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Hydropower dams, river drought and health effects: A detection and attribution study in the lower Mekong Delta Region

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ABSTRACT

The upstream construction of hydropower dams may drastically intensify climate change impacts due to changing the natural river flood-drought cycle and reducing the amount of water that flows into the lower Mekong Delta river, leading to hydrological and environmental health impacts. However, until now the influence of drought on residents' health in the lower MDR, where river drought is highly sensitive to recently built hydropower plants, has not been examined. The objectives of this study are, for the first time, to detect the health impacts of river drought on residents and to evaluate the contribution of hydropower dams to the impacts of drought on health in the lower Mekong Delta Region (MDR). We applied the multi-step approaches of a Detection and Attribution study. First, we detected the effects of the river drought on the risk of hospitalization using a Multivariable Fractional Polynomials algorithm (MFP). Second, we linked the long-term changes of the river water level (RWL) to the operation of the first hydropower dam in the upper MDR using the interrupted time-series model (ITS). Finally, we quantified the hospitalizations and related economic loss attributed to the river drought. The results show that the percentage changes in risk of all-cause, respiratory, and renal hospitalizations attributed to the river drought were 2%, 2%, and 7%. There were significant reductions in average level and trend of the RWL during the post-1995 period, when the first hydropower dam began operation in the upper MDR, even though the cumulative rainfall in the MDR had not changed. The all-cause hospitalizations attributed to the river drought were 1134 cases during the period 1995–2014, which resulted in total additional cost at two provincial hospitals of US $360,385. This current study demonstrates the link between hydropower dams, river drought, and health impacts. As the MDR is highly vulnerable to climate change, these findings about the devastating impacts of

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hydropower dams and environmental change have important implications for the lives of downstream residents.

1. Introduction

The lower Mekong Delta Region (MDR) is one of the areas most vulnerable to climate change in the Southeast Asia region (Yusuf, 2009). The projected impacts of climate change by 2050 in the MDR include such serious consequences as reduced water availability, increases in extreme temperatures, decreased food production, sea-level rise, and related health effects (Parry et al., 2007; Phung et al., 2016; Talukder et al., 2017). Many residents' capacity to adapt to climate change-related issues is limited due to their low socio-economic status. The incidence of poverty varied from 16 to 28% among country members, and 4 to 29% of the population do not have access to clean water (Mekong River Commission (MRC), 2021). In addition to the impacts of their limited adaptive capacity of the population, the impacts on the population's health may be drastically intensified by the construction of upstream hydropower dams that change the natural river flood-drought cycle and reduce the amount of water that flows into the lower MDR (International Rivers, 2021). Although the impact of hydropower dams on water levels has been recorded along the Laos-Thailand border, the effect on environmental change and related health consequences for residents in the lower MDR is not well understood. Based on our rapid scoping review using the keywords "hydropower*health*Mekong Delta" and Google scholar database (with a cut-off at the first 200 papers), we found that the previous studies mostly focused on the impacts of hydropower dams to the river ecology, food securities, and economical loss, then these evidence were used as the implications to the health impacts of the MDR residents (Ziv et al., 2012; Grumbine and Xu, 2011; Pearse-Smith, 2012; Kuenzer et al., 2013). Nevertheless, none of these studies directly examined the potential effects of hydropower dams related factors to residential health (i.e. using actual health data such as morbidity and mortality).

Hydropower dams cause unnatural river drought and flood-like conditions because they often divert water around entire sections of rivers, making them dry or worse (Richter et al., 2003). Dry river is one of the factors escalating hydrological drought, especially in lower river streams, and results in a wide range of environmental and human health impacts. Previous studies have revealed that drought reduces both quantity and quality of residents' nutritional intake and results in elevated risk of nutrition-related morbidity and mortality (Taye et al., 2010; Scrimshaw, 1987; Orr et al., 2012; Pittock et al., 2017; Golden et al., 2019). For instance, (Golden et al., 2019) estimated that by 2030, relative to 2010, hydropower-related inadequate intakes would result to additional millions of people at risk of nutritional deficiencies in the lower MDR for some essential nutrition such as protein, zinc, niacin, thiamine, riboflavin, and calcium (Golden et al., 2019). Drought leads to poorer water quality due to a higher concentration of chemical and biological

