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PERSPECTIVE

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Hydropower development in South Asia: Data challenges, new approaches, and implications for decision-making

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Abstract

In recent years scholars have advanced our understanding of the biophysical, socioeconomic, and geopolitical impacts of dams and hydropower infrastructure around the globe. Databases and maps have emerged that allow global comparisons between countries and river basins. However, reliable and freely available data do not exist for many regions. As a result, data limitations and quality issues persist, which limit the quality of analyses based on these datasets. This is particularly true in regions where hydropower infrastructure development is proceeding most rapidly, including South Asia's Third Pole region. We identify and describe serious quantitative and qualitative data dilemmas of existing databases. We divide these into location, size, type, and status. At the most basic level, these dilemmas mean that incorrect location and, more importantly, massive underrepresentation of existing and future projects generates incorrect conclusions. That underrepresentation results largely from uncritically equating absence of data with absence of infrastructure. We also argue that project function should be more reliably recorded (for both dams and hydropower projects), that project status should be clear (many existing projects are still passed off as future), and that smaller projects should be systematically recorded (their cumulative importance is often underestimated). These four dilemmas all have important implications for analyses based on existing datasets. The World Index of Hydropower, Dams, and Reservoirs (WIHDR) described here represents a major advance on all four points. For the first time, 652 existing hydropower plants (277 large and 375 small), 162 under construction, and 720 planned hydropower plants have been georeferenced and systematically recorded for the Indus-Ganga-Brahmaputra region.

This article is categorized under:

- Science of Water > Water and Environmental Change
- Water and Life > Stresses and Pressures on Ecosystems
- Science of Water > Methods

KEYWORDS

dams, georeferenced database, hydropower, rivers, South Asia, Third Pole

1 | INTRODUCTION

The "Third Pole"—the Tibetan Plateau and its adjoining mountain ranges—is the largest freshwater reserve outside the polar regions, and the source of some of Asia's largest river basins. In the past two decades, hydropower construction has boomed in these basins, with a more than threefold increase from 2000 to 2020 (Harlan & Hennig, 2022). Much of this development has occurred in China and Southeast Asia, but also in South Asia, with the Indus, Ganga, and Brahmaputra basins (IGB) experiencing rapid growth in installed hydropower capacity.[1] Hydropower in these basins is an important electricity source for 200–300 m people in the Indo-Gangetic Plain (Nie et al., 2021). Many hydropower reservoirs in IGB basins also provide flood protection, irrigation and drinking water.

But rapid hydropower development also threatens adjacent and downstream ecosystems and communities. Dams and reservoirs modify watershed physiography and hydrology, altering river flow and sediment load, deepening and dewatering river channels, and blocking fish migrations (Best, 2019). These changes can deplete fisheries, limit flood pulses, and imperil livelihoods (Tilt et al., 2009). Reservoirs also inundate homes and farmland, requiring resettlement. In transboundary basins such as the IGB, hydropower can generate geopolitical tension and water conflicts (Grumbine & Pandit, 2013). Untangling these cross-border impacts and interdependencies at the basin scale is urgently required in the context of the current boom.

Yet current hydropower data for the IGB region is unreliable, impeding comparative analysis across borders. Most South Asian countries do not have publicly available georeferenced databases of hydropower projects in operation, under construction, or planned. This limitation forces analysts to compile their own databases based on out-of-date and often unverified public records (e.g., province- or state-level records, generation and grid company reports, local news, or CDM documents). The result is a high probability for error, including mistaking all dams for hydropower projects, mis-recording the location of powerhouses, ignoring plants below a certain installed capacity, and misjudging the status of future projects.

The purpose of this perspective piece is twofold. First, we identify and describe four data dilemmas that hamper hydropower analysis and decision making in South Asia and globally: type, location, size, and status. We then introduce a new database developed by Author 1—the World Index of Hydropower, Dams, and Reservoirs (WIHDR)[2]—to illustrate how these dilemmas can be resolved. We focus specifically on data limitations and WIHDR's contributions to understanding present and future hydropower development in South Asia's IGB basins.

2 | CURRENT DATABASES

Several global dam and hydropower databases are currently in use. The International Commission on Large Dams (ICOLD) is the largest with 58,700 records, but it is not georeferenced and is rarely used by scholars. Three others—the Global Reservoir and Dam Database (GRAnD) (Lehner et al., 2011), Future Hydropower Reservoirs and Dams (FHReD) (Zarfl et al., 2015), and GlObal geOreferenced Database of Dams (GOODD) (Mulligan et al., 2020)—were combined into a fully georeferenced consensus database called Global Dam Watch (GDW). These databases together hold approximately 50,000 records, though with significant overlap and only limited relevance for existing hydropower. Other georeferenced databases include some existing hydropower projects (e.g., GEO/Global Energy Observatory, GPPD/Global Power Plant Database, OIM/Open Infrastructure Map), but the representativeness and accuracy of the spatial data is limited and highly variable across watersheds or political boundaries. Moreover, smaller mapping initiatives such as maps produced by the South Asian Network on Dams, Rivers, and People (SANDRP) and Alley et al. (2014) show existing and planned hydropower installations on a number of Indian Rivers.[3] Data for these maps was derived from and cross-checked with multiple non-governmental organizations and groups, such that data quality is high.

Many studies have used GRAnD, FHReD, GOODD, and other databases for important scientific advances: assessing river fragmentation and how it affects freshwater biodiversity (Grill et al., 2019); analyzing how site selection influences environmental impacts (Winemiller et al., 2016); and understanding how hydropower development affects land-use change and climate resilience (Moran et al., 2018). Yet while these databases represent significant advancements over the paucity of data previously available, limitations remain.

3 | FOUR DATABASE DILEMMAS

3.1 | The location dilemma

The first limitation arises from incomplete or inaccurate georeferencing in the IGB basins. The GRAnD database has relatively accurate coordinates, but excludes many projects completed after 2000 and does not provide any hydropower-specific information (esp. installed capacity). FHReD is very error-prone in its locational data, and in many regions (including IGB basins) it represents only a limited selection of future projects. In most cases, determining the spatial location FHReD's projects is very difficult or impossible. Many coordinates are simply wrong, or discrete projects are intermingled in the data (especially in multi-dam cascades).

Figure 1 visualizes this dilemma on a 100-km stretch of the Sutlej in the Indus basin, located in the Indian state of Himachal Pradesh. GRAnD and FHReD list eight future projects and no existing large reservoirs for this stretch. Yet most of their site data is inaccurate, at minimum several kilometers from the actual site, and in several cases on a different watercourse. Such inaccuracies are symptomatic for the whole study area and also for many regions worldwide.

WIHDR addresses this locational dilemma by using multiple sources (satellite imagery, maps, publicly available documents) to cross-check coordinates for existing powerhouses and larger dams. WIHDR also includes a systematic survey of all planned hydropower projects >10 megawatts (MW), including their planned location. This time-consuming process allows us to provide reliable data (including current status) and to pinpoint exact locations of projects. The result is a major qualitative and quantitative advance to current data limitations. On the Sutlej in Figure 1, for example, WIHDR offers coordinates for 43 hydropower plants, more than five times that of GRAnD and FHReD, and with greater accuracy.

3.2 | The size dilemma

A second dilemma concerns the lack of data on small hydropower projects in IGB basins. In general, large dams are better studied and documented than small dams. Similarly, large hydropower projects are better known than small projects. This limitation is important, as small projects can have major negative environmental and social impacts that cumulatively surpass those of individual large projects (Kibler & Tullos, 2013). Moreover, small hydropower is booming alongside large hydropower in many parts of the world, especially in our study area (Ptak et al., 2022).

