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Dams in the Mekong: A comprehensive database, spatiotemporal distribution, and hydropower potentials

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Abstract. Dams have proliferated along the Mekong, spurred by energy demands from economic development and capital from private companies. Swift dam evolution has rendered many databases outdated, in which mismatches arise from differing compilation methods. Without a comprehensive database, up-to-date spatial assessment of dam growth is unavailable. Looking at future development, hydropower potential specifically within the Mekong remains to be systematically evaluated. In this paper, we offer (1) an open-access and unified database of 1,055 dams, (2) a spatiotemporal analysis of dams on a sub-basin and country level from the 1980s to the post-2020s, and (3) a grid-based assessment of the theoretical basin-wide hydropower potential, using present-day discharge from the CaMa-Flood model (2011-2015, 0.05 degree), and future discharge from the WaterGAP2 model used for ISIMIP2b (2021-2030, 0.5 degree). The dam count of 1,055 is more than twice the largest existing database, with 608 hydropower dams generating a boom in hydropower capacity from 1,242 MW in the 1980s to 69,199 MW post-2020s. While China had the largest capacity increase from the 2000s to the 2010s (+16,854 MW), Laos has the most planned dams and the highest projected growth post-2020s (+18,223 MW). Based on present-day discharge, we estimate a basin-wide hydropower potential of 1,334,683 MW, where Laos is the highest at 514,887 MW. Based on future discharge modeled with climate change, hydropower potential could grow to over 2,000,000 MW. Laos and China are the highest at around 900,000 MW each, together forming over 80% of the total potential. Our database facilitates research on dam-induced hydrological and ecological alterations, while spatiotemporal analysis of hydropower capacity could illuminate the complex transboundary electricity trade. Through both spatiotemporal and hydropower potential evaluation, we address the current and future vulnerability of countries to dam construction, highlighting the need for better planning and management in the future hydropower hotspot Laos. The Mekong dam database is publicly available at https://doi.org/10.21979/N9/ACZIJN (Ang et al., 2023).

https://doi.org/10.5194/essd-2023-417
Preprint. Discussion started: 3 November 2023

1 Introduction

Dams have been constructed to control and harness the flow of water for human needs over thousands of years. Within the Mekong Basin, the longest river in Southeast Asia, dams have burgeoned in response to rising energy demands for economic development and growing populations (Hecht et al., 2019; MRC, 2023; Zarfl et al., 2015). Despite being an attractive alternative to depleting fossil fuels, the proliferation of dams comes with environmental and social trade-offs (Schmitt et al., 2018). Dams modify water flow and block migratory pathways, fragmenting habitats and disrupting the breeding and feeding patterns of aquatic species (Barbarossa et al., 2020; Grill et al., 2014). This has crippled the world's largest inland fishery and threatened the income of over four million Laotians and Cambodians in the fishing industry (Dugan et al., 2010). Dams reduce sediment and freshwater discharge downstream, and when coupled with rising sea levels, lead to erosion and saltwater intrusion in the Mekong Delta (Li et al., 2017; Park et al., 2022; Yoshida et al., 2020). Considering that the Mekong is home to two of the global top five rice exporters – Vietnam and Thailand – where the Vietnam Delta and the Khorat Plateau in Thailand produce 75% of the rice in the Lower Mekong Basin (LMB), dam-induced agricultural losses are jeopardizing regional food security (Kang et al., 2021; The Anh et al., 2020). The livelihoods of locals are further affected by forced resettlements to make way for dams, especially with insufficient policies to assist locals in adapting to new living environments and finding alternative sources of income (Soukhaphon et al., 2021). This multitude of dam impacts, alongside disputes over water resources, have created a complex geopolitical landscape across the six countries that share the Mekong Basin (Cooley et al., 2009; Cronin, 2009; Hirsch, 2016).

The dam distribution in the Mekong is constantly evolving. Dams are a relatively low-cost electricity source, making them an attractive fuel for economic development (IRENA, 2022). Nevertheless, poor planning and management, together with embezzlement of construction funds, leave dams just as easily canceled as they were approved (Matthews, 2012). The dam network therefore changes erratically, yet data on it is necessary to assess the socio-environmental implications of dams, manage operations across the network, and guide policy making regarding water and energy resources (Galelli et al., 2022; Speckhann et al., 2021). Various databases have been published to track the dams. Globally, the AQUASTAT database by the United Nations Food and Agricultural Organization (FAO) contains 14,000 dams, of which only 31 lie in the Mekong, as updated in 2015 (X. Wang et al., 2022). More recently, the Global Reservoir and Dam Database (GRanD) updated in 2019 consists of detailed information on 7,320 dams, although only 38 are in the Mekong (Lehner et al., 2011). The Global georeferenced Database of Dams (GOODD) contains 38,667 dams (319 in the Mekong), but the increase in quantity is compromised by a lack of dam attributes (Mulligan et al., 2020). With both quantity and details, the Georeferenced global Dams and Reservoirs (GeoDAR) consists of 24,783 dams (105 in the Mekong), yet its attributes from the paid-access World Register of Dams are not openly available (J. Wang et al., 2022). On the regional and national scales, numerous databases are made available by Open Development Mekong (ODM, 2023; Tiwari et al., 2023). Even so, they are from different sources, resulting in mismatches across databases. As such, while much information on dams exists, they are scattered across

https://doi.org/10.5194/essd-2023-417
Preprint. Discussion started: 3 November 2023

different platforms, spatial scales, and time frames, complicating data collection and analysis. The mismatches across six main databases are illustrated as a Venn diagram in Fig. 1, emphasizing the need for an organized and integrated database.

Without a comprehensive database, dam evolution over space and time up-to-date remains to be assessed. Some studies have investigated the spatiotemporal impacts of dams, such as on land cover in the Lower Mekong (Cho and Qi, 2021) and geomorphological changes in the Mekong Delta (Li et al., 2017). However, such studies are limited by the availability and recency of dam data, and no existing study focuses directly on dam growth, which would highlight regions most concentrated with dams and encourage targeting management efforts towards those regions, as well as illuminate connectivity across the dam network, especially the cumulative impacts of cascades (Kummu and Varis, 2007). Spatiotemporal analysis of planned dams projects upcoming dam development, but understanding distributions in hydropower potential could further highlight sites with greater potential for continued dam construction and provide insights on future dam growth. Hydropower potential has been estimated globally and regionally through grid-based assessments (e.g., Pokhrel et al., 2008; Tefera and Kasiviswanathan, 2022). Nonetheless, it has yet to be systematically evaluated across the Mekong, where only general estimates from a decade ago are available – 30,000 MW in the Lower Mekong and 28,930 MW in the Upper Mekong (Lebel et al., 2007; MRC, 2011).

In this paper, we offer (1) a publicly available and integrated database of 1,055 dams in the Mekong, (2) a spatiotemporal analysis of dams on a decadal timescale, and (3) a grid-based assessment of the theoretical hydropower potential along the river network. We compile data across global, regional, and national databases, validated using satellite imagery in Google Earth and public literature like reports and news articles (Lehner et al., 2011; Mulligan et al., 2020; J. Wang et al., 2022; Zarfl et al., 2015). Using our database and a GIS analysis of geographic and hydrological dam attributes, we evaluate the distribution of the dams on a sub-basin and country level from the 1980s to the post-2020s. With 608 hydropower dams, the hydropower capacity soars from 1,242 MW in the 1980s to 69,199 MW post-2020s. While China had the most substantial expansion in installed capacity from the 2000s to the 2010s, Laos has the most planned dams and is expected to have the greatest increase post-2020s. We estimate a basin-wide hydropower potential of 1,334,683 MW, based on discharge from the CaMa-Flood model (2011-2015, 0.05 degree) (Dang et al., 2022), where Laos is the highest at 514,887 MW (Meijer et al., 2012; Pokhrel et al., 2008). Hydropower potential could grow to over 2,000,000 MW with climate change, based on future discharge from the WaterGAP2 model used for ISIMIP2b (2021-2030, 0.5 degree) (Gosling et al., 2023). Laos and China are the highest at around 900,000 MW each, together forming over 80% of the total potential.

The significance of this study lies in three aspects. *Firstly*, our database provides a one-stop access to data for research on dam-induced hydrological alterations, such as sediment trapping and river-bed incision associated with “hungry waters”, and its implications on the hydrological modeling of parameters like discharge and water level (Ang et al., 2022; Dang et al., 2022; Kondolf et al., 2014; Shin et al., 2020). Comprehensive dam data is needed to calculate trapped sediments, and hence

https://doi.org/10.5194/essd-2023-417
Preprint. Discussion started: 3 November 2023

Open Access Earth System Science Data Discussions

the rate of erosion of the delta, which would affect agriculture and food security (Li et al., 2017). *Secondly*, we provide the first detailed and spatially-explicit evaluation of dam evolution over time, which showcases the complications in managing the Mekong Basin, due to its transboundary nature and complex regional electricity trade amidst high energy demands for economic growth (Galelli et al., 2022; Soukhaphon et al., 2021). The Mekong is a representative case study of a major river being transformed by anthropogenic activities, thus evaluating the evolution of dam patterns in the Mekong holds similar implications as large river basins worldwide. *Thirdly*, this paper illustrates vulnerability at the sub-basin and country levels, identifying dam hotspots that require stronger management and policies, such as more evidence-based dam planning, stricter criteria for project approval, more comprehensive environmental impact assessments, and proper resettlement of displaced locals (Zawahri and Hensengerth, 2012).