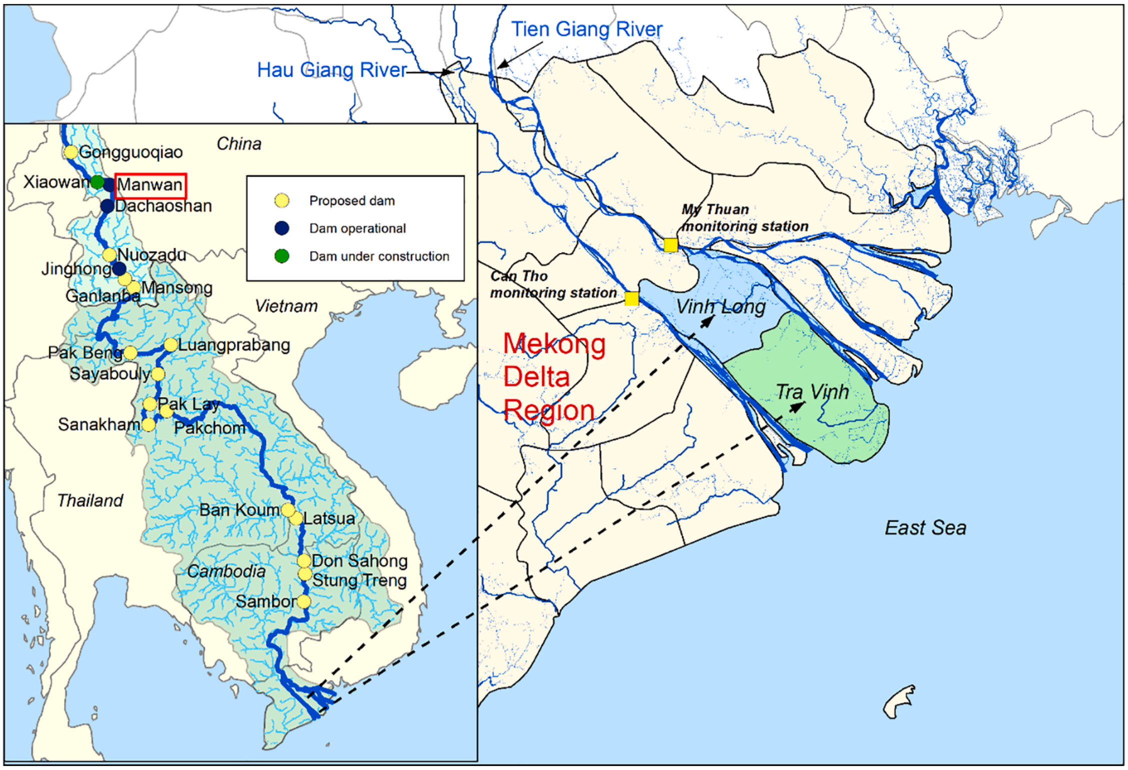

Fig. 1. Locations of hydropower dams in the upper MDR, water monitoring stations (Can Tho & My Thuan), and two research provinces (Vinh Long & Tra Vinh).

contamination (Endale et al., 2011; Kuntz and Murray, 2009), diminished water supply, and consequent poorer hygiene behavior (Burr et al., 1978). These phenomena are associated with increased risk of water-related and vector-borne diseases including diarrhea (Burr et al., 1978); skin, eye, and louse-borne diseases (Thacker et al., 1980); dengue fever; and malaria (Pontes et al., 2000; Gagnon et al., 2002). Air pollution and related health problems such as respiratory and cardiovascular diseases are also associated with drought due to increases in dust events (Kwon et al., 2002). Studies also suggest that mental health issues among farmers can be attributed to drought due to business-related pressures, emotional stress, and financial loss (Stanke et al., 2013). In addition, some other health consequences such as injury, cancer, zoonotic disease, and health effects of heatwaves and wildfire, migration, and damage to the healthcare system and infrastructure are also associated with drought conditions (Stanke et al., 2013). A recent study by Berman et al. (2017) found that the all-cause mortality risk significantly increased (by 1.55% (95%PI: 0.17,2.95) among USA adults during a drought period of high severity (Berman et al., 2017). The risk of drought-related health impacts varies widely by location and depends highly on the severity of drought events, baseline population vulnerability, health and sanitation infrastructure, and mitigative resources (Stanke et al., 2013).

Until now the influence of drought on residents' health in the lower MDR, where river drought is highly sensitive to recently built hydropower plants, has not been examined. The objectives of this study are to detect the health impacts of river drought on residents in the lower MDR, to evaluate the contribution of hydropower dams on the upper MDR to river drought in the lower MDR, and to suggest the geopolitical factors that have shaped these risks and must necessarily be involved in seeking solutions.

2. Material and methods

2.1. Study site

The Mekong Delta Region (MDR) has an area of 39,000 km^2 (ARCBC, 2015) (Supplement 1). The MDR comprises 13 provinces and has a total population of 17.33 million people (GSO, 2012). It has a tropical climate with two main seasons: the dry season (December-April) and the wet season (May-November). The main industries in the MDR are agriculture and fishing, which are considered to be the most productive in Vietnam. As a low-lying coastal region, the MDR is remarkably vulnerable to changes in hydro-meteorological factors such as rising temperatures, sea level rises and floods (Phung et al., 2015). In recent times, increases in both infectious diseases and non-communicable diseases have been a concern of health authorities in the MDR.

Among 13 Vietnamese provinces located in the MDR, Vinh Long Province (VL) and Tra Vinh Province (TV) surrounded and influenced by both Tien River and Hau River, the two lowest end rivers of the MDR, were selected for this study (Fig. 1). VL and TV have a total population of 2,428,000 people. These two provinces have a tropical climate with two main seasons: the dry season (December-April) and the wet season (May-November). Located between two rivers and the low-lying coastal region, VL and TV are especially vulnerable to hydrological changes from the upper part of the MDR.

2.2. Measurement of exposures and covariates

The daily river water level (RWL) was obtained from two hydrological monitoring stations (Can Tho and My Thuan) located on the two rivers (Fig. 1). The timespan of RWL data was from 1978 to 2014. Daily meteorological data were obtained from the provincial hydrometeorological stations for the period of January 2011 – December 2014. The data comprise daily minimum, maximum, and average temperatures (°C), relative humidity (%), and daily cumulative rainfall (mm).

In this study, we extracted precipitation measurements of Mekong River Delta from Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation (APHRODITE) daily gridded precipitation data, a well-known and extensively used dataset with 0.25-degree spatial resolution in regions over Asia. APHRODITE (V1101) was first available for 67 years from 1951 to 2007 and then an extensive version (V1101EX_R1) was released to expand the time range to 2015 (http://aphrodite.st.hirosaki-u.ac.jp/download/). We merged the two versions and extracted complete daily precipitation of the entire Mekong Delta Basin and Vietnamese MDR for our study period from 1978 to 2014. We need rainfall data of the whole Mekong River Delta basin to find out whether potential RWL changes were caused by changes in precipitation or by dam construction. As the Mekong River watershed covers a large area over 6 different countries, point-based rainfall measurements provided by unevenly and sparsely distributed rain gauges cannot meet the needs of hydrologically related research. In contrast, gridded precipitation products have wider spatial coverage and high spatiotemporal resolution. Among them, gauge-based precipitation datasets generally have longer available time-series data covering several decades. There were no missing data observed for both RWL and precipitation.

2.3. Measurement of the health outcome

Daily counts of all-cause hospital admissions excluding external causes and including cardiovascular diseases (I00-199, excluding acute rheumatic fever, I00-102, and chronic rheumatic heart diseases, I05-109), and respiratory diseases (J00-99; excluding lung diseases due to external agents, J60-70), and certain infectious and parasitic diseases (ICD10-Code: A00-B99; excluding infections with a predominantly sexual mode of transmission, A50-64, HIV, B20-24, Helminthiases, B65-83, sequelae of infectious and parasitic diseases, B90-94) were obtained from the hospital records of two provincial (tertiary) hospitals for the period January 2011 – December 2014. Data extracted from the hospital records comprise primary and discharge diagnoses, dates of admission and discharge, age, sex, and address of the individual patients. Patients who were transferred from other areas for admissions and non-residential addresses were excluded from the analysis. This study is one of a bigger research project in climate change and health in the Mekong Delta Region. The project was approved by the ethical committee of Griffith University (GU Ref No: ENV/23/15/HREC) and Health and Environment Management Agency, the leading agency of the health sector responsible for climate change and health in Vietnam (1290/MT-SKCD).

2.4. Statistical analysis

We selected the multi-step approaches of Detection and Attribution (D&A) described by Stone et al. (2013) and Ebi et al. (2017) for our data analysis. First, we detected the effects of the extreme low RWLs (referred to as river drought) on the risk of all-cause and cause-specific hospitalizations. Secondly, we linked the long-term changes of the RWL to the operation of the first hydropower dam in the upper MDR and quantified the hospitalizations and related economic loss attributed to the river drought.

In the first step, we applied the Multivariable Fractional Polynomials algorithm (MFP) proposed by Royton and Altman (1994) and Sauerbrei et al. (2006) using a generalized linear regression with the family of Poisson distributions to model the association between the RWLs and all-cause and cause-specific hospitalizations. The MFP included two-term fractional polynomial functions of the RWLs and temperatures to allow non-linear effects of these two variables, and one-term functions of humidity, rainfall, month, year, day of the week, and province to adjust the potential confounding effects of other weather factors, seasonal and long-term trend, day of week, and province. The MFP algorithm is described below:

$$\ln(Y) = \alpha + \beta_1 RWL^{p1} + \beta_2 RWL^{p2} + \beta_3 T^{p1} + \beta_4 T^{p2} + \beta_5 H + \beta_6 R + \beta_7 Month + \beta_9 DOW + \beta_{10} Province \quad (1)$$

where, RWL is river water level (cm); T is average temperature (°C); H is average humidity (%); R is the cumulative rainfall (mm); DOW is day of the week; and *p1* and *p2* are two power terms which are selected from a predefined set $P = \{-2, -1, -0.5, 0, 0.5, 1, 2, 3\}$ (Pearse-Smith, 2012), so that a set of 36 trend functions, including U-shaped and J-shaped relations, could be accommodated. Backward elimination was combined with an adaptive algorithm that selected the best MFP for the RWL and temperature, the two continuous variables, in turn.

In order to determine the threshold of RWL, which is defined as the RWL associated with the lowest number of hospitalizations, we first plotted the graph of the overall relationship between RWL and hospitalizations predicted from Eq. (1) and then visually checked the possible range of the threshold. In the next step, we iteratively estimated Akaike Information Criteria (AIC) values for the MFP model using 10 cm increments in the RWLs within the identified range of thresholds from visual inspection using the threshold models described in the previously referenced study (Phung et al., 2016). Finally, the risk of hospitalizations attributed to the extreme low RWL, which was defined as the RWL at the 5th percentile, was estimated in comparison with the risk of hospitalization at the identified threshold RWL.

In the second step, we applied the interrupted time-series design to evaluate the temporal change of the RWL in relation to the operation time of the first hydrological power dam in the upper MDR. Among all commissioned hydropower dams, Manwan, which was the first dam to operate, starting in 1995 (Fig. 1), was selected for this analysis since we wanted to evaluate the change of the RWL originally attributed to the first dam but not the accumulated effects from the multiple dams set up eventually. The daily average of the RWL was calculated from the RWLs obtained from two river water monitoring stations, Can Tho and My Thuan (Fig. 1). To model the impact of Manwan operation on the RWL, we used a segmented regression model to quantify the change (the y-intercept) and trend (the slope) of the RWL during the period 1996–2014, after the operation of Manwan, in comparison with that during the period 1978–1995, before the operation of Manwan. The model is described as below:

$$Y = \alpha + \beta_1 Timebefore + \beta_2 ManwanOperation(1995) + \beta_3 Timeafter \quad (2)$$

where, α is constant, β_1 is the estimated change in the daily RWL, which occurs before the period of operation of Manwan (i.e. baseline level). *Timebefore* is an ordinal variable indicating time in days starting from the beginning of the observation period. β_2 is the estimated average change in the daily RWL following the start of operations of Manwan in comparison with the pre-Manwan period. *ManwanOperation* is a categorical variable (0: 1978–1995, 1: 1996–2014). β_3 is the estimated change in the trend of the daily RWL after operation began compared with the trend before operation began. *Timeafter* is an ordinal variable indicating days following the beginning of operation.

Finally, the frequency of the river drought (less than 5th percentile of the RWL used in the first step) was used to quantify the number of additional hospitalizations attributed to the river drought per year. The formula is described as below:

$$\Delta Hospitalizations = Y_b \times AF \times RWL_d \quad (3)$$

where, Δ*Hospitalizations* is additional hospitalizations attributed to extremely low RWLs; Y_a is the baseline daily hospitalizations at the threshold RWL; AF is the daily attributable fraction of the extreme RWL derived from Eq. (1); RWL_d is the number of days of river drought condition (less than 5th percentile of the RWL).

All statistical analyses were performed using Stata version 15 (Stata Corporation, College Station, TX, USA).

3. Results

3.1. Descriptive statistics

The total number of all-cause hospital admissions (with noted exceptions) observed over the period 2011–2014 was 214,334 with daily means of 87 (Sd, 26) in TV province and 83 (Sd, 20) in VL province. There were total admissions of 30,913 cases with a daily mean of 12 (Sd, 5.9) for infectious diseases; 29,734 with a daily mean of 12 (Sd, 6) for respiratory diseases; 37,906 with a daily mean of 15 (Sd, 5.8) for cardiovascular diseases; and 15,969 with a daily mean of 6 (Sd, 6.1 for renal diseases. During the study period, the daily means of the RWL were 115 cm (Sd, 32) at My Thuan station and 127 cm (Sd, 31.4) at Can Tho station. The average daily temperatures were nearly identical for the two provinces (27.1 °C and 27.4 °C), and the same was true for humidity (84.0% and 84.3%) and rainfall (3.8 mm and 3.8 mm). The variation in the RWL (the average of two monitoring stations) and all-cause hospitalizations are visually highly correlated as shown in Fig. 2.

3.2. Detection of health effects of the river drought

Fig. 3 shows the pattern of the association between the RWL and all-cause and cause-specific hospitalizations. The exposure–response curve of the RWL-hospitalizations reveals a U-shaped relationship between the RWL and the risk of hospital admissions due to all causes. The dose–response curves of the association between the RWL and cause-specific hospitalizations also indicate a U-shaped relationship (Fig. 3), of which the lower RWLs were significantly associated with respiratory and renal diseases but inconsistently associated with infectious and cardiovascular diseases. The thresholds of RWL associated with the lowest hospitalizations fell in the range of 90–160 cm. Further examination using the threshold models showed that the threshold RWLs, which have the lowest RWL-associated hospitalizations, were 110 for all-causes, and 90 for infectious diseases, 110 for respiratory diseases, 90 for cardiovascular diseases, and 160 cm for renal diseases. The percentage changes in risk of all-cause, respiratory, and renal hospitalizations attributed to the river drought (the RWL at the 5th percentile: 77.5 cm) compared with the threshold RWL were 2% (RR: 1.02; 95%CI: 1.01–1.03), −1% (RR: 0.99; 95%: 0.98–1), 2% (RR: 1.02; 95%CI: 1.00–1.05), 0% (RR:1.0; 95%CI: 0.99–1), and 7% (RR: 1.17; 95%CI: 1.01–1.13). RR refers to Relative Risk, and CI refers to Confidence Interval. In this study, we did not discuss the effects of floods (extreme high RWLs), which have been previously published and under review elsewhere (Phung et al., 2014).

3.3. Attribution of river drought to the dam

The frequency of lower daily RWL after 1995, when the first hydropower dam (Manwan) began operation, is significantly higher than before 1995; in contrast, the frequency distribution of rainfall in the whole Mekong Delta Basin (MDB) and the Mekong Delta Region (MDR) in Vietnam were very similar (Fig. 4). The results of univariate t-tests indicate that the post-1995 daily RWL (mean: 113.5 cm, Sd: 29.3) was significantly lower than the prior-1995 daily RWL (mean: 134 cm, sd: 25.2) ($p < 0.01$). On the contrary, the monthly and yearly cumulative rainfalls for the entire MDB did not differ between the two time periods (monthly mean: 107.2 mm vs.

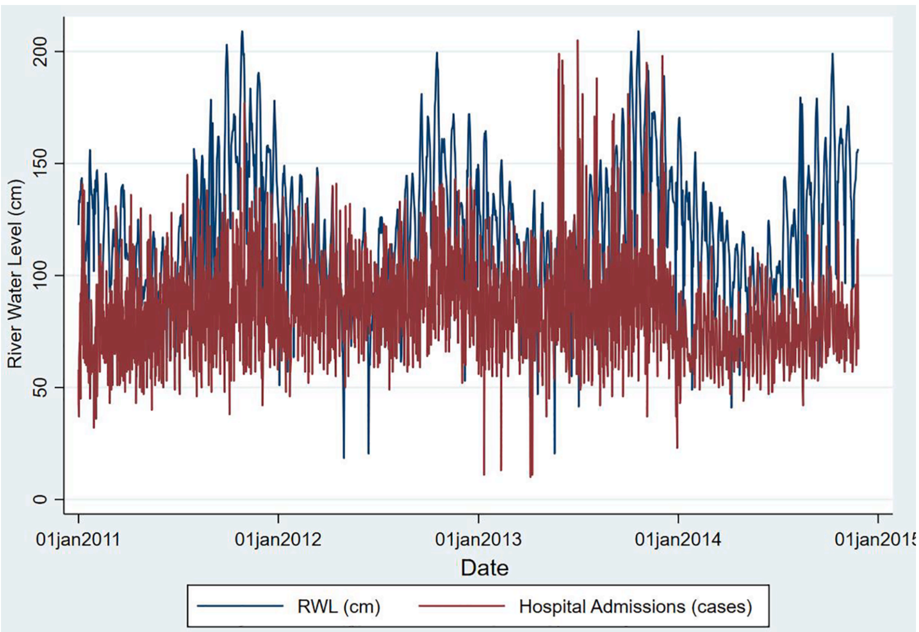

Fig. 2. Daily river water levels and all-cause hospitalizations.

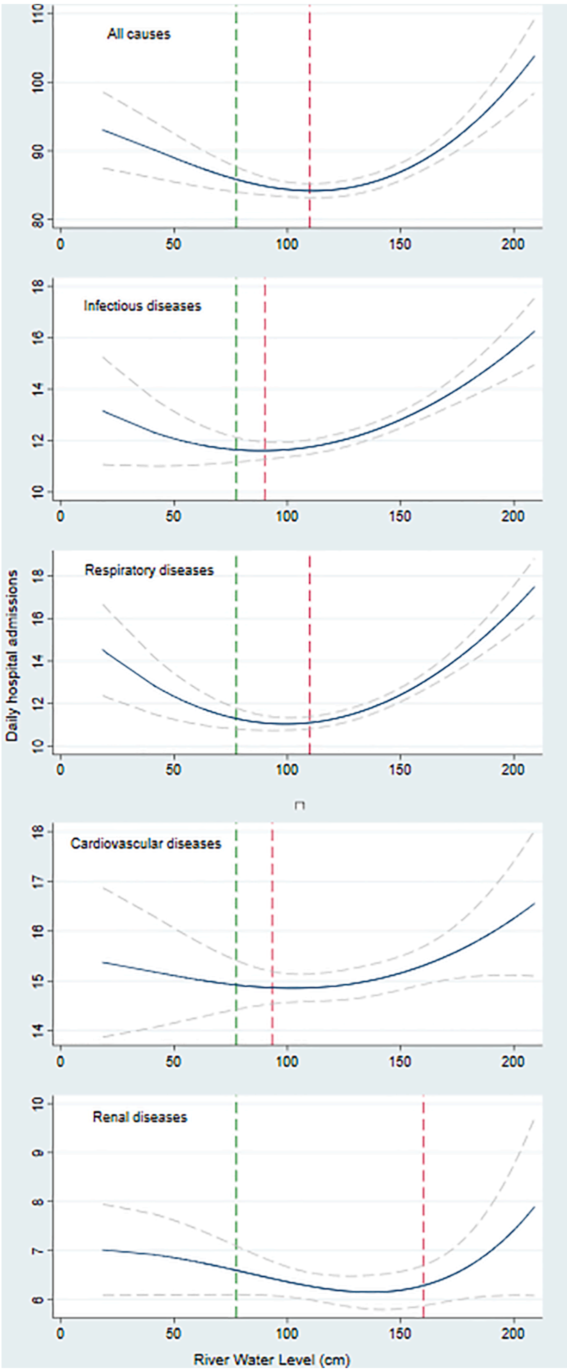

Fig. 3. The overall effect of RWL on hospitalizations modelled using the MFP algorithm (changes in hospital admissions associated with changes in river water level). The grey dash lines are 95%CI. The blue line is the number of daily hospital admissions and the dashed line is the 95% Confidence Interval. The vertical red dash lines are threshold RWL and the vertical green dash line is the RWL at 5th percentile. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

103.9 mm, $p = 0.7$; yearly mean: 1286 mm vs. 1247 mm, $p = 0.2$).

It is noteworthy that these cumulative rainfalls in the Vietnam MDR following 1995 were marginally but significantly higher than before 1995 (monthly mean: 135.3 mm vs. 119.5 mm, $p = 0.09$; yearly mean: 1623.4 mm vs. 1433.8 mm, $p < 0.01$). The results of interrupted time-series regression revealed significant reductions in both average level and trend of the RWL in dry and wet seasons during the post-1995 period compared with the prior-1995 period (Dry season: trend prior-1995, coef. 0.002 cm/day, $p < 0.01$; change in level: −37.8 cm, $p < 0.01$; trend post-1995: −0.00005 cm/day, $p = 0.9$. Wet season: trend prior-1995, coef. 0.0005 cm/day, p <