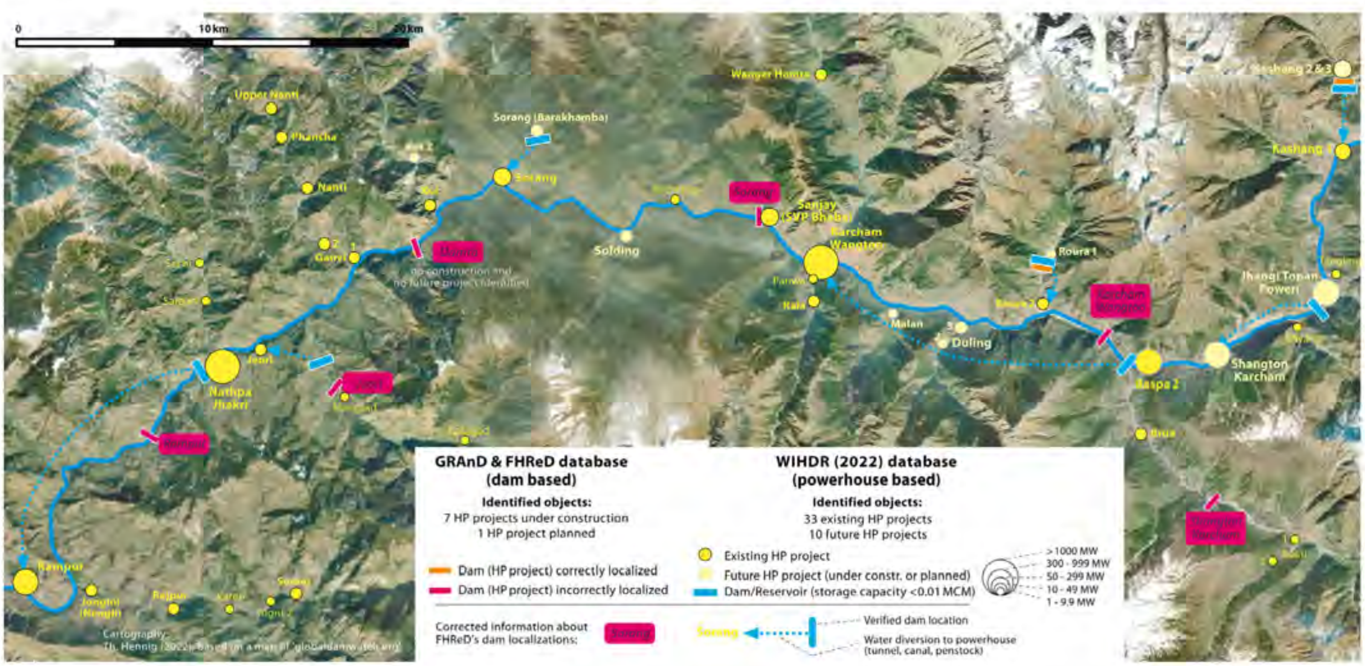

FIGURE 1 Example region Sutlej river (Indus basin): Qualitative and quantitative comparison of the databases (GRAnD/FHReD lists no existing and eight future projects, while WIHDR records 33 existing and 10 future projects).

Two main issues give rise to this small hydropower data limitation. The first is the lack of a global definition of "small." The United Nations Industrial Development Organization (UNIDO) categorizes all projects <10 MW as small (UNIDO, 2019). Yet few countries have adopted this definition (Kelly-Richards et al., 2017). Instead, definitions range from <5 MW (Laos) to <50 MW (China) (ICSHP 2016). This fuzziness extends to current databases, with some using installed capacity, and others using dam length/height and/or reservoir capacity.[4] As a result, small plants are de-emphasized or not included in these databases.

The second issue is that relevant information for small hydropower is very difficult to collect. Often, key data such as location, installed capacity, type (diversion-type, dam-type, run-of-river), and status are not publicly accessible or updated. Small hydropower projects below a certain size are often approved by local governments, such that higher-level officials may not have the most current information. Moreover, small hydropower projects can also be built more rapidly than large hydropower, so that databases require constant updating.

WIHDR largely resolves this dilemma by including an estimated 80%–90% of current small hydropower projects in IGB basins. In this novel contribution, we identify approximately 520 operating small hydropower projects <50 MW with a combined capacity of 5.8 gigawatts (GW) in the IGB region (of these, 373 are <10 MW). Some 80% of those were built after 2000, making them a substantial part of the current boom. Figure 2 shows all hydropower plants we have identified with generating capacities from 1 MW to more than 1000 MW in the region. The density of dams, even relatively small ones, will have significant biophysical, socioeconomic, and geopolitical impacts.

3.3 | The type dilemma

A third dilemma arises from confusion around hydropower projects and reservoirs, and the fact that dams built for hydropower tend to come under greater scrutiny, and receive greater backlash, than dams designed strictly for flood control, drinking water, or irrigation. Moreover, dam-type hydropower projects are also viewed as more harmful than

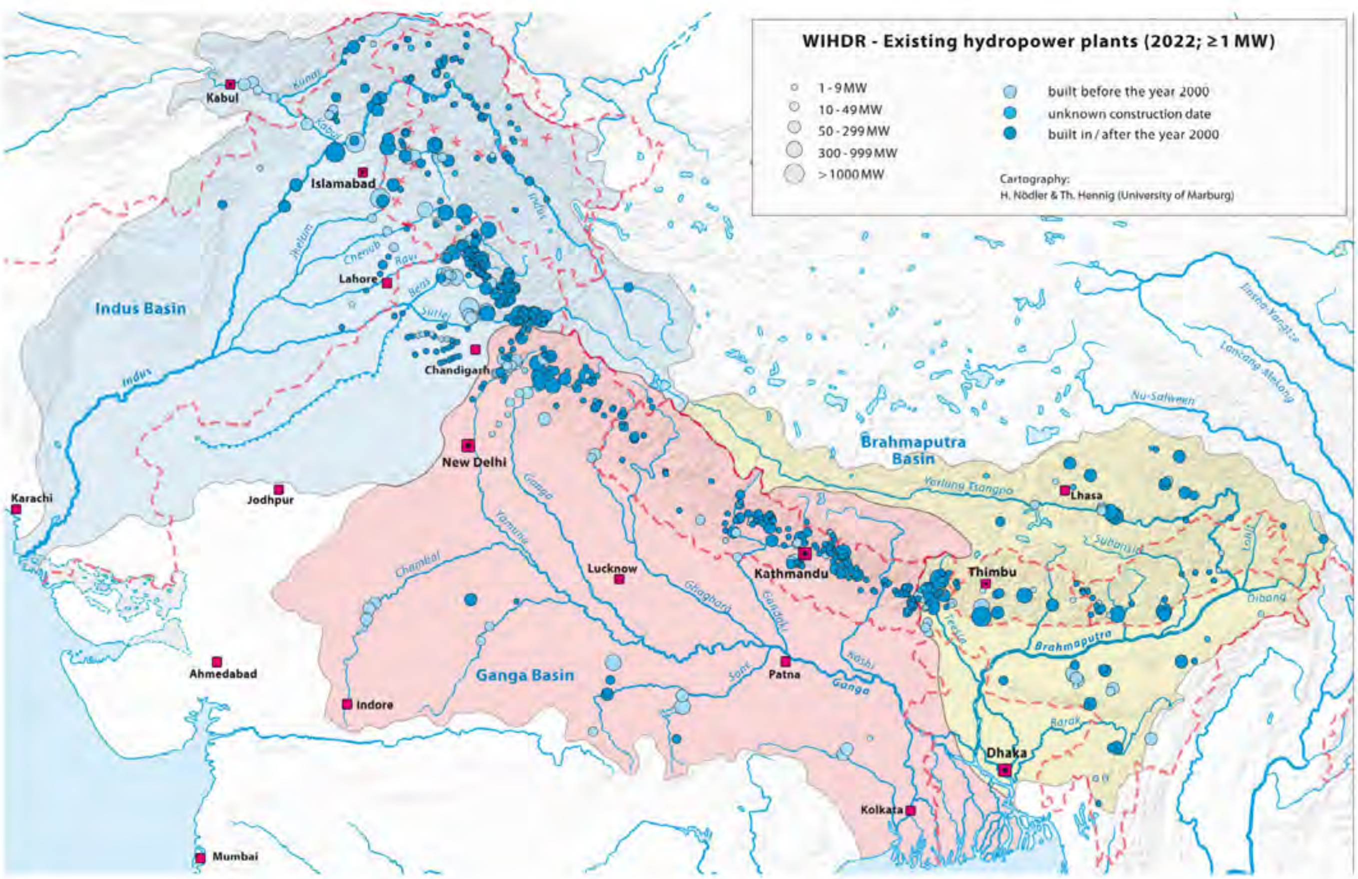

FIGURE 2 Map of existing hydropower plants (>1 MW) in the IGB basins.

run-of-river projects, despite ongoing debates about the significant (and cumulative) impacts of the latter (see Anderson et al., 2015). Regardless of whether such increased scrutiny is justified or not, the size and structure of a particular hydropower project and (if applicable) its dam and reservoir are vital criteria for evaluating that project's biophysical and socioeconomic impacts. A large hydropower project may indeed have a large reservoir, but not necessarily, and many large reservoirs have nothing to do with hydropower. A database that systematically describes key attributes of hydropower projects is crucial for advancing understanding of the impacts of those projects, and from the synergistic impacts arising on basins having multiple projects.

In our IGB basin study area (including its Deccan section), WIHDR identifies 132 existing large HPs (≥50 MW) and a comparable number of 94 existing large reservoirs (≥100,000 m^3) and 31 large diversion barrages (see Figure 3); in 88 of those reservoirs or barrages hydrogeneration plays no or only a negligible role. The situation in the Karakorum-Himalaya-Tibetan Plateau region is different. There, we identify 110 large hydropower projects and 36 large reservoirs; in 30 of those reservoirs hydropower plays a key role, and the number of dams meeting ICOLD's "large" definition (≥15 m high) is much higher. In this area, most of the hydropower dams have small to moderate water storage, meaning limited flow regulation capability. In the plains, however, regulation capacity resulting from water storage projects is much more relevant.

Each hydropower project in the WIHDR database has at least one dam, and most large hydropower projects fulfill the ICOLD criteria for large. Still, the storage capacity of the associated reservoirs is often extremely low. Among the three major basins, the existing storage volume in the Indus basin is 47 km^3—four times that of the current combined storage volume in the Ganga and Brahmaputra basins. The Indus and most of the Ganga have large barrages in the Himalayan foothills used for agricultural water diversion. In the Indus basin, which receives the greatest amount of glacial meltwater, most storage is due to large storage schemes in the upper reaches.

In the Karakoram-Himalaya we identified 29 proposed large storage schemes (≥1 km^3), having a combined future storage capacity of about 120 km^3. The future schemes and storage capacity in the Ganga and Brahmaputra basins are

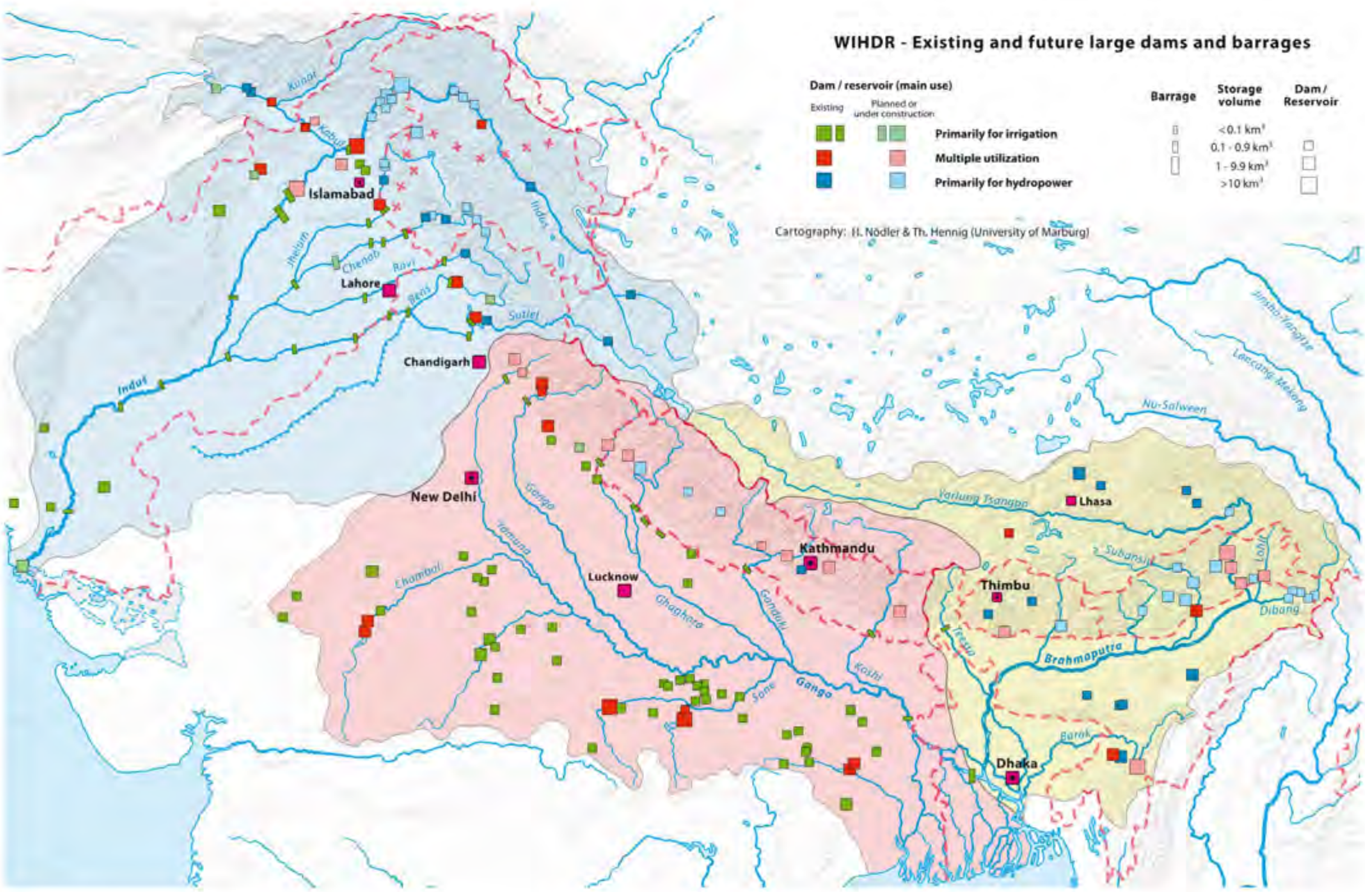

FIGURE 3 Larger storage schemes (dams/reservoirs >100 MCM) and their primary use, as well as major barrages (water diversion schemes feeding large irrigation canals).

