Hydropower versus irrigation—an analysis of global patterns

2017 Environ. Res. Lett. 12 034006

(http://iopscience.iop.org/1748-9326/12/3/034006)

Environmental Research Letters

OPEN ACCESS

RECEIVED
21 November 2016

REVISED
3 February 2017

ACCEPTED FOR PUBLICATION
8 February 2017

PUBLISHED
28 February 2017

LETTER

Hydropower versus irrigation—an analysis of global patterns

Ruijie Zeng[1], Ximing Cai[1,3], Claudia Ringler[2] and Tingju Zhu[2]

[1] Ven Te Chow Hydrosystems Laboratory, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, United States of America
[2] International Food Policy Research Institute, Washington, DC 20006, United States of America
[3] Author to whom any correspondence should be addressed.

E-mail: xmcai@illinois.edu

Keywords: hydropower, irrigation, reservoir operation, global hydroelectric datasets, food-energy-water nexus

Supplementary material for this article is available online

Abstract

Numerous reservoirs around the world provide multiple flow regulation functions; key among these are hydroelectricity production and water releases for irrigation. These functions contribute to energy and food security at national, regional and global levels. While reservoir operations for hydroelectricity production might support irrigation, there are also well-known cases where hydroelectricity production reduces water availability for irrigated food production. This study assesses these relationships at the global level using machine-learning techniques and multi-source datasets. We find that 54% of global installed hydropower capacity (around 507 thousand Megawatt) competes with irrigation. Regions where such competition exists include the Central United States, northern Europe, India, Central Asia and Oceania. On the other hand, 8% of global installed hydropower capacity (around 79 thousand Megawatt) complements irrigation, particularly in the Yellow and Yangtze River Basins of China, the East and West Coasts of the United States and most river basins of Southeast Asia, Canada and Russia. No significant relationship is found for the rest of the world. We further analyze the impact of climate variables on the relationships between hydropower and irrigation. Reservoir flood control functions that operate under increased precipitation levels appear to constrain hydroelectricity production in various river basins of the United States, South China and most basins in Europe and Oceania. On the other hand, increased reservoir evaporative losses and higher irrigation requirements due to higher potential evaporation levels may lead to increased tradeoffs between irrigation and hydropower due to reduced water availability in regions with warmer climates, such as India, South China, and the Southern United States. With most reservoirs today being built for multiple purposes, it is important for policymakers to understand and plan for growing tradeoffs between key functions. This will be particularly important as climate mitigation calls for an increase in renewable energy while agro-hydrological impacts of climate change, population and economic growth and associated dietary change increase the need for irrigated food production in many regions round the world.

1. Introduction

Reservoirs are generally built with multiple functions in mind, and irrigation and hydroelectricity generation are often the main functions. The construction and operation of reservoirs has led to tradeoffs (negative relationships) and complementarities (or positive synergies) among these functions within the food-energy-water (FEW) nexus (Perrone and Hornberger 2014). Reservoirs or dams with both hydropower and irrigation functions buffer the fluctuations of natural streamflow and can provide reliable water supply for irrigation during dry periods. At the same time, reservoirs are operated to store water to build up a hydraulic head and then release water to generate hydroelectricity. When water stored in reservoirs is reserved for a future irrigation season, the elevated hydraulic head would increase hydroelectricity generation; similarly, water released for irrigation may reduce reservoir storage, thereby reducing hydroelectricity generation, especially during dry and hot periods, when demand for irrigation and energy might be largest (Tilmant *et al* 2009).

Several national and regional case studies have investigated the relationships between hydropower and irrigation. For example, Cai *et al* (2003) studied irrigation development in the Aral Sea region and found tradeoffs between upstream and downstream needs. Upstream Kyrgyzstan's need to save summertime runoff in its reservoirs for hydroelectricity generation during winter months conflicted with the downstream republics' need for irrigation in the summer crop growing season. The authors proposed that downstream countries could provide alternative energy sources to Kyrgyzstan in exchange for releasing irrigation water during the irrigation season, essentially reverting to the Soviet era flow release regime. On the other hand, Räsänen *et al* (2015) found that multipurpose cascade reservoirs on a transboundary tributary of the Mekong created considerable irrigation potential at the expense of a relatively small hydroelectricity generation loss. Another study in the Nam Ngum, a sub-basin of the Mekong, similarly showed that full hydropower development allowed irrigation water use to triple and also improved environmental flow requirements during low-flow periods (Lacombe *et al* 2014). Both studies concluded that hydropower development increased and would continue to increase dry-season streamflow, the main water source for dry-season irrigation due to the monsoon climate of this region. Studies in Pakistan (Yang *et al* 2016), Tanzania (Kadigi *et al* 2008), Turkey (Yüksel 2010), Sri Lanka (Molle *et al* 2008) and for the Western US (Chatterjee *et al* 1998) also reported differing relationships between irrigation and hydropower.

The purpose of this paper is to provide a global assessment of the relationships between hydropower and irrigation. We explore if there are tradeoffs, complementarities or no strong linkages between these two key functions of reservoirs globally. We also highlight the spatial distributions of the various relationships at the global scale, and discuss associated potential risks for the food and energy sectors under growing resource demands and changes in key climatic variables. As a result of growing populations, both irrigation and hydropower needs are expected to grow, especially in the group of developing countries (Zarfl *et al* 2015). According to International Energy Agency (IEA 2016), hydroelectricity accounted for more than 85% of global renewable electricity generation in 2015. Similarly, irrigation has been critical in sustaining food security around the world (Rosegrant *et al* 2009), and irrigated area continues to grow in key developing regions. Hydropower construction has slowed considerably during the past decades due to growing attention to its social and environmental impacts (WCD 2000), but both climate change impacts and climate mitigation policies under both the Sustainable Development Goals (SDGs) and the Paris Climate Agreement have renewed interest in this key and currently largest renewable source of electric power. Similarly, investments in irrigation slowed down during the 1980s and 1990s in response to various factors, such as declining food prices, high costs and competition with other demands for water, but climate change and more volatile food prices and, more recently, the SDGs have contributed to somewhat faster development over the last decade.

In this global context, we explore both the current relationships between hydropower and reservoir-supported irrigation in different regions and the potential evolution of these relationships. Climate change is expected to modify hydrological regimes in many regions, increasing uncertainties in water availability for both hydropower and irrigation (IPCC 2014). We therefore also analyze how changes in key climatic variables affect these relationships. The rest of this paper introduces the datasets and methods for deriving hydropower-irrigation relationships used in this study (section 2), presents the spatial pattern of hydropower-irrigation relationships (section 3), discusses how changing climatic conditions might affect multi-purpose reservoir operations and hydropower-irrigation relationships (section 4), and draws conclusions (section 5).

2. Datasets and methods

Hydropower datasets, including installed hydropower capacity and annual hydroelectricity generation between 2005 and 2013, were collected from multiple public sources, including the BP Statistical Review of World Energy (BP 2012), the World Energy Council (WEC 2016), the International Hydropower Association (IHA 2016), and the International Commission on Large Dams (ICOLD 2016). In addition, subnational level data were obtained from annual statistical bulletins published by national governments or hydropower companies for the largest hydroelectricity producer countries, such as Canada (CHA 2016), China and the U.S. (EIA 2016).

The spatial unit used for this global analysis is the Food Production Unit (FPU) defined as cross-sections between river basin and national boundaries in the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) (Cai and Rosegrant 2002, Robinson *et al* 2015). A high-level of similarity in climatic and hydrological characteristics essential for food production commonly exists within the boundary of each FPU. The various hydropower datasets were aggregated (for Canada, China and the U.S., where hydropower datasets are available at the state or province level) or disaggregated (national and regional datasets, where hydropower datasets are available at the national or regional level) into

320 FPUs covering the globe. The disaggregation was largely based on dam locations from the ICOLD (2016) and FAO geo-referenced dam database (FAO 2016). Further, the locations of recently commissioned dams that were not included in the ICOLD and FAO databases were obtained from individual governmental sources and Wikipedia. Scale conversion is not conducted for those countries or regions that are relatively small by area and are delineated as separate FPUs in the IMPACT model.

Annual time series data of installed hydropower capacity were temporally interpolated from the survey taken every three years (i.e. 2004, 2007, 2010 and 2013) by WEC (2016). In total, the processed dataset includes around 900 000 Megawatt of installed hydropower capacity and 3000 terawatt-hours of actual generation, globally. Note that the hydropower dataset does not include hydroelectricity generation from small-scale hydropower (SSH) since there is no spatial information for assigning the SSH data to FPUs. The complete references for the data sources and comparison among different data sources is included in tables S1 and S2 in the supporting information available at stacks.iop.org/ERL/12/034006/mmedia.

Annual irrigation water uses between 2005 and 2013 in each FPU were generated by IFPRI's IMPACT model (Robinson *et al* 2015). The core model of IMPACT is a partial equilibrium, multi-market economic model. It couples economic, water resources, and crop models to represent biophysical and socioeconomic dynamics around food supply and demand out to 2050. Irrigation water use was calculated by minimizing the water supply deficit across all water-using sectors, considering water availability, irrigation and non-agricultural water requirements, capacities of water storage and withdrawal infrastructures, environmental flow requirements, in addition to sector-wise water supply priorities and economic water productivity of crops (Robinson *et al* 2015).

To summarize, the datasets compiled for the assessment of hydropower-irrigation relationships include hydroelectricity generation, installed hydropower capacity, irrigation water use and climate variables (i.e. precipitation and potential evapotranspiration) between 2005 and 2013 at the FPU level. In total, 93 out of the 320 global FPUs included the necessary information and were further analyzed. Their spatial coverage is shown in figure 2. The rest of the FPUs were not included in the analysis because irrigation water consumption was negligible and/or hydropower was not developed in these FPUs.

Hydroelectricity generation is concentrated in a relatively small number of countries. Brazil, Canada, China, France, India, Japan, Norway, Russia, Sweden, Turkey, United States and Venezuela each account for more than 2% of global hydroelectricity generation and jointly for 72% of global production. Of note, during 2005–2013, China experienced a significant increase in both installed capacity and hydroelectricity generation, with the latter doubling from 400 terawatt-hours in 2005 to 800 terawatt-hours in 2012. The installed hydropower capacity in other major producer countries remained relatively stable.

As expected, we find a strong correlation between hydroelectricity generation and installed hydropower capacity. Therefore, classical regression methods failed to detect the contribution from other variables (e.g. precipitation and potential evaporation), since the corresponding regression coefficients would be very small. Thus we explored the hydropower-irrigation relationship using support vector machines (SVM), a machine learning technique which has been widely used for regression and surrogate modelling in environmental modeling (Xu *et al* 2014, Schnier and Cai 2014). Classical regression methods such as linear or polynomial regression fit observed data by assuming a specific type of functions (e.g. linear or quadratic). SVM is not subject to this assumption, and is hence more flexible. In addition, SVM utilizes various kernel functions to classify the nonlinearity embedded in the data. SVM first projects the input variables to a higher dimensional feature space using a kernel function, and then performs linear regression in the feature space. In this study, the radial basis kernel was used; and the resulting feature space is infinite dimensional. The training and validation of SVM followed four procedures sequentially: 1) Clustering: Given the limited data availability (i.e. only 8 year time series of irrigation use and hydroelectricity generation), meaningful relationships between hydropower and irrigation were unlikely to be derived for each FPU. We therefore conducted an initial clustering to classify the 93 FPUs into three groups based on the correlation between irrigation water use and hydroelectricity generation. Eventually, one SVM was constructed for each group of FPUs characterizing the heterogeneities within the group. 2) Scaling: Since the magnitudes of irrigation water use and hydropower vary significantly among FPUs due to differing FPU size and geographies, all data were log-transformed so that the SVMs were built in a scaled space. The results were interpreted after being transformed back into values with physical units. 3) SVM training: The input variables for an SVM include annual precipitation, potential evaporation, installed hydropower capacity and irrigation water use, and the output is hydroelectricity generation. For each SVM, hyper-parameters controlling the model complexity and goodness of fit were tuned according to 70% of the data, which were randomly selected for each group. The training data were randomly divided into ten equal subsets for cross-validation; during each cross-validation nine subsets were used to tune the hyper-parameters, and the remaining one was used to calculate root-mean-square error (RMSE). The procedure was repeated ten times so that each subset was used to train the SVM

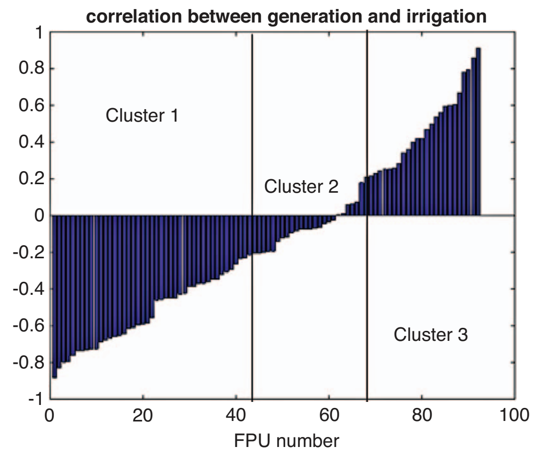

Figure 1. Correlation coefficient between hydroelectricity generation and irrigation of individual FPUs.

nine times and to calculate RMSE once. The optimal hyper-parameters were set under the minimal average RMSE in ten-fold cross-validation. 4) Validation of SVM: The remaining 30% of data in each group were compared with trained SVMs and the goodness-of-fit was calculated to evaluate the performance of the trained SVMs. Readers are referred to Chang and Lin (2011) for the details of the SVM toolbox used in this study.

3. Results

3.1. Clustering of the correlation levels between irrigation water use and hydroelectricity generation

The correlation coefficients between annual irrigation water use and hydroelectricity generation for the 93 FPUs are displayed in figure 1. In total, the 93 FPUs have installed hydropower capacity of 817 560 Megawatt (about 87.4% of the global installed capacity) and the mean annual hydroelectricity generation (2895 Tera-watt-hours) accounts for about 90% of the global total. In 62 FPUs, hydroelectricity generation is negatively associated with irrigation water use, indicating that hydroelectricity generation is competing with irrigation water use. The remaining 31 FPUs exhibit a positive correlation between hydroelectricity generation and irrigation water use, implying a complementary relation between the two. For the purpose of further analysis, the 93 FPUs are divided into three groups: 1) Competing relationship where the correlation coefficient is less than −0.2; 2) complementary relationship where the correlation coefficient is larger than 0.2; and 3) insignificant relationship where the correlation coefficient is between −0.2 and 0.2. There are 56, 19 and 18 FPUs in Clusters 1, 2 and 3, accounting for 54.3%, 8.4% and 24.8% of global installed hydropower capacity, respectively.

The competing group contains about half of all FPUs studied, and the complementary and insignificant groups each contain about one quarter of FPUs. An SVM is built for each group to quantify the factors contributing to hydroelectricity generation. The R-squared values for SVM validation for each group are 0.9407, 0.6088 and 0.7487, respectively. The values assessed from the various data sources are compared with those from the SVM prediction in both training and validation, as shown in figure S1 in the supplementary information.

3.2. Response of hydroelectricity generation to irrigation water use

The response of hydroelectricity generation to climatic inputs and irrigation water use is obtained through sensitivity analysis for the trained SVMs. Each independent variable (i.e. precipitation, potential evaporation and irrigation water use) is perturbed by one standard deviation around its mean value, and the corresponding change of the hydroelectricity generation is compared to that calculated from the mean value of the perturbing variable. Figure 2 presents the sensitivity of hydroelectricity generation to irrigation. The FPUs with positive sensitivity values (i.e. in red and yellow color depicting complementary hydroelectricity- irrigation relationships) are mostly located in Southeast Asia, the Yellow and Yangtze rivers of China, the East and West Coast of the U.S., Russia, Canada and FPUs along the Andes. That is, storage for hydroelectricity generation in these FPUs enhances water supply for irrigation. Reservoirs constructed for hydroelectricity regulate streamflow, which benefits irrigation. Moreover, water stored during the wet season for irrigation in the dry season elevates the water head in reservoirs, leading to larger hydroelectricity generation, and the timing of the two is complementary, i.e. demands for hydroelectricity and for irrigation are complementing each other. Thus the constructed infrastructure and its operation contribute to the complementarity between hydroelectricity and irrigation.

FPUs with negative sensitivity values (i.e. in blue color showing competing hydroelectricity-irrigation relationships) are mostly located in regions such as the Central U.S., Northern Europe, India, Central Asia and Oceania. In these FPUs, increased hydropower coincides with reduced irrigation. Some of these regions have limited streamflow, especially during the irrigation season. In other regions, timing between demands for irrigation and hydropower releases differs. For example, an upstream region or country holds water in the summer irrigation season for hydroelectricity generation during the following winter, as is the case in the Syr Darya River Basin in Central Asia (Cai *et al* 2003). Given the limited water resources in these regions, the tradeoff relationship between irrigation and hydropower may be mitigated through changes in food and energy trade with other regions. For example, Cai *et al* (2003) proposed that downstream countries could provide energy in other forms (e.g. coal) to reduce the demand

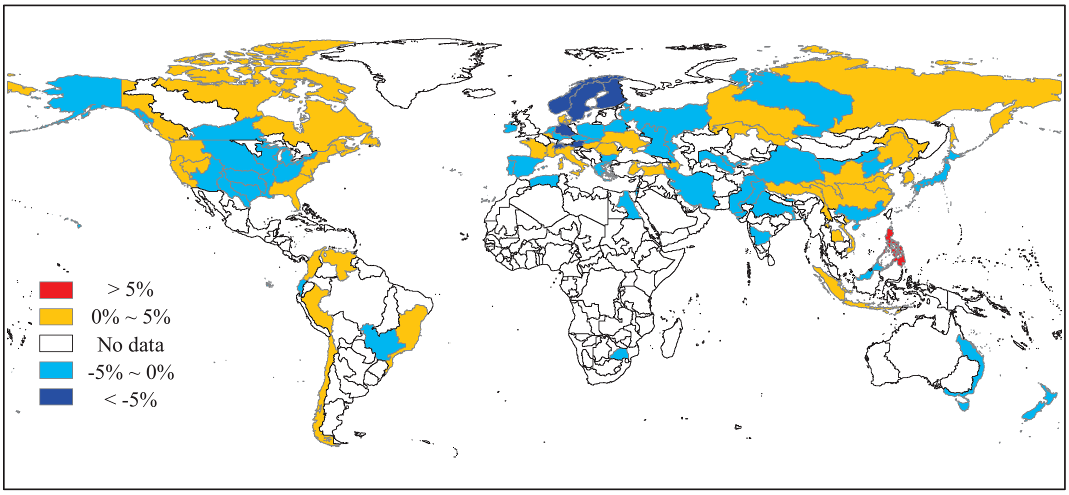

Figure 2. The sensitivity of hydropower generation to irrigation (percentage change of mean hydropower generation corresponding to one standard deviation change of irrigation water use in each FPU).

for hydroelectricity generation and increase summer water releases for irrigation from upstream countries. In some regions, profits from food production can also be used to compensate for losses in hydroelectricity generation. Although hydroelectricity generation does not result in large consumptive water use (except for reservoir evaporative losses and seepage in some places), irrigation water access of downstream regions may suffer from streamflow regulation through reservoir operations. In other regions, reservoir storage capacity may not be large enough to properly regulate streamflow such as to meet both hydroelectricity and irrigation demand. Reservoir operations in those regions have to partition water stored in the reservoir between hydropower and irrigation, and deal with the tradeoffs between the two functions. In these places, reservoir construction might help to alleviate these tradeoffs. In yet other places, storage augmentation might not address tradeoffs, at least not during climate extremes. Harou *et al* (2010) found, for example, that a 'mega-drought' in California would not allow to fill existing reservoirs, and thus expanding storage capacity would be useless to address ensuing increased tradeoffs.

4. Discussion

4.1. Climatic factors influencing the hydropower—irrigation relationship

The relationship between hydropower and irrigation can be better understood by considering climate conditions, since both water supply and demand for hydropower and irrigation are substantially affected by climate. Irrigation water requirements are calculated as the difference between effective precipitation and evaporative demand determined from potential evapotranspiration. Data on actual irrigation water consumption used in SVM regressions from IMPACT furthermore take into account water availability for irrigation in each FPU, which depends both on climatic factors and non-irrigation water demands that are prioritized over water uses for irrigation. Furthermore, hydroelectricity generation can be affected by flood regulation due to excessive rainfall or by low reservoir inflow during drought periods. High hydraulic head is favorable for hydroelectricity production and flexible irrigation supply (lower water pumping and delivery cost). Meanwhile the elevated hydraulic head results in increased water surface area, leading to evaporative losses, especially in arid and semi-arid regions. Furthermore, reservoir operations may consider both short-term and long-term climate conditions, which are subject to uncertainty.

The sensitivity of hydroelectricity generation to precipitation is shown in figure 3. FPUs with positive sensitivity values, such as those in Northern China, India, Central Asia and Canada, (i.e. in red and yellow color) indicate that hydroelectricity generation will be larger under increased precipitation. This means that current hydropower capacity in these FPUs is possibly constrained by water availability and greater precipitation may increase hydroelectricity generation with existing facilities. FPUs with negative sensitivity values, that is, where hydroelectricity generation will be lower with increased precipitation, are located in most basins in the U.S., Southern China, and most basins in Europe and Oceania, as shown in blue color in figure 3. In these cases, hydropower production can decline by more than 5%, such as in the East Coast of Australia, parts of Southeast Asia, South Korea and parts of the Southeastern U.S. Since these FPUs generally have abundant rainfall which may result in high streamflow and thus flooding, a possible explanation for the reduced hydroelectricity generation is that flood control purposes of the reservoirs in these FPUs constrain hydropower generation. During the flooding season, reservoir storage is held below a

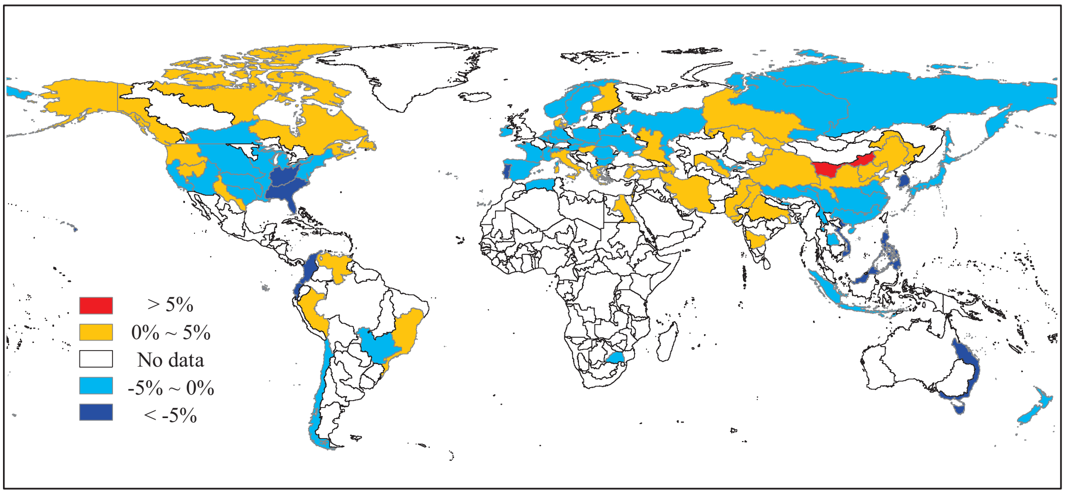

Figure 3. The sensitivity of hydropower generation to precipitation (percentage change of mean hydropower generation corresponding to one standard deviation change of precipitation in each FPU).

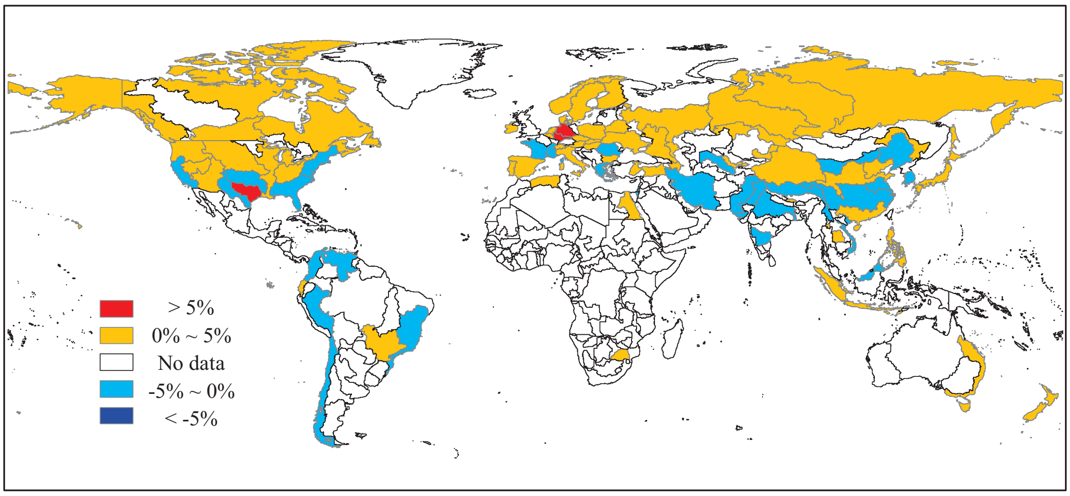

Figure 4. The sensitivity of hydropower generation to potential evaporation (percentage change of mean hydropower generation corresponding to one standard deviation change of potential evaporation in each FPU).

certain level so that sufficient storage is reserved for receiving flood waters during a storm. The decreased hydraulic head can lead to losses in hydroelectricity generation during increased precipitation and preparations for potential flooding.

The sensitivity of hydroelectricity to potential evaporation is shown in figure 4. Potential evaporation is an indicator of available radiative energy and evaporative demand. The FPUs with positive sensitivity values (in red and yellow color) are generally located in high latitude cold or cool regions (such as Russia, Canada, most basins in Europe). In these regions, an increase in potential evaporation indicates a warmer condition that may change the amount and timing of snow water storage (e.g. less snow, or larger/faster glacier melting) and can result in larger runoff in these FPUs. Thus, higher hydroelectricity generation is expected due to increased streamflow and elevated hydraulic head. Those FPUs with negative sensitivity values (in blue color) are mostly located in regions with warmer climate (such as India, South China, and some areas in the Southern U.S.). In these warm or hot regions, an increase in potential evaporation indicates more intensive evaporative loss from reservoirs and larger irrigation water requirements. Both conditions will result in either lower hydraulic head or decreased water availability, resulting in unfavorable conditions for hydroelectricity generation. In those FPUs, tradeoffs between irrigation and hydropower might well further increase due to the high evaporative loss from reservoirs.

The analysis of the sensitivity of hydropower-irrigation relationships to climate variables helps identify regions vulnerable to, as well as those that might benefit from a changing climate. Regions, such as parts of Canada, Russia and Northern China that would benefit from both increased precipitation and increased evaporative demand could start to expand cross-border energy trade or develop regional power pools with those regions or countries where decreased precipitation or higher potential evaporation reduces hydroelectricity generation. The latter countries and regions, such as California or Florida, in turn, could focus on expanding renewables that are less dependent on these climatic variables or others, like in parts of Southern China could additionally consider to strengthen irrigated food exports in return for energy purchases from other regions. In general, regions vulnerable to future climatic changes would want to find solutions, such as enhanced food or energy trade from other regions to alleviate adverse impacts on hydroelectricity and/or irrigated food production.

4.2. Extension of the global hydropower and irrigation analysis

The hydropower versus irrigation assessment in this study can be extended in several aspects. First, the study does not explicitly consider the impact of evaporation losses from reservoir surfaces and also not seepage losses. When large volumes of water with large open water surfaces are stored, evaporative and seepage losses can be considerable. Both types of losses reduce water availability for irrigation and hydroelectricity generation, although the decrease in hydroelectricity generation can be partially offset by the increased hydraulic head. Such losses affect irrigation water availability even when the timing of hydropower and irrigation needs coincide, especially in arid and semi-arid regions where potential evaporation is high. Several recent studies estimated the impact of evaporation losses on hydroelectricity generation, but the results vary significantly depending on the definitions and methods to calculate of reservoir water loss (Zhao and Liu 2015, Mekonnen and Hoekstra 2012, Herath *et al* 2011, Arnøy 2012, Liu *et al* 2015). The uncertainty from different reservoir water consumption estimation methods would be larger in regions where hydroelectricity generation is sensitive to potential evaporation. To address this, losses due to hydroelectricity generation with a dam should be compared to evaporative losses prior to dam construction. In addition, the partitioning of reservoir water into different functions depends not only on physical conditions, such as reservoir geometry and meteorological conditions, but also on reservoir operation decisions and institutional regulations, which can affect water uses for the various purposes such as hydropower and irrigation.

The relationships assessed in this study mainly reflect those between surface water use and hydropower. However, groundwater irrigation is a major source of agricultural water in many regions (Siebert *et al* 2010). Although hydropower generation may not directly affect groundwater irrigation, groundwater use may indirectly affect hydropower generation through stream depletion (Zeng and Cai 2014) through joint management of surface- and groundwater resources (Sophocleous 2002) and there might well be increased incentives to tap groundwater resources for irrigation in those areas where hydropower and irrigation are highly competitive. This could be an important area for further study.

Due to data and model limitations, this study cannot assess intra-FPU spatial heterogeneity of hydropower and irrigation relationships. However, the location of an irrigation district relative to that of a reservoir can have significant impacts on their relationship. For example, a reservoir generally does not deliver water to an upstream irrigation district; and an upstream irrigation district may reduce reservoir inflows. In contrast, water stored in a reservoir is able to provide water for downstream irrigation. Further disaggregation of the FPUs should be considered in future studies.

Finally, while the study does not implement climate change analysis, the sensitivity analyses showed that the relationship between hydroelectricity generation and irrigation varies with changing climatic factors. Future studies should analyses the relationships under various future climate and socioeconomic scenarios. As discussed by Berga (2016), hydropower can contribute to climate change mitigation and also play an important role in climate change adaptation by regulating variable streamflows to increase water availability for irrigation and other purposes; at the same time, depending on the hydroclimatic manifestations of climate change, hydroelectricity production can be either positively or negatively affected Rheinheimer *et al* (2013), which in turn would affect irrigation outcomes and vice versa. In addition, the influence of hydropower generation on meeting environmental flow requirements has become a growing concern (Rheinheimer *et al* 2016). Thus, a future task will be to assess the resilience of all, or at least several additional of the multiple purposes of reservoir systems under changing natural and social conditions.

5. Conclusions

In this study, we presented a global-scope analysis of the relationships between hydroelectricity generation and irrigation water consumption. Data for the analysis on inter-annual variability of climate, hydropower and irrigation water consumption were compiled from existing, publicly-available survey and modeling data. The correlation between hydroelectricity generation and irrigation was derived from the data set. A machine learning technique was applied to quantifying the tradeoffs and positive synergies between the two key reservoir functions within each of several clusters identified by correlation coefficients.

The study has identified global spatial patterns of the tradeoffs and synergies between hydropower and irrigation. By analyzing 96 FPUs, which account for about 90% of the global total mean annual hydroelectricity generation (2895 Terawatt-hours), we find that hydropower and irrigation relationship matter in only a relatively small part of the globe. Second, when relationships do exist, they are largely competitive in nature: hydropower and irrigation compete for water in 56 FPUs with installed hydropower capacity of 507 thousand Megawatt (or 54.3% of the global total) and mean annual hydroelectricity generation of 1860 Terawatt-hours (or 57.6% of the global mean annual hydroelectricity generation). The relationship is competitive in FPUs in the Central U.S., Northern Europe, India, Central Asia and Oceania. The competing relationships can be attributed to multiple causes, including low streamflow availability, the inconsistent timing of hydropower and irrigation, as well as the evaporation water losses from the reservoir surface in warmer climates. The relationships are complementary in Southeast Asia, the Yellow and Yangtze River Basins of China, the East and West Coast of the U.S. and Canadian and Russian river basins, covering 19 FPUs, which account for 79 thousand Megawatt (or 8.4% of the global installed hydropower capacity). The mean annual hydroelectricity generation (229 Terawatt-hours) in these FPUs accounts for only 7.9% of the global total.

Third, we find that climate conditions such as precipitation and potential evaporation introduce further complexity into hydropower-irrigation relationships. The FPUs currently constrained by limited water availability compared to storage (such as those in North China, India, Central Asia and Canada) may generate more hydroelectricity with increased precipitation; meanwhile hydropower in FPUs with increased excessive rainfall (including the U.S., South China, most basins in Europe and Oceania) may be constrained by flood control regulations. Increase in potential evaporation can enhance hydropower generation in high latitude cold or cool regions (including Russia, Canada, and some basins in Europe) due to increasing streamflow from additional snowpack and glacier melting. Increased reservoir evaporative losses and irrigation requirements due to larger potential evaporation may lead to larger tradeoffs and competition for water use in those regions with warm climates, such as India, South China, and parts of the Southern U.S.

The global assessment of hydropower-irrigation relationships will be used for global food, energy and water modeling to assess the FEW nexus and the impact of further hydropower development (as well as irrigation development) in some regions, as well as climate change in the future. Local irrigation and hydropower development may have far-reaching impacts due to their linkages with global and regional food and energy trade. The virtual water embedded in agricultural commodities and hydroelectricity links reservoirs and rivers that are hydrologically separated, propagating local tradeoffs and synergies within a global virtual water network (Konar *et al* 2011).

As an example, regional power grids such as the Southern African Power Pool connect hydroelectricity generation from different watersheds and countries (Conway *et al* 2015). It is thus possible that changes in energy demand in one country propagate through power grids and affect the irrigation water availability and thus food security in another country. The global assessment in this study thus provides a basis for the global analysis of the water, food and energy nexus underlying the connections in international food and energy trade. Furthermore, research on the relationship between hydropower and irrigation should take into account the role of and impacts on environmental flow requirements, especially under climate change.

Acknowledgements

This research was conducted with funding from the CGIAR Research Program on Water, Land and Ecosystems (WLE) through the project 'Hydropower-Irrigation Linkages' led by the International Food Policy Research Institute (IFPRI) with the University of Illinois at Urbana-Champaign with support from CGIAR Fund Donors including: the Australian Department of Foreign Affairs and Trade (DFAT), Bill and Melinda Gates Foundation, Netherlands Directorate-General for International Cooperation (DGIS), Swedish International Development Cooperation Agency (Sida), Switzerland: Swiss Agency for Development Cooperation (SDC). We are grateful to Kevin Wallington for editorial assistance.

References

Arnøy S 2012 Water footprint approaches in Life Cycle Assessment: state-of-the-art and a case study of hydroelectric generation in the Høyanger area

Berga L 2016 The role of hydropower in climate change mitigation and adaptation: a review *Engineering* **2** 313–8

BP B P 2012 *BP Statistical Review of World Energy* (London: British Petroleum)

Cai X, Mckinney D C and Rosegrant M W 2003 Sustainability analysis for irrigation water management in the Aral Sea region *Agr. Syst.* **76** 1043–66

Cai X and Rosegrant M W 2002 Global water demand and supply projections: Part 1. A modeling approach *Water Int.* **27** 159–69

Chang C-C and Lin C J 2011 LIBSVM: a library for support vector machines *ACM Trans. Intell. Syst. Technol.* **2** 1–27

Chatterjee B, Howitt R E and Sexton R J 1998 The optimal joint provision of water for irrigation and hydropower *J. Environ. Econ. Manag.* **36** 295–313

Canadian Hydropower Association (https://canadahydro.ca/facts/) (Accessed: October 2016)

Conway D *et al* 2015 Climate and southern Africa's water-energy-food nexus *Nat. Clim. Change* **5** 837–46

Food and Agriculture Organization (FAO) 2016 FAO geo-referenced dam database (www.fao.org/nr/water/aquastat/dams/index.stm) (Accessed: October 2016)

Harou J J, Medellín-azuara J, Zhu T, Tanaka S K, Lund J R, Stine S, Olivares M A and Jenkins M W 2010 Economic consequences of optimized water management for a prolonged, severe drought in California *Water Resour. Res.* **46** W05522

Herath I, Deurer M, Horne D, Singh R and Clothier B 2011 The water footprint of hydroelectricity: a methodological comparison from a case study in New Zealand *J. Cleaner Prod.* **19** 1582–9

International Commission on Large Dams (ICOLD) 2016 (www.icold-cigb.net/GB/World_register/data_base_presentation.asp) (Accessed: October 2016)

International Energy Agency (IEA) 2016 (www.eia.gov/electricity/data/browser/) (Accessed: October 2016)

International Hydropower Association (IHA) 2016 (www.hydropower.org/country-profiles) (Accessed: October 2016)

IPCC 2014 *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed C B Field *et al* (Cambridge: Cambridge University Press)

Kadigi R M J, Mdoe N S Y, Ashimogo G C and Morardet S 2008 Water for irrigation or hydropower generation?—Complex questions regarding water allocation in Tanzania *Agr. Water Manage.* **95** 984–92

Konar M, Dalin C, Suweis S, Hanasaki N, Rinaldo A and Rodriguez-Iturbe I 2011 Water for food: the global virtual water trade network *Water Resour. Res.* **47** W05520

Lacombe G, Douangsavanh S, Baker J, Hoanh C T, Bartlett R, Jeuland M and Phongpachith C 2014 Are hydropower and irrigation development complements or substitutes? The example of the Nam Ngum River in the Mekong Basin *Water Int.* **39** 649–70

Liu J, Zhao D, Gerbens-Leenes P W and Guan D 2015 China's rising hydropower demand challenges water sector *Sci. Rep.* **5** 11446

Mekonnen M M and Hoekstra A Y 2012 The blue water footprint of electricity from hydropower *Hydrol. Earth Syst. Sci.* **16** 179–87

Molle F, Jayakody P, Ariyaratne R and Somatilake H 2008 Irrigation versus hydropower: sectoral conflicts in southern Sri Lanka *Water Policy* **10** 37

Perrone D and Hornberger G M 2014 Water, food, and energy security: scrambling for resources or solutions? *Wiley Interdiscipl. Rev. Water* **1** 49–68

Räsänen T, Joffre O, Someth P, Thanh C, Keskinen M and Kummu M 2015 Model-based assessment of water, food, and energy trade-offs in a cascade of multipurpose reservoirs: case study of the Sesan Tributary of the Mekong River *J. Water Resour. Plann. Manage.* **141** 05014007

Rheinheimer D E, Liu P and Guo S 2016 Re-operating the Three Gorges Reservoir for Environmental Flows: a preliminary assessment of trade-offs *River Res. Appl.* **32** 257–66

Rheinheimer D E, Yarnell S M and Viers J H 2013 Hydropower costs of environmental flows and climate warming in California's Upper Yuba River Watershed *River Res. Appl.* **29** 1291–305

Robinson S, Mason-D'Croz D, Sulser T, Islam S, Robertson R, Zhu T, Gueneau A, Pitois G and Rosegrant M W 2015 *The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Description for Version 3* (Washington, DC: International Food Policy Research Institute)

Rosegrant M W, Ringler C and Zhu T 2009 Water for agriculture: maintaining food security under growing scarcity *Ann. Rev. Environ. Resour.* **34** 205

Schnier S and Cai X 2014 Prediction of regional streamflow frequency using model tree ensembles *J. Hydrol.* **517** 298–309

Siebert S, Burke J, Faures J M, Frenken K, Hoogeveen J, Döll P and Portmann F T 2010 Groundwater use for irrigation—a global inventory *Hydrol. Earth Syst. Sci. Discuss.* **7** 3977–4021

Sophocleous M 2002 Interactions between groundwater and surface water: the state of the science *Hydrol. J.* **10** 52–67

Tilmant A, Goor Q and Pinte D 2009 Agricultural-to-hydropower water transfers: sharing water and benefits in hydropower-irrigation systems *Hydrol. Earth Syst. Sci.* **13** 1091–101

The World Commission on Dams (WCD) 2000 *Dams and Development: A New Framework for Decision-making: the Report of the World Commission on Dams* (London: Earthscan)

U.S. Energy Information Administration (EIA) 2016 (www.iea.org/Textbase/npsum/MTrenew2015sum.pdf) (Accessed: October 2016)

World Energy Council (WEC) 2016 (www.worldenergy.org/data/resources) (Accessed: October 2016)

Xu T, Valocchi A J, Choi J and Amir E 2014 Use of Machine Learning methods to reduce predictive error of groundwater models *Groundwater* **52** 448–60

Yang Y C E, Ringler C, Brown C and Mondal M A H 2016 Modeling the agricultural water-energy-food Nexus in the Indus River Basin, Pakistan *J. Water Resour. Plann. Manage.* **142**

Yüksel I 2010 Hydropower for sustainable water and energy development *Renew. Sust. Energ. Rev.* **14** 462–9

Zarfl C, Lumsdon A, Berlekamp J, Tydecks L and Tockner K 2015 A global boom in hydropower dam construction *Aquat. Sci.* **77** 161–70

Zeng R and Cai X 2014 Analyzing streamflow changes: irrigation-enhanced interaction between aquifer and streamflow in the Republican River basin *Hydrol. Earth Syst. Sci.* **18** 493–502

Zhao D and Liu J 2015 A new approach to assessing the water footprint of hydroelectric power based on allocation of water footprints among reservoir ecosystem services *Phys. Chem. Earth, Parts A/B/C* **79–82** 40