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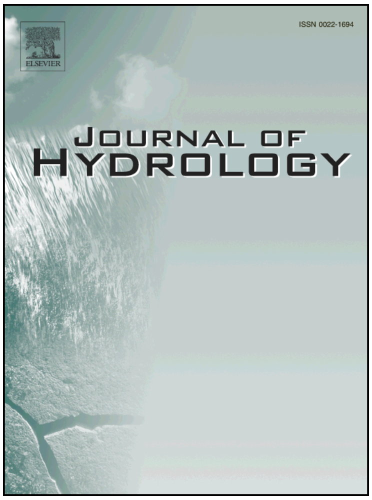

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Hydropower generation, flood control and dam cascades: A national assessment for Vietnam

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Abstract

Vietnam is a country with diverse terrain and climatic conditions and a dependency on hydropower for a significant proportion of its power needs and as such, is particularly vulnerable to changes in climate. In this paper we apply SWAT (Soil and Water Assessment Tool) derived discharge simulation results coupled with regression analysis to estimate the performance of hydropower plants for Vietnam between 1995 to mid-2014 when both power supply and demand increased rapidly. Our approach is to examine the watershed formed from three large inter-boundary basins: The Red River, the Vietnam Coast and the Lower Mekong River, which have a total area of 977,964 km^2. We then divide this area into 7,887 sub-basins with an average area of 131.6km^2 (based on level 12 of HydroSHEDS/HydroBASINS datasets) and 53,024 Hydrological Response Units (HRUs). Next we simulate river flow for the 40 largest hydropower plants across Vietnam. Our validation process demonstrates that the simulated flows are significantly correlated with the gauged inflows into these dams and are able to serve as a good proxy for the inflows into hydropower dams in our baseline energy regression, which captures 87.7% of the variation in monthly power generation In other results we estimate that large dams sacrifice on average around 18.2% of their contemporaneous production for the purpose of flood control. When we assess Vietnam's current alignment of dams we find that the current cascades of large hydropower dams appear to be reasonably efficient: each MWh/day increase in upstream generation adds 0.146 MWh/day to downstream generation. The study provides evidence for the multiple benefits of a national system of large hydropower dams using a cascade design. Such a system may help overcome future adverse impacts from changes in climate conditions. However, our results show that there is still room for improvement in the harmonization of cascades in some basins. Finally, possible adverse hydro-ecological impacts due to the proliferation of large upstream dams, including those located beyond Vietnam's border, need to be carefully considered.

Keywords: Hydropower, climate change, Vietnam, large scale, cascade, flood control.

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1 Introduction

Hydropower, which utilizes running or falling water as the chief input into electricity generation, is the leading renewable source for electricity generation globally, supplying 71% of all renewable electricity. Reaching 1,064 GW of installed capacity in 2016, it generated 16.4% of the world's electricity from all sources (World Energy Council, 2017). Although attractive as a cheap, long-lasting, flexible and low-polluting renewable energy source, it is sensitive to changes in hydrology as a result of variation in weather conditions particularly rainfall and temperature (Kumar et al., 2011; IFC, 2015). To assess the state of a hydropower system requires an evaluation of water availability. However, the absence of a consistent data at the country level means such an evaluation can be challenging. In many cases, measures of the inflow into a hydropower dam is not available or accessible. Modelling hydropower production is further complicated by hydrpower dams being increasingly spatially connected so that they form cascades.[1]

There is a small but growing literature that incorporates rainfall-runoff models and regression analysis to estimate the energy generation from a hydropower system conditional on weather-induced variations in river flow. Rainfall-runoff models, in conjunction with remote-sensing datasets, are one of the solutions employed to overcome the lack of consistent data on a large scale. Meanwhile, regression analysis enables the researcher to establish the relationship between water availability and power generation. Notable papers include Cole et al. (2014) who use the GeoSFM model and regression techniques to assess the potential risks to energy supply in hydro-dependent African countries under different IPPC climate change scenarios.[2] Studies for Vietnam include Gebretsadik et al. (2012) who employ the CLIRUN-II model to simulate river flow for Vietnam in an integrated study while (Arndt et al., 2015) evaluate the impact of climate change on multiple water-dependent sectors including energy in Vietnam.[3] However, these studies do not take into account the multiple purpose use of hydropower dams and the interactions between them. Indeed, a recent paper by de Faria et al. (2017) looking at the local socio-economic impact of large dams highlights the lack of (1) quantitative studies looking at impacts over an extended period and (2) a lack of studies that consider multiple projects in the context of a developing country.

The purpose of this paper is fill this gap in the literature and to estimate the performance of the hydropower system across the whole of Vietnam using new data and advanced regression modelling techniques. More specifically, our main contribution is to estimate the

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[1] In addition to power production, hydropower dams typically serve multiple purposes including, but not limited to, flood control, irrigation, and navigation

[2] The GeoSFM model is a semi distributed, physically based catchment scale hydrological model originally developed by the National Centre for Earth Observation and Science (EROS) to support the Famine Early Warning System Network (FEWSNET) through river flow monitoring. See Cole et al. (2014) for more details.

[3] CLIRUN-II is the latest in a family of hydrologic models developed specifically for the analysis of the impact of climate change on river-runoff. See Gebretsadik et al. (2012) for details.

impact of water availability, flood control and the interconnected cascades of dams on hydropower production for the period 1995 to 2014. With floods being the most common natural disaster in the country and with climate change predicted to lead to more extreme weather patterns it is important that we gain a better understanding of the role of hydropower dams in both the mitigation of floods and droughts as well as providing a reliable and clean source of energy.[4] Our methodological approach allows us to answer a number of questions relevant for water resource management and Vietnam future energy strategy: (1) How is national hydropower generation affected by variations in weather and is it robust to extreme hydrological changes? (2) What is the trade-off between power generation and flood control? and (3) Is the location of large hydropower dams appropriate to enable coordination among dams through the use of dam cascades and how do cascades affect production? A second contribution is that our methodology will allow future researchers to identify how variations in weather may impact those economic activities that are dependent on electricity via variation in power supply. This source of exogenous variation is useful as it allows researchers to address a number of endogeneity concerns in studies of the relationship between firm performance and electricity provision (Allcott et al., 2016; Fisher-Vanden et al., 2015; Alam, 2013) or household welfare and electrification (Grogan, 2016; Khandker et al., 2009; Walle et al., 2013).

To model river flow we use the HydroSHEDS/HydroBASINS dataset (Lehner, 2014; Lehner et al., 2008), which is derived from the detailed SRTM DEM at three arc-seconds.[5]

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[4] Flooding is the most common weather-related disaster and is estimated to affect 2.3 billion people (mainly in the Asia) (CRED, 2015). In Vietnam, floods rank second among natural disasters. According to national statistics, natural disasters in Vietnam are responsible for 750 deaths annually and economic losses equivalent to 1.5% of GDP (IFAD, 2010). In October 2017 floods killed 72 people and damaged 22,000 hectares of rice with deforestation being blamed for the floods being more severe than usual (https://www.nytimes.com/reuters/2017/10/16/world/asia/16reuters-asia-storm-vietnam.html).

[5] A digital elevation model (DEM) is a digital model or 3D representation of a terrain's surface created from terrain elevation data. Source: https://en.wikipedia.org/wiki/Digital _ elevation _ model. DEM data is stored in a format that utilizes three, five, or 30 arc-seconds of longitude and latitude to register cell values.

Consequently, the river network and nested basin system created by HydroSHEDS/HydroBASINS has a higher resolution than the popular Hydro1K dataset.[6] As a result we are able to undertake our analysis at a more disaggregated spatial level which we believe is necessary if one is to accurately model dam interactions. To the best of our knowledge, we are also the first to apply the SWAT model for Vietnam at the national scale.

To model river-flow we use the SWAT (Soil and Water Assessment Tool) river-runoff model. SWAT is "one of the most widely used water quality watershed and river basin–scale models and is applied extensively to a broad range of hydrologic and/or environmental problems" (Gassman et al., 2014, p. 1). SWAT has been applied to large-scale watersheds all over the world, for example China (Hao et al., 2004), West Africa (Schuol and Abbaspour, 2006), and Europe (Abbaspour et al., 2015). For a summary of SWAT applications for the US and EU see Arnold and Fohrer (2005).

There is also an emerging literature that applies the SWAT model to Vietnamese watersheds. For example, it has been used to study the hydrological process and sediment transport in the trans-boundary basin of Lower Mekong River (LMR), which is shared by Cambodia, Laos, Thailand, Myanmar, and Vietnam (Rossi et al., 2009; Piman et al., 2013). A part of the LMR, the Sesan, Srepok, and Sekong rivers (widely referred to as the 3S rivers) shared by Vietnam, Laos and Cambodia is particularly attractive to researchers because of the recent boom in hydropower (Wild and Loucks, 2014; T.Piman et al., 2013; Shrestha

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The geographic reference system treats the globe as if it were a sphere divided into 360 equal parts called degrees. An arc-second represents the distance of latitude or longitude traversed on the earth's surface while travelling one second (1/3600th of a degree). At the equator, an arc-second of longitude approximately equals an arc-second of latitude, which is 1/60th of a nautical mile (or 101.27 feet or 30.87 meters). Arc-seconds of latitude remain nearly constant, while arc-seconds of longitude decrease in a trigonometric cosine-based fashion as one moves toward the earth's poles. Source: http://www.esri.com/news/arcuser/0400/wdside.html.

[6] The Hydro1K dataset which is a comprehensive global geographic database at a resolution of 1 km that includes streams, drainage basins and ancillary layers derived from the 30 arc-second digital elevation model (DEM) of the world (GTOPO30) generated by the U.S. Geological Survey (USGS, 2015) and has been used for large scale river flow modelling by (Cole et al., 2014; Gebretsadik et al., 2012).

et al., 2016). There are also a series of studies that apply SWAT to separate basins in different parts of Vietnam: the North (Wang and Ishidaira, 2012; Phan et al., 2011; Ngo et al., 2015), the Central Coast (Giang et al., 2014; Le and Sharif, 2015), the Central Highland (Vu et al., 2012; Tram et al., 2014; Vu et al., 2015; Quyen et al., 2014), and the South (Ho et al., 2013; Khoi and Suetsugi, 2014). Although a frequent application of SWAT is to assess the impact of climate change on hydrological processes (Phan et al., 2011; Giang et al., 2014; Le and Sharif, 2015; Vu et al., 2015) they have also been used to evaluate the impact of human activities that take into account deforestation (Khoi and Suetsugi, 2014), forest planting, soil protection, crop conversion (Ngo et al., 2015; Quyen et al., 2014), and hydropower construction and operation (Wang and Ishidaira, 2012; Le et al., 2014). Although the application of these models varies they all attempt to inform policy makers on various aspects of water management, agricultural land use, and energy supply. However, none of these papers examine Vietnam at a national scale.