comparable (Ganga 12 projects, about 45 km^3; Brahmaputra 12 projects, about 50 km^3). More than half of the future storage capacity (60 km^3) comes from only seven multipurpose projects. Currently four multipurpose projects are under construction (Kishau, Lower Subansiri, Diamer Basha, and Kurram Tangi) and another 10 are in advanced planning (most of them are also multipurpose projects). Most storage schemes planned for the upper sections are primarily intended for hydropower generation. Independent from storage capacity, we identified at least 100 proposed dams exceeding 50 m in height (there are likely more than this for which data are not yet available). These dams present some risk in the event of seismic events or failures.[5]

A comparison of the IGB region to other parts of Asia is instructive. Southwestern China has experienced a recent boom in dam construction, with significant water storage structures, mostly hydropower-related, now developed in Yunnan, Sichuan, and the Tibetan Autonomous Region (and more are on the way). Storage capacity on the Lancang River (upper Mekong), is already comparable to that of the entire Indus basin, while storage in the upper Yangtze tributaries alone exceeds that of the entire IGB area. Farther to the west, the mountainous areas of Central Asia and their endorheic rivers also hold significant water storage, most of which is dedicated to irrigation.

Understanding project type and storage volume is crucial for understanding socioeconomic impacts. Existing storage projects in the IGB region have already displaced 250,000–300,000 people. Hundreds of thousands more have also been displaced outside the IGB. Not surprisingly, projects in densely-populated downstream areas are often heavily contested, such as the Lower Subansiri dam in Arunachal Pradesh, which was stalled for more than 10 years before finally recommencing in 2020. Other projects in advanced planning phases have seen similar delays. Climate change presents its own set of risks to large storage schemes, ranging from increases in the number of noxious species to declines in water quality.

In transnational basins, large upstream hydropower projects are often vulnerable to geopolitical tremors, mainly related to water storage (flow regulation) and potential water diversion. Geopolitical tensions exist in the Indus basin about possible non-fulfilments of conditions laid down in the Indus Water treaty. Tensions have also increased in Brahmaputra basin, especially on the main river (named here Yarlungzangbo in Tibet and Siang in Arunachal). In 2021, when China renewed its commitment to build the controversial Medog Dam (the world's largest hydropower plant), India responded by prioritizing its plan to build Middle Siang, one of the largest reservoirs in the entire Himalaya-Karakoram. The site is in close proximity to the Chinese project and would be India's largest hydropower plant.

On the other hand, some IGB large (multipurpose) storage schemes require greater cooperation between neighbors, especially regarding water usage (irrigation) and electricity usage (export of hydroelectricity). This is especially relevant for proposed projects in Nepal and Bhutan.

Reliable data on dams and related water-control infrastructure is vital to understanding those structures' impacts on environmental flows, fish passage, and other ecological outcomes.

3.4 | The status dilemma

Increasing renewable energy is one of the UN's Sustainable Development Goals, and hydropower remains key to that effort (International Energy Agency, 2021). Modeling future hydropower is crucial if we are to accurately assess benefits (e.g., expected contribution to renewable output) in relation to costs (e.g., ecological and social impacts). In the IGB region, a solid understanding of future trends will allow researchers to assess challenges such as how flow regimes may change in response to climate change, what proportion of the region's growing energy demand can be met by hydropower, and how to plan for mitigating the impacts of hydropower development.

While many governments have conducted hydrogeological studies to identify suitable sites for future hydropower development, the only significant attempt to aggregate and spatially display these data is FHReD. Based on this dataset, Zarfl et al. (2019) identified a global total of 3700 hydropower dams with generating capacity >1 MW, either under construction or in the planning phase, as of 2014. These data and other smaller databases compiled by national governments (Sharma et al., 2022) have been used for estimating the spatial overlap of future dam development and freshwater biodiversity (Zarfl et al., 2019); identifying trade-offs between energy production, conservation and sustainability goals (Winemiller et al., 2016); and improving environmental laws and policies (Grumbine & Pandit, 2013; Moran et al., 2018; Sharma et al., 2022).

Data availability and quality, however, remain key challenges for such studies. Because of rapid hydropower expansion globally, more than 75% of extant projects (>1 MW) in the IGB basins were built after the year 2000. Depending on the definition, the number of "future projects" can vary considerably. At what point—surveying, planning, designing, or otherwise—should a potential project be considered a future hydropower project? Erring on the liberal side (including hydropower projects that are not actively under construction but have been identified in geological studies or economic feasibility studies) risks including an overly large number of projects, many of which may never be built. On the other hand, erring on the conservative side by including only projects under construction or close to commissioning risks leaving out potentially important cases and underestimating future impacts. This decision whether

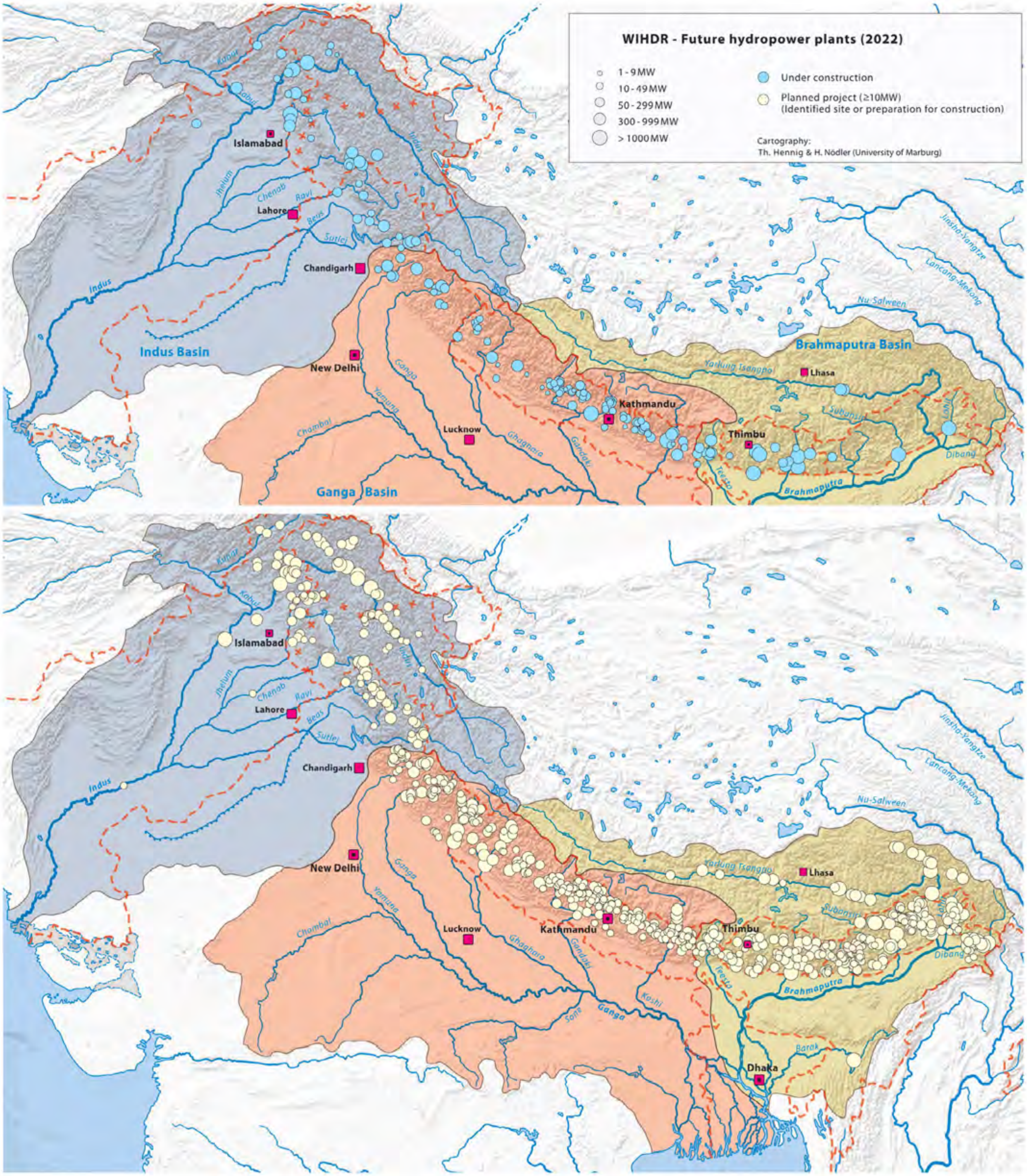

FIGURE 4 Future projects in the IGB (under construction and planned).

or not to include "future projects" is further complicated by the long timeframes, multiple phases, and chronic delays associated with hydropower in the IGB—what Lord et al. (2020) describe as complex "temporalities" of hydropower development.

