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Research papers

Hydrologic changes, dam construction, and the shift in dietary protein in the Lower Mekong River Basin

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ABSTRACT

This study links the changing hydrology in the Lower Mekong River Basin (LMRB) caused by accelerated dam construction to a dietary shift from fish to land-animal meat (meat hereafter) as a primary source of protein. A shift toward a westernized diet in the LMRB countries (i.e., Cambodia, Lao PDR, Thailand, and Vietnam) has been observed in the recent past. However, neither the hydrological changes from dam construction as a cause for the dietary shift nor the effects of increasing shift from fish to meat on virtual water have been adequately studied. Here, we derive a univariate relationship between fish catch and flooded areas by using a hydrodynamic model and yearly fish catch data. We find a strong correlation between catch per capita and yearly flood occurrence in the LMRB. Results suggest that fish catch in the Tonlé Sap Lake region may reduce by ~8% under a scenario of altered flood occurrence caused by potential reduction in peak flow in the main stem Mekong by 50%. The same reduction in peak flow could, however, lead to an increase in catch within a larger LMRB subregion but such increase would be marginal. Next, based on the historical production and consumption of meat, we find an increase in meat production and consumption per capita over time. Further, analysis of land use change suggests a 2% cropland expansion mainly due to an increase in meat production. Finally, from the virtual water trade (VWT) network we find that the total VWT of the LMRB tripled from 1988 to 2016 due to a significant rise in trade partners.

1. Introduction

Dam construction, driven by regional socio-economic growth and rising energy demands, is causing a radical shift in the natural hydrologic regime of the Lower Mekong River Basin (LMRB), which in turn is adversely affecting fish productivity, diversity, and catch. There is growing evidence that some of the existing dams have modified the flood dynamics and impacted livelihoods through changes in fisheries (Arias et al., 2014; Baran et al., 2015; Baran and Myschowoda, 2009; Brownell et al., 2017; Dugan et al., 2010; Kondolf et al., 2014; Kummu and Sarkkula, 2008; Lu and Siew, 2006; Wild et al., 2019; Xue et al., 2011). Concomitantly, rapid population growth and strong social reforms have led the diet of the LMRB nations (i.e., Cambodia, Lao PDR, Thailand, and Vietnam) to gravitate toward water-intensive sources of protein (Orr et al., 2012a; Pittock et al., 2017). Further, the region is expected to add a significant number of additional large dams (16 in the main stem and ~110 in the tributaries) in the foreseeable future (Pokhrel et al., 2018a). It is expected that these new dams would cause widespread alterations of flood pulse dynamics and loss in fish productivity and diversity (Grumbine and Xu, 2011; Keskinen et al., 2012; Lauri et al., 2012; Stone, 2011; Winemiller et al., 2016; Ziv et al., 2012).

In the past two decades the Mekong River underwentfaed significant changes due to the construction of dams (Arias et al., 2014; Baran et al., 2015; Baran and Myschowoda, 2009; Brownell et al., 2017; Dugan et al., 2010; Kondolf et al., 2014; Kummu and Sarkkula, 2008; Lu and Siew, 2006; Wild et al., 2019; Xue et al., 2011). The ~53,000 MW potential hydropower generation in the main stem of the river, and an additional 35,000 MW in its tributaries, has attracted significant international attention toward harnessing this vast potential by building large-scale hydropower dams (Grumbine and Xu, 2011; ICEM, 2010; Keskinen et al., 2012; Lauri et al., 2012; Pokhrel et al., 2018a; Stone, 2011; Winemiller et al., 2016; Ziv et al., 2012). This is bound to disrupt the river's natural hydrology and hinder fish reproduction by changing the natural hydrologic regime and blocking migratory pathways (Pokhrel et al., 2018b). For example, studies have found unprecedented and unpredictable flow fluctuations during dry and wet seasons in the region caused by the Yali Falls dam in the Sesan River, which caused severe damages to downstream crops, livestock, fisheries, and thus livelihoods (Pearse-Smith, 2012; Wyatt and Baird, 2007). In addition,

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dam construction has impacted the region's ecology; for instance, a drop in migratory fish biomass by up to 51.3% was recorded in 2012 (Ziv et al., 2012). As a result, 100 fish species were suggested to have joined the critically endangered list (Ziv et al., 2012).

Drastic physical manipulations of river flow contribute to a decline in fish populations as well, especially that of migratory fish, which account for 71% of the fisheries yield in the LMRB (Barlow et al., 2008). For instance, a strong association between fish catch and water level during 1998–2001 period was reported for the Tonlé Sap Lake (TSL), which captures the importance of flood variation and its effect on fish catch and migration patterns (Van Zalinge et al., 2003). Another study by McIntyre et al. (2016) suggested a relationship between river discharge and fish catch, which they used to downscale fish catch over the major global river basins and study freshwater fishery. Sabo et al. (2017) took a different approach, deriving a multivariate relationship between fish population and flood anomalies of the Mekong River, suggesting a strong dependence between the two. However, the impacts of dams on hydrology and in turn on fish catch have not yet been adequately studied. There have been some studies (e.g., Sabo et al., 2017; Ziv et al., 2012) but they have only considered the effects of dams as physical barriers on fish migration or hydrological anomalies on fish populations separately. Thus, given that significant number of dams are planned to be constructed in the LMRB, it is critical to understand how fish catch will be impacted directly from the flood pattern alterations.

Today, the livelihoods of 80% of the 60 million inhabitants of the LMRB is reliant on fisheries and agriculture that depend heavily on seasonal rainfall and flood patterns (Baran and Myschowoda, 2009; ICEM, 2010). The hydrological regime of the Mekong River is characterized by a seasonal flood pulse, producing a strong unimodal flow pattern (Junk et al., 1989), which secures the reproduction of most migratory fish (ICEM, 2010). Such flood pulse pattern can be largely modified by dams that alter the magnitude, timing, and flow amounts (Delgado et al., 2012; Haddeland et al., 2006; Hanasaki et al., 2006; Lauri et al., 2012; Pokhrel et al., 2016, 2012; Sabo et al., 2017; Shin et al., 2019; Veldkamp et al., 2017). Using observed river discharge data, a study has shown that cascade dams in the upper Mekong (i.e., the Lancang river in China) have already caused significant changes in river flow patterns, causing 29–36% dampening and 34–155% increase in seasonal flows during the wet and dry seasons, respectively (Räsänen and Kummu, 2013). Additionally, Pokhrel et al. (2018b) investigated the potential impacts of dam construction on the flood pulse dynamics of the LMRB by considering varying flow regulation scenarios that typically result from reservoir operation. They showed that a dampening of peak flow in the main stem Mekong by 10–50% would cause a change in flow reversal by 11–80% and 15–88% at the outlet of TSL and the Prek Kdam station in the Tonlé Sap River, respectively. Flood pulse reduction is an important factor to be considered when examining fish population decline, however, physical barriers created by dams is another heavily studied variable. Such barriers prevent spawning of migratory species, which are of biological and economic importance (Dugan et al., 2010). The large number of proposed dams could add further stress and significantly impact the flood pulse pattern, affecting the magnitude, duration, and timing of flooding in the LMRB. Such changes will affect the fishery, as noted above, however none of the mentioned changes deal with fish population response as a direct result of hydrological changes from dam construction. This calls for a critical need for robust and thorough examination of the likely impact of changing flooding patterns on fish catch in the LMRB (especially the flooded area around TSL and Mekong Delta).

Annual fish catch is affected by hydrologic changes caused by dams and climate change. However, additional factors also play important roles. For example, local demand, consumption, and market conditions (trade) can have implications for dietary patterns, which in turn affect fish catch. Also, a dietary shift of protein from fish to meat (e.g., cattle, chicken, pig, sheep, goat, and horse) in the LMRB nations has been widely reported (Orr et al., 2012a; Pittock et al., 2017), which puts water resources, surrounding ecosystems, and biodiversity under increasing pressure. Meat, as opposed to fish, is predominantly a water intensive product. Hence, the concept of virtual water trade (VWT), which is the total amount of transported water embedded in the production of a commodity, also known as water footprint, has been employed as a tool for measuring the quantity of water involved in trade (Chapagain and Hoekstra, 2008). Since the water footprint of meat protein surpasses that of fish, a suggested effort to reduce fresh-water use globally is optimizing VWT (Dalin et al., 2012). Balancing water use through food production is crucial because it is the highest freshwater consuming process taking up to 80% of the world's water resources (Rost et al., 2008). Thus, the concept of water savings (WS), which is described as the difference in water use during the production of a commodity between specific geographical locations, is used to derive a balanced approach to the production of meat commodities (Chapagain et al., 2006). VWT and WS have been studied at different spatial and temporal scales (Liu et al., 2019) however, these concepts have not yet been applied in the LMRB region.

Given the above background, here we present the first study that examines the connection between potential hydrological variations stemming from dam construction and changes in fish catch in the LMRB and constructs a 28-year historical VWT network for the region. Our study is driven by the following science questions: Is there a relationship between fish catch and potential hydrological variations induced by dam construction in the LMRB? What is the impact of a dietary shift from fish to livestock products on VWT between the LMRB and the rest of the world (ROW)? How might we optimize WS by balancing meat production between the LMRB and the ROW? We pursue the following specific objectives to address these science questions: (1) Develop a univariate relationship between fish catch and flooded areas to downscale fish catch data using results from a hydrological model and examine fish catch temporal variability; (2) construct a VWT network using virtual water content (VWC) of meat commodities and trade data to study the impacts of adopting a higher meat-based diet; and (3) compare the estimated effects of domestic (i.e., within LMRB countries) and internationally (i.e., the ROW) produced meat commodities in terms of WS to determine optimal production locations for each commodity.

These science questions and objectives are addressed by using results from a hydrodynamic model, along with data on international trade, production, and consumption of fish and meat. The impacts of operational dams on hydrology and fish catch are analyzed through downscaling historical catch data and distributing these data to the LMRB. The potential impacts of future dams are estimated by combining hydrological results from Pokhrel et al. (2018b) and the distribution principles of the catch. Next, the ramifications of multifaceted processes that channel a dietary shift in the LMRB such as land use and land cover (LULC hereafter) change and increased water usage for agriculture that the new protein source pattern brings to the LMRB nations are explored. Specifically, LULC changes are analyzed for a 24-year period. Additionally, we examine meat commodities in terms of VWT by constructing a VWT network.

2. Study area

The study area is the LMRB (Fig. 1), located in Southeast Asia, which has a total area of ~606,000 km^2, covering ~76% of the entire Mekong River Basin with a total area of ~795,000 km^2 (Frenken, 2012). The LMRB is shared by four countries: Cambodia, Lao PDR, Thailand, and Vietnam (area contribution summarized in Table S1). The Mekong River's mean annual water discharge is approximately ~475 km^3/year or ~15,000 m^3/s making it the 10th largest river in the world in terms of annual flow at its mouth (MRC, 2005). It flows through ~2600 km of channels from the Golden Triangle to the South China Sea at the Mekong Delta (MRC, 2010, 2005). The LMRB is characterized by flat-fertile lands that stretch over long distances and

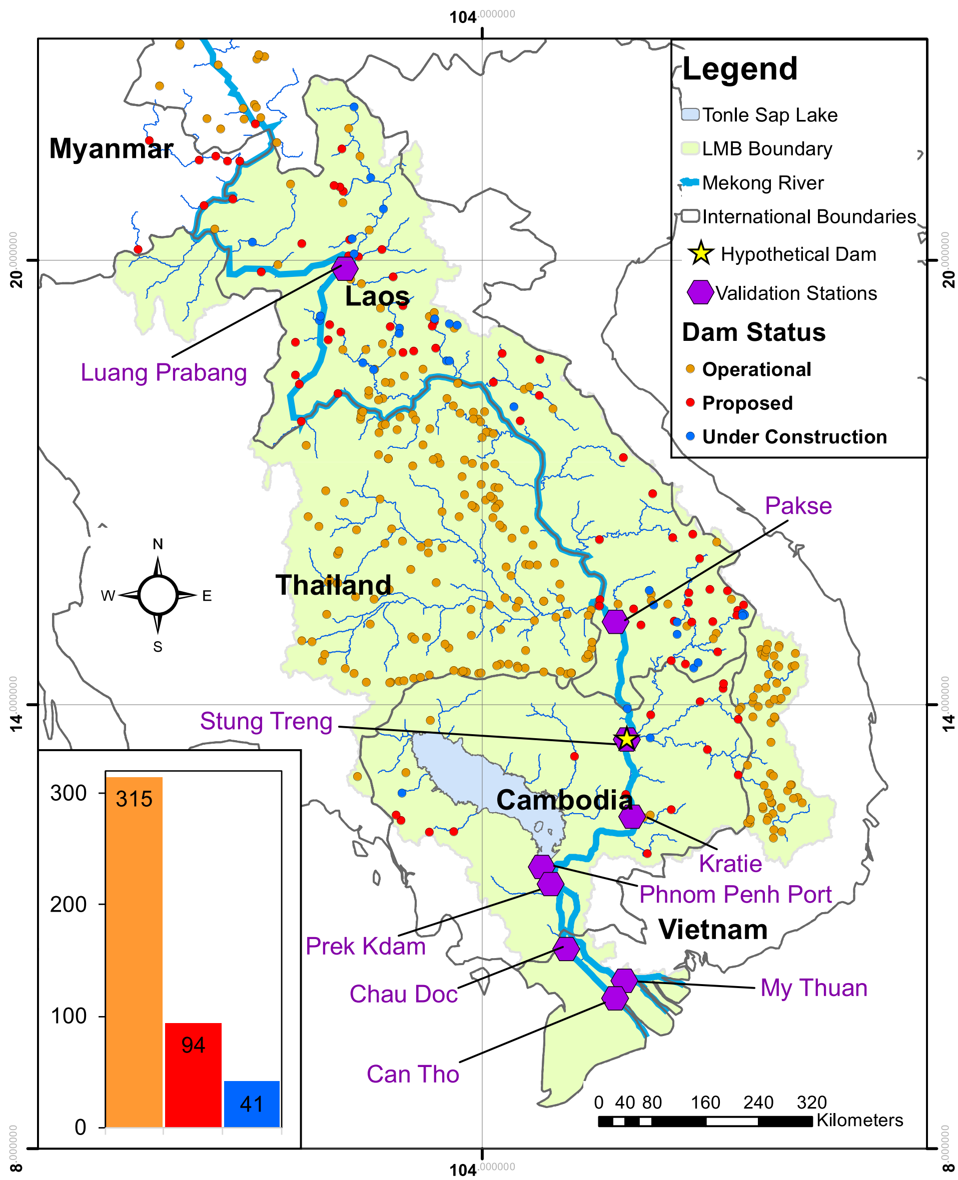

Fig. 1. The Lower Mekong River Basin (LMRB). Purple hexagons show validation stations for which river discharge observations were obtained from the MRC. Color coded circles show the location of dams that are operational, under construction, or proposed. The lower left inset shows the total number of dams under different categories. The database for the dams was obtained from the Research Program on Water, Land and Ecosystems (WLE), Greater Mekong. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

by strong climatic gradients. Human development and a plethora of managed ecosystems are co-evolving in the basin resulting in rapidly emerging global issues such as land cover change, river flow regulation, and habitat loss (Pokhrel et al., 2018a).

Compared to other major river basins of the world the Mekong River Basin (MRB) remains relatively unaltered by dams (Grumbine and Xu, 2011; Nilsson et al., 2005). Despite having many dams constructed over the past few decades, the effects on the main stem Mekong are still relatively small because most existing dams are located in the tributaries (Fig. 1) and capture only a small portion of the annual flow volume (Grumbine and Xu, 2011; Winemiller et al., 2016). The river system at hand still manifests distinctive wet and dry seasons as direct outcomes of the seasonal variability in precipitation, which supports highly productive riverine ecological systems and agriculture. Food production in the LMRB is heavily reliant on timely rainfall that modulates the seasonal flood pulse (Fredén, 2011). These hydro-climatic characteristics allow the LMRB to house an important ecosystem responsible for the largest inland fishery which feeds local inhabitants, as well as a significant fraction of rest of the world (Ziv et al., 2012). To put this into perspective last decade's estimate of 2.2 Mega Tonnes (Mt) of wild fish harvest from the Mekong was worth between $2.2–3.9 billion at first scale and $4.3–7.8 billion on retail markets (Hortle, 2009).

3. Methods, data, and model

3.1. Production and consumption of commodities

The production and consumption of commodities, specifically fish and meat, are analyzed using the data from the U.N. Food and Agricultural Organization (FAO). Production and consumption of meat for each of the LMRB countries individually and the total for all nations is analyzed for the 1988–2013 period. The same process is followed for fish. This study then investigates important points in time by calculating statistical changepoints for each category.

3.2. Fish catch downscale

Fish catch is downscaled by using the flooded areas simulated by the hydrodynamic model CaMa-Flood (Pokhrel et al., 2018b). Results of CaMa-Flood model for the LMRB have been extensively validated in previous studies, including our own (Pokhrel et al., 2018b; Yamazaki et al., 2014, 2011). Here, for completeness, we revisit the validation of the simulated river discharge (Fig. S1 in the supplementary materials), which is a primary determinant of the simulated flooded areas. As seen in this figure, river discharge is well simulated by the model over the entire LMRB except for some locations in the delta region, due to the lack of tidal effects in the model.

An exponential function that describes the relationship between flooded area and catch is developed by comparing nationwide historical catch data to the results of flooded areas from the CaMa-Flood model (see Section 3.6 for model details). The data are transformed to a logarithmic function, and, through linear regression, a univariate model is derived following the approach used by McIntyre et al. (2016); the newly derived function is expressed as $C = 0.6604A_{fl}^{1.071}$ (see Fig. S2), where C is potential fish catch (tonnes/year) and A_{fl} is annual flooded area (m^2).

Next, we use the model results to calculate potential fish catch in the LMRB. In particular, we use the simulated flooded areas and flood depth from CaMa-Flood at 10 km grid resolution, with simulation settings identical to that in Pokhrel et al. (2018b). Any grid cell with an average water depth under 20 cm is excluded since the reported catch data from FAO is only reported by large fisheries that target deeper areas. Next, flooded areas for 1981–2010 period are run through the univariate model, which yields yearly raster data of potential catch. These values are then used to apportion the reported annual catch data from FAO using a weighted average approach, expressed as $C_i = C_{p(i)} \times C_{actual}/\Sigma C_{p(i)}$, where C_i is the observational fish catch distributed to grid cell i, $C_{p(i)}$ is potential fish catch of grid cell i, C_{actual} is the observational fish catch of the country in which the grid cell is located, and $\Sigma C_{p(i)}$ is the total potential fish catch over the given country.

Then, we analyze the downscaled fish catch for wet and dry years since the effects of flow regulation on flood patterns vary significantly during years with low discharge and precipitation (dry years) and years with high discharge and precipitation (wet years). The wet years (i.e., 2000, 2001, 2006, 2007) were chosen from an analysis of the total yearly flooded area in the LMRB from 1981 to 2010. Likewise, the dry years (i.e., 1998, 2003, 2004, 2005) were selected from the same analysis by choosing those years with the least flooding. We choose only the most extreme years from the decade between 1998 and 2008, in an attempt to avoid the highest fish catch growth years, which can be attributed to fishing technological advances from the 1990s (Sverdrup-Jensen, 2002). The wet and dry year analysis of catch data is normalized by computing catch per capita before carrying out the spatial distribution to reduce the effect of demand increase stemming from population growth. Here, the goal is to analyze the isolated effects of changes in flooded areas. These results are distributed following the same procedure described above.

3.3. Change in fish catch

Potential changes in fish catch due to flow regime change is estimated using the aforementioned univariate fish catch model of flooded area ($C = 0.6604A_{fl}^{1.071}$). For in-depth analysis, we specify two domains: the Lower Mekong sub-region and the TSL region (see Section 4.2). To represent the potential effects of upstream flow regulation and climate change on flooded areas in those regions, we set scenarios where the magnitude of peak flow—based on the average daily hydrograph for 1981–2010 period—at the inlet of those regions (near Stung Treng; yellow star in Fig. 1) is reduced by 10, 20, 30, 40, and 50%. The daily hydrograph is then adjusted to preserve annual water balance (Pokhrel et al., 2018b). The flow is altered at this particular location because fish migration from the Mekong Delta and TSL region generally occurs up to this point, which is under Khone Falls; the majority of known spawning and nursing grounds of different fish species are downstream of this location (Cowx et al., 2015; Poulsen et al., 2002). The location is also near the most downstream dam of the among planned and commissioned dams in the Mekong river (i.e., Sambor dam). For each scenario, the monthly flooded areas of those two regions are calculated, and the monthly potential change in fish catch is accordingly estimated. For details of model setup, readers may refer to Pokhrel et al. (2018b).

3.4. Virtual water

Understanding the quantity of virtual water that flows in and out of nations is crucial when optimizing water use at regional and global, or even local, levels. A complete analysis of this concept includes the calculation of virtual water exports as well as virtual water imports. In Section 4.4 we summarize the virtual water flows of each LMRB country as well as the total for all nations. Important fluctuations over the study period are analyzed by calculating changepoints using the R changepoint package (Killick and Eckley, 2014). The rise in water use that compensates for elevated meat consumption is examined by constructing a meat VWT network from 1988 to 2016. The VWC, which is the amount of water required to produce a given commodity, of each commodity considered was retrieved from Chapagain and Hoekstra (2003). For greater details on how virtual water content from feed is calculated, the reader is referred to Hoekstra (2003). VWT export values are estimated by multiplying the trade data from FAOSTAT (FAO Statistics) by its corresponding VWC using the following equation:

$$VWT_{i,j,x}^{LMB} = VWC_{i,x} \times T_{i,j,x}^{LMB}$$

where $VWT_{i,j,x}^{LMB}$ is the local virtual water trade in volume (kg_{water}) of commodity x exported from a LMRB country i to a ROW country j through trade. $VWC_{i,x}$ is the virtual water content ($kg_{water}/kg_{product}$) of commodity × produced in country i. $T_{i,j,x}^{LMB}$ is the volume of commodity × ($kg_{product}$) produced in the LMRB and exported from i to j.

Similarly, VWT for the importing values are estimated using the following equation:

$$VWT_{i,j,x}^{for} = VWC_{ROW,x} \times T_{i,j,x}^{for}$$

where $VWT_{i,j,x}^{for}$ is the foreign (from ROW countries) virtual water trade in volume (kg_{water}) of commodity x exported from an LMRB country i to a ROW country j through trade. $VWC_{i,ROW}$ is the virtual water content ($kg_{water}/kg_{product}$) of commodity × produced in foreign country i. $T_{i,j,x}^{LMB}$ is the volume of commodity × ($kg_{product}$) produced in the ROW and exported from i to j.

3.5. Data

To downscale fish catch we use the following datasets: the historical (1981–2010) annual fish catch data from FAO FishStat (http://www.fao.org/fishery/statistics/en), hydrodynamic modeling results from CaMa-Flood (1981–2010) (Pokhrel et al., 2018b), and historical human population data (1986–2010) from the International Monetary Fund (IMF; the October 9th, 2018 iteration; https://www.imf.org/en/Data). The CaMa-Flood results relevant to this study include river discharge, flood depth, and flooded area. Changes in historical LULC change are calculated from the database of the European Space Agency-Climate Impact Initiative (ESA-CCI: https://www.esa-landcover-cci.org/, accessed on June 27th, 2019). For the analysis of meat and fish production and consumption, we use production FAOSTAT data (http://www.fao.org/faostat/en/#data/QL) and supply FAOSTAT data (http://www.fao.org/faostat/en/#data/CL) for both meat and fish, and fish catch from the aforementioned FAO FishStat in the place of fish production. The trade matrix meat (e.g., cattle, chicken, and pork) data required for VWT network construction are obtained from FAOSTAT (http://www.

fao.org/faostat/en/#data/TM) and VWC values are retrieved from Chapagain and Hoekstra (2003).

3.6. Model

The model used in this study is the global hydrodynamic model named CaMa-Flood (Yamazaki et al., 2014, 2011). CaMa-Flood is selected for this study because it simulates the channel bifurcation process, which is important in the LMRB (Yamazaki et al. 2014), and because it has been validated for the MRB (Yamazaki et al. 2014; Pokhrel et al., 2018a,b). Details can be found in Yamazaki et al. (2014, 2011); here we highlight key features of the model for completeness. Version 3.6 of the model simulates river-floodplain hydrodynamics by solving the shallow water equation for open channel flow. CaMa-Flood was set up at a 10 km resolution with regional level settings for the MRB (Yamazaki et al., 2014). Relevant output variables used in this study from CaMa-Flood, including inundated area and water level, are diagnosed from water storage from each unit catchment. River discharge is calculated using the shallow water equation. All simulation settings and parameters are identical to those in Pokhrel et al. (2018b).

4. Results and discussion

4.1. Downscaled fish catch

Fig. 2A presents the downscaled fish catch for the 1981–2010 period. These results suggest a monotonous growth in total fish catch over time. This is apparent throughout the domain (Fig. 2A); however, the areas of highest concentration (e.g. the TSL) show the most obvious increase in fish catch, which is likely because the primary driver of increased fish catch is market demand, which is driven by population and economic growth. Thus, to minimize the effect of population we normalize the yearly data, which allows for a per capita based downscaling, facilitating a more appropriate catch comparison with hydrology by eliminating the large fluctuations caused by population growth. The downscaled data at the country level are provided in Supplementary Tables S2 and S3.

Fig. 2B shows the distribution of fish catch per capita for four historically dry years. It is found that most of the fish catch is distributed in the TSL and the Mekong Delta regions. Year 1998 is by far the driest year (Section 3.2), coinciding with the lowest fish catch density. The fish catch of Cambodia—the country in which TSL fish production occurs—shows a sudden growth spurt in 1998 (Fig. S4) when the Asian financial crisis ended and better fishing technology was adopted, following many years of low fish production and consumption (Costales, 2004). The growth in fish catch in TSL is evident even through the dry years (Fig. 2B). Further, 1998 coincides with calculated changepoints for Cambodia, Laos and the LMRB overall and continuous and stable growth can be seen through 2005 (Fig. S4), hence, the years chosen for analysis fall within this range. Further, although the results show growth in fish production until 2005 (Fig. S4), Fig. 2B shows lower fish catch in Thailand in 2005 than in 2003 and 2004, which is especially evident in regions north of TSL, between latitude 14°N and 17°N. This is in congruence with the decline in fish consumption in Thailand (Fig.

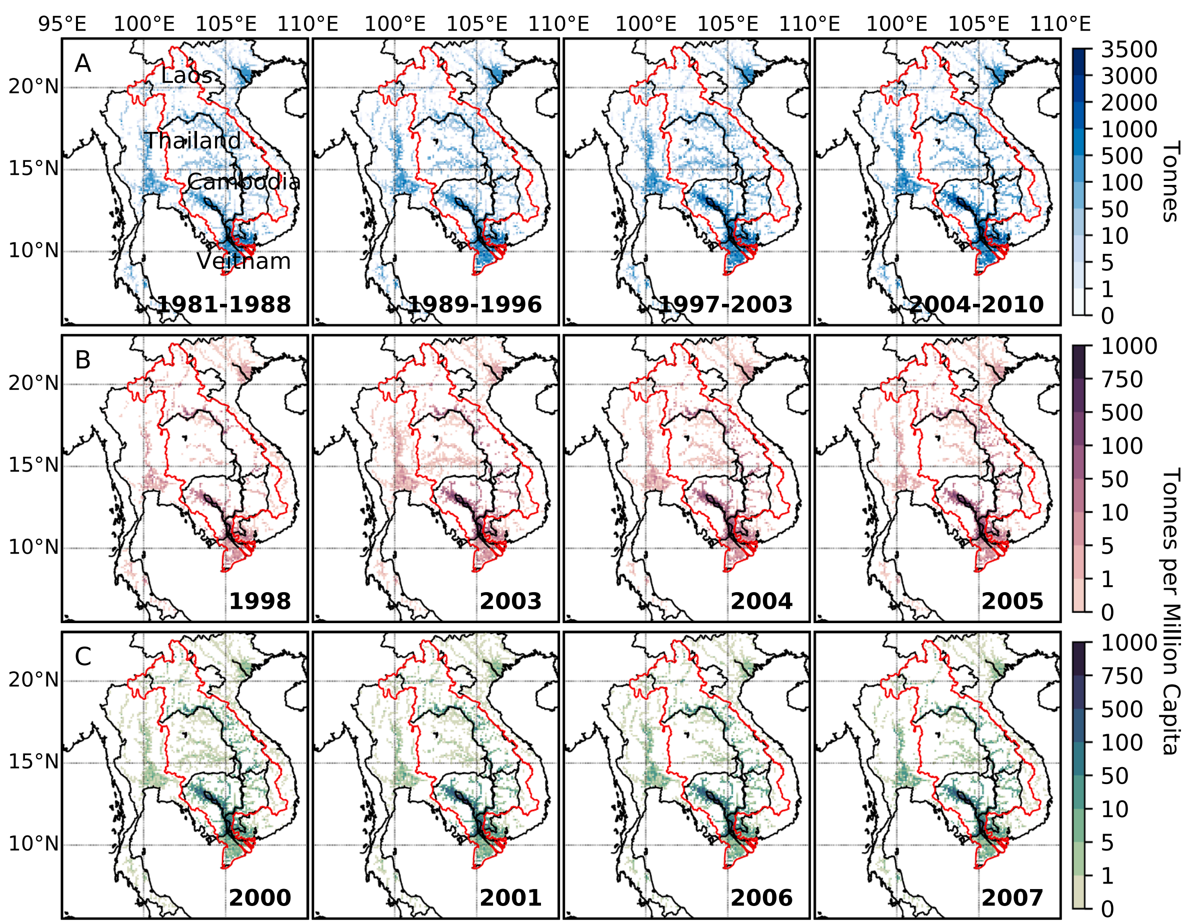

Fig. 2. : (A) Fish catch distribution shown as multi-year averages from 1981 to 2010. Freshwater fish catch data from FAO FishStat was distributed onto 10 km grids using the derived relationship between catch and flooded area. Flooded area and depths data are taken from the CaMa-Flood model (Pokhrel et al., 2018b). Countries and the LMRB are marked by black and red lines, respectively. (B) Fish catch distribution for dry years: 1998, 2003, 2004, and 2005. (C) Fish catch distribution for wet years: 2000, 2001, 2006, and 2007. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

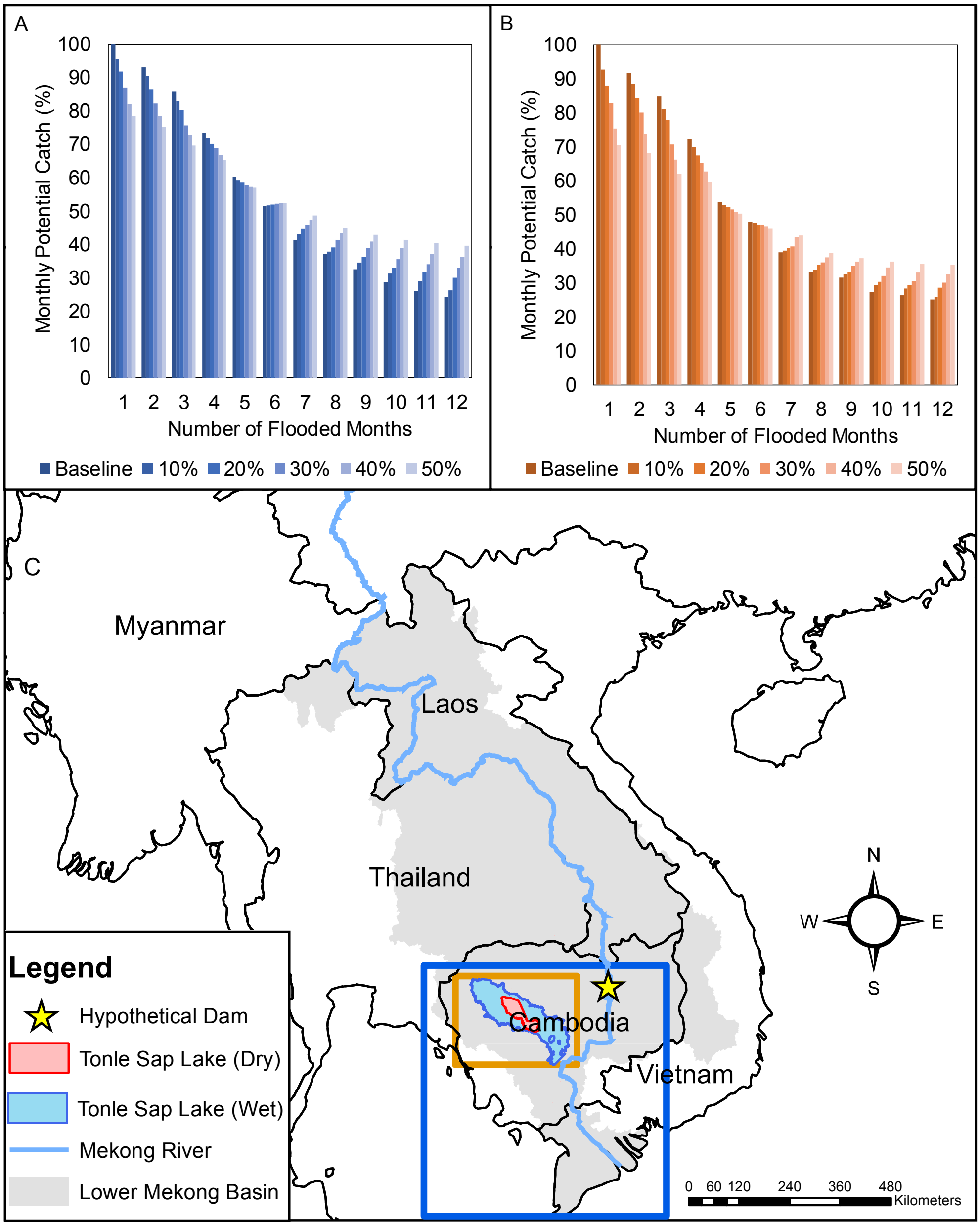

Fig. 3. Potential changes in fish catch under varying flooded areas caused by the alteration in peak flow (10–50%) totalled for two regions: (A) LMRB sub-region and (B) TSL, shown as blue and orange rectangles, respectively, in (C). The location where the flow is altered is marked by a yellow star in (C). "Baseline" represents unaltered flow conditions. Note that the results shown here represent potential fish catch normalized by the catch for the maximum flooded extents (i.e., areas flooded for 1 month of a year). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

S4). Conversely, in Vietnam the highest catch can be seen between latitude 15°N and 20°N in 2005 out of all the dry years (Fig. 2). This is, again, in congruence with the growth in fish production (Fig. S4). Other historically dry years (i.e., 2003–2004), show small levels of consumption and production, which is consistent with our correlation between flooded areas and catch.

Fig. 2C shows the fish catch per capita distributed for four historically wet years. A generally denser distribution of fish in the LMRB and the outer basin compared to that in the dry years (Fig. 2B) is readily discernable in Fig. 2C. This is especially noticeable between latitude 12°N and 13°N in Thailand, and inside the LMRB with the exception of the TSL. The barely discernible differences in the TSL are expected as this water body is a suitable location for fishing for a wide range of water levels because of its large size and ability to remain filled for a significant portion of the year. Overall, it is found that fish catch is strongly impacted by the abundance or lack of flooded areas in the LMRB. Year 2000 shows the highest density of fish catch compared to years 2001, 2006, and 2007, further suggesting a strong correlation between flooded area and catch. This is highlighted between latitudes 17°N and 20°N at the border between Laos and Thailand. Again, wet years (i.e., 2006–2007) show rapid growth (Fig. S4) in overall fish production and consumption.

4.2. Change in fish catch

Fig. 3 shows how potential fish catch within the LMRB sub-region (including the Mekong Delta) and TSL (blue and orange boxes, respectively, in Fig. 3C) could be affected by the potential changes in flood dynamics due to upstream flow alteration by dams. Results shown are for the baseline (unaltered flow) and five flow alteration scenarios (see Section 3.3 for more details), and are arranged according to areas flooded for a given number of months in a year. For the Lower Mekong

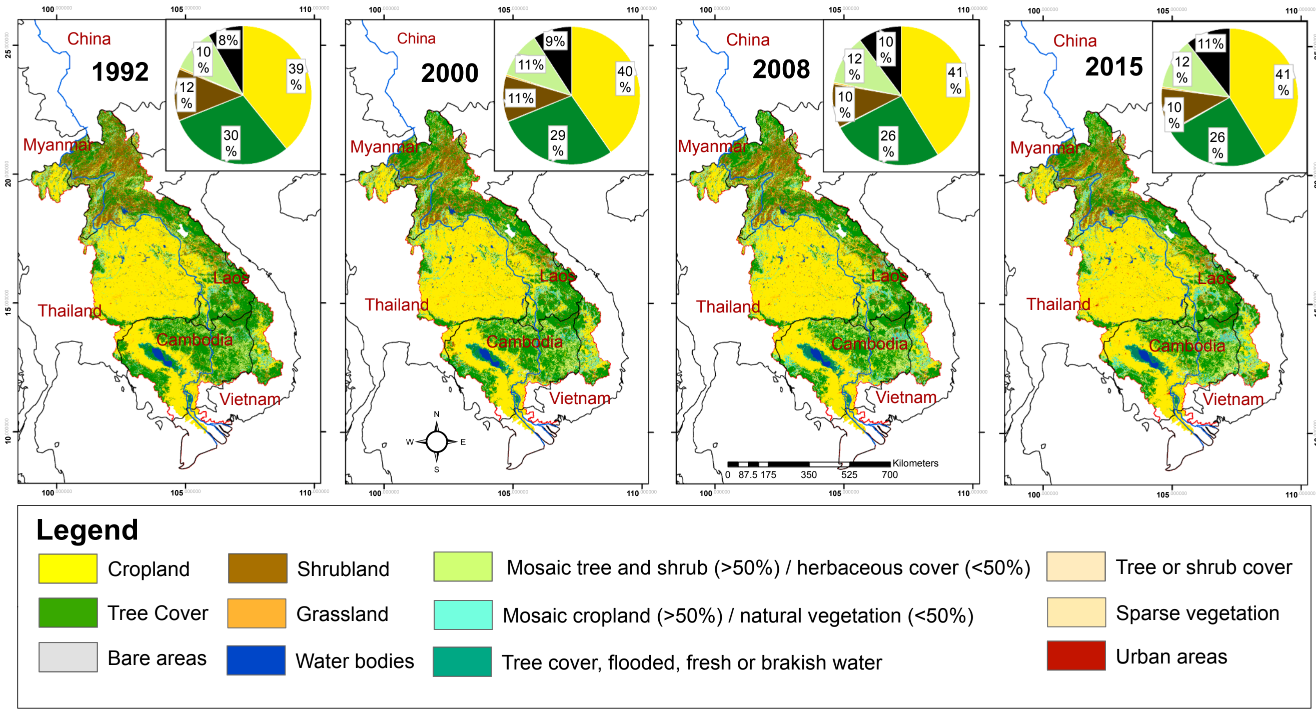

Fig. 4. Land use and land cover types for 1992, 2000, 2008, and 2015. The embedded pie charts show the fraction of the main land cover types with matching color coding except for the black pieces which are a lumped representation of the land use types not explicitly shown. The urban areas are excluded from the pie charts since they represent a negligible area. Data source: European Space Agency-Climate Impact Initiative (ESA-CCI: https://www.esa-landcover-cci.org/; accessed on July 27th, 2019).

sub-domain (Fig. 3A), results suggest that fish catch could decrease due to flow alteration in areas that are flooded for 1 to 5 months per year, and the impact proportionately increases with the degree of peak flow reduction. The opposite is true for areas flooded for 6 to 12 months. On an annual basis, changes in catch are both positive and negative under different flow alteration scenarios (Table S4) but the magnitudes are rather small with an increase by 0.23% under the highest flow alteration scenario. This increase is caused by an overall increase in permanently flooded (12-month flood occurrence) areas, which shows how the compensation of the newly flooded areas created by the dampened seasonal flood pulse may benefit potential catch.

Similar results (Fig. 3B) are found for the TSL region (orange rectangle in Fig. 3C). Those areas with short flood occurrence in the TSL region—flooded for 1 to 6 months—show a decreased fish catch potential under increased flow alteration scenarios. Conversely, the areas with relatively long flood occurrence—flooded for 7 to 12 months—show progressively higher potential fish catch with increase in the degree of flow alteration. On an annual basis, fish catch could potentially decline in this region under all flow alteration scenarios (Table S5) with the highest reduction by 8% under the 50% alteration scenario.

The TSL results (Table S5) highlight how fish catch in one of the most productive areas in the LMRB could be directly impacted by potential hydrological alterations by dams. However, these results should be interpreted with caution for various reasons. First, the study does not account for the physical barriers that the future dams will impose on the migratory species as this information is not available. Second, the study does not account for changes in habitat and actual fish population losses because this is a multifaceted process which falls outside the scope and capacity of our modeling framework. Third and last, potential fish catch variations do not account for the response of different species (i.e., migratory, non-migratory), to the hydrological variations of the Mekong River. Undoubtedly, these potential changes in fish catch would be devastating to livelihoods in the surrounding LMRB communities. It is known that this is starting to occur, and a major dietary shift has already been taking place in the LMRB countries (Orr et al., 2012b; Pittock et al., 2017).

4.3. Land use and land cover change

Next, we examine a 24-year LULC change in the LMRB in an effort to relate these changes to observed dietary shift in the region. Fig. 4 depicts historical transitions in LULC categories in the LMRB. Results indicate a two percent increase in cropland as well as mosaic tree and shrub/herbaceous cover between 1992 and 2015 (Fig. 4). The majority of the increase in cropland areas and other land use types comes from a drop in tree cover area, which is estimated at 4% in 24 years. To put that into perspective, a one percent change in land use is equivalent to 60,600 km^2, meaning that a total of 242,400 km^2 of tree cover was lost in the past two decades. The majority of the region's cropland is used to grow crops such as maize and soy, and literature suggests these crops are used primarily for livestock feed. In the United States, for example, 87% of maize yields are evenly split between animal feed and ethanol production, leaving only 13% for human consumption (Ranum et al., 2014). An FAO report estimated that at least 50% of grain production globally is fed to livestock (FAO, 2004). Regarding land use, this translates to 75% of all agricultural land, including crop and pasture, being dedicated to animal production (Foley et al., 2011). That is, of the ~121,200 km^2 of cropland added in the past 2.5 decades (Fig. 4), ~90,900 km^2 is indirectly caused by increases in meat production.

As fish consumption per capita declines in the LMRB countries, the loss of protein is expected to be replaced eventually by land-based animal protein. Local production of meat in the LMRB countries continues to rise (Fig. S5), requiring more feed and grazing land for livestock. To understand how dietary habits are changing over time in the LMRB countries, we next discuss the dynamics of meat exports and imports in terms of water use (i.e., virtual water).

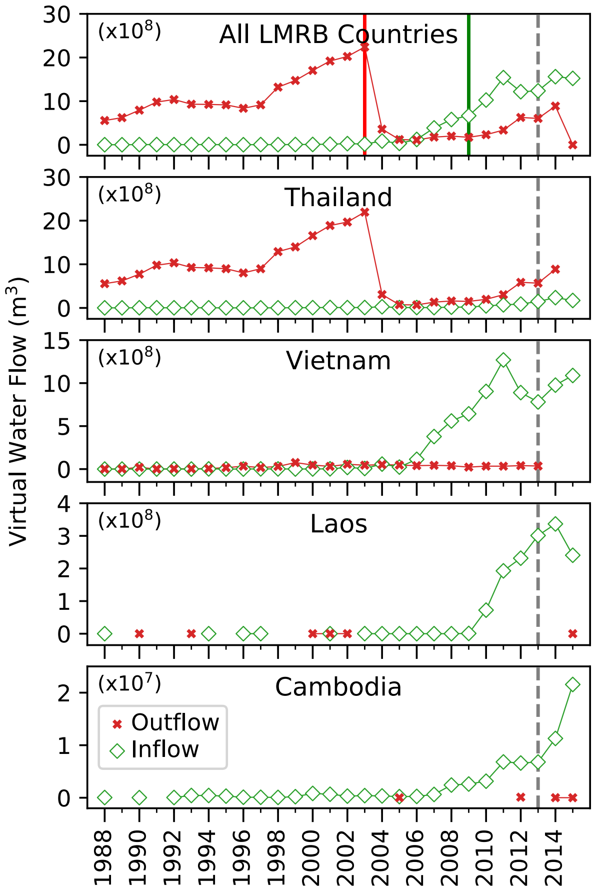

Fig. 5. Virtual water flows of meat products between the LMRB countries and the ROW between 1988 and 2016. Data shown are derived from VWT calculations, VWC data is retrieved from Chapagain and Hoekstra (2003), and trade data is retrieved from the FAOSTAT detailed trade matrices.

4.4. Virtual water flows

Fig. 5 summarizes VWF of meat products including cattle, pig, sheep, goat, chicken, and horse. The VWF of the LMRB countries during 1988–2005 period was largely dominated by trade fluctuations in Thailand. Thailand produces more meat products than it consumes (Fig. S5), thus the gap between production and consumption is equal to the quantity of meat products exported (i.e., virtual water outflow). The same is true for the three smaller economies, except that in their case, consumption grows at a higher rate than production, meaning that these nations import a significant amount of virtual water in the form of meat.

The statistically calculated changepoint corresponding to VWF exports falls in year 2003. This is the same year that the poultry industry in Thailand was affected by the Highly Pathogenic Asian Avian Influenza (HPAI) outbreak, resulting in plummeting chicken production and trade (NaRanong, 2007). This serves as an independent confirmation for the validity of the observational trade data as well as the methodology used for VWF calculations. The second calculated changepoint corresponds to inflow, and it falls in year 2009, which is in line with spikes observed in meat consumption in Vietnam and Cambodia (Fig. S5). A rise in the flow of virtual water into Laos for this same year can be observed, however, this is not in congruence with the reported production and consumption of meat products, where an equivalent production and consumption fluctuation is observed. An expected near-zero inflow of virtual water to Thailand can be from 1988 to 2013 (Fig. 5). Presumably, some of the meat products imported to Thailand are not part of their main production commodities.

The year 2014 shows a recuperation in Thailand's virtual water outflow combined with a drop in virtual water inflow, meaning that local production is picking after the HPAI outbreak and the country is able to sustain the local and global demand for meat products. The virtual water outflow of Thailand stands out the most, as it follows a strong increase in meat exports until 2003 when it drops dramatically, only recovering a decade later (i.e., in 2013). While this drop is consistent with the decline in production, results (Fig. S5) indicate a recovery in three years (2004–2006). The VWF however, shows a 10-year recovery period (Fig. 5), which is because chicken was the most affected, yet is also the main export product, and also one of the most water intensive meat products (Costales, 2004). As previously mentioned, the literature points to the HPAI outbreak as the main cause for the drop in VWF (outflow from chicken). However, there are limited studies on why the recovery process took ten years. We identified three plausible explanations: first, lost business relationships with partnering nations; second, extended contracts being formed between former partner nations and the replacement of suppliers; and third, the inability of the meat industry to overcome the financial burden of losing such massive amounts of products.

In the case of Cambodia, an expected near-zero inflow of virtual water can be seen from 1988 to 2007. From 2007 to 2016 an accelerated rate of meat imports is observed, which coincides with the inflow changepoint of 2008 for the LMRB (Fig. 5). This is the same period (specifically, 2007–2013) during which consumption exceeds production (Fig. S5). Additionally, virtual water outflow results are only available for the years 2005, 2011, 2014, and 2015 (Fig. 5). Thus, 2005 and 2011 are the only years where the production of meat products exceeded consumption (Fig. S5). This, again, acts as an independent validation of the methodology behind the VWT calculations and the trade data retrieved. Similarly, this is the case for Vietnam with near-zero inflow and outflow reported until 2007, when meat consumption increased at a faster rate than production, opening an import gap. The observed rise in meat imports also coincides with the changepoint for virtual water inflow in the LMRB (Fig. 5). The inflow of Vietnam peaks by 2011 and then drops, which coincides with the years when a gap between meat consumption and production decreases in that country. As consumption was slightly higher than production between 1998 and 2006 (Fig. S5), only a small quantity of virtual water inflow can be seen in Fig. 5. Similar to Cambodia, between the years 2007 and 2013, Vietnam consumed more meat than it produced (Fig. S5), and this is precisely the period when the virtual water inflow of meat rises significantly.

Finally, for the outflow of virtual water of Laos, 1990, 1993, 2000, 2001, 2002 and 2015 are the only years with reported exports of meat. Out of all of these instances, none of the datapoints shows a noticeable difference between production and consumption (Fig. S5). The years with reported outflow (Fig. 5), have very small values, so it is likely that the difference between production and consumption is simply not visible. Conversely, inflows were small until 2009, when the export of virtual water tripled. It is important to note, however, that the scale at which Laos experienced this growth is still small relative to that of Thailand and Vietnam. Nonetheless, individually speaking, the VWF and production and consumption behaviors are not in perfect harmony, which points to some reliability issues and limitations of the reported data for Laos.

To further investigate the VWT of meat commodities in the LMRB countries, a VWT network is constructed and presented in the following section. This will highlight the trade dynamics of the LMRB countries with the ROW and provide an in-depth understanding of the effects of a dietary shift in the four nations on the ROW.

4.5. Virtual water trade network

The magnitude and direction of virtual water flows embedded in meat products (e.g., cattle, chicken, pig, sheep, goat, and horse) is

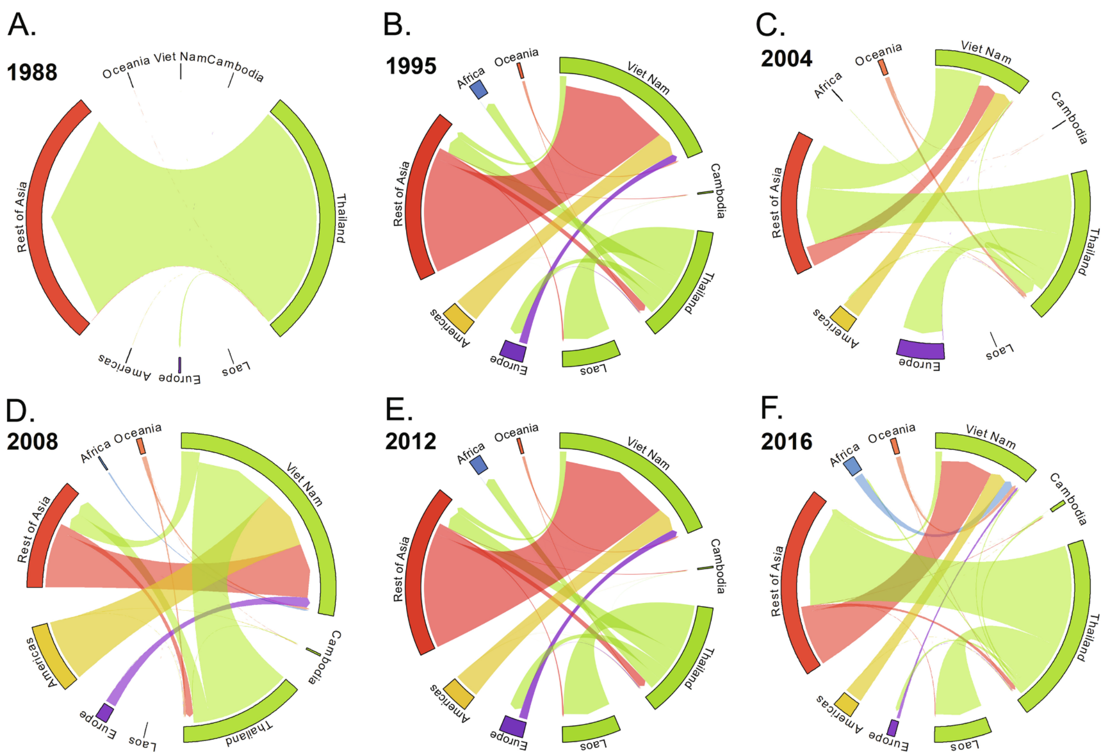

Fig. 6. VWT flows of animal-based protein products (cattle, pig, sheep, goat, chicken, and horse) between 1988 and 2016. The width of each band represents quantity of water in (km^3) traded. The LMRB countries are represented with green bands while the rest of Asia and other continental regions are individually color coded. The circular figure areas are scaled to the total area traded. Data retrieved from Chapagain and Hoekstra (2003) and FAOSTAT detailed trade matrices. This figure was created using the network visualization tool, Circos (Krzywinski et al., 2009). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

presented in Fig. 6 as a VWT circle plot. It is obvious from Fig. 6A that the majority of the virtual water outflow in 1998 came from Thailand (green) and was destined for the rest of Asia (i.e., the remaining Asian countries excluding Thailand, Cambodia, Vietnam, and Laos; red). It is also apparent that none of the other regions traded meat products; however, due to the nature of these plots, the thickness of the arrows represents the magnitude of flow transferred from one region to the other compared to that of the remaining transfer regions. That is, Thailand's exports were so large compared to that of the other regions that the trade among the ROW becomes negligible, thus, very narrow in Fig. 6A. Further, the production and consumption of meat commodities match (e.g., between 1988 and 2003 for Vietnam; Fig. S5), suggesting almost no international trade of these products despite the presence of growth. Fig. 6A, C, F show noticeably large interactions between Thailand and the rest of Asia because, historically, Japan has been the main importer of poultry from Thailand (Costales, 2004). Additionally, this has been mainly attributed to the introduction of evaporative-cooling and to poultry taking over the livestock market share of Thailand in early years (1998–2001) rising from 30% to 53% (Costales, 2004). Moving forward to 1995, Fig. 6B shows a dramatic increase in intercontinental virtual water flows when Vietnam became a large importer from the rest of Asia, the Americas, and Europe. This does not mean that Thailand reduced its exports to Japan, it merely suggests that the other regions with higher export bands became larger virtual water exporters than Thailand. In 2004 (Fig. 6C), Thailand's chicken export declined to such a significant extent that its virtual water export became on par with that of Vietnam. This is a result of the (HPAI) outbreak, which resulted in a ban by most importers of frozen broiler meat from Thailand in 2004 (NaRanong, 2007).

On the flip side, in 2005, following large economic growth, Vietnam displays a boom in meat consumption despite local underproduction of the commodity (Hansen, 2018). This is corroborated by the calculated consumption changepoint in 2005 (Fig. S4). By 2008, Thailand can be seen to be recovering by beginning to export meat products to neighboring nations, where its largest trade partner becomes Vietnam. This explains why Thailand does not show any signs of recovery (Fig. 5) while production levels still rise (Fig. S5). Fig. 6D highlights the growth in meat consumption of Vietnam as it becomes the highest LMRB importer of virtual water. The first noticeable trade interaction for Laos can be seen in 2012 (Fig. 6E) when it becomes Thailand's largest virtual water importer. Thailand also shows signs of economic recovery by branching out its trade to regions such as Africa and Europe. Fig. 6F indicates that Thailand recovered and surpassed its trading capacity to that of 1988 (Fig. 6A). Overall, the LMRB countries show significant changes in trade dynamics during the period studied (1988–2016). More importantly, however, the overall growth and addition of all of the trading partners from 1988 to 2016 tripled the total magnitude of VWT in the LMRB (Table S6). In other words, water demand from a dietary shift towards meat increased three-fold.

5. Conclusions

This paper investigates two overarching topics; the first is an exploration of fish catch dynamics in the LMRB and the second is a construction of a VWT system for meat products in the LMRB countries. The newly devised relationship between fish catch and flooded areas suggests that there is a strong correlation between the two. This relationship is studied by normalizing the catch data by removing population growth from the observable trend to estimate catch per capita and comparing it to flooded area in dry and wet years. Results indicate that if future dams restrict the peak flow in the main stem Mekong by 50%, the effects on flood dynamics could be responsible for ~8% fish catch loss in the TSL region. In a larger Lower Mekong sub-region that includes the Mekong Delta, flow alteration could increase fish catch as a result of increased permanently flooded areas, but such an increase in catch is found to be marginal.

Next, to examine the impact of dietary shifts in the LMRB on land use, LULC types are mapped for four separate years between 1992 and 2016. Results indicate an area of 242,400 km^2 of tree cover loss and a gain in 121,200 km^2 of cropland area in the past two and a half decades. As most of the cropland is used to grow crops for feed, this is one of the measured impacts from the dietary protein shift, which is exacerbated by population and economic growth in the region. The impact of the dietary shift on water resources is further studied by constructing yearly VWT networks from 1988 to 2016. These results indicate that the total VWT of the LMRB tripled from 1988 to 2016 due to a significant increase in number of trade partners (Fig. 6 and Table S6).

There are several limitations of this study. First, the effects of fish catch derived from our model do not take into consideration fish species, population, and habitat, which could all be affected by altered streamflow and flooding patterns; future studies could address this issue. Second, our catch model does not consider migratory fish movement blockage by dams even though the location used to modify the flow is around the uppermost point where fish migration from the Tonlé Sap Lake and Mekong Delta regions generally stop (Cowx et al., 2015; Poulsen et al., 2002). Third, this study uses potential flow alteration scenarios without considering the planned or proposed dams in the LMRB because significant uncertainties remain about the actual size, location, and timing of the planned dams. These issues will be addressed in our future studies that will simulate the effects of individual dams. Fourth, future studies could also consider accounting for uncertainties behind the VWT computations as this is an area that remains understudied. Lastly, the concept of water savings should be explored in this context since it would provide insights on improved water resource management for the production and supply of meat commodities. Future studies should focus on these issues in order to further the discussion and aid policy makers in making the right decisions in the interest of the environment and the economy.

CRediT authorship contribution statement

Mateo Burbano: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization. **Sanghoon Shin:** Validation, Resources, Writing - review & editing, Software, Visualization. **Khanh Nguyen:** Validation, Writing - review & editing. **Yadu Pokhrel:** Conceptualization, Resources, Writing - original draft, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2019.124454.

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