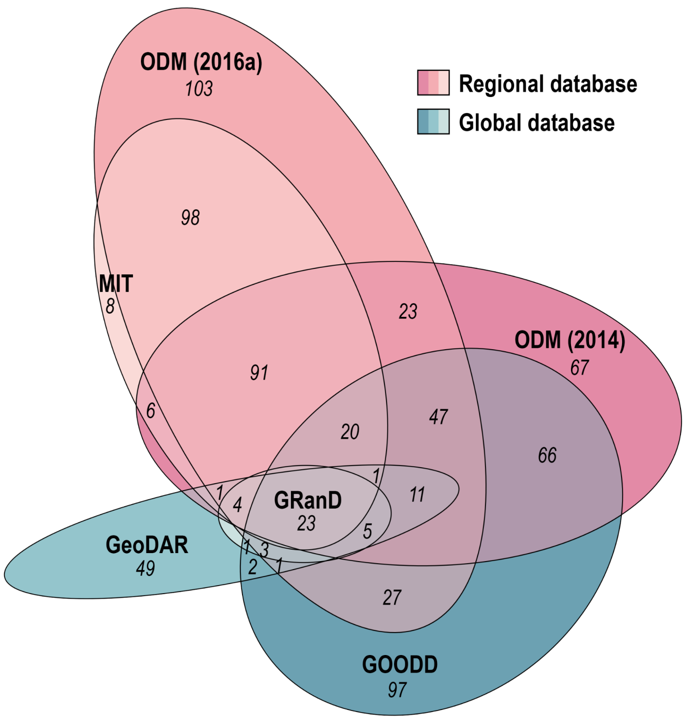

Figure 1: Venn diagram illustrating the overlaps and differences across six main databases. The pink ellipses are regional databases, while the blue ellipses are global databases, corresponding to the color scheme in Fig. 2.

2 The Mekong Basin: Hydrology and Development of Dams

Flowing 4,800km from the Tibetan Plateau into the South China Sea, the Mekong is the third largest in Asia in terms of sediment load, emptying 160 million tons of sediment into the sea annually (Lu et al., 2014). The Mekong Basin of 795,000 km^2 is shared across six countries (Gao et al., 2022). China (21% of the basin area) and Myanmar (3%) lie in the Upper Mekong Basin (UMB), while four countries lie in the Lower Mekong Basin (LMB): Laos (25%), Thailand (23%), Cambodia

https://doi.org/10.5194/essd-2023-417
Preprint. Discussion started: 3 November 2023

(20%) and Vietnam (8%) (Hecht et al., 2019). The monsoonal rainfall in the LMB controls the annual flood pulse, with 85% of flow taking place in the wet season (May to October) (Li et al., 2017). The remaining 15% of flow occurs in the dry season (November to April) from snow melt in the UMB (Binh et al., 2020). The Mekong can be divided into six physiographic homogenous subregions, with the (1) Tibetan Plateau and (2) Lancang Basin located in the UMB, the (3) Mekong Highlands mostly in Laos, the (4) Mekong Lowlands largely in Cambodia, (5) Intensive Cultivation mainly in Thailand, and (6) Tonle Sap/Mekong Delta at the southernmost tip of the basin (Leinenkugel et al., 2013). The Mekong Delta is the third largest delta on earth, contributing to 27% of Vietnam's GDP and 40% of agricultural production, as well as 15% of international rice export (Tri, 2012; Xue et al., 2010).

Dam planning and construction began to intensify in the Mekong in the 1990s to 2000s due to energy demands from economic expansion, population growth, and rural-urban migration, as well as a shift from public funding to commercial partnerships between governments and private companies that brought in capital supply for dam projects (Grumbine et al., 2012; Kondolf et al., 2014; Pearse-Smith, 2012). The dam cascade that first began construction on the mainstem is in the UMB in China (P. Wang et al., 2014). While two dams are under construction and one has been canceled, 11 operational dams now make up the cascade. The cascade will be expanded, with another canceled dam and seven planned dams lying further upstream (Grünwald et al., 2022). Downstream in the LMB, a cascade of 11 mainstem dams has been planned (MRC, 2011, 2016). Two of the dams are in Cambodia, while nine dams are in Laos, with two already operational (IR, 2023). Laos exports the majority of its energy to neighboring countries, aiming to become the "Battery of Southeast Asia" (Galelli et al., 2022; Soukhaphon et al., 2021). In 2020, Laos was the third largest exporter of electricity globally, exporting \$1.93 billion in electricity, of which \$1.76 billion was imported by Thailand (Observatory of Economic Complexity, 2023). Laos' current cross-border export of 6,000 MW (90% from the hydropower sector) is set to increase to 20,000 MW by 2030 (Chowdhury et al., 2020; Energy Market Authority, 2022; ODM, 2020).

3 Methodological Framework

3.1 Initial compilation of dam databases

Dams across the Mekong are first compiled from georeferenced data. We accessed six global databases – the FAO AQUASTAT (FAO, 2015), the Future Hydropower Reservoirs and Dams (FHReD) (Zarfl et al., 2015), the Georeferenced global Dams and Reservoirs (GeoDAR) (J. Wang et al., 2022), the Global georeferenced Database of Dams (GOODD) (Mulligan et al., 2020), the Global Reservoir and Dam Database (GRanD) (Lehner et al., 2011), and the Open Street Map Dams (OSM). Regional and national databases used include the Stimson Mekong Infrastructure Tracker (MIT) (MIT, 2021), International Rivers (IR) (IR, 2014), and the datasets in the Open Development Mekong Datahub (ODM) (ODM, 2023). We extract dams within the Mekong and standardize file formats for cleaning, excluding entries with missing or duplicate coordinates. Considering that 0.0001 decimal degrees is approximately 11m and dams are larger than that, we standardize all

https://doi.org/10.5194/essd-2023-417
Preprint. Discussion started: 3 November 2023

coordinates to four decimal degrees. The databases reviewed and their respective dams count (excluding duplicates within the same database) are summarized in Table 1.

3.2 Integration of dam coordinates

Extracting unique coordinates, we visualize the dam distribution in ArcGIS. Groups of coordinates are found close by, where each database records slightly different coordinates of the same dam. These differences are possibly due to (1) updates in satellite imagery used for georeferencing over the years, (2) variations in information sources used for each database (e.g., International Commission on Large Dams versus CGIAR's Research Program on Water, Land, and Ecosystems) (Table 1) and (3) human discretion in positioning dam points, such as at the center of the dam, side of the dam, or the center of the associated reservoir. To account for such differences, points lying within 100m of one another are merged and their average taken. 100m was visually chosen after plotting buffers of different sizes and comparing them against the sizes of coordinate clusters.

Subsequently, we extracted key attributes for inspection: name, country, year of operation, status, and purpose. Dam entries are merged based on same/similar names through a manual check in excel. If the same name is correlated with different coordinates, one coordinate was extracted based on one of the following: the most common coordinate, the coordinate from the most up-to-date database, or the average of all unique coordinates, excluding coordinates over one decimal degree away. We corrected any spelling mismatches in the names and standardized the naming conventions, such as for the attribute column headers, countries, and dam purposes. Dam statuses are simplified into five: operational, under construction, planned, canceled, and closed, where dams under study and proposed are considered planned. Should attributes across databases differ, the most common entry or information from the most up-to-date databases are prioritized.

3.3 Validation of dam coordinates

Coordinates of operational dams are validated using satellite imagery in Google Earth. Unvalidated coordinates are removed, misplaced coordinates are edited, while multiple coordinates referring to the same dam are merged. For reservoirs with multiple dams, all dams are considered as one, as similarly done for GeoDAR (J. Wang et al., 2022). Dam statuses are validated or updated, confirming operational dams, and changing planned dams to under construction should construction works with barren ground be visible. Two dams are deemed closed, with the dam structure no longer visible and dam breach reported online (VietNamNet, 2013; VnExpress, 2017). At this stage, 776 unique dams are obtained.

Based on the coordinates, six representative databases (763 dams) – three global and three regional – are illustrated using a Venn diagram (Fig. 1). Only 3.0% of the 763 dams are in all six databases, yet nearly half are only in one database, suggesting the lack of corroboration across existing databases. Moreover, the scattered overlaps and differences in dam entries complicates data collection, thus a unified one-stop database is needed. The diagram illustrates six out of 18 dam databases to minimize visual complexity and to keep the error low at 2.1%, while still representing 97.2% of dams at this stage (755 dams). The slight error is due to the inherent limitations of Venn diagrams, but such figures are still the simplest and most intuitive to interpret (Chen & Boutros, 2011; Larsson & Gustafsson, 2018).

