 countries, which covers 85% global population and 92% of global GDP in 2015. It should be noted that due to availability of the latest year of 2015 for the dataset, we analyzed the change of GDP only on 448 dams (i.e., 71% of 631 dams that were commissioned on 2012 and before). Using data of MODIS (Moderate Resolution Imaging Spectroradiometer)/Terra+Aqua Land Cover Type Yearly L3 (MCD12Q1.006 Product) with 500-m spatial resolution and 1-y temporal resolution from the US Geological Survey (USGS), urban land data were extracted from the class Urban and Built-up Lands, following the Annual International Geosphere–Biosphere Program classification (49). Remote-sensing data on NTL emission of the earth provided researchers an alternative source of urbanization, population density, and economic growth (50). The NTL data reflects the artificial light used in our built environment, including buildings, transportation infrastructures, and other facilities. Annual NTL data at 1-km spatial resolution was based on Defense Meteorological Program Operational Linescan System (DMSP-OLS) and Suomi National Polar-orbiting Partnership Visible Infrared Imaging Radiometer Suite (51–54). This dataset was intercalibrated to reduce inconsistency among sensors using the method described in Zhao et al. (55). Population density data were derived from the LandScan with 1-km spatial resolution and 1-y temporal resolution from Oak Ridge National Laboratory (56, 57). NDVI was derived from MODIS Vegetation Indices (MOD13Q1.006 Product) with 250-m spatial resolution and 16-d temporal resolution provided by the USGS (58). We masked out water area using maximum water extents derived from Global Surface Water products provided by the European Commission's Joint Research Centre for NDVI data (47). The annual averaged NDVI was then calculated by averaging all NDVI data of the year via Google Earth Engine. Each value is summarized for Zones 1, 2, and 3 and the reference zone. We use NDVI change as an indicator of greenness fluctuations around the hydropower dams, as NDVI has been used to imply environmental changes in some previous research (59).

Methods. We evaluated the economy and population in nearby areas of dams to address the first research question. Using the population density data (1-km resolution), we first calculated the total population of a region by summing up the population values of all 1 km × 1 km grid cells in a region. Using the dam dataset, we then drew NAHDs around all (newly constructed) dams. We calculated the NAHD population of a region by summing up the populations of grid cells that are in NAHDs of a region. We then divided the NAHD population by total population to get the proportion of population located in NAHDs of the newly constructed dams for that region. To calculate the proportion of GDP in NAHDs, we use a similar method as for population.

We assessed economy, population, and greenness in nearby areas of recently constructed dams to answer research question 2. To check the impacts of dams, we subtracted values in T1 (i.e., 1 y before the dam construction) from those in T2 (i.e., 3 y after the commission), as in Eq. **1**:

$$\Delta Imp_{ibk\Delta T} = V_{ibkT2} - V_{ibkT1}, \qquad [1]$$

where V_{ibkT1} represents the average value of variable i in T1 in buffer zone b of dam k and V_{ibkT2} represents the average value of a variable i in T2 in buffer zone b of dam k. Here, i represents one of the five indices that are measured, and b represents Zones 1, 2, and 3 and NAHD (the sum of Zones 1, 2, and 3), respectively; k represents one of the selected dams. A positive value for $\Delta Imp_{ibk(T2\text{-}T1)}$ indicates an increased value, whereas a negative value for $\Delta Imp_{ibk(T2\text{-}T1)}$ indicates a decreased value of V_{ibk} from T1 to T2. Here we use 1 y before dam construction as T1 to capture the original state of the location in five variables. We chose 3 y after the commission of dam as T2 to evaluate the stabilized impact of dam construction. Biological systems generally take much-longer time to stabilize to reflect the impact of dam construction, as Kingsford found that the water annual flow influence is initially 2% but increases to 21% within 23 y due to dam construction (18). However, Song and Mo, who studied the temporal perspective to dam management in terms of dam influence on the fishery, found that about 90% of fish biomass loss occurs within 5 y of dam construction (60). On average, dam construction for the 631 dams took 6 y, and T2 is set at 3 y after commission (i.e., on average, 9 y after construction), making it a reasonable time to evaluate the stabilized impacts of dam construction, particularly on economy (GDP, urban land, and NTL), population, and greenness. We assume that the nearby area would have followed the same general trend as the larger region (i.e., the reference area) from T1 to T2 if the dam had not been constructed. Therefore, the values of indices in reference area provided contextual information on how the area would have evolved from T1 to T2. Specifically, if the values for $\Delta Imp_{ibk\Delta T}$ of reference areas and NAHD zones have opposite signs (i.e., positive versus negative or vice versa), it implies that dam construction may have led to the opposite trend of the indices' value for NAHDs. For small- and medium-sized dams for which we do not have the construction year, we used 6 y before the commission year as T1, assuming it takes about 5 y for the construction. Readers will be able to access the associated code and materials at the following link: https://github.com/choms516/extract_dam_radius (61).

Data Availability. Associated code and materials have been deposited in GitHub (https://github.com/choms516/extract_dam_radius) (61). All other study data are included in the article and/or supporting information.

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