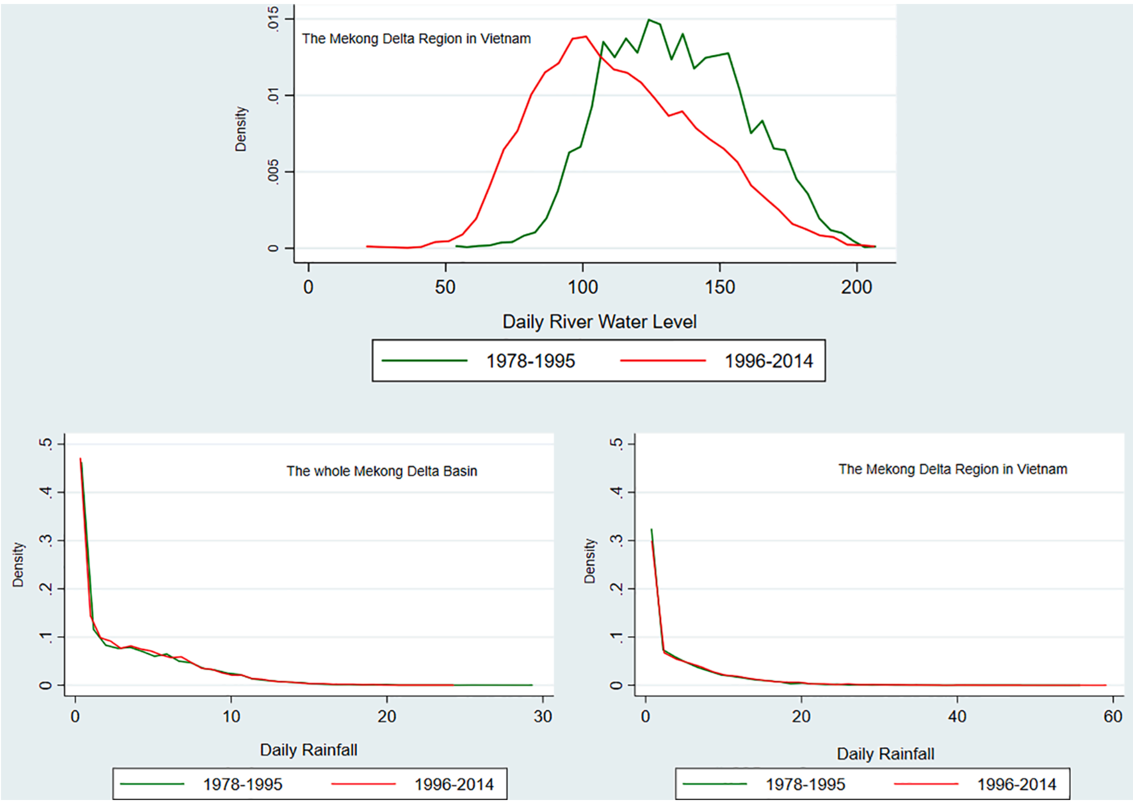

Fig. 4. The river water level pre- and post-operation of the first hydropower dam (1995) in the upper MDR (A). The cumulative rainfall pre- and post-operation of the first hydropower dam (1995) in the whole Mekong Delta Basin and in the lower MDR (B&C).

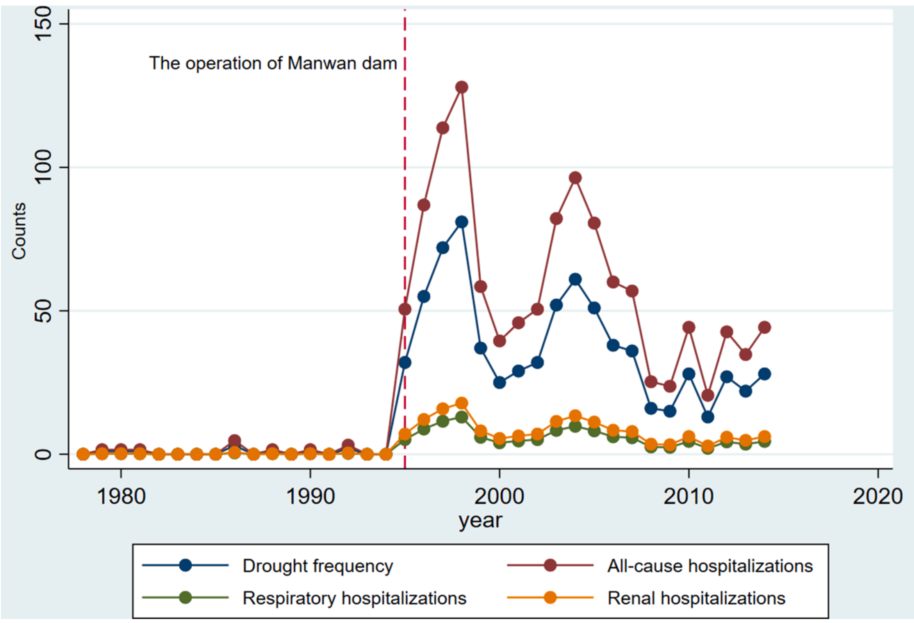

Fig. 5. Frequencies of river drought (blue line) and attributed hospitalizations in the two tertiary hospitals for all causes, respiratory, and renal diseases (brown, green, and yellow lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

0.01; change in level: −15.7 cm, $p < 0.01$; trend post-1995: −0.0007 cm/day, $p = 0.01$).

The yearly frequency of days with RWL ≤ 77.5 (the 5th percentile) rose remarkably in the year 1995 (range: 13–81 days; mean: 38 days, Sd: 19.3), but then trended downward from 1995 to 2014 (Fig. 5). Additional hospitalizations due to all causes, respiratory, and renal diseases attributed to the river drought are also shown in Fig. 5. Hospitalizations attributed to the river drought were 1134 for all causes, 115 for respiratory diseases, and 158 cases for renal diseases during the period 1995–2014. Assuming that the average number of days hospitalized for all diseases was 7 days and the average hospital cost at a tertiary hospital in Vietnam was US $45.4 per day for the period 2000 – 2005, as estimated by WHO (2010); the total additional cost paid for the RWL-drought-related hospitalizations at the two tertiary hospitals in this study would be US $360,385 with a yearly average of USD $19,620.

4. Discussion

This is the first study of the health effects of river drought in the lower Mekong Delta Region attributed to the operation of hydropower dams operating in the upper MDR. The study detected a significant association between river drought and the increased risk of hospitalizations due to all causes, respiratory, and renal diseases among lower MDR residents. It demonstrated that the extremely low RWLs in the lower MDR were attributable to the operation of the hydropower dam in the upper MDR. Finally, the additional hospitalizations and the related economic burden attributed to the river drought caused by hydropower operations were quantitatively measured.

Drought can be categorized as meteorological, agricultural, socioeconomic, or hydrological, based on the methods of measurement (NDMC, 2012; NOAA, 2004). Hydrological drought is associated with shortfalls in either precipitation or surface water supply (i.e. streamflow, reservoir, and groundwater), and it is often measured by watershed or river basin scale. Thus, extremely low RWL can be used as an alternative measurement of hydrological drought or river drought. Previous studies have demonstrated that drought is associated with increased morbidity and mortality due to multiple causes. Nutrition-related illnesses and mortality are well recognized as demonstrating the health impact of drought (Taye et al., 2010; Scrimshaw, 1987). High incidences of mortality and prevalence of malnutrition and morbidities such as diarrhea, respiratory diseases, and other infectious diseases have been observed in times of drought (Mason et al., 2010; Chotard et al., 2010; Control, C.f.D. and Prevention, 2000; Assefa et al., 2001; Black et al., 2008). The mechanisms of drought's effect on nutrition-related illnesses are often indirect and complex. It is believed that drought influences ecosystems, leading to a reduction in food supplies. As a result, the reduction in quantity and quality of nutrition intakes causes increases in the risk of illnesses and mortality (Stanke et al., 2013). Although the evidence is still scarce, some water-related diseases have also been observed in association with drought. Previous studies have provided evidence on the association between drought and outbreaks of cholera (Tauxe et al., 1988; Bradley et al., 1996), E Coli infection (Effler et al., 2001), and leptospirosis (Jackson et al., 1993). Infectious skin diseases such as scabies and impetigo as well as eye infections are likely associated with drought-related conditions (Thacker et al., 1980). Plausible mechanisms of the drought- or water-related disease associations are increased risk of water contamination by animal and human feces or urine (Shehane et al., 2005), with a lack of personal hygiene due to shortage of water (Burr et al., 1978; Thacker et al., 1980). Vector-borne diseases including dengue and malaria have also been associated with drought conditions due to a shortage of public water supplies. For instance, an outbreak of dengue in Brazil in 1994 was found to relate to a lack of public water supplies due to prolonged drought; the abundance of mosquitoes was attributed to the storage of water in an elevated number of uncovered household vessels and with interrupted government dengue suppression activities (Pontes et al., 2000). The increased risk of hospital respiratory admissions found in this study supported the evidence observed in previous studies. A study by Gomez et al. (1992) reported a significant increase in self-reported respiratory problems such as coughing and wheezing, during a Canadian drought in 1987–1989 (Gomez et al., 1992). An observation using data from routine health surveillance systems conducted by Pappagianis (1994) showed a significant rise in cases of clinical Coccidioidomycosis (Valley fever) after a drought followed by heavy rains in California 1991–1992 (Pappagianis, 1991). A plausible explanation for this phenomenon is the widespread increase of dust during the dry season; the health effects of drought-related dust are similar to those of dust in general (De Longueville et al., 2013). Increased mental health problems have been found, especially among farmers during drought periods. Drought has been associated with stress (Stain et al., 2008; Stehlik et al., 2000), increased alcohol consumption (Alston and Kent, 2004; Hossain et al., 2008), and anxiety due to various experiences of business-related pressures and loss as a consequence of drought (Rigby et al., 2011; Polain et al., 2011). For example, a study by Edwards et al (Edwards et al., 2008) reported a doubling of the rate of mental health problems among Australian farmers during drought compared with non-drought seasons (Edwards et al., 2008). Another study by Cielho et al (2004) revealed significantly higher levels of state-and-trait anxiety among residents in drought-affected communities than in drought-free communities in north-eastern Brazil (Coêlho et al., 2004).

Multiple-cause hospitalizations and mortality have been seen in industrialized as well as developing countries. A recent study conducted by Berman et al. (2017) in parts of the western USA found a significant increase (1.55%) in mortality during periods of high-severity drought. However, the respiratory admissions were significantly decreased (by approximately 2%), and cardiovascular admissions did not differ during drought compared with non-drought periods (Berman et al., 2017). This may be explained by assuming that people were unable to work in the fields and didn't suffer as many occupational health problems.

In this study, we found a significant decrease in river water levels in the lower section of the Mekong Delta Region following the year 1995 when the first Chinese hydropower dam began operation. As a result, the frequency of extreme low river water levels, rarely seen before 1995, has risen remarkably during the post-hydropower period. This finding is supported by evidence from recently published reports. A study by Basist & William (2020) found that the lowest river level ever measured in the lower MDR in 2019 was significantly influenced by the restriction of water flowing from the upper MDR during the operation of the hydropower dams (Basist and Williams, 2020). This evidence was corroborated by a 2020 report by Brian et al. (E, B., R. K, and C. W, 2020). The summary of that report stated: "*New data shows that during a severe drought in the lower Mekong Basin in 2019, China's upper basin enjoyed high rainfall and snowmelt and China's upstream dams restricted nearly all of the record rainfall and snowmelt from the downstream. If China's dams did not restrict flow, portions of the Mekong along the Thai-Lao border would have experienced above average flows from April 2019 to the present instead of suffering through severe drought conditions*". Beyond the MDR, a number of studies have reported the effects of hydropower dams on the depletion of river water around the world (Anderson et al., 2006; Robson, 2013; Habit et al., 2007) (Jesus et al., 2004). For example, a study by Robson et al (2013) in the River Tay Catchment, Scotland, found that flows were depleted by 36% of total flow following the opening of a 0.68–3.0 MW installed-capacity hydropower dam. Studies by Anderson et al (2007) in Puerto Viejo River, Costa Rica, and by Habit et al (2006) on the Rucue River, Chile, reported flow reduction in depleted stretches up to 90% as the consequence of a hydropower operation. Our study indicated that hydropower dams cause a significant reduction in the flow and discharge of water in the lower river section. Previous studies have focused on the impacts on physical habitat and ecological systems, but none of them have investigated the effects on human health. It is noteworthy that our study detected a significantly elevated risk of hospitalizations associated with extremely low RWLs in the lower MDR, which have been attributed to the installation and operation of hydropower dams in the upper MDR. This health impact is likely to become much more severe because ten more dams have been commissioned in the upper MDR during the period 2002–2012, and nearly 100 dams have been proposed and planned around the Mekong Delta Basin (Basist and Williams, 2020; WLE, 2020). We found that the worst effect was observed a few years after the first dam commission, then the effects were fluctuated and attenuated in the following years (Fig. 5). This might be explained by the potential adjustment in the dams' operations because a lots of multi-country dialogues between the lower MDR countries and China toward the reduction in the water flow to the lower MDR had been implemented.

How the hydropower dams influence the river water level is explained in the following description. A hydropower station established at an upper river location, which is called Run of River hydropower (ROR), operates by the flow within a river channel without water storage. Channel obstructions (typically weirs) control water levels, allowing a proportion of flow to be diverted down a secondary channel to a turbine before it is recharged to the main channel further downstream. The diversion of flow through a hydropower scheme generates a stretch of river (from the point of abstraction to return) that is depleted of water while the scheme is operating (Anderson et al., 2015). In our study, why the threshold of RWLs for different diseases are different and their relation to the elevated risk of the diseases is still be an open question for further study. Based on our own literature review, there was so far no study looking at the thresholds of river drought associated with the specific diseases. The RWL-disease related thresholds maybe explained by the different plausible mechanisms of drought-disease relationships (discussed above). Another reason is that drought is not only exposure escalating the disease incidences but a whole change of risk factors (e.g. household socioeconomic, unemployment, etc.) are also responsible for (Stanke et al., 2013).

This study has some limitations. First, the health outcome used for detecting the effect of the river drought was hospitalizations at tertiary-level hospitals, where the most severe cases were admitted. Relevant cases with minor signs and symptoms for which patients might have been admitted to lower-level facilities (i.e. district and commune health clinics) and then recovered were not taken into account. Second, the availability of hospital admission records was for a time span of only four years, so we were unable to evaluate the long-term effects of the river drought. We recommend the establishment of a surveillance system to monitor cause-specific morbidities that are significantly associated with river drought (respiratory and renal diseases) in relation to the long-term changes in the river water level in the future. For river drought indicators, we were restricted to using the river water level as the representative exposure factor of the river drought. We were unable to collect data on other indicators of drought conditions such as shortage of water supplies that might play a direct role in influencing residents' health. A future study should involve other indicators of drought (i.e., meteorological, social, and agricultural) for greater comprehensiveness. Third, lacking hospitalization data for the period of January 2011 to December 2014 made the study limited to examine the accumulated effects of the dams commissioned later. An updated study should be conducted for this purpose once the data is sufficient enough. Finally, the health-related economic burden attributed to the hydropower-related river drought was quantified based on the assumption of a 7-day average of hospitalization costs but without data on the actual costs of individual patients. We recommend that a study in the future should enhance the evidence by involving individual factors (i.e., sociodemographic, economic, and co-morbidities such as chronic conditions) while examining the residents' health effects and related economic burden.

5. Conclusion

The results of this study reveal a significant association between river drought and the increased risk of hospitalizations among residents living along the lowest river sections of the Mekong Delta Region. The study also indicates that the elevated frequency of river drought is attributable to the operation of the first Chinese hydropower dam in the upper MDR. These findings demonstrate the link between hydropower dams, river drought, and serious residential health impacts. As the MDR is highly vulnerable to climate change, especially increased temperatures and salinity induced by sea-level rise, these findings about the devastating impacts of hydropower dams and environmental change have important implications for the lives of downstream residents. Reduction or cessation of the operations of established dams and a halt to the construction of new dams, along with programs for public health adaptation and intervention (e.g. improving health systems, raising community awareness, developing early warning systems) should be implemented to protect residents in the lower MDR.

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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