3.4 Incorporation of dam attributes

Including the remaining attributes in the 18 dam databases, such as dam height, dam length, and reservoir volume, the dam attributes are verified with information from public literature: reports (e.g., IR, 2013; MRC, 2016), research papers (e.g., Schmitt et al., 2018; Souter et al., 2020), news articles (e.g., Ezell, 2021; Poindexter, 2018), and websites (e.g., EDL-Generation Public Company, 2023; Hobo Maps, 2023; Power Technology, 2023). During the online search, 34 new dam entries were added, bringing the total dam count to 810. For dams with minimal information, attributes are estimated using Google Earth. The dam name is taken from the label of the dam, reservoir or nearby locality, the river name is taken from the nearest labeled river (if any), and the year of completion (and year of closure, if any) is taken from the earliest imagery the dam structure is visible (and no longer visible). To estimate the dam's purpose, if hydropower infrastructure is visible (e.g., powerhouse, penstock), the dam is deemed for hydropower. Nearby farmlands indicate an irrigation dam, a reservoir suggests a dam meant for water supply, while settlements downstream imply flood control (Yuen et al., 2023).

Additional attributes are added through GIS. We extract elevation and slope from the 30m SRTM DEM (USGS, 2023), stream order from HydroRIVERS, and sub-basin from HydroBASINS, with reference to the Mekong River Commission's sub-basin delineation (HydroSHEDS, 2023; MRC, 2023). Although elevation and sub-basin are available in some databases, not all entries have such data and discrepancies exist across databases, hence we use GIS instead. To extract the catchment area of each dam, flow direction and accumulation are derived from the DEM, and dam points are snapped to a nearby cell of highest accumulation. The snap distance for each dam is adjusted if necessary – 300 to 400m for smaller dams, and 800 to 2000m for larger dams. Dam catchments delineated are unnested, hence we sum them to obtain the area of nested catchments. The database includes the mean annual discharge at each dam over five years (2011 to 2015) (Dang et al., 2022), and mean total annual rainfall volume (2011 to 2015) in each dam catchment: mean annual rainfall from CHIRPS (CHIRPS, 2023) multiplied by the nested catchment area. The list of attributes compiled in excel is in Table 2.

While compiling from the dam databases and online literature, a portion of the dams were found to lack specific coordinates, but their names, hydropower capacity, status, and nearest locality (e.g., province) are known. These dams are mostly planned dams lying in Laos, as determined from the MIT database and corroborated with reports online (e.g., MRC, 2015; The World Bank, 2017). For the few operational dams, their year of completion was estimated from the year of the report they were found in. We identify the unique dams as much as possible based on their names, and estimate the dam coordinates from the nearest known locality. 245 dams are obtained, but set aside from the 810 dams with known specific coordinates, totaling to a final count of 1,055 dams in the database.

https://doi.org/10.5194/essd-2023-417
Preprint. Discussion started: 3 November 2023

3.5 Spatiotemporal analysis

Using the year of completion (and year of closure, if any), dams are filtered by decade – 1980s, 1990s, 2000s, 2010s, post-2020s – with the last group including dams that began operation in 2020 or later, dams under construction, and planned dams with available information. Canceled dams are excluded from analysis. The spatiotemporal distribution of the dams is evaluated, including comparing the growth in the number of dams and hydropower capacity over the decades across countries and major sub-basins, and identifying key regions with the largest growth thus far and regions with the highest projected growth. We visualize the distribution of dams in each country by their attributes, namely status, purpose, elevation, slope, rainfall, discharge, nested catchment area, stream order, and hydropower capacity. Focusing on the 810 dams with known specific coordinates, we analyze the relationship between hydropower capacity, and the four parameters of elevation, slope, rainfall, and discharge. The nested catchment area of each dam is divided by the total area of the Mekong Basin, to compare the distribution of upstream and downstream dams across countries.

3.6 Calculating hydropower potential

To calculate the theoretical hydropower potential, we adopt the approach by Pokhrel et al. (2008),

$$P = \gamma \times Q \times h \times \eta \,, \tag{1}$$

where P is the hydropower potential in Watts, γ is the weight density of water (9810 N/m^3), Q is the discharge in cubic meters per second, h is the elevation in meters, and η is the overall electrical efficiency. η, which accounts for energy losses from equipment like turbines and generators, ranges from 50% to 95% in studies, thus we use an average efficiency of 70% (Cuya et al., 2013; Zhou et al., 2015). $\gamma \times Q$ can also be understood as the gravitational acceleration (9.81 m/s^2) multiplied by the mass of water flow ($Q \times$ 1000 kg/m^3, where 1000 kg/m^3 is the density of water).

Elevation is defined relative to the downstream cell to take river flow into consideration. Using the 30m SRTM DEM, we calculate the slope along the stream network, before converting it into a raster matching the resolution and alignment of the discharge data, and multiplying it by the cell length to obtain the elevation difference between each cell and its downstream cell (Meijer et al., 2012). We calculate hydropower potential using present-day discharge from the CaMa-Flood model (2011-2015, 0.05 degree) (Dang et al., 2022), as well as future discharge from the WaterGAP2 model used for ISIMIP2b (2021-2030, 0.5 degree) (Gosling et al., 2023). WaterGAP results have been used and validated globally (Gudmundsson et al., 2021; Pokhrel et al., 2021), and both datasets consider the effect of dams on discharge. Future discharge is affected by climate change, modeled based on four Representative Concentration Pathways (RCP 2.6, 4.5, 6.0, 8.5), which are greenhouse gas concentration scenarios used by the Intergovernmental Panel on Climate Change (IPCC). For each calculation, we sum the grids to obtain the total hydropower potential in each country and across the whole basin. The flow of data processing is outlined in Fig. 2.

https://doi.org/10.5194/essd-2023-417
Preprint. Discussion started: 3 November 2023

Open Access Earth System Science Data Discussions

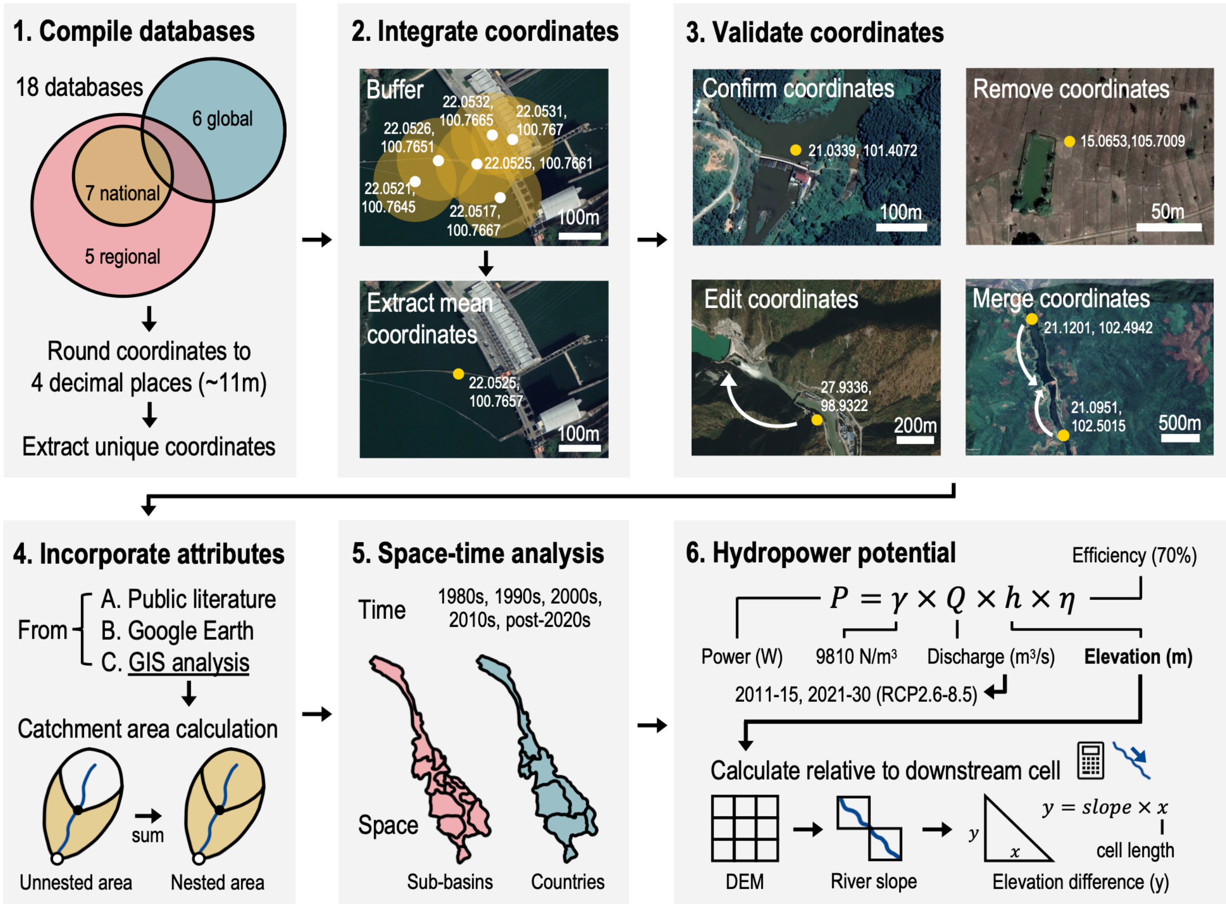

Figure 2: Methodological flowchart outlining the six main steps in data cleaning, compilation, validation, and analysis. The simplified Venn diagram in step 1 reflects the observed hierarchy across the global, regional, and national databases. The images in steps 2 and 3 are taken from Google Earth to exemplify the process. Maps Data: Google, © 2023 Maxar Technologies, CNES / Airbus. For steps 4 to 6, selected key parts of the calculations are shown.