The WIHDR database includes approximately 160 hydropower projects currently under construction in the IGB area and 720 large projects (≥10 MW) in the development pipeline (see Figure 4), as well as all projects designated for future construction. The database also includes 1020 small hydropower projects (<10 MW) that are under construction or planned. Most of these do not appear in the FHReD database on future dams.[6]

In terms of projects currently under construction, the IGB area leads the world, both in number and in total generating capacity. In the Brahmaputra Basin, we identified 330 projects greater than 10 MW currently in the development pipeline, with a combined future capacity of nearly 140 GW, making it the world's most important future basin in hydropower terms. On the Yarlung Tsangpo, the Brahmaputra's largest tributary, Chinese officials in 2021 announced plans for the 60 GW Medog Dam, with three times the generating capacity of the Three Gorges Dam. Such megaprojects carry great risks, particularly given the tense relationship between India and China (Donnellon-May, 2022).

4 | CONCLUSION

We have identified and described four basic data dilemmas—location, size, type, and status—that currently hamper science and decision-making on hydropower. These dilemmas apply globally but are perhaps most pronounced in the Third Pole region, which contains the greatest volume of ice and snow after the Arctic and Antarctic. Even as climate models project decreased snow cover and loss of glacial mass leading to long-term flow reductions (Nie et al., 2021), installed hydropower capacity in the Third Pole grew fourfold between 2000 and 2020 (Harlan & Hennig, 2022). Such a disconnect brings into question the logic of billions of dollars of infrastructure investments, the long-term impacts on human communities and ecosystems fragmented by such development, and the local and transboundary peace and stability in a region known for water-related uncertainty.

It is crucial that scientists and policy makers acknowledge the limited availability and quality of existing data and work to address these gaps. Focusing on the Indus, Ganga, and Brahmaputra basins, we have described here a new database—the World Index of Hydropower, Dams, and Reservoirs (WIHDR)—that takes steps toward addressing existing dilemmas, giving us better insight into the sustainability of current and future hydropower development in this region. We recognize that WIHDR is also a snapshot of reality, and that "comprehensive" database of water infrastructure projects will always be so. The combination of exhaustive georeferencing and careful attribute validation; however, positions WIHDR to be a valuable tool for future research that will advance the state of knowledge of hydropower dams and their impacts.

AUTHOR CONTRIBUTIONS

Thomas Hennig: Conceptualization (equal); data curation (lead); funding acquisition (lead); investigation (lead); methodology (lead); writing – original draft (supporting); writing – review and editing (supporting). **Tyler Harlan:** Conceptualization (lead); writing – original draft (equal); writing – review and editing (supporting). **Bryan Tilt:** Conceptualization (equal); project administration (lead); writing – review and editing (equal). **Darrin Magee:** Conceptualization (supporting); project administration (supporting); writing – review and editing (equal).

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CONFLICT OF INTEREST STATEMENT

The authors have declared no conflicts of interest for this article.

DATA AVAILABILITY STATEMENT

Data available on request from the authors. Sample data provided to reviewers.

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ENDNOTES

[1] "Capacity" can refer to a dam's reservoir volume or the size of its hydroelectric generators. Watts (or multiples thereof, like kW, MW, GW) are used for generating capacity, while cubic meters (m^3, MCM, km^3) indicate reservoir volume.

[2] The WIHDR database draws upon both existing georeferenced databases and non-georeferenced documents from specific countries. Georeferenced databases include GRAnD, FHReD, GEO/Global Energy Observatory, GPPD/Global Power Plant Database, and OIM/Open Infrastructure Map. These databases have much missing data and inaccuracies, but together provide a starting point for WIHDR. Non-georeferenced documents include country-specific hydropower/dam registries and maps such as: State Profiles for Hydro Development and AHEC-IITR/SHP Reports on Indian States (India), Pakistan Water & Power Development Authority (Pakistan), Nepal Water Resource Portal (Nepal), and National Transmission Grid Master Plan (Bhutan). WIHDR also uses project design documents for infrastructure financed by the Clean Development Mechanism. For all existing plants and those under construction, exact locations were cross-checked using Google Earth, Google Maps, and Open Street Maps.

[3] SANDRP maps are available at https://sandrp.in/themes/basin-maps/; Nepal Hydropower Portal is available at (https://hydro.naxa.com.np/). The latter was first developed in 2015 where it was initially designed as a public-facing decision support tool, responding to data scarcity in Nepal.

[4] FHReD includes dams with a hydropower capacity >1 MW. GRAnD includes dams with reservoir capacity >0.01 ha. GOODD includes dams with a reservoir length >500 m and a dam wall length >150 m.

[5] For more on seismic risk in Nepal and India, see Huber (2019), Butler and Rest (2017), and Lord (2018).

[6] FHReD represents ~40% of WIHRD's large projects (georeferenced) and ~15% WIHDR's small projects (non-georeferenced).

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