The remainder of this paper is organised as follows. Section 2 describes the evolution of hydropower in Vietnam. Section 3 describes our methodology and data including the materials needed for our hydrological simulation, the SWAT model, the consolidation and transformation of hydropower and the regression techniques used in the paper. We present our results in Section 4. The final section concludes.

2 Hydropower in Vietnam

Understanding the hydrology of Vietnam is important for the reasons highlighted in the introduction. Located in the south-east of the Indochinese peninsula, Vietnam's terrain is dominated by tropical hills and densely forested highlands. This means that Vietnam's lowlands, which are suitable for agricultural cultivation, cover less than 25% of its area with production concentrated in the Red River Delta (in the North) and the Cuu Long River Delta (in the South). The majority of water resources (63.9% of total flows) are concentrated in these basins while other parts of the country, that occupy more than 75% of the total area of Vietnam, receive just over 35% of the national total river-runoff. Yet Vietnam is abundant in water resources with 2,360 rivers above 10 km in length and 16 river basins above 2,500 km^2 in area. The annual run-off volume is around 847 km^3. However a population of nearly 100 million means that the total water volume per capita is still only around 9,560m^3 per year compared to an average of global value of 10,000m^3 according to the International Water Resources Association (IWRA) (MONRE, 2012).

In the future, a rapidly growing economy and continued urbanization is expected to increase pressure on water resources. In addition, Vietnam's river network is connected to neighbouring countries with 72% of its largest combined basin of about 1.167 million km^2 located beyond its border (MONRE, 2012). This means Vietnam's water availability could be severely affected if upstream countries were to change their demand or decide to divert or manipulate the river flow. Finally, although the monsoon tropical climate brings about a high average of annual rainfall of around 1940mm, the mountainous and hilly terrain causes a high degree of inter-annual rainfall variability. As a result, Vietnam's water availability can change dramatically throughout the year. This means that foods and prolonged droughts can occur within the same year and region. As a rule, the dry season lasts around 6 – 9 months (with exact times varying across the country) and accounts for only 20-30% of annual run-off. At the same time, half of the 15 major basins experience a shortage of water (MONRE, 2012).

Under such challenging circumstances, dams, reservoirs, and their associated irrigation systems play an important role in the water management of Vietnam. The combined total storage capacity of reservoirs across the country is about 37 billion m^3, which is equivalent to 4.5% of Vietnam's average annual run-off. The network of over 7,000 dams means that Vietnam is one of the most dammed in the world alongside the US and China (Pham and Pham, 2014).

Our study covers the period 1995-2014 which is a time when Vietnam experienced rapid growth in the demand for electricity. Between 1995-2005, demand for electricity grew on average by 15% per annum as a result of an economic growth rate of around 7.5% per year (Huu, 2015). At current growth rates, projections are that Vietnam's energy supply will need to triple by 2020 with additional supply coming chiefly from petroleum, coal, natural gas, and hydropower (ADB, 2015*b*). As a result, per capita energy consumption is projected to increase to 5,400 kilowatt-hours by 2030 from 985 kilowatt-hours in 2010 (ADB, 2013). As an inexpensive and available source of power, hydropower is a key component of the national energy mix. The ten major rivers suitable for hydropower construction have an approximate total potential capacity of 21,000-24,000 MW (UNIDO and ICSHP, 2013).[7] In the last two decades, Vietnam has increased construction of hydropower plants to the extent that it has exploited nearly 70% of its theoretical hydropower potential (Huu, 2015).[8] Hydropower currently contributes 44% of Vietnam's installed power capacity (ADB, 2015*a*). As part of its development plan looking ahead to 2035 (PDP7 revised) (Prime Minister, 2016), Vietnam continues to prioritise the development of hydropower, especially multi-purpose projects that combine flood control, irrigation, and electricity generation. The total capacity of hydropower plants is planned to increase from approximately 17,000 MW (2016) to 21,600

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[7] For comparison, the total power installed capacity of Vietnam in 2015 is 38,642 MW. Hence, if hydropower's potential was to be fully exploited it could account for 54% - 62 % of the total power installed capacity in 2015.

[8] Compared to a global average rate of 35%

MW (2020)[9]. In addition, the pumped storage electricity plants are scheduled to have a total capacity of 1,200 MW in 2025 and 2,400 MW in 2030.[10]

3 Material and methods

3.1 Material for hydrological simulation

To develop the SWAT model for Vietnam we use data generated through remote sensing. For the administrative boundary maps, we use the Global Administrative unit layers (GAUL) (version 2015), which provides "the most reliable spatial information on administrative units for all countries in the world" (FAO, 2015). Our hydrographic data comes from HydroSHEDS (Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales) (Lehner et al., 2008) and its subset HydroBASINS (Lehner and Grill, 2013). HydroSHEDS is a derivative of the digital elevation model (DEM) at a 3 arc-second resolution of the Shuttle Radar Topography Mission (SRTM). The elevation data was void-filled, hydrologically processed, and corrected to produce a consistent and comprehensive suite of geo-referenced data that enables the analysis of upstream and downstream connectivity of watersheds. Among the subsets of the HydroSHEDS database, the polygon layers that depict watershed boundaries and sub-basin delineations at a global scale critical for hydrological analysis are termed HydroBASINS. HydroBASINS delineates and codes sub-

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[9] However, the share of hydropower in national electricity production is predicted to fall to 29.5% by 2020 and 15.5% by 2030 (due to faster growth of other components of the energy sector).

[10] Vietnam is predicted to be among the countries likely to be most affected by climate change (WB & MPI, 2016). This vulnerability has come to the attention of the government and international organizations (ADB, 2013; FAO, 2011; IFAD, 2010, 2014; IMHEN, 2010; IPCC, 2007; ISPONRE, 2009; MONRE, 2003, 2009, 2010, 2011; WB, 2010, 2011; WB and MPI, 2016) with the main threats being increasing temperature, altered rainfall patterns, and rising sea levels. For hydropower, higher temperatures are thought to lead to an increase in demand for energy (MONRE, 2010) whilst also affecting stream flows into hydropower plants (WB, 2011).

basins purely based on topographic and hydrographic bases without any local information (for example the name of rivers/ basins). To mitigate this, we utilize the basin and river layers of the dataset named “Rivers in South and East Asia” derived from HydroSHEDS by FAO (2014) which provides a river and basins network that simplifies HydroBASINS to include annotated attributes, such as the name of each large river and basin and the tentative classification of perennial and intermittent streams.

For our analysis we require a large amount of consistently collected weather data. Although Vietnam has an intensive network of meteorological stations, access to the data to such a large number of stations over a long time period is prohibitively costly. Even if access were possible, inconsistencies in data availability (especially the missing data in weather series) prevents us using this data for watershed analysis on a large scale. In addition, since Vietnam shares river basins with Laos, Cambodia and China, the weather data outside of Vietnam would also be needed since variations in rainfall and temperature in the neighbouring countries could affect the discharge of downstream rivers in Vietnam. Our solution is to use a high quality gridded weather database that supports SWAT applications from the Climate Forecast System Reanalysis (CFSR) by the US’s National Centers for Environmental Prediction (NCEP) (Saha et al., 2010, 2014). To obtain information on soil profile, we use the Digital Soil Map of the World (DSMW) version 3.6 (FAO, 2007). The (physical and chemical) characteristics of each soil unit are tabulated by Schuol et al. (2008). For land cover information, we use the University of Maryland Department of Geography (UMD) Land Cover classification collection at the 1km pixel resolution (Hansen et al., 1998, 2000). The resolution of materials for the simulation are summarized in Table 1.

[Table 1 about here]

3.2 The SWAT hydrological simulator

SWAT (Arnold et al., 1998) is a continuation of thirty years of non-point source modelling by the US Department of Agriculture (USDA), the Agricultural Research Service (ARS), and Texas A&M University.[11] The model is a physically based, continuous, semi-distributed model that was initially developed to project the impact of land management practices on water, sediment and agricultural chemical yields in large complex catchment areas under various soil conditions, land use and management over a long time period (Neitsch et al., 2009). More recently it has been incorporated into a variety of GIS interfaces such as SWAT/GRASS (Srinivasan and Arnold, 1994), ArcView-SWAT (AVSWAT) (Di Luzio et al., 2004) and ArcSWAT (Olivera et al., 2006).

SWAT enables the simulation of numerous physical and chemical processes: discharge, erosion, nutrients, pesticides and management (rotations and water use) (Neitsch et al., 2009). It divides a given watershed into a number of sub-basins mainly based on topography characteristics given a chosen number or size of sub-basin. This process is typically referred to as watersheds delineation. However, each sub-basin is not treated as a lump but instead each sub-basis in broken down into different hydrologic response units (HRU) each considered as a homogenous unit with their own unique set of land cover, soil and management features. The hydrological cycle of a watershed is simulated based on two processes. First, the land phase controls the amount of water flowing to the main channel of each sub-basin and second, the routing phase controls the movement of water through the channel (river) network to an outlet of the watershed.

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[11] Other federal agencies also contributed to the model, including the US Environmental Protection Agency, the Natural Resources Conservation Service, the National Oceanic and the Atmospheric Administration and the Bureau of Indian Affairs.

The land phase The land phase of the hydrological cycle is based on the water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^{t} \left(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw} \right) \ (mm\ H_2O) \tag{1}$$

where the final soil water content (SW_t) is made up of the sum of initial soil water content (SW_0) and a daily-time-step summation of the difference between the amount of precipitation $\left(R_{day}\right)$, and the sum of the amount of surface runoff $\left(Q_{surf}\right)$, evapotranspiration (E_a), percolation and bypass flow exiting the soil profile bottom $\left(w_{seep}\right)$, and return flow $\left(Q_{gw}\right)$.

Equation (1) captures potential pathways of water movement simulated by SWAT. Once precipitation descends, it is either intercepted or held in the vegetation canopy or falls to the soil surface. Water on the soil surface infiltrates into the soil profile or flows overland as runoff. Runoff moves relatively quickly toward a stream channel and contributes to a short-term stream response. Infiltrated water is either held in the soil and later evapotranspried or slowly makes its way to the surface water system via underground paths. Different crops and soils appear with varying evapotranspiration. Runoff is projected individually for each HRU then combined to obtain a total runoff for the watershed. Details about each phase can be found in Arnold et al. (1998); Neitsch et al. (2009).

Routing phase The lump of runoff in each sub-basin is calculated and then routed to the main channel through the stream network using either the variable storage coefficient method by Jimmy (1969) or the Muskingum routing method. The underlying principle is that water discharges downstream except for that part that is lost due to evaporation and transmission through the bed of the channel and the removal for agricultural and human use.

3.3 Hydrological simulation

In this paper we simulate river flow for Vietnam using the ArcSWAT 10.2 interface (SWAT model incorporated in ArcGIS 10.2).

The first step is to delineate the watershed. The watershed we study is a combination of three large basins as defined by the “FAO Rivers in South and East Asia”: Red River (165,007 km^2), Vietnam Coast (186,187 km^2), and a part of Mekong River (similar to Lower Mekong River with an area of 626,771 km^2). The total area of the watershed is 977,964 km^2.

Figure 1 shows the transboundary watershed shared by Vietnam, China, Myanmar, Lao PDR, Thailand and Cambodia. The area within Vietnam accounts for 32.22% the total area of the watershed and covers 96.15% (315,122 km^2/327,727 km^2) of Vietnam’s mainland area. The remainder belongs to the Bang Giang – Ky Cung river basin, which makes no meaningful contribution to Vietnam’s overall hydropower production. ArcSWAT offers two options for breaking the watersheds into smaller sub-basins: burning a river network from a DEM input or using layers that predefine sub-basins and the river network. We chose the second option to take advantage of the HydroBASINS dataset. Hence, the watershed is divided into 7,887 sub-basins at level 12 of HydroBASINS.

[Figure 1 about here]

Table 2 summarises the sub-basin data and shows that their areas vary from 0.2 km^2 to 368.6 km^2, with a mean of 131.6 km^2. The use of HydroBASINS has two advantages over using DEM. First, HydroBASINS was derived from HydroSHEDS, which already hydrographically conditioned DEM. DEM like SRTM has some characteristics, artefacts, and anomalies unfavourable for hydrologic application (Lehner, 2013).[12] Second, HydroBASINS provides two nested coding systems (Pfafstetter codes and HydroSHEDS ID). These codes are a useful for our spatial analysis as they help us to determine systematically the upstream- downstream relationship between dams. Despite using predefined basins, a DEM is still required to calculate the topography characteristics of each basin and hence we used the HydroSHEDS void-filled DEM for this purpose.

[Table 2 about here]

ArcSWAT divides each sub-basin into HRUs using a combination of soil, land use and slope layers. The soil and land use layers are listed in subsection 3.1. The slope layer was created by ArcSWAT using the HydroSHEDS void-filled DEM. We determined three classes of slope in line with the soil slope classification of DSMW: 0-8% (class 1), 8-30% (class 2) and above 30% (class 3), which respectively contribute 64.12%, 31.51%, and 4.37% to the area of the watershed. Based on the above layers, ArcSWAT assigned multiple HRUs to each watershed given our sensitivity thresholds (5% for land use and soil and 20% for slope). In our final data set the watershed is divided into 7,887 sub-basins and 53,024 HRUs. Daily data for each sub-basin on the maximum and minimum temperature, precipitation, wind speed, relative humidity, and solar radiation were supplied from 2,755 weather gridded-stations from the CFSR/NCEP dataset.

We simulated monthly river flow for the whole watershed for the period January 1995 to July 2014. The simulation period was chosen to best fit the available performance data of

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[12] HydroSHEDS reduces errors by deepening open water surfaces, weeding coastal zones, burning stream, filtering, moulding valley courses, filling sinks and carving through barriers.

hydropower plants, subject to the availability of weather data. The model was also run for 5 years prior to this period for warming up purposes, which helps to establish the equalized initial condition of soil water before simulation. The simulation used the method integrated in ArcSWAT (Arnold et al., 1998; Neitsch et al., 2009) that modify the SCS curve number procedure (SCS, 1972) to take into account the varying conditions of land uses and soil types to estimate surface runoff and use the Penman-Monteith method (Allen, 1986; Allen et al., 1989; Monteith, 1981) to estimate evapotranspiration.

3.4 Hydropower data consolidation and transformation

Our analysis focuses on river flow to the 40 largest hydropower plants in Vietnam, which belong to the 12 basins shown in Figure 2 and listed in Table 3. The location of these hydropower dams is mapped using a GIS software (ArcGIS) based on information from various sources including the Vietnam Energy Map of Japan External Trade Organization (JETRO), WB (2014), United Nations Framework Convention on Climate Change - Clean Development Mechanism (UNFCCC-CDM) database, hydropower companies' websites, and local news websites. Finally, we validated and refined the dataset using observations from Google Earth.

[Figure 2 about here]

[Table 3 about here]

Our hydropower operation data at the plant level is from Electricity of Vietnam (EVN, 2015). The report provides information on total capacity, monthly gauged river flow data of each plant, and electricity generation of 40 of the largest hydropower plants of Vietnam between 1995-2014. Vietnam classifies hydropower plants into two categories: small (under 30 MW and managed by local governments) and large (above 30MW and managed by central government). WB (2014) further divides the latter group into medium (from 30MW to under 100MW) and large hydropower plants (above 100 MW). The majority of plants on our list of 40 are defined as large and all of them are managed by the central government. Figure 3 shows that the combined installed capacity of these plants accounts for 75-85% of all hydropower sources which in turn accounts for 35% -53% of all energy sources across Vietnam.

[Figure 3 about here]

As part of the data cleaning process we transformed the data in a number of ways. The original power generation data was monthly and measured in million kWh. However, the number of days within a month varies between 28 to 31. Our solution is to divide the monthly electricity generation by the number of days per month and re-scale it into MWh. Initially we had a simple measure of the installed capacity of plants after full installation. However, as there were no additional developments to existing hydropower plants during our period of analysis, this variable is time-invariant and would be absorbed by the fixed effects in our regressions. In other words, under such circumstances, we would n2ed to exclude the capacity variable as there would be perfect multicollinearity between it and the dam fixed effects, which already capture any time-invariant dam-specific characteristics. To mitigate this, we take advantage of the fact that each plant is comprised of several generators that are typically commissioned at different times. More precisely, it can take a plant months or even years to be fully operational after the commissioning of its first generator. Hence, in reality the installed capacity of each plant is time varying during the installation phase and time-invariant from that point onwards. We gather information on the operation date of each generator from the website of plants or local online newspapers, and then adjust the installed capacity of each plant to reflect the real operation of each generator. Fortunately, the first run of each generator in a large hydropower plant is an important event to investors and local residents and hence this information is fully recorded. As a result, the installed capacity variable, after transformation, became time-varying and can be included in a regression with fixed effects. All plants in our sample are of the storage type and many have large government regulated reservoirs. The total capacity of reservoirs ranges from 30.4 million m^3 to 9.8 billion m^3 and the mean size is 1.1 billion m^3. [13]

To enable us to investigate the interaction between dams on the same river system, we need to determine the upstream-downstream relationship between dams. To do this we use the HydroSHEDS identifiers from the HydroBASINS dataset at the most disaggregated level. HydroBASINS provides two systems of basin coding: HydroSHEDS identifiers and Pfafstetter code (Verdin and Verdin, 1999). We use the former as the HydroSHEDS identifiers is more consistent and each sub-basin is assigned one unique identifier and routed to (only) one immediate downstream sub-basin or the sea/itself (if it is an outlet) or an outlet (if it is an endorheic sink).[14] Table 4 shows that, after tracing all routes, that there are 13 hydropower cascades detected in 9 of the 12 basins studied comprised of 36 upstream-downstream pairs. We then consolidated with local information (websites of hydropower plants, local newspapers and so on). The distance between each upstream plant and its downstream counterparts in Table 4 is measured by the number of HydroSHEDS sub-basins

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[13] Information about these reservoirs is from the 11 most recent PM decisions on inter-reservoir management procedures in 11 basins: Ba (1077/QD-TTg -2014), Sesan (1182/QD-TTg 2014), Srepok (1201/QD-TTg 2014), Ca (2125/QD-TTg 2015), Huong (2482/QD-TTg 2015), Kon Ha Thanh (1841/QD-TTg 2015), Ma (1911/QD-TTg 2015), Tra Khuc (1840/QD-TTg - 2015), Red River (1622/QD-TTg -2015), Vu Gia Thu Bon (1537/QD-TTg 2015), Dong Nai (471/QD-TTg -2016). For smaller reservoirs, data were collected from internet sources. The smallest plant among those studied has a full installed capacity of 44 MW. The largest one is more than 50 times greater (2,400 MW) and the average one is about 300 MW.

[14] Because of the challenges in the latter in determining the downstream plants; for example, the difference in routing between inter-basins and basins and the skip of coding due to endorheic sinks and islands.

shared between them. The exception is Ham Thuan and Da Mi where the zero-distance reflects the fact that the dams are located in the same sub-basin.

[Table 4 about here]

We create two proxies for the operation of an upstream dam: the combined installed capacity of upstream dams and the combined production of upstream dams. Some dams have many upper dams that are operated at different times and we need to fill in all missing values before aggregating. The installed capacity and production of plants before they begin their operation are assigned zero values. Any missing values from upstream dams are filled in using the predicted values of a double log regression of non-missing production values on its installed capacity and simulated discharge.[15] The double-log regression has lower predictability than the double-level regression; however, it ensures that the predicted values are positive. The variable coefficients then measure the average impact of upstream dams nationwide.

Table 5 provides summary statistics for our key variables of interest. We model monthly hydropower generation using data on installed capacity and simulated discharge. We consider the period from January 1995 to July 2014 and since the majority of Vietnam's hydropower plants were commissioned after 1995, the panel is unbalanced. Our final sample includes 2,984 observations with a mean generation of 4.39 MWh per day. The highest production record is 46.8 MWh (Son La on August 2014). Recall that the installed capacity, disaggregated at the generator level, is time variant and ranges from 22MW to 2,400 MW with a mean of 376.3 MW. The simulated flows in the sample vary from 0.12 – 9,105 cubic metres per second and the combined installed capacity of upstream dams varies from 0 to

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[15] The model for each plant (i) is $ln(Gen_t) = \beta_0 + \beta_1 ln(CAP_t) + \beta_2 ln(Flow_t) + \varepsilon_t$.

2,820 MW. The combined production of upstream dams varies from 0 to 45,781 MWh/day.

[Table 5 about here]

3.5 Simulation validation

To evaluate the performance of the river flow model in general and the SWAT application in particular, a common approach is to compare the gauged flow with the simulated flow based on statistics established and documented prior to the modelling. There are numerous statistics that can be used for this purpose that are usually put into 3 different categories: standard regression, dimensionless, and error index (Moriasi et al., 2007). In this study, since river flows are simulated to serve as as an explanatory variable in subsequent regression analyses, we are interested in the variation in discharge rather than the level. Hence, for validation we intend to use two standard regression statistics: Pearson's correlation coefficient r and the coefficient of determination R^2. The gauged data for validation are monthly average inflows to dams from the same source as hydopower generation data. The data are only available for dams during their operation time hence the length of gauged series vary across dams. It should also be noted that there are many missing values hence gauged series are shorter than the generation series. Validation is applied for dams with gauged series long enough (at least 30 observations) to provide statistically reliable results.

Pearson's correlation coefficient r measures the degree of the linear relationship between two types of data, ranging from -1 (perfect negative correlation) to 1 (perfect positive correlation) (Krause et al., 2005; Moriasi et al., 2007). To have confidence in our simulated data we expect a sensible river flow model to have a positive r with a magnitude close to one. As we do not have any guide on specific threshold to classify the fit of the model based on r, we report the significance at conventional levels (i.e., whether two variables are significantly correlated or not).

$$r = \frac{\sum_{i=1}^{n}\left(Y_i^{obs} - \bar{Y}^{obs}\right)\left(Y_i^{sim} - \bar{Y}^{sim}\right)}{\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - \bar{Y}^{obs}\right)^2}\sqrt{\sum_{i=1}^{n}\left(Y_i^{sim} - \bar{Y}^{sim}\right)^2} \tag{2}$$

The coefficient of determination R-squared measures the percentage of the change in observed data explained by a best-fit regression line using simulated data as an explanatory variable. The value is bounded between 0 and 1, and the higher it is, the better the match between observed data and simulated data. A value above 0.5 is considered acceptable (Santhi et al., 2001; Van Liew et al., 2007).

3.6 Regression method

To estimate hydropower generation using simulated flows, we rely on the linear panel data model and the pooled ordinary least squares (POLS) estimator. See Appendix A for more details. For inference purposes, we make minimal assumptions about the error term and rely on standard errors that are robust to heteroscedasticity and contemporaneous and lagged spatial correlation computed by statistical package STATA and command *xtscc* (Hoechle, 2007). They are derived from the non-parametric covariance matrix estimator by Driscoll and Kraay (1998) adjusted for an unbalanced panel . Driscoll and Kraay (1998) standard errors are used because the normal i.i.d assumptions are not appropriate as the variances in the errors are likely to be larger for the larger plants. In addition, power generation from different plants, especially those within the same basin, are likely to be correlated with each other. Finally, the electricity generation from any given plant at a particular time is not independent of its lagged values. To assess the goodness-of-fit of our models, we consider the adjusted R-squared ($\bar{R}^2$) that measures the percentage of variation in the dependent variable explained by a model with a penalty for excessive regressors. We employ a number of specifications to model hydropower generation as follows:

Baseline regression In the first stage we examine the degree to which simulated river flow explains the production of electricity from hydropower plants. Our baseline specification follows Cole et al. (2014) and assumes that the main determinants of hydropower generation (Gen) are a quadratic function of river flow ($Flow$) and dam capacity (CAP):

$$Gen_{it} = \beta_0 + \beta_1 Flow_{it} + \beta_2 Flow_{it}^2 + \beta_3 CAP_{it} + \lambda_t + \mu_i + \varepsilon_{it} \tag{3}$$

where subscripts i and t refer to a hydropower plant and our unit of time, respectively. λ_t is included to capture all time-specific factors (monthly) that have a uniform effect on all hydropower plants. μ_i is the unobservable time-invariant hydropower plant fixed effect and ε_{it} is an idiosyncratic error term. One should note that our specification differs from Cole et al. (2014) in that they studied hydropower generation on a continental scale for Africa at yearly intervals, while our study is on a national scale for Vietnam using monthly data.

The calculation of electricity production from a hydropower plant is given by:

$$P = \eta \times \rho \times g \times Q \times H \tag{4}$$

where P is the power produced at the transformer (million MW), η is the overall efficiency of the power plant, ρ is the density of water (1000 kg/m^3), g is the acceleration due to gravity (9.81 m/s2), Q is the volume flow rate passing through the turbine (m^3/s), and H is the net head (m). By assigning a typical overall efficiency of 87% (IFC, 2015) it reduces the formula to:

$$P(kW) = 8.5 \times Q \times H \tag{5}$$

The installed capacity is one of the most prominent features of a hydro plant, which can be calculated by equation (4) using design discharge, net head, and the overall efficiency for a given design discharge. If the river flow rate passing through a turbine is equal to its design discharge, the production of electricity is proportionate to the installed capacity. If the flow rate is higher or lower than the design discharge, there will be more or less electricity generated. The gap between the flow rate and the design discharge can be sensibly proxied by the variation in the river flow into a hydropower plant. We expect positive signs for both explanatory variables in a linear specification ($\beta_1, \beta_3 > 0$). The linear function of the inflow's impact on hydropower electricity generation is based on the assumption of constant overall efficiency. In practice, efficiency is a non-linear function of the deviation between the turbine discharge and the optimal value, the outcome of which is subject to the type of turbine. Figure 4 presents a stylized version of the efficiency profiles of different turbine types and shows that plant efficiency is low when the discharge is far below the optimal value, and then increases. This suggests that a quadratic function of discharge with a negative coefficient for the squared term ($\beta_2 < 0$) is a more appropriate functional form to model hydropower production.

[Figure 4 about here]

Besides the key determinants, our baseline model includes two-way fixed effects (λ_t + μ_i + ε_{it}). Dam fixed effects μ_i are included to account for the unobserved features that are unchanged overtime. As our SWAT model has not been calibrated, the parameters in the rainfall-runoff model can not be considered optimal. Hence, the relationship between simulated and actual inflows into a dam depends in part on the heterogeneous characteristics of each sub-basin (for example soil composition, land cover distribution and topographic features) and are partially absorbed by dam fixed effects. Dam fixed effects also capture variations in turbine efficiency across dams. We include time fixed effects to control for common trends over time. For example, the performance of satellite data on which our SWAT model relied may varying across the months of a year and across years. Likewise, time fixed effects will control for any time-varying fluctuations in the demand for electricity that is common across the country. Finally, besides measurement error, the idiosyncratic error term (ε_{it}) captures any unobserved factors that vary across either time or dams, for example, production adjustments due to regional changes in demand, deviations from overall turbine efficiency, the storage and releasing of water from dam reservoirs, and any hydropower plant interactions.

Flood control regression A key feature of hydropower plants is they important role they play in flood control. In Vietnam, 3 basins have reservoirs with a flood control capability namely Hong–Thai Binh River, Ma River and Huong River (MONRE, 2012).[16] Even hydropower plants without a specific flood control function are able to store flood water as a means to smooth electricity production across time.

To quantify the degree to which the flood control function of dams affects production of

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[16] Lo–Gam–Chay River and Da River are parts of larger Hong–Thai Binh River.

hydropower we extend the baseline specification to include proxies for floods. We estimate three alternative specifications: (1) a dummy variable $Flood_{it}$ (defined as flows that exceed the mean flow at each hydropower plant by at least one standard error), (2) its interaction terms with inflows into hydropower plants and (3) both (1) and (2) together. The final specification is given by:

$$Gen_{it} = \beta_0 + \beta_1 Flow_{it} + \beta_2 Flow_{it}^2 + \beta_3 CAP_{it} + \gamma_0 Flood_{it} + \gamma_1 Flow_{it} \times Flood_{it} + \lambda_t + \mu_i + \varepsilon_{it} \quad (6)$$

where the assumption is that utilizing a dam's flood control role is at the expense of a reduction in hydropower generation even though this shortfall in power generation may be considered socially and economically desirable. We expect the estimated coefficients on our flood variables to be negative ($\gamma_0, \gamma_1 < 0$).

Dam interactions Finally, a little understood issue is how hydropower plants interact with each other. Hydropower generation in many basins requires coordination between plants that share a common water resource. Knowledge of how these interactions work could facilitate improvements in the allocation of existing water resources.

There are a number of reasons why an upstream plant may potentially influence the power generation of downstream plants that can be related to either their construction or operation. For example, the building of a hydropower plant is typically associated with a degree of deforestation and hence an increase in river-runoff. As a result, downstream discharge and electricity generation may increase.[17] Alternatively, some hydropower plants

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[17] A report from the National Assembly reveals that 160 hydropower projects in 29 cities and provinces

construct weirs that diverts water to an ‘off-site’ facility that enables it to create a higher head for electricity generation (Hecht and Lacombe, 2014) but at the cost of a reduction in river flow into downstream rivers which in turn lowers the production of hydropower plants in those down stream locations. In terms of operation, upstream plants with large storage facilities and no water diversion normally adjust outflows in a way that favours downstream electricity generation. By reducing extreme inflows into downstream plants it means that the turbines can operate at higher efficiency levels leading to higher levels of electricity production.

The actual effect of dam interactions is therefore an empirical question. To capture the cascade effect our solution is to include a proxy for the operation of upstream dams into our baseline specification. As part of our robustness checks we include the combined upstream capacity and combined upstream production variables (as described in Subsection 3.4). We further decompose the impact of cascades by adding interaction terms between upstream operation variables and categorical variables of hydrological conditions (flood, normal and drought). Finally, we investigate the heterogeneity in dam interaction across basins. According to PanNature (2011), basin-based water management was adopted in Vietnam fairly early.[18] As basins have historically been managed by different organizations, dam interaction could vary across basin. We explore this heterogeneity by adding the interaction terms

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over the period 2006-2012 converted an area of 19,792ha of forest land into land suitable for the location of hydropower plants (Le and Tran, 2016).

[18] Water Resources Law issued in 1998 sketched river basin plan regulation and the role of the River Basin Planning Management Commissions. The commissions then established the management of water resources in Cuu Long (Mekong) River (2001), Dong Nai River (2001), Hong–Thai Binh River (2001), Vu Gia–Thu Bon (2005) by MARD. Similarly, River Basin Councils with the participation of local governments and the involvement of communities were created to manage the Srepok River (2006) and Ca River. Subsequently, the water resource management function was passed from MARD to the newly set-up MONRE with the establishment of a number of River Basin Environment Protection Commissions in Cau River (2007), Dong Nai River (2008), and Nhue-Day River (2009). The ineffectiveness of various basin management organizations mentioned above was addressed by the Decree 120/2008/ND-CP on River Basin management, which sought to establish consistent basin-based water resources management and proposed the establishment of the River Basin Commissions to coordinate and supervise the activities of ministries, and local governments related to water resources planning and management.

between the proxies for upstream operation and dummies for each basin.

4 Results and discussions

4.1 Simulated discharge validation

The validation is made for simulated inflows to 24/40 studied hydropower dams (belonging to 11/12 studied basins) that have at least 30 gauged observations for comparison.[19] The assessment results are shown in Table 6. Overall, all simulated flows are positively correlated with the gauged flows. The magnitude of the Pearson correlation coefficients (r) ranges from 0.33 (An Khe - Kanak) to 0.90 (Thac Mo). The mean and median of these coefficients are 0.70 and 0.72 respectively. Almost every correlation is significant at 1%. The exceptions are An Khe - Kanak and Quang Tri, which are significant at 10% and 5% respectively. The coefficients of determination (R^2) vary between 0.11 and 0.8. Based on the threshold of 0.5 for the this statistic, our rainfall-runoff model could be labelled as 'acceptable' for inflows to 13/24 dams. Both the mean and median of these R^2 are 0.52 and exceed the threshold.

[Table 6 about here]

There are a number of reasons why the simulated data does not perfectly match the observed data. Firstly, the model may inherit errors in the data, especially when we need to rely on remote-sensing data for our large scale study. For example, the HydroSHEDS dataset is known to be exposed to error in coastal areas (Lehner, 2013) due to SRTM satellite operation characteristics (Farr et al., 2007). The problem is amplified as Vietnam is a coastal

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[19] The only basin that has no dam validated is the Huong River Basin.

country and stretches along the sea. Our model perform better for basins in the North and the South rather than those in the Central part of the country. It is indeed difficult to accurately model discharge in small, narrow coastal basins like Huong River, or Thach Han River due to the strong influence of the tide. In addition, we simulated the model with assumptions of no change in topography, soil profile and land cover. We acknowledge that this is a reasonably strong assumption over a long period of time.

As our time period covers a time when Vietnam experienced rapid economic development, the change in land cover could be considerable (for example deforestation and urbanization). A boom of hydropower in Vietnam and countries upstream may also have a considerable impact on river flow regimes and sediment patterns. Finally, as our SWAT model was not calibrated, the default parameters that we rely on may not be optimal for Vietnam. An appropriate adjustment of the parameters ET, lateral flow, surface runoff, return flow and tile flow processes (Arnold, Moriasi, *et al.*, 2012) may improve the performance of the model. However, we were not able to execute such an approach in this study due to a shortage of longer observed flows that would be necessary for calibration.

Nevertheless, by exploiting information on the variation of discharge data rather than its level, the simulated flows appears to be useful given the significant and relatively high correlation with gauged flows. The introduction of fixed effects and dam interconnection modelling in regressions are expected to help mitigate some of the problems mentioned above. The above assessment also indicates that there are substantial similarities in SWAT model performance for dams in the same basin. This is a signal of potential spatial correlation besides possible serial correlation and motivates our decision to adjust the standard errors following Driscoll and Kraay (1998). See subsection 3.6 for details.

4.2 Regression results

4.2.1 Hydropower generation (baseline model)

First, to arrive at the baseline specification we add each regressor sequentially which enables us to consider the contribution of each explanatory variable to the operation of hydro-plants. The results from Columns (1) to (5) in Table 7 show that all the regressors in the baseline specification appear with the expected signs and significance at the conventional levels. Column (1) shows that discharge is the main explanatory variable for hydropower electricity production with its variation alone explaining 64.4% of the variation in electricity generation. The non-linear specification in Column (2) provides additional explanatory power and adds 1.5% to the goodness-of-fit. A negative and significant quadratic term suggests that higher discharge increases production but at a decreasing rate before it reaches a turning point. Our finding is similar to that for African hydropower production shown in (Cole et al., 2014). The reason for the inverted U is due to the variation in efficiency of turbines discussed in Subsection 3.6.[20] In Column (3) we include installed capacity which is found to be positive and significant and increases the adjusted R-squared by a further 19.3-percentage points to 0.853 and reduces the coefficients on both discharge and its squared term by roughly a half. The inclusion in Columns (4) and (5) of plant and time fixed effects respectively only marginally increases the goodness of fit. Our final baseline specification in Column (5) explains 87.7% of the variation in hydropower electricity generation.

[Table 7 about here]

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[20] The average turning point is estimated to be approximately 9,820 (m^3/s), which is out of range of the discharge sample.

4.2.2 Flood control

Column (6) of Table 7 includes a dummy for a flood and indicates that, on average, a plant during those months of flooding produces 795.5 MWh per day less than during normal operation conditions (which is equivalent to 18.2% of the mean production of the sample). In Column (7) we include the interaction term which suggests that a higher reduction in electricity production mitigates a more severe flood. On average, a plant reduces its production by 1 MWh/day to mitigate 1 (m^3/s) increase in flood flow. When we add both a dummy for a flood and its interaction term with discharge in Column (8), only the coefficient of the latter is statistically different from zero and the estimate of the coefficient is just below -1 (m^3/s). It should be noted that as we do not model dynamics, the sacrifice of electricity generation for flood control purposes should be interpreted as a contemporaneous response rather than a permanent trade-off.[21] Dams can use water stored during periods of flooding to generate electricity at a later date. The large and significant coefficients estimated here provide evidence of the substantial benefits of large dams to mitigate the adverse impact of extreme weather events.

4.2.3 Hydropower plant cascade interactions

In Table 8 we present our estimates for the impact of hydropower cascades on hydropower production. In addition to our proxy for the operation of upstream dams we also include year and dam fixed effects. Our upstream dam proxies in Columns (1) and (3) are the sum of hydropower capacity installed upstream and the sum of hydropower generated upstream. The results show that upstream plant have a positive and significant impact on hydropower

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[21] We thank an anonymous referee for raising this point.

production although capacity is only significant at the 10 percent level. The interpretation of the coefficients is straightforward. Each additional MW of hydropower capacity installed upstream increases the daily production of a downstream plant by 1.332 MWh (Column 1). This is equivalent to 0.03% the mean production of the sample. Column (3) shows that an increase by 1 MWh in the production of upstream plants adds 0.146 MWh to downstream production.

[Table 8 about here]

In Columns (2) and (4) we include interaction terms to evaluate the synergies under different hydrological conditions. Column (2) suggests that for downstream electricity generation, on average each extra MW upstream adds 1.28 MWh in normal conditions, 2.721 MWh under extremely dry conditions and reduces production by 0.167 MWh under extremely wet conditions. Column (4) indicates that a 1 MWh increase in upstream production induces a rise in downstream production by 0.161 MWh under normal discharge conditions, by 0.0634 MWh under flood conditions and 0.341 MWh in a drought. The differences between the coefficients under extremely dry conditions and normal conditions is significant at the 1% level.

Our results highlight that hydropower cascades can be successfully used to improve the reliability of power supply and as an adaptation measure against future extreme weather conditions. During period of drought an upstream plant can roughly double the production of downstream plants but has a negligible effect during extreme wet conditions. The logic is simple. Upstream plants store water during floods and release water during droughts, which in both cases improves the efficiency of downstream plants.

To investigate the cascade effect further, in Table 9 we include hydropower dam interactions at the basin scale. Since there are no cascades among the plants in the basins of the Thach Han River, Kon-Ha Thanh River and Vu Gia–Thu Bon River, the results in Table 9 estimate the spillover effects for 9 basins only.[22] Our results now suggest that the spillover effect of upstream plants is not always positive. While synergies are found for the Da River, Sesan River, and Srepok River, we find a negative spillover effect for the Dong Nai River, Ba River, Ca River, Huong River, and Ma River. Although all of the positive synergies are significant, the only negative and significant impact is for the Dong Nai River and the Ca River.

[Table 9 about here]

An important question is whether these synergies were anticipated before the construction of new upstream plants. If this is the case, if well coordinated, the construction of an upstream plant can be equivalent to extending downstream storage such that downstream plants can store and release stored water to maximize power generation. An example of coordinated construction comes from Srepok where the construction of the Buon Tua Srah dam (86 MW) was predicted to enhance the generation of the Buon Kuop and Srepok 3 dams by 77 million kWh and 34.8 million kWh, respectively (VINACONEX, 2017). In the Da River basin, the installation of Son La dam (2400 MW), the largest hydropower dam of Vietnam (and in Southeast Asia), was expected to increase the annual production of Hoa Binh dam by 1.26 billion kWh (Vietnam National Committe on Large Dams and Water Resources Development, 2006). Similarly, the operation of Ban Chat dam (220MW), upstream of Son La dam since 2013, was expected to add nearly 0.4 billion kWh per year to two downstream dams (Vietnam National Committe on Large Dams and Water Resources

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[22] The estimates for Ca River, Huong River and Srepok River using interaction terms for upstream dams installed capacity were dropped due to the perfect multicollinearity with dam fixed effects.

Development, 2015). Finally, in the Sesan river, the most upstream hydropower plant (Plei Krong 1 – 100 MW) was supposed to increase the installed capacity of downstream plants (Yaly, Sesan 3 and Seasan 4) by 157.3 MW and to increase production by 217.1 million kWh/year (Ialy Hydropower Company, 2017)

The negative spillovers are most likely the result of the deliberate diversion of water by upstream dams. Given the multi-purpose nature of dams, this negative impact may be intentional. The claim is that the Dai Ninh dam and Dong Nai 3 dam in the Dong Nai River were constructed to help prevent flooding in downstream districts of Lam Dong province and to reduce the flooding pressure on the most downstream hydropower dams in this basin (Tri An dam) (Pham, 2014). At other times, droughts caused by hydropower dams is unintended and undesirable. One of the most frequently criticised is the case of An Khe–Kanak dam (173 MW) which, after starting operation, began to store water from the Ba River but to discharges water into the Kon River to create a higher head and to improve its own production (MONRE, 2012). The result was that a downstream segment of Ba River became dry and adversely affected the welfare of nearby residents.

Although our results are robust to different specifications, it is worth noting that while we control for dam heterogeneity and time heterogeneity, there may still be some omitted variable bias if there are unobserved factors that vary both spatially and temporally. One example might be variations in weather conditions such as temperature and rainfall which are correlated with discharge and therefore could simultaneously affect hydropower supply through changes in demand for electricity. In this case, hot weather induces higher demand for cooling. However, over our time period, power transmission and distribution in Vietnam was centrally managed which should mean that these factors have a uniform impact on plants and hence be absorbed by time fixed effects. In addition, as hydropower was the cheapest form of electricity generation, it is used to cover the base load and hence should be less sensitive to demand fluctuations than other energy sources. A second concern is that physical processes like land cover changes, soil degradation and sediment transportation that were excluded from our SWAT model, could bring about a degree of measurement error. For simplicity, we assume that this source of error is exogenous. Finally, Vietnam is located downstream of a large number of international rivers, such that upstream changes could affect the discharge into Vietnam's basins. Although our SWAT model already accounts for variations in weather in upstream sub-basins outside Vietnam, the construction and operation of neighbouring countries' hydropower plants is beyond the scope of this study. For example, the construction of new hydropower plants in China has been blamed for worsening the drought that hit Southeast Asia (The Diplomat, 2016). Vietnam and Laos are also predicted to be the most badly affected from the proliferation of new hydropower plants along the Mekong River (The Economist, 2012, 2016).

5 Conclusions

In this paper we apply the SWAT river flow model combined with regression analysis to explain the operation of hydropower plants on a national scale in a hydro-dependent country with a diversity of terrain and climate conditions. Although Vietnam has experienced a period of rapidly-growing demand for energy (12-15% per year), it also faces the challenge of potentially adverse impacts of climate change.

As far as we are aware, this is the first study to build a river flow model using SWAT for Vietnam as a whole. To take into account the high level of inter-connectivity between Vietnam's rivers and upstream sources beyond its border, the extent of our river flow model covers a large part outside Vietnam. It includes three inter-boundary basins: Red River, Vietnam Coast, and Lower Mekong River, in which Vietnam shares water resources with China, Laos, Cambodia, Myanmar and Thailand. The watershed of 977,964 km^2 is divided into 7,887 sub-basins with a mean area of 131.6km^2 and 53,024 HRUs. Such a detailed analysis is possible thanks to a variety of high-resolution datasets, especially HydroSHEDS/HydroBASINS, which is finer than Hyro1K and a topographic and hydrographic dataset widely used in previous economic studies using river flow models. River-flow was simulated for the period from 1995 to mid-2014, coinciding with a period when both power supply and power demand of Vietnam increased dramatically. Since it is mainly dependent on global datasets derived from satellite data, the method described within this study could be easily replicated for other countries and regions.

Our regression analysis uses panel data fixed effects regression models to explain the operation of large hydropower plants across Vietnam. Simulated discharge is shown to be a good proxy for inflows into hydropower plants. Our results are similar to those of Cole et al. (2014) and show that installed capacity and a quadratic function of discharge are the key determinants of hydropower generation. Furthermore, our model shows evidence of a flood control benefit of large hydropower plants across Vietnam.

Finally, we used simulated flows to evaluate the coordination and the spillover effect among hydropower plants in Vietnam. Overall, the construction and operation of upstream plants improves the generation efficiency of downstream plants. The effect is particularly large during periods of drought, with a smaller but still positive effect for floods. However, the impact is not the same across all basins. The two basins that are the most important for hydropower provide contrasting results with a negative impact found for the Dong Nai River (in the South), although this is compensated for by a stronger flood control role to protect the downstream area, while we find a strong positive synergy for the Da River (in the North).

In future research it would be interesting to also consider more carefully changes in power demand, land cover, soil degradation, and sediment transportation. In addition, more detailed calibration could improve the accuracy of the river flow model. However, due to current data limitations we leave this for future research. Nevertheless, using simulated discharge still manages to explain up to 87.7% of the monthly variation in hydropower generation (using the two-way fixed effect regressor including installed capacity, discharge and its squared term). This suggests that river flow simulated from a SWAT model, even without calibration, serves as a good predictor for hydropower electricity generation. We acknowledge that our flood measure is relatively coarse and is not able to capture all aspects of floods in a monsoon context (to be able to differentiate the impacts of beneficial vs disaster floods) and our static model of flood control benefit is not appropriate to model the long run impact. Improvements in either flooding data or dynamic modelling techniques would be useful for future research. Finally, our study concentrates on large dams and excludes the impact of medium and small plants, which grew dramatically after 2010 and may impact the hydropower plant cascade effect. Compared to large hydropower plants, the lack of supervision, coordination and regulation with regards to the construction and operation of small and medium hydropower in Vietnam is problematic (PanNature, 2010). Hence, one should not generalize the results in this paper for hydropower dams of all sizes.

Our study has a number of policy implications. First, we provide evidence to that an hydropower operation with large reservoirs and cascades of hydropower plants can strengthen the resilience of the national power supply system against the adverse impact of future climate change. However, harmonizing the operation of plants that share common water resources is not simple, as evidenced by the finding of significant and negative spillovers for some basins. Finally, although we only quantify the impact of hydropower plants on downstream electricity generation, it is implicitly made clear that upstream plants can have an important impact on downstream flow regime (seasonality, water availability and so on). This implies potentially large impacts on downstream ecosystems and other economic activity using water resources (i.e. agriculture), as well as the welfare of downstream inhabitants. Given the numerous interconnections between Vietnam's rivers and those of its neighbours, our findings also raise concerns about possible hydro-ecological consequences associated with the proliferation of large upper dam projects on the Mekong River. The challenges associated with inter-basin dam operation management are likely to be even harder when cross-border coordination is required.

A Appendix: Regression estimators

Our method is based on the linear panel data model:

$$y_{it} = \mathbf{x}_{it}'\boldsymbol{\beta} + \varepsilon_{it}; i = 1, 2, ..., N; t = 1, 2, ..., T$$

where i and t are respectively indices for dam and time, scalar y is the dependent variable, $\mathbf{x}$ is a $K \times 1$ vector of independent variables, which may contain an intercept, dummies and non linear variable (interaction and/or quadratic terms). $\boldsymbol{\beta}$ is a $K \times 1$ vector of unknown coefficients, which are restricted to be common across time and dam. However, change in parameters across dam or time are permitted by the inclusion of appropriate regressors in $\mathbf{x}$ (for example time dummies or dam dummies).

Our coefficients are estimated using a pooled ordinary least squares (POLS) estimator:

$$\hat{\beta} = \Big(\sum_{i=1}^{N}\sum_{t=1}^{T}\mathbf{x}'_{it}\mathbf{x}_{it}\Big)^{-1}\Big(\sum_{i=1}^{N}\sum_{t=1}^{T}\mathbf{x}'_{it}y_{it}\Big) \tag{A1}$$

The estimator is shown to be consistent (Wooldridge, 2010, pg. 192) as long as $E(\mathbf{x}'_t\varepsilon_t) = 0$, for $t = 1, 2, ..., T$ (exogeneity condition) and $\text{rank}\Big[\sum_{t=1}^{T}E(\mathbf{x}'_t\mathbf{x}_t)\Big] = K$ (no perfect collinearity condition).

The goodness-of-fit of regressions are computed as:

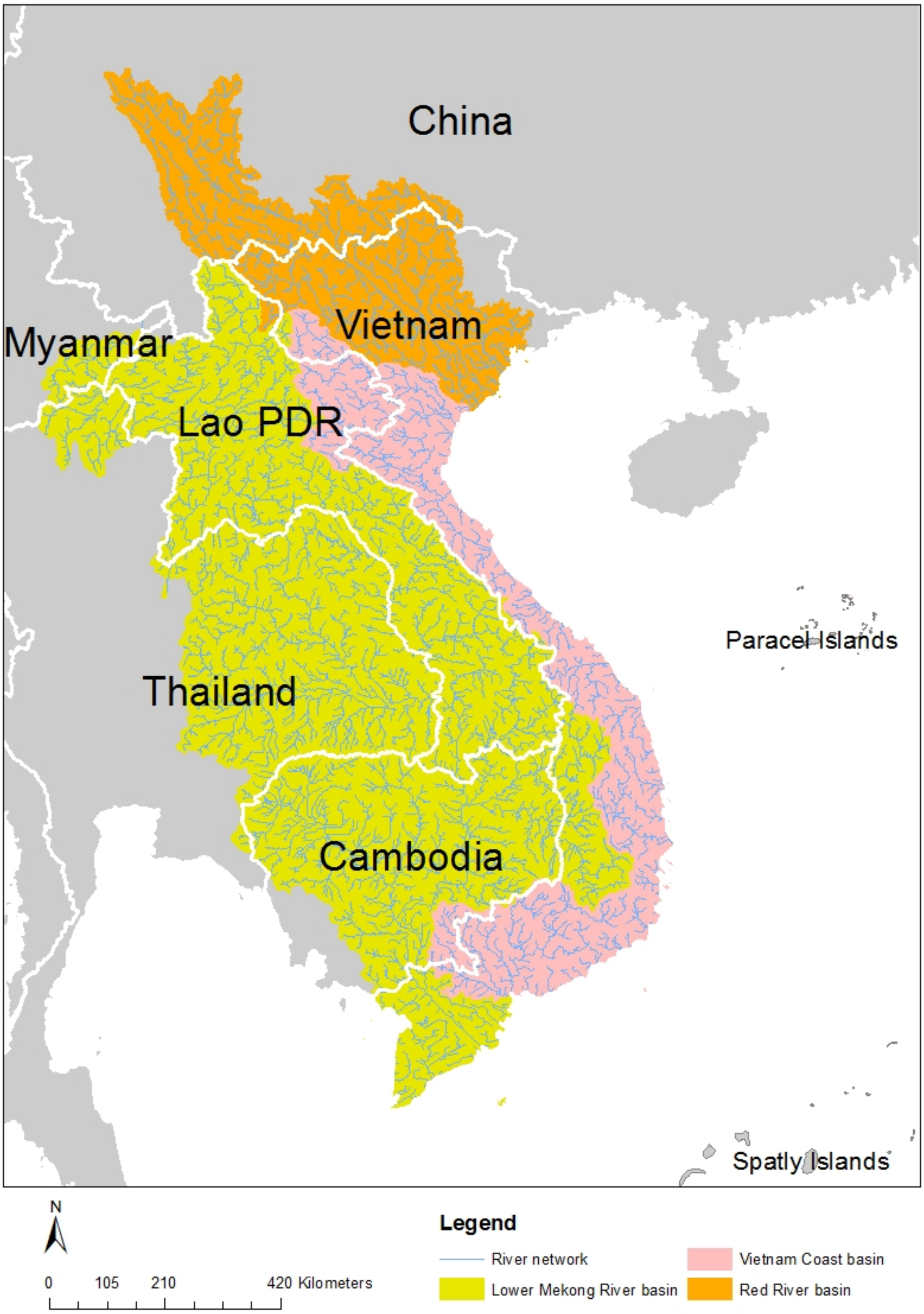
$$R^2 = \frac{\sum(\hat{y}_{it} - \bar{y})^2}{\sum(y_{it} - \bar{y})^2} \tag{A2}$$

$$\bar{R}^2 = 1 - \frac{n-1}{n-K}(1 - R^2) \tag{A3}$$

where $\hat{y}_{it}$ and $\bar{y}$ are respectively the predicted values and the mean of the observed values of the dependent variable. n is the number of observations. R^2 is bounded by 0 and 1. $\bar{R}^2$ never exceeds R^2 and can be negative if a poorly-performing model includes too many redundant regressors. In general, a model with higher R^2 or $\bar{R}^2$ fits the observed data better.

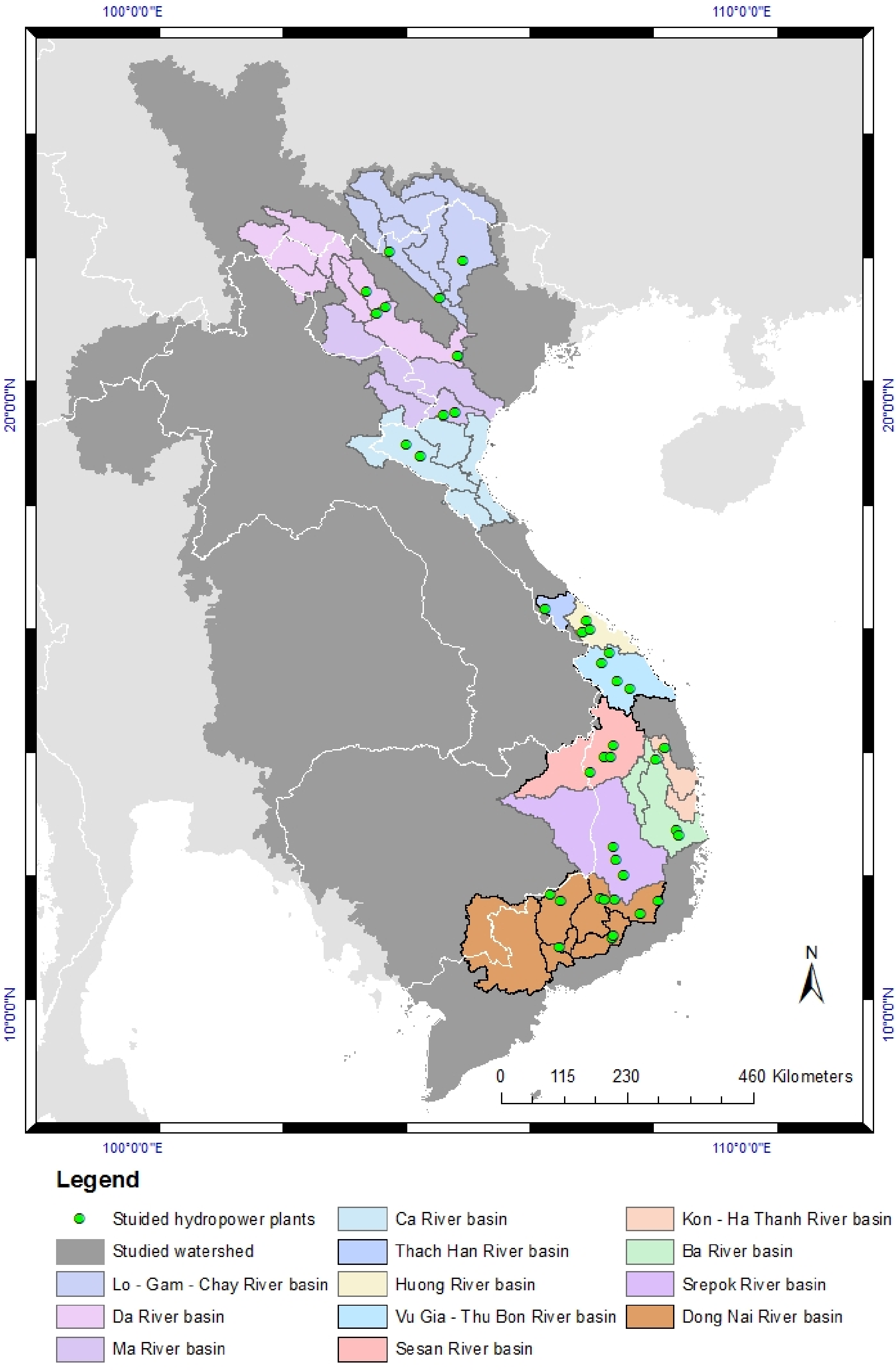
Figures

Figure 1: Watershed delineation



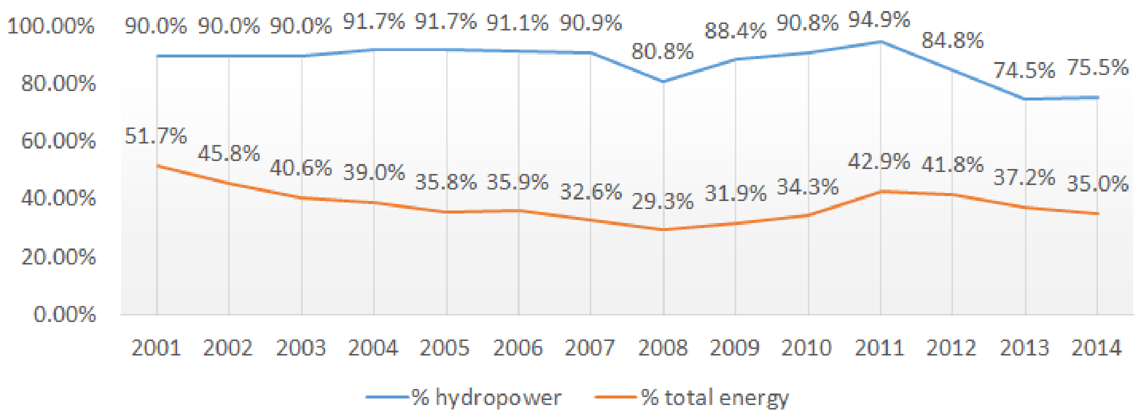
Source: Authors compiled from HydroSHEDS/HydroBASINS (Lehner et al., 2008; Lehner and Grill, 2013) and 'Rivers in South and East Asia' (FAO, 2014). Note: The resolution of HydroSHEDS void-filled DEM is 3 arc-seconds. The resolution of HydroBASINS river network is 15 arc-seconds.

Figure 2: Studied basins and hydropower plants



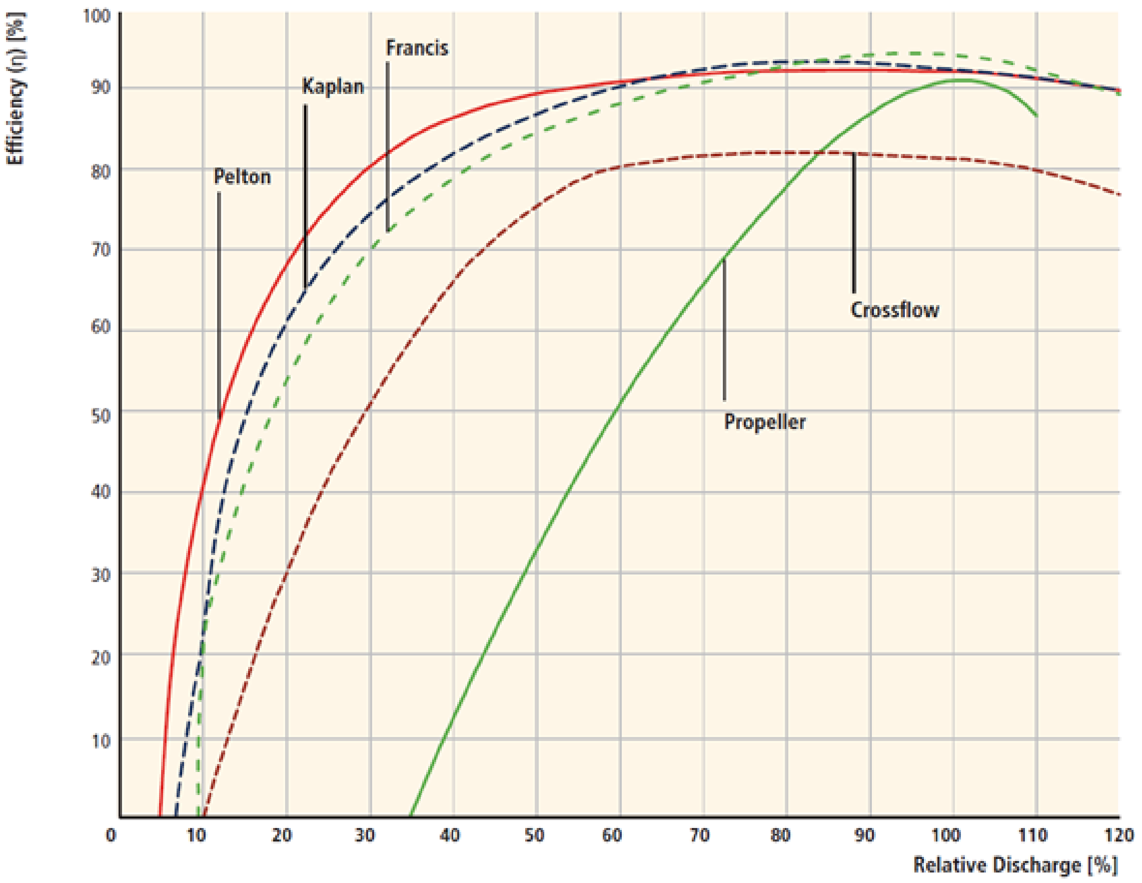
Source: Basins are derived from "FAO Rivers in South and East Asia" and MONRE (2012).

Figure 3: Total installed capacity of studied hydropower plants, as percentage of national energy capacity



Source: Authors calculated from EVN (2015).

Figure 4: Typical efficiency curves for different types of hydropower turbines



Source: (Kumar et al., 2011, p. 453)

Tables

Table 1: Data description and sources for SWAT simulation

Data types	Sources	Resolution
Predefined basins	HydroBASINS http://www.hydrosheds.org/page/hydrobasins	15 arc-seconds
and river networks	Rivers in South and East Asia http://ref.data.fao.org/map?entryId=dc2a5121-0b32-482b-bd9b-64f7a414fa0d	30 arc-seconds
Digital Elevation Model (DEM)	HydroSHEDS void-filled DEM http://www.hydrosheds.org/	3 arc-seconds
Soil	Digital Soil Map of the World version 3.6 http://www.fao.org/geonetwork/srv/en/metadata.show?id=14116	5 arc minutes
Land cover	UMD Land Cover classification collection http://glcf.umd.edu/data/landcover/	1km pixels
Weather	CFSR-NCEP https://globalweather.tamu.edu/	19 arc-seconds

Note: See text for more details

Table 2: Summary statistics of subbasins

VARIABLES	(1) N	(2) mean	(3) sd	(4) min	(5) max
All sub-basins within the watershed					
Area of the sub-basin	7,887	131.6	56.52	0.2	368.6
Total upstream area	7,887	15,443	77,756	0.4	774,282
Distance to the next downstream sink	7,887	951.4	754.4	0	3,628
Distance to the most downstream sink	7,887	957	751.3	0	3,628
Sub-basins within Vietnam					
Area of the sub-basin	2,617	131.9	58.4	0.2	368.6
Total upstream area	2,617	7,812	59,053	0.4	774,282
Distance to the next downstream sink	2,617	341.4	417.2	0	2,506
Distance to the most downstream sink	2,617	343.6	416.4	0	2,506

Source: Authors compiled from HydroBASINS dataset (level 12).

Note: N=Number of observations. sd= standard deviation

Table 3: Studied hydropower plants

Basin	Dams
Lo - Gam - Chay	Thac Ba (120 MW), Tuyen Quang (342 MW), Bac Ha (90 MW)
Da	Hoa Binh (1920 MW), Son La (2400 MW), Nam Chien (200 MW), Ban Chat (220 MW)
Ma	Hua Na (180 MW), Cua Dat (97 MW)
Ca	Khe Bo (100 MW), Ban Ve (320 MW)
Thach Han	Quang Tri (64 MW)
Huong	A Luoi (170 MW), Binh Dien (44 MW), Huong Dien (71 MW)
Vu Gia – Thu Bon	Song Tranh 2 (190 MW), Dak Mi 4 (190 MW), A Vuong (210 MW), Song Con (63 (MW)
Kon – Ha Thanh	Vinh Son (66 MW)
Sesan	Sesan 4 (360 MW), Sesan 3 (260 MW), Yaly (720 MW), Plei Krong 1 (100 MW)
Ba	Song Hinh (70 MW), Song Ba Ha (220 MW), An Khe-Knak (173 MW)
Srepok	Buon Tua Srah (86 MW), Buon Kuop (280 MW), Srepok 3 (220 MW)
Dong Nai	Tri An (400 MW), Da Mi (175 MW), Ham Thuan (300 MW), Dai Ninh (300 MW), Da Nhim (160 MW), Thac Mo (150 MW), Dong Nai 3 (180 MW), Dong Nai 4 (340 MW), Dak R'Tih (144 MW), Can Don (78 MW)

Table 4: The cascades of hydropower

Updam	**Bac Ha**	**Ban Chat**	**Nam Chien**	**Hua Na**	**Ban Ve**	**A Luoi**	**Plei Krong 1**	**An Khe - Kanak**	**Buon Tua Srah**	**Thac Mo**	**Da Nhim**	**Dai Ninh**	**Ham Thuan**
Basin	*Lo - Gam - Chay*	*Da*	*Da*	*Ma*	*Ca*	*Huong*	*Sesan*	*Ba*	*Srepok*	*Dong Nai*	*Dong Nai*	*Dong Nai*	*Dong Nai*
Distance													
0													Da Mi
1													
2				Cua Dat		Huong Dien				Can Don			
3					Khe Bo		Yaly						
4		Son La					Sesan 3		Buon Kuop				
5													
6												Dong Nai 3	
7												Dong Nai 4	
8							Sesan 4		Srepok 3		Dong Nai 3	Dak R’Tih	
9											Dong Nai 4		
10											Dak R’Tih		
14	Thac Ba												
15													Tri An
16													
17													
18								Song Ba Ha					
20			Hoa Binh										
21													
23												Tri An	
25		Hoa Binh									Tri An		

The upstream-downstream relationship was determined by the HydroSHEDS ID system of HydroBASINS dataset.
Distance was measured by the number of sub-basins (at level 12 of HydroSHEDS dataset) between each upstream and downstream dams.

Table 5: Summary statistics

VARIABLES	(1) N	(2) mean	(3) sd	(4) min	(5) max
Dam statistics					
Year of Operation	40	2005	10.5	1964	2013
Total storage capacity (million m^3)	40	1,164	2,098	30.4	9,862
Full installed capacity (MW)	40	294	455	44	2,400
Production statistics (Jan 1995 – Jul 2014)					
Average production (MWh/day)	2,984	4,393	6,754	0	46,833
Installed capacity (MW)	2,984	376.3	521.4	22	2,400
Flow to dam (m^3/s); SWAT simulation	2,984	465.5	979.5	0.120	9,105
Upstream capacity (MW)	2,984	141.9	360.9	0	2,820
Upstream production (MWh/day)	2,984	1,615	4,161	0	45,781

Note: N=Number of observations. sd= standard deviation

Table 6: Simulated discharge validation

Dam	Basin	Capacity (MW)	N	*r*	R^2
Thac Ba	Lo - Gam - Chay	120	235	.82***	.67*
Tuyen Quang	Lo - Gam - Chay	342	70	.8***	.64*
Hoa Binh	Da	1920	235	.88***	.78*
Son La	Da	2400	43	.81***	.65*
Cua Dat	Ma	97	31	.75***	.56*
Ban Ve	Ca	320	31	.68***	.47
Quang Tri	Thach Han	64	31	.41**	.17
A Vuong	Vu Gia - Thu Bon	210	31	.6***	.36
Vinh Son	Kon - Ha Thanh	66	209	.7***	.49
Sesan 3	Sesan	260	31	.54***	.29
Yaly	Sesan	720	171	.73***	.53*
Plei Krong 1	Sesan	100	31	.82***	.68*
Song Hinh	Ba	70	171	.86***	.73*
Song Ba Ha	Ba	220	31	.69***	.48
An Khe - Kanak	Ba	173	31	.33*	.11
Buon Kuop	Srepok	280	31	.71***	.5*
Tri An	Dong Nai	400	235	.82***	.67*
Da Mi	Dong Nai	175	122	.42***	.17
Ham Thuan	Dong Nai	300	160	.53***	.28
Dai Ninh	Dong Nai	300	70	.68***	.46
Da Nhim	Dong Nai	160	235	.65***	.42
Thac Mo	Dong Nai	150	223	.9***	.8*
Dong Nai 3	Dong Nai	180	31	.85***	.73*
Can Don	Dong Nai	78	31	.86***	.74*

Note: Capacity indicates full installed capacity. N indicates number of observations. Significance level for Pearson correlation coefficient (*r*): *** p<0.01, ** p<0.05, * p<0.1. For the coefficient of determination (R^2) to indicate acceptable model (Santhi et al., 2001; Van Liew et al., 2007): * ($R^2 \geq 0.5$).

Table 7: Production regression using simulated discharge

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
VARIABLES				Average production (MWh/day)				
Intercept	1,818***	1,382***	76.50	1,645***	901.4***	899.6***	825.5***	826.9***
	(155.3)	(121.4)	(106.5)	(217.7)	(229.7)	(232.8)	(237.5)	(236.1)
Flow to dam (m^3/s); SWAT simulation	5.533***	7.459***	3.108***	4.198***	4.478***	4.627***	4.641***	4.647***
	(0.339)	(0.487)	(0.370)	(0.464)	(0.554)	(0.574)	(0.587)	(0.594)
Flow to dam (m^3/s); SWAT simulation squared		-0.000392***	-7.39e-05	-0.000212**	-0.000228**	-0.000233**	-0.000102	-0.000105
		(0.000105)	(8.71e-05)	(8.64e-05)	(9.24e-05)	(9.25e-05)	(0.000108)	(0.000118)
Installed capacity (MW)			7.858***	6.319***	5.856***	5.904***	5.996***	5.996***
			(0.375)	(1.118)	(1.186)	(1.185)	(1.190)	(1.190)
Flood						-795.5***		-48.06
						(266.1)		(286.5)
Inflow*Flood							-1.001**	-0.981**
							(0.386)	(0.454)
Observation number	2,984	2,984	2,984	2,984	2,984	2,984	2,984	2,984
R-squared	0.644	0.660	0.854	0.875	0.889	0.890	0.892	0.892
Adjusted R-squared	.644	.659	.853	.873	.877	.879	.881	.881
Dam dummies				Y	Y	Y	Y	Y
Time dummies					Y	Y	Y	Y

Driscoll-Kraay standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1.

Table 8: The synergies of hydropower cascades

	(1)	(2)	(3)	(4)
VARIABLES	Average production (MWh/day)			
Variables for dam operation				
Installed capacity (MW)	5.876***	5.880***	5.859***	5.834***
	(1.182)	(1.176)	(1.190)	(1.184)
Flow to dam (m^3/s); SWAT simulation	4.476***	4.984***	4.359***	4.865***
	(0.544)	(0.554)	(0.559)	(0.568)
Flow to dam (m^3/s); SWAT simulation squared	-0.000225**	-0.000275***	-0.000216**	-0.000267***
	(9.19e-05)	(9.17e-05)	(9.14e-05)	(9.11e-05)
Variables for upstream dam operation				
Upstream capacity (MW)	1.332*	1.280		
	(0.705)	(0.853)		
Upstream capacity (MW)*Flood		-1.447**		
		(0.689)		
Upstream capacity (MW)*Drought		1.441**		
		(0.574)		
Upstream production (MWh)			0.146**	0.161**
			(0.0598)	(0.0695)
Upstream production (MWh)*Flood				-0.0976*
				(0.0541)
Upstream production (MWh)*Drought				0.180***
				(0.0446)
Intercept	-429.8	-553.0	-430.3	-523.5
	(464.2)	(456.5)	(468.7)	(464.6)
Observation number	2,984	2,984	2,984	2,984
R^2	.891	.893	.892	.895
Adjusted R^2	.88	.88	.88	.88

*** p<0.01, ** p<0.05, * p<0.1.

Dam fixed effects and time fixed effects are included. Driscoll-Kraay standard errors are in parentheses.

Table 9: The synergies of hydropower cascades by basin

	(1)		(2)	
VARIABLES	Average production (MWh/day)			
Installed capacity (MW)	5.724***	(1.165)	5.716***	(1.164)
Flow to dam (m^3/s); SWAT simulation	4.719***	(0.533)	4.625***	(0.545)
Flow to dam (m^3/s); SWAT simulation squared	-0.000247***	(8.69e-05)	-0.000246***	(8.54e-05)
Interaction: Updams operation*Ba	-3.818	(2.699)	-0.170	(0.247)
Interaction: Updams operation*Ca			-0.697*	(0.402)
Interaction: Updams operation*Da	2.157***	(0.783)	0.220***	(0.0685)
Interaction: Updams operation*Dong Nai	-2.136***	(0.501)	-0.135***	(0.0428)
Interaction: Updams operation*Huong			-0.618	(0.711)
Interaction: Updams operation*Lo - Gam - Chay	1.289	(3.862)	-0.307	(0.555)
Interaction: Updams operation*Ma	-1.495	(2.252)	-0.166	(0.222)
Interaction: Updams operation*Sesan	2.314	(9.777)	0.215***	(0.0427)
Interaction: Updams operation*Srepok			0.577***	(0.0639)
Observation number	2,984		2,984	
R^2	.896		.897	
Adjusted R^2	.885		.886	
Upstream operation	Installed capacity		Production	

*** p<0.01, ** p<0.05, * p<0.1.

Dam fixed effects and time fixed effects are included. Driscoll-Kraay standard errors are in parentheses. Upstream operation indicates which variable is used to proxy for operation of upstream dams: (combined upstream) installed capacity (MW) or (combined upstream) production (MWh/day)

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