Table 1. Global, regional, and national dam databases compiled.

Scale	Database	Dams Count	Sources
Global	AQUASTAT (FAO, 2015)	31	ICOLD, national data, public literature
	FHReD (Zarfl et al., 2015)	123	Public data and literature
	GeoDAR v1.1 (J. Wang et al., 2022)	105	ICOLD, GRanD, Google Maps
	GOODD v1.1 (Mulligan et al., 2020)	319	Google Earth
	GRanD v1.3 (Lehner et al., 2011)	38	Public data and literature
	OSM (2017)	10	OSM tags
Mekong	MIT (2021)	313	National data, public data and literature
	ODM (2014)	398	GRanD, WLE, IR, national data

	ODM (2016a)	466	ODM, WLE, IR
	ODM (2020a)	145	GMDO, WLE, MIT, public data
	ODM (2022)	102	Public data and literature
China	IR (2014)	29	National data, public literature
Myanmar	ODM (2017a)	8	IFC
	ODM (2017b)	6	ICEM
	ODM (2018)	8	IFC, WLE
Thailand	ODM (2020b)	6	National data
Cambodia	ODM (2015)	50	National data
	ODM (2016b)	51	National data

Abbreviations: Food and Agriculture Organisation of the United Nations (FAO), International Commission on Large Dams (ICOLD), Future Hydropower Reservoirs and Dams (FHReD), Georeferenced global Dams and Reservoirs (GeoDAR), Global Reservoir and Dam Database (GRanD), Global georeferenced Database of Dams (GOODD), Open Street Map (OSM), Mekong Infrastructure Tracker (MIT), Open Development Mekong (ODM), CGIAR's Research Program on Water, Land, and Ecosystems (WLE), International Rivers (IR), International Finance Corporation (IFC), International Centre for Environmental Management (ICEM).

Table 2. Dam attributes in the database.

Category	**Attribute**	**Description**
Name	ID	Identification number
	Name1	Name of dam
	Name2	Alternative name of dam
Location	Lat	Latitude in decimal degrees
	Lon	Longitude in decimal degrees
	Country	Country
	Locality	Nearest locality (for 245 dams with estimated coordinates)
Operation	Status	Operating, under construction, planned, closed or canceled
	Completion	Year of completion
	Closure	Year of closure (if any)
Hydrology	River	Tributary
	Basin	Sub-basin (HydroSHEDS, 2023)
	Order	Stream order (HydroSHEDS, 2023)
	Rain_m3	Mean annual rainfall volume in cubic meters (CHIRPS, 2023)
	Discharge_m3	Mean annual discharge in cubic meters (Dang et al., 2022)

https://doi.org/10.5194/essd-2023-417
Preprint. Discussion started: 3 November 2023

Specifications	Capacity_MW	Dam capacity in megawatts
	Energy_GWh	Mean annual energy in gigawatt hour
	Height_m	Dam height in meters
	Length_m	Dam length in meters
	Area_km2	Reservoir area in square kilometers
	Volume_milm3	Reservoir volume in million cubic meters
	Catch_km2	Unnested upstream catchment area in square kilometers
	Catch_nest_km2	Nested upstream catchment area in square kilometers
	Elevation_m	Dam elevation in meters (USGS, 2023)
	Slope_m	Dam slope in meters
Purpose	Use1	Primary purpose (e.g., hydropower)
	Use2	Secondary purpose (e.g., irrigation)
Others	Add_Ref_1	Additional online reference 1
	Add_Ref_2	Additional online reference 2
	Add_Ref_3	Additional online reference 3
	From_GE	Dam attributes estimated from GE
	Est_Coord	Y indicated for 245 dams with estimated coordinates

4 Results and Discussion

4.1 Current distribution of dams

Based on our database, there are 1,055 dams in the Mekong, including 661 operational, 54 under construction, 331 planned, 2 closed, and 7 canceled (Fig. 3A). The operational dams are mainly in Thailand and the downstream portion of China, while the planned dams are predominantly in Laos, Cambodia, and the upstream portion of China. The total dam count is more than twice that of the largest existing database of 466 dams last updated in 2016 (Table 1), reflecting the rapid rate at which the dam network is evolving. 79% of dams are found at lower elevations of 1,000m and below, compared to 21% of dams found above 1,000m (Fig. 3B). Dams at lower elevations mostly lie in the Lower Mekong Basin (LMB), while dams at higher elevations are generally in the mountainous Upper Mekong Basin (UMB), with some lying in the Mekong Highlands of Laos (Leinenkugel et al., 2013). The two dams of highest elevation are Longqingxia and Angsai in China, at 4,638m and 4,282m respectively. Most of the dams (84%) are small dams with a hydropower capacity of 50 MW and below (Fig. 3C). These small dams include 447 non-hydropower dams, classified into three purposes: water supply, flood control, and irrigation. Considering the monsoonal climate of the Mekong Basin with a distinct dry and wet season, water supply and flood control dams are used in regulating water flow, to provide water for nearby settlements in the dry season, and to lower

https://doi.org/10.5194/essd-2023-417
Preprint. Discussion started: 3 November 2023

flood risk in the wet season (Yuen et al., 2023). Small irrigation dams are concentrated in Thailand, where the Khorat Plateau is intensively cultivated for agricultural exports (Kondolf et al., 2014; Li et al., 2017). As for the remaining hydropower dams, 14% are medium dams of over 50 to 1,000 MW, and 2% are large dams of over 1,000 MW (Fig. 3C). The two dams of highest capacity are Nuozhadu and Xiaowan in China, at 5,850 MW and 4,200 MW respectively. Large dams are mainly located along the mainstream in China, Laos, and Cambodia (Fig. 3A). The dam cascade on the mainstem in the UMB in China has a total operational reservoir volume of 45 billion m^3 and hydropower capacity of 21,250 MW, which increases to 63 billion m^3 and 30,566 MW respectively should dams under construction and planned dams be considered. Downstream in the LMB in Laos and Cambodia, the two operational mainstem dams have a combined reservoir volume of 2 billion m^3 and hydropower capacity of 2,085 MW, which is set to increase to 12 billion m^3 and 13,326 MW after the planned cascade is completed.

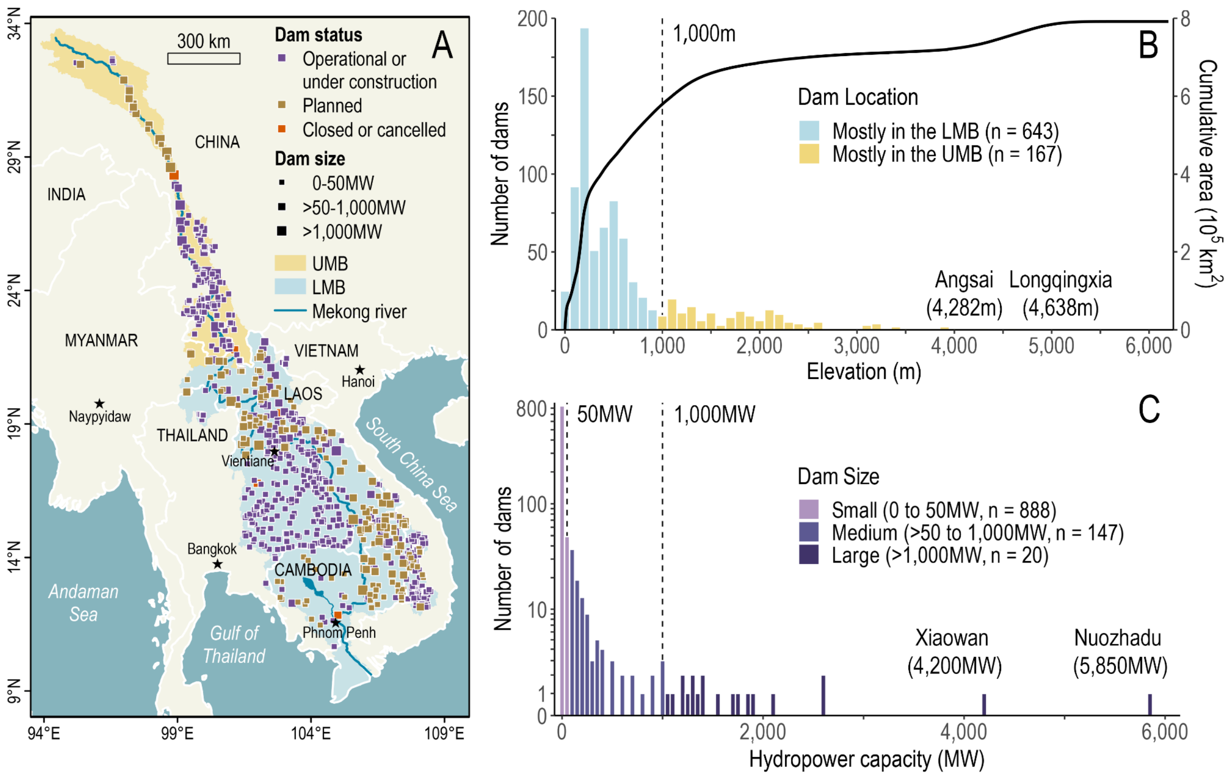

Figure 3: A. Map of the current dam network, with operational dams or dams under construction in purple, planned dams in yellow, and closed or canceled dams in red. B. Distribution of dams based on their elevation. Most dams of elevation below 1,000m lie in the Lower Mekong Basin (LMB), while most dams of elevation above 1000m lie in the Upper Mekong Basin (UMB). Around 75% of the Mekong Basin is below 1,000m, as shown by the hypsometric curve of cumulative area in the basin against elevation, derived from the 30m SRTM DEM. C. Distribution of hydropower dams based on their size (hydropower capacity), including the 245 dams without known specific coordinates. Small dams are 0 to 50 MW, medium dams are over 50 to 1,000 MW, while large dams are over 1,000 MW.

https://doi.org/10.5194/essd-2023-417
Preprint. Discussion started: 3 November 2023

4.2 Spatiotemporal analysis of dam growth

The total hydropower capacity has expanded exponentially from 1,242 MW in the 1980s to 33,914 MW in the 2010s, with a jump of 24,717 MW from the 2000s to the 2010s (Fig. 4A). This corroborates with a reported spike in hydropower dams after 2005 to 2010, associated with rising energy demands from increased economic development and demographic growth (Binh et al., 2020; Dugan et al., 2010; Hecht et al., 2019; Li et al., 2017). The total hydropower capacity of currently operational dams is 36,058 MW. Since hydropower remains as an attractive low-cost energy source in a region rich in water resources (IRENA. 2022), the growth in dams is expected to continue – hydropower capacity is projected to nearly double to 69,199 MW in the post-2020s, after taking dams under construction and planned dams into consideration (Fig. 4A). China has the largest capacity, with a notable increase from 5,326 MW in the 2000s to 22,180 MW in the 2010s, being the earliest country to start harnessing the Mekong's hydropower potential (Cronin, 2009). 96% of the capacity stems from the 11-dam cascade along the mainstream. Although China currently has the highest installed capacity, Laos has the most planned dams (61) and is expected to have the greatest growth from 7,525 MW in the 2010s to 25,748 MW post-2020s (Fig. 3A and 4A). The expansion of capacity in Laos is in line with the country's aim to become the "Battery of Southeast Asia" (Galelli et al., 2022; Soukhaphon et al., 2021).

Hydropower capacity relates to geography and hydrology, hence we visualize the distribution of dams by elevation, slope, mean total annual rainfall, and mean annual discharge (Fig. 4C to 4F). Considering that potential energy depends on *height* and *mass*, elevation and slope reflects the *height* of the dam location, while rainfall and discharge reflects the *mass* of the water flowing through the dam (Lehner et al., 2005; Pokhrel et al., 2008). Since slope is a measurement of change in elevation, a fairly similar trend can be observed between elevation and slope. Likewise, since discharge is dependent on the available rainfall, a similar trend can be seen between rainfall and discharge. The elevation of dams and the total range in slope (including outliers) is the highest in the UMB in China, which contributes to the large hydropower capacity of the country. The UMB, which includes part of the Tibetan Plateau and Three Rivers Area, is highly mountainous and steep – along the Mekong mainstream in China, elevation drops 700m within just 750km (Biba et al., 2012; MRC, 2023). Significant elevation and slope are also observed in Laos, where the Mekong Highlands (Northern Mountains and Annamite Range/ Eastern Highlands) generally lie in (Leinenkugel et al., 2013). Together with high rainfall and high discharge along the mainstream, the estimates corroborate with the large capacity in Laos. Myanmar also has relatively high slope and discharge, but the hydropower capacity is limited by area: Myanmar only occupies 3% of the 795,000 km^2 of basin area (Gao et al., 2022; Hecht et al., 2019) (Fig. 4B).

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Preprint. Discussion started: 3 November 2023

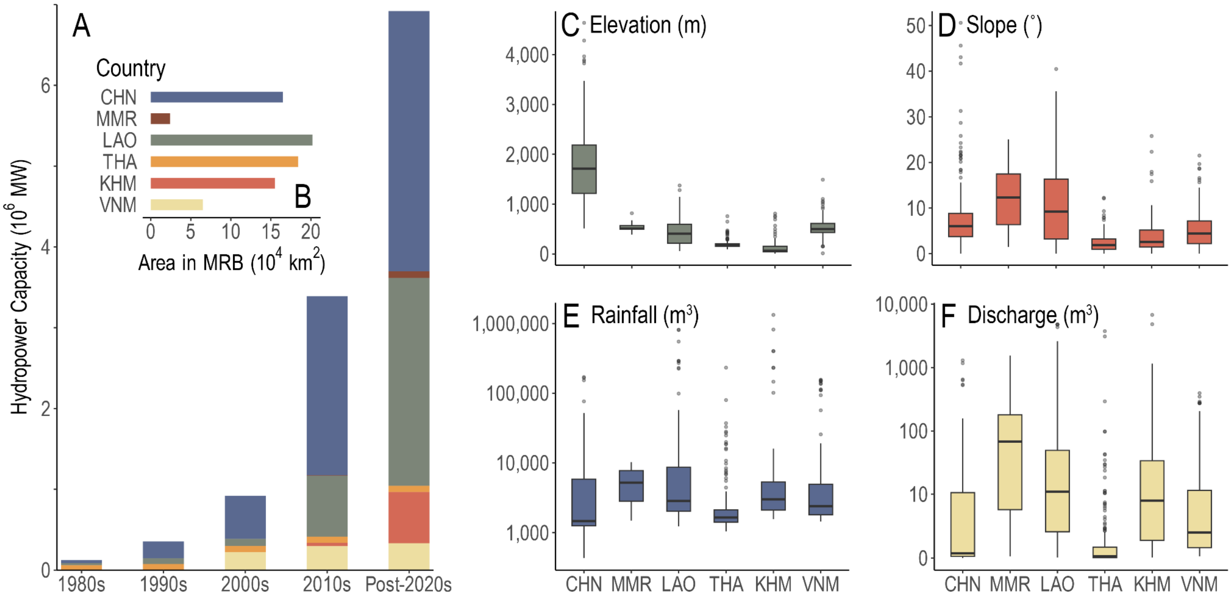

Figure 4: A. Total hydropower capacity of dams per country in each decade, from the 1980s to post-2020s, of which 36,058 MW is the total hydropower capacity of currently operational dams. The color and order of each country is indicated in B. B. Area of each country within the Mekong River Basin (MRB) (Rossi et al., 2009). C-F. Box plots per country showing the distribution of dam elevation, dam slope angle, mean total annual rainfall volume within each dam's nested catchment (2011-2015), and mean annual discharge at each dam (2011-2015) (Dang et al., 2022). Countries are labeled by their three-letter codes, ordered from upstream to downstream (similarly in Fig. 6 and 7).

The expanding dam network and hydropower capacity in China and Laos are mapped per decade from the 1980s to post-2020s in Fig. 5, a spatial representation of Fig. 4A – each sub-figure in Fig. 5 corresponds to each bar plot in Fig. 4A. Growth is evident in the 2010s and post-2020s, with numerous new large dams along the mainstream indicated in red in Fig. 5D and 5E, and a sudden increase in hydropower capacity of LMB sub-basins, such as Nam Ou (Fig. 5G), indicated in dark purple in Fig. 5I and 5J. Notable growth is also seen in Vietnam from the 2000s to post-2020s, within the upstream portion of the 3S sub-basin (Fig. 5G to 5J), where relatively high elevation and slope contribute to the hydropower capacity (Souter et al., 2020) (Fig. 4C and 4D). Nevertheless, the capacity in Vietnam is restricted by the country's area coverage (8% of the basin) (Fig. 4B). Similarly in Myanmar, area limits the planned dams post-2020s (Fig. 4B and 5E). The dam network and hydropower capacity remain generally the same in Thailand and its major sub-basin Nam Mun (Fig. 5G), given that most of the dams are for irrigation and operational since the 1980s (Fig. 4A and 5). For instance, the Khorat Plateau in Thailand is a key agricultural area, producing large volumes of global exports like rice (Kang et al., 2021; Kondolf et al., 2014). The low capacity in Thailand is associated with its low dam elevation and slope, and mostly low rainfall and discharge (Fig. 4C to 4F). While Cambodia has minimal elevation and slope within the Mekong Lowlands, high rainfall and discharge allows for some hydropower capacity (Leinenkugel et al., 2013) (Fig. 4). Dam growth is concentrated in the downstream portion of the 3S basin, and along the mainstream, where two large dams form part of the LMB cascade (Fig. 5E).

https://doi.org/10.5194/essd-2023-417
Preprint. Discussion started: 3 November 2023

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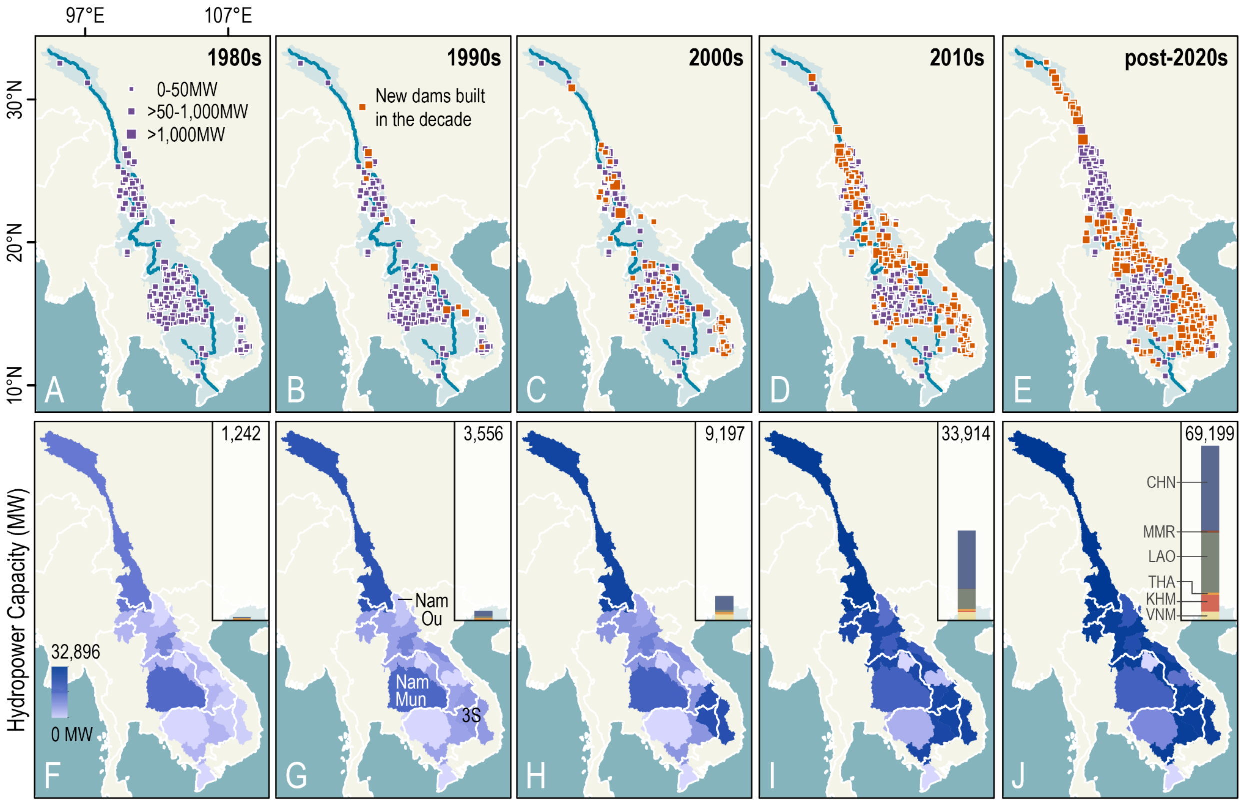

Figure 5: A-E. Distribution of the dams in each decade from the 1980s to post-2020s. Newly built dams in each decade are indicated in red. F-J. Total hydropower capacity of operating dams per major sub-basin, in each decade from the 1980s to post-2020s, with three notable basins labeled (Nam Ou, Nam Mun, 3S). Each sub-figure corresponds to each bar plot in Fig. 4A, labeled with the total hydropower capacity of the Mekong basin per decade.

4.3 Hydropower potential

The total theoretical hydropower potential in the Mekong basin based on present-day discharge (2011-2015) is an estimated 1,334,683 MW (Fig. 6A). Calculations of hydropower potential in Asia vary quite widely in previous studies, ranging from 2,402,511 MW to 12,121,000 MW (Meijer et al., 2012; Pokhrel et al., 2008) (Table 3). Asia is the continent richest in hydropower, contributing to around half of the world's total potential (Table 3). Considering that the Mekong is the longest river in Southeast Asia and third longest in Asia (MRC, 2023), our estimated 1,334,683 MW in the Mekong is largely comparable with previous estimates. Hydropower potential that can be harnessed in reality will be lower, given restrictions such as economic feasibility, legal factors, and socio-political concerns, but our results suggest that the current estimates of 30,000 MW for the LMB and 28,930 MW for the UMB may be too low (Lebel et al., 2007; MRC, 2011; Tefera and Kasiviswanathan, 2022). Should the basin-wide potential be limited to 58,930 MW, more than half is already installed (36,058 MW), and it will soon be exceeded by the planned capacity post-2020s (69,199 MW). Moreover, just one large dam

https://doi.org/10.5194/essd-2023-417
Preprint. Discussion started: 3 November 2023

is over 1,000 MW, and the current largest operational dam is almost 6,000 MW, hence it is likely that the hydropower potential in the Mekong exceeds 58,930 MW (Fig. 3C).

Projecting into the future based on four Representative Concentration Pathways (RCP), 2021-2030 discharge data from the ISIMIP2b WaterGAP2 model is observed to be of higher values than the present-day discharge data, and hydropower potential may grow correspondingly to over 2,000,000 MW under the influence of climate change (Fig. 6B to 6E) (Gosling et al., 2023). This value may be exaggerated by the difference in resolution between the discharge data currently available for present-day and future calculations. The finer resolution (0.05 degree) of present-day calculations shows more localized differences, while the coarser resolution (0.5 degree) of future calculations obscures details, is not perfectly aligned with the Mekong basin boundary, and introduces a larger elevation difference between each cell and its downstream cell. Nevertheless, the projected increase in hydropower potential suggests that the Mekong basin may be even more vulnerable to dam construction and its associated environmental and social trade-offs in the future (Grill et al., 2014; Park et al., 2022; Schmitt et al., 2018).

Comparing across the countries, almost 40% (514,887 MW) of the present-day potential lies in Laos, while more than 80% of the future potential lies in China and Laos (Fig. 6F to 6J). China has a mountainous terrain with high elevations and a steep slope along the UMB mainstream, while Laos has high discharge along the LMB mainstream and relatively significant elevation and slope in the Mekong Highlands (Fig. 4C to 4F) (Biba, 2012; Leinenkugel et al., 2013). The hydropower potential distribution appears to be similar across the RCPs, but the total hydropower potential varies slightly with RCP – lower in RCP4.5 and 8.5, but higher in RCP2.6 and even higher in 6.0 (Fig. 6B to 6E). Matching this trend, hydropower potential is slightly higher in China for RCP4.5 and 8.5, but higher in Laos for RCP2.6 and 6.0, especially in 6.0 (Fig. 6I). These observations could be associated with the greenhouse gas concentration in each RCP scenario during 2021 to 2030 – higher in RCP4.5 and 8.5, but lower in RCP2.6 and lowest in 6.0 (IPCC, 2014; Hanna et al., 2019). Interestingly, hydropower potential across the RCP scenarios remains generally constant in most of the countries, but changes significantly in Laos, peaking in RCP6.0 (Fig. 6G to 6J). The large hydropower potential in Laos and its fluctuation with RCP suggest that Laos may be more vulnerable to climate change, and the most implicated by future dam expansion.

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Preprint. Discussion started: 3 November 2023

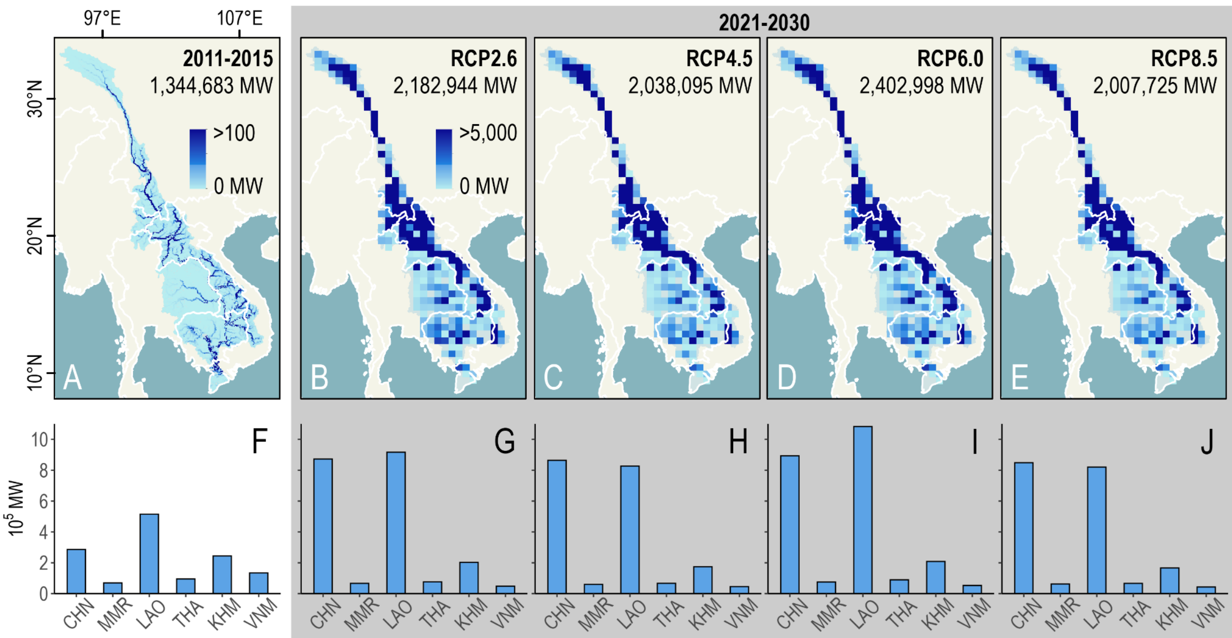

Figure 6: A. Theoretical hydropower potential in the Mekong Basin, estimated from gravity, elevation (relative to the downstream cell), and average annual discharge in 2011 to 2015. B-E. Hydropower potential estimated from average annual discharge in 2021 to 2030, modeled based on four Representative Concentration Pathways (B: 2.6, C: 4.5, D: 6.0, E: 8.5). F-J. Bar graph of the total hydropower potential in each country, corresponding to A-E.

Table 3. Literature values of theoretical hydropower potential (MW) globally and in Asia.

Scale	Pokhrel et al. (2008)	Meijer et al. (2012)	Zhou et al. (2015)	Tefera and Kasiviswanathan (2022)	This study
Mekong	–	–	–	–	1,344,683
Asia	2,402,511	12,121,000	5,901,941	10,559,361	–
Global	6,568,493	19,943,000	14,563,356	21,023,973	–

4.4 Comparison of stream order of dams

Visualizing the distribution of dams by Strahler stream order, the number of dams generally decreases as stream order increases (Fig. 7A). Dams of low stream order are found in small tributaries, whereas dams of high stream order are along major tributaries and the Mekong mainstream, suggesting that the dams in the basin are predominantly smaller tributary dams. This corroborates with Fig. 3C, where 84% of the dams are small dams with a hydropower capacity of 50 MW and below. Some of the dams of lower stream order are in Vietnam and China, but most are irrigation dams in the Nam Mun sub-basin of Thailand – the largest tributary to the Mekong based on area and the site of the largest irrigation scheme in the basin (Cochrane et al., 2014; MRC, 2023). Dams of high stream order are mainly in China and Laos, as China has the most mainstream dams, while Laos has a significant number of both mainstream and major tributary dams. Few dams are of the

https://doi.org/10.5194/essd-2023-417
Preprint. Discussion started: 3 November 2023

highest stream order eight, which are only located along the LMB mainstream in Laos and Cambodia. Comparing the nested catchment area of each dam to the total area of the Mekong Basin, the derived ratios reflect the relative position of each dam in the basin, where dams with larger ratios are of higher stream order and likely located further downstream (Fig. 7B). Dams of highest ratios are along the mainstream, identified by the same colors in Fig. 7B and 7C. The 11 dams in the LMB mainstream cascade are of ratios 0.28-0.81, with the ratio increasing downstream from Pak Beng in Laos to Sambor in Cambodia. The next group with high ratios (0.05-0.18) are the 23 dams in the UMB mainstream cascade in China, where the planned dams upstream are of lower ratios. Similar to how most dams are of low stream order (Fig. 7A), most of the dams are of low ratio, especially in Thailand and Vietnam.

This prevalence of tributary dams was first driven by energy needs and public funding (Hirsch, 2010). Thailand's electricity demands surged in the 1990s, while Laos endeavored to profit from selling its natural resources, spurring the development of tributary dams in Laos. Many of the dam projects were financed by public institutions like the Asian Development Bank, and the electricity produced was imported by Thailand. The situation likely served as a trigger, encouraging the spread of tributary dams across the basin. Nevertheless, with a continued growth in regional energy demands, the construction of the mainstream dam cascade in China, and a shift towards investment from private and Chinese institutions, there is now a renewed focus on building mainstream dams in the LMB (Grumbine et al., 2012; Pearse-Smith, 2012; Urban et al., 2013). Mainstem dams are usually perceived to have more devastating environmental and socioeconomic repercussions across the region, causing river fragmentation and threatening the species richness found at higher stream order, in turn jeopardizing the agricultural and fishing industry dependent on the mainstream (Grill et al. 2014; Reyes-Gavilán et al., 1996). Yet, some suggest that tributary dams are also highly damaging, blocking alternative habitats crucial for fish migration, reproduction, and biodiversity – 169 out of 245 fish species decreased in population or disappeared upstream of the tributary Pak Mun Dam in Thailand (Amornsakchai et al., 2000; Tang et al., 2021). Small tributaries include headwater streams that make up 60% to 80% of the basin, and damming them could diminish important water and nutrient supplies from headwaters (MacDonald and Coe, 2007). These implications could be amplified through the cumulative effect of the widespread tributary dams (Sun et al., 2023; Ziv et al., 2012).

Similarly, such discussions exist when comparing the impacts of upstream and downstream dams. Concerns have traditionally focused on the transboundary effect of upstream dams on lower riparian countries. For example, upstream dams modify the volume and seasonality of discharge downstream, which reduces natural floods that give fishes access to floodplain habitats and replenish floodplains with nutrients for agriculture (Biba et al., 2012; Grill et al., 2019; Poff et al., 2002). By trapping sediments, upstream dams can also cause far-reaching hydrological alterations like channel incision, bank retreat, and riverbed coarsening (Li et al, 2021). However, dams of the LMB cascade in Laos and Cambodia regulate the largest upstream area, as they are located on the Mekong mainstem of Strahler stream order eight (Fig. 7). These dams could together contribute to the capture of up to 96% of river sediments, before they can be deposited at the delta (Kondolf et al.,

https://doi.org/10.5194/essd-2023-417
Preprint. Discussion started: 3 November 2023

2014). The decrease in sediment supply could lead to the shrinking of the Mekong delta, threatening agricultural production and livelihoods (Li et al., 2017). Perhaps there is a tradeoff no matter where the dam is along the river network, and ultimately, the scale of a dam's impact is not only dependent on its location, but also on other factors like how it is operated, whether mitigation efforts like fish ladders are in place, and its proximity to critical river junctions (Gao et al., 2022; Grill et al. 2014; P. Wang et al., 2014).

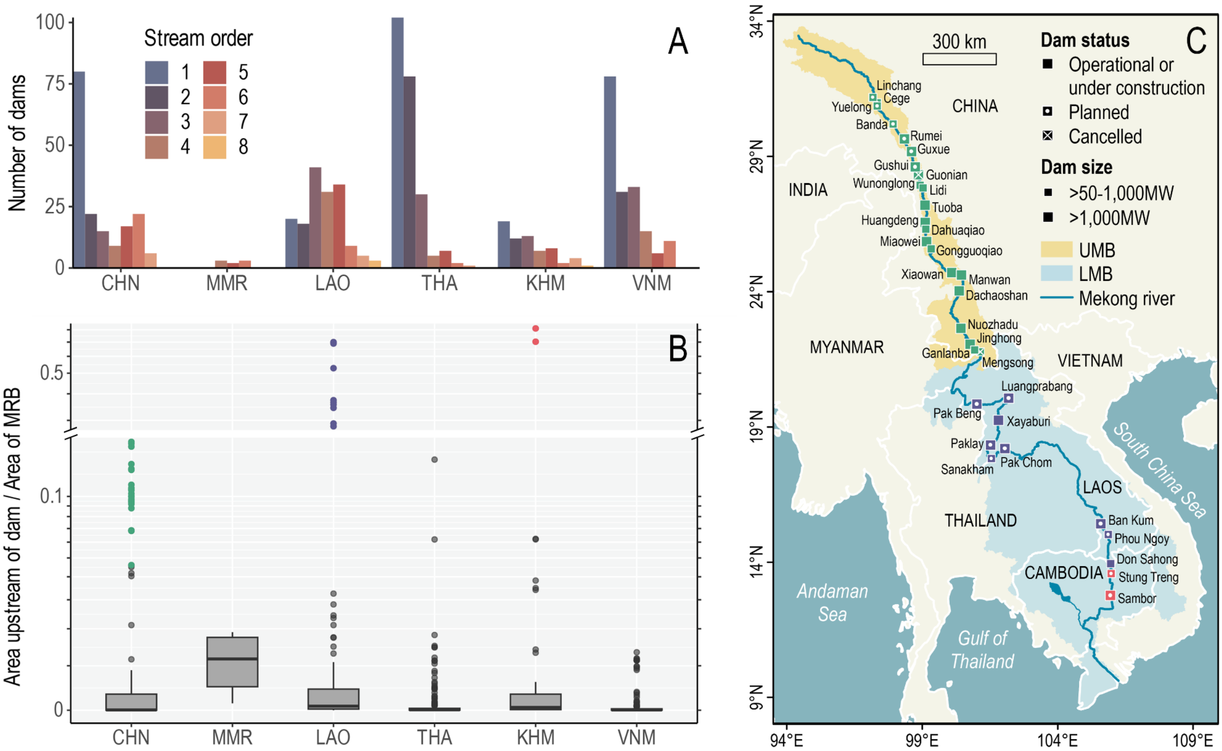

Figure 7: A. Distribution of dams based on the Strahler stream order per country. B. Box plots per country showing the ratio of area upstream of each dam to the total area of the Mekong River Basin (MRB) (Xu et al., 2021). The mainstream dams (as colored) have the highest ratios, located in China (green), Laos (purple), and Cambodia (red). C. Map of dams along the mainstream, with colors corresponding to B. Dam symbols are differentiated by status and size (capacity).

4.5 Implications: hydrology, ecology, and dam management

Our free-access database strives to improve both the quantity of dams identified, and the quality of dam attributes recorded in the Mekong. With an extensive record of 1,055 dams, and detailed attributes including nested catchment area and rainfall provided, the database can facilitate further research on the hydrology of the basin, such as quantifying the impact of dams on sediment loss, river fragmentation, downstream channel incision, and delta erosion (Grill et al. 2014; Li et al, 2021). These hydrological impacts implicate the livelihoods of people in the region, such as the rice-based farmers in the Vietnam Delta (Kang et al., 2021; Yoshida et al., 2020). Through our spatiotemporal analysis of dams, including planned dams post-2020s, the impacts on hydrology and local communities could be projected into the future to inform decisions made

https://doi.org/10.5194/essd-2023-417
Preprint. Discussion started: 3 November 2023

regarding sustainable dam planning, construction, and operation. The dam database can also be used in the hydrological modeling of river discharge and water level, taking into account the modification of discharge volume and seasonality by dams (Dang et al., 2022; Kondolf et al., 2014; Shin et al., 2020). This could aid in the prediction of extreme events and the adoption of mitigation approaches against droughts and floods (Le et al., 2007; W. Wang et al., 2017).

Hydrological impacts are closely tied with ecological impacts of dams. River fragmentation disrupts migratory pathways for fish species and isolates populations, reducing breeding, gene flow, and biodiversity (Tang et al., 2021). Modified discharge seasonality and downstream river-bed incision alters the feeding patterns of aquatic species and limits river-floodplain connectivity, separating fishes in the main channel from floodplain habitats (Ang et al., 2022; Barbarossa et al., 2020; Poff et al., 2002). Our comprehensive dam database contributes to further understanding of the impacts of damming on the basin-wide river connectivity (upstream and downstream, and between river and floodplain), especially with the inclusion of smaller tributary dams, which are less represented in global dam databases (Grill et al., 2019; Sun et al., 2023). This could assist in fish monitoring, conservation, and mitigation measures like fish ladders and barrier removal, not only for regional ecology, but also to safeguard food security and the livelihoods of locals in the world's largest inland fishing industry (Dugan et al., 2010).

Besides facilitating research on dam impacts, this paper contributes to water resource and dam management in the basin, by identifying vulnerable dam hotspots for targeted management. Through our spatiotemporal analysis of projected dam growth and hydropower potential assessment, Laos is likely the most vulnerable to future dam development. Thailand has the most operational (irrigation) dams and China has the highest hydropower capacity, and many discussions focus on the impact of upstream dams in China on the lower riparian states (Biba, 2012; Zawahri and Hensengerth, 2012). However, Laos has the most planned dams and largest expected growth in capacity. With high hydropower potential, even more dams could be commissioned in Laos (Pholsena and Phonekeo, 2004). Compared to the 16% of the Mekong River flow originating from China, Laos makes up 25% of the total basin area and 35% of the river flow, thus intensive dam construction in Laos could devastate regional hydrology and ecology (Baird, 2007; MRC, 2011). Our results suggest focusing planning and management in Laos, such as stricter protocols enforcing environmental impact assessments and proper resettlement of affected locals prior to construction, in order to harness the advantages of dams while protecting ecosystems and native communities (Barbarossa et al., 2020; Yoshida et al., 2020). Regionally, our spatiotemporal assessment could shed light on the complex power trade driven by high energy demands (Galelli et al., 2022; Soukhaphon et al., 2021). The electricity market involves partnerships between governments and companies, hydropower exports for national revenue, and cross-border investments in dam construction, while downstream countries are subjected to the impacts of upstream dams, entangling the countries in a mix of shared interests and water conflicts (Binh et al., 2020; Cronin, 2009). The Mekong is a characteristic example of a complex transboundary basin, where understanding of the electricity trade, water politics, and dam patterns could be applied to other large river basins worldwide.

https://doi.org/10.5194/essd-2023-417
Preprint. Discussion started: 3 November 2023

5 Data Availability

The dam database of the Mekong Basin is available to the public at https://doi.org/10.21979/N9/ACZIJN (Ang et al., 2023), including 1 file of the dam database, and 5 files for the spatiotemporal analysis, with each file corresponding to the dams in each decade from the 1980s to post-2020s. All files are in comma-separated values (CSV) format. The dam attributes are detailed in Table 2.

6 Conclusion

This study presents (1) a comprehensive free-access database of 1,055 dams in the Mekong, (2) a spatiotemporal analysis of the dams over sub-basins and countries by decade from the 1980s to post-2020s, and (3) a grid-based theoretical hydropower potential of the basin. We extracted unique dam records from six global, five regional, and seven local databases, visually validated using Google Earth. The dam records and attributes are supplemented with online information (e.g., reports, papers, articles), and a GIS analysis of hydrological characteristics (e.g., catchment area, stream order, rainfall). The final dam count of 1,055 is more than twice the largest existing database, of which 661 are operational, 54 under construction, 331 planned, 2 closed, and 7 canceled. With 608 hydropower dams, hydropower capacity has surged from 1,242 MW in the 1980s to 33,914 MW in the 2010s, and is expected to double to 69,199 MW post-2020s. Although capacity expanded by 16,854 MW in China from the 2000s to the 2010s, Laos has the most planned dams and is projected to have the highest growth of 18,223 MW post-2020s. Using present-day discharge from the CaMa-Flood model (2011-2015, 0.05 degree), we estimate a basin-wide hydropower potential of 1,334,683 MW, of which 514,887 MW lies in Laos. Using discharge from the ISIMIP2b WaterGAP2 model (2021-2030, 0.5 degree) based on four Representative Concentration Pathways (RCP 2.6, 4.5, 6.0, 8.5), future hydropower potential could grow to over 2,000,000 MW with climate change, where Laos and China are the highest at around 900,000 MW each. China's hydropower potential largely stems from high elevations and steep river slopes, while Laos has high discharge along the lower mainstream, and relatively high elevation and slope in the Mekong Highlands. Considering the large projected hydropower capacity and potential of Laos, it will likely become the country most vulnerable to dam construction, highlighting the need for better dam planning and mitigation measures in Laos. Our unified database aids in research on the implications of dams on the hydrology, ecology, and people in the region, and contributes to sustainable water resource and dam management in the basin. The spatiotemporal analysis potentially furthers understanding on the dam patterns, electricity trade, and water politics in the Mekong, which could be applied to other transboundary basins fragmented by human water infrastructure.

Author Contribution

Wei Jing Ang: Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Edward Park:** Conceptualization, Data curation, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing. **Dung Duc Trans:** Writing – review & editing. **Ho Huu Loc:** Writing – review & editing. **Yadu Pokhrel:** Data curation, Resources, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

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