The effects of dam removal on sea level and the Mekong River region as a proxy for climate sensitive communities

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Abstract: Little research has been done on the short and long term effects of dam removal on local and global sea level. Local communities neighboring dams, specifically in areas that are already vulnerable to the risks of sea level rise, need a better understanding of how dam removal will impact them before considering the removal process. As the longest river in Southeast Asia, the Mekong provides water and food to millions of people before draining into the South China Sea. With 11 main hydroelectric dams along the course of the river, the distribution of energy, water, and fish vary for neighboring communities. Fisheries are notably affected as dams obstruct passageways as well as reduce necessary inland flood areas crucial for species reproduction. Recently, in Vietnam and other developing countries, dam collapses have become more common given inadequate planning and preparation for disasters, prompting consideration of dam removal in these areas. Additionally, the communities surrounding the drainage area of the Mekong River are notably at risk for rising sea levels due to climate change (Clark et al., 2016). To better assess the consequences of dam removal along the coast of Southeast Asia, we use the unique spatial patterns of sea level change associated with reservoir impoundment and removal to project local sea level changes under two different dam removal scenarios. These projections are then analyzed in relation to local demographics of the affected areas. While changes in water impoundment will not have a significant impact on global sea level projections when compared to other components of sea level rise, including thermal expansion and glacial melt, our findings yield noticeable changes in local sea level, including sea level falls near megacities such as Bangkok and Ho Chi Minh City. Southeast Asia is highly vulnerable to sea level related damages and relocations; the removal of dams will result in less severe coastal flood levels and support continuous availability of fish to dependent regions along the river, potentially supporting dam removal initiatives in this area and other climate-sensitive regions.

Introduction:

In light of the most recent reports regarding the status of global climate change, it has become increasingly clear in recent years that changes to our environment have far-reaching effects. Additionally, certain countries and cities are more vulnerable than others to impacts such as sea level rise, the displacement of people, and the undermining of food security (IPCC, 2018). Oceanic thermal expansion and glacial melting together account for 75% of the observed sea level rise since the start of the 20th century (Church et al., 2018). For 1.5 ℃ of average global temperature rise, climate models predict an average range of 0.26 to 0.77 meters of global sea level rise by 2100 (IPCC, 2018). The continued instability of the marine ice sheets in Antarctica and the irreversible loss of the Greenland ice sheet could potentially lead to a multi-meter rise in global sea level, leaving small island nations, low-lying coastal cities, and delta regions at extremely high risk. However, only 70% of global coastlines are projected to experience a relative sea level change within 20% of global mean level change (Church et al., 2018). This unequal distribution of global sea level puts low-lying coastal cities, particularly those near river deltas at risk for more than average sea level rise, negatively affecting the land-use and livelihoods of large populations.

Built in direct proximity to a river delta on a low-lying coast lies the overpopulated and developing cities and communities of the Mekong Delta region. This region is an ideal case study for the impacts of sea level rise and related societal implications given its geography and largely underdeveloped population. For example, Ho Chi Minh City, having a population of just over 8.6 million (2019), lies on the southern coastal region of Vietnam with an average elevation of just 0.5-1 meter above sea level (Vietnam Climate Adaptation Partnership, 2019). This city and other cities in proximity to the Mekong Delta in Vietnam and Thailand face numerous risks stemming from rising sea level, increased ocean and river flooding, and declining food and water resources.

High sensitivity demands potential solutions to counteract rise in sea level in this region. One of these solutions involves the proper use of infrastructure, such as dams, to aid in the promotion of sustainable development from hydropower and the management of river flooding. The Mekong River, the longest river in Southeast Asia, has until recent years remained mostly undammed, providing the potential for hydropower in wealthy Southeast Asian countries such as Vietnam, Thailand, and China (Grumbine, 2011). In 2011 and 2012, Vietnam contributed more to the increase in hydroelectricity production than any other country except China, and hydropower accounted for 40% of the country's total electricity with the production of 56.94 TWh in 2013. In the same year, Vietnam's total commercial power production was 115 billion kWh (Pham Huu, 2015). Looking forward, Vietnam plans to continue to exploit this hydropower potential with 179 small projects currently under construction throughout the country. Aiming to accomplish hydropower goals by 2030, the country's electricity development plan intends to increase hydropower production from 9,200 MW in 2010 to 17,400 MW by 2020 (Pham Huu, 2015). The promotion of socio-economic sustainable development and the insurance of electricity to Vietnam's 95.5 million people are just two of the many motivations behind the planning and construction of dams for hydroelectric power. However, dam collapses, the displacement of people, and unknown ecological effects during this period of global climate crisis put into question the future construction of dams as being a responsible use of land and infrastructure. Additionally, the reconsideration of the construction of new dams as well as the prompt decommissioning of pre-existing dams over the coming decades could provide opportunities to counteract sea level rise and reduce negative impacts to rivers, flood plains, and local fisheries.

Despite high demand for hydropower, dams have been removed at an increasing rate over the past 40 years (Foley et al., 2017). Examining past research on dam removal reveals that most studies focus primarily on the removal's effect on river and species restoration; however, the removal of dams, particularly large dams, that have happened thus far have provided insight into other consequences removal may have. Many previous studies have focused on important criteria for evaluating dams in preparation for removal, including dam size, operations, level of damage, and public safety (Poff et al. 2012). The National Inventory of Dams for the United States has documented more than 84,000 large dams on the nation's rivers and streams, many of which are situated close to the coastline. The average age of these dams, before being considered for the decommissioning process, is between 50 and 100 years (Langseth et al., 2016). Similarly, out of India's 5,000 plus dams, 500 are over 50 years old and 100 are over 100 years old (Agoramoorthy, 2015). Deciding whether to remove aging dams and how to do so with minimal adverse impacts however, is difficult. A gap remains in research that is able to address the complexities of interactions between ecological and political systems that culminate at the consideration and process of these removals (Bellmore et al., 2017). One little-discussed consideration for the removal of dams is dam removal's potential ability to counteract rising sea levels.

Globally, sea level rise is not uniform, but varies spatially based on a number of both global and local factors. This spatial differentiation in sea level rise can be attributed to local climate variations, wind patterns, and geodynamic factors (Fiedler et al., 2010). Research performed by Chao et al. (2008) suggests that ~10,800km^3 of water has been impounded by dams since 1900, leading to an equivalent sea level fall of ~30mm. The load from impounded water depresses the earth's surface near dams and elevates the geoid, resulting in a locally increased relative sea level (RSL). This dam-induced spatial variability in sea level is theorized to have played a part in masking the sea level "fingerprint" of sources of glacial unloading, such as the Greenland ice sheet; furthermore, the fingerprint of dam impoundment can become more exaggerated on a local scale along coastlines near the largest dams (Fielder et al., 2010).

To best determine the impact of water impoundment on global sea level rise (GSL), past studies have begun by ranking the world's reservoirs constructed since ~1900 by volume, followed by the formulation of a standardized calculation to determine a specific magnitude for the amount of water impounded by each dam (Chao et al, 2008). This research has further been improved by the inclusion of spatial mapping, which allows for local changes in sea level over time to be estimated as dams are constructed around the world (Fielder et al., 2010; Hawley et al., 2019). Past research of water impoundment and its resulting impact on the spatial variability of sea level could then, for the purposes of our research, be applied in the reverse. As dams are taken out of commission, our research aims to determine the resulting sea level change proximate to large dams along the Mekong River region in Vietnam and Thailand.

Following our investigation of dam removal's impact on sea level rise in the region, we expand our research to other implications of large dams in the region as additional considerations and support for their removal. Specifically, large infrastructure poses a threat to the Mekong region's freshwater fisheries. The economies and populations of Vietnam and Thailand depend heavily on the success of its freshwater fisheries. With over 60 million residents of the Mekong River Basin relying on consistent catches, the progression of dam construction may potentially alter reproductive and migratory habits of local species, lowering the nation's annual 9.4 billion dollar revenue (Dugan, 2008).

This study explores the removal of dams in the Mekong River delta region and removal's implications for local sea level and, more broadly, the food security of the local population. By projecting sea level changes due to water impoundment in the future, we assess how the removal of different dams in the area will affect sea level years into the future. Using the respective sizes and locations of dams in Vietnam and Thailand in proximity to the Mekong Delta, we postulate scenarios for the removal of individual dams. By projecting the local sea level change due to different dam removal scenarios, we witness changes in local sea level into the future. Comparing the measurements under two various dam removal scenarios to a control scenario where no dams are removed allows us to evaluate how the removal of existing dams could alter local sea level. We expanded our research to dam's impacts of the populations of the Mekong region, focusing specifically on fisheries, food security, and the internal displacement of people.

Methods:

Data Acquisition

The core datasets we will be using to guide our research into the impacts of dam removal on global sea level come from Hawley et al. (2019). The data contains basic information surrounding reservoirs including year built, total water impounded, surface area, and geographical coordinates for each dam through the Global Reservoir and Dam database

(GRanD). The GRanD database was constructed in an effort to supplement dam data from the International Commission on Large Dams (ICOLD) with georeferences (Lehner et al., 2011).

Table 1: Data as it appears in *reservoirs.txt* file. Numbers are provided as references for the variables described above.

	Variable Name	Description
1	Res. No	Corresponding volumetric rank of each dam
2	Vol	Total water impounded measured in 10^6 m^3
3	Year	Year of dam construction
4	Lon/Lat	Latitude and longitude of the dam in decimal degrees
5	Cumulative vol	Total water impoundment of corresponding dam and all preceding larger dams (10^6 $m^{3)}$
6	Cumulative vol fraction	The cumulative fraction of corresponding dam and all global water impoundment

As laid out in Table 1, the variables that are relevant in our research include reservoir number (i.e., volumetric rank), total water impoundment, year of construction, geographic coordinates, the cumulative volume of the corresponding dam and all larger dams, and the fraction of global total water impoundment that the cumulative volume represents. This dataset and the provided georeferences allow us to easily visualize the global picture of water impoundment (Fig. 1).

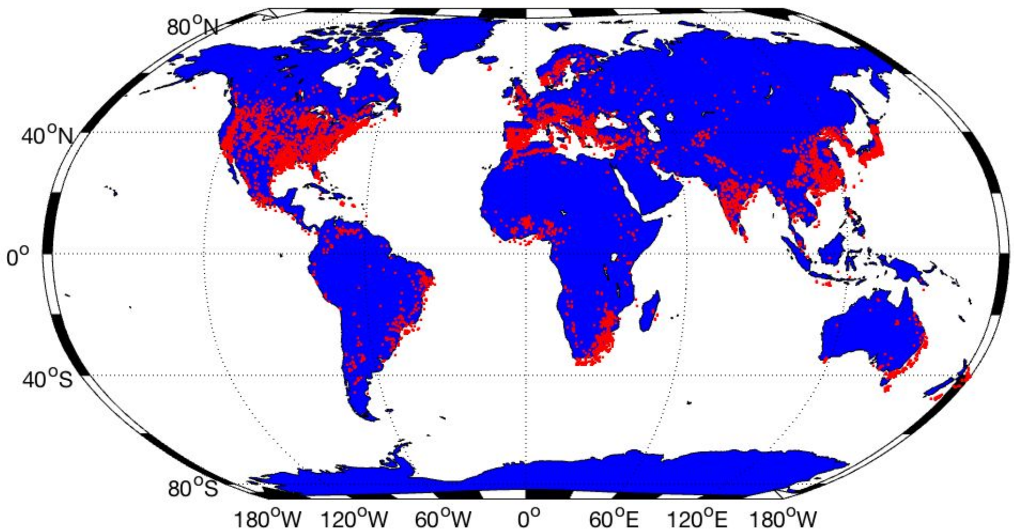

Figure 1: Location of every reservoir in the database.

We will also be using numerous sea level fingerprints associated with impounding the world's largest 930 reservoirs. Sea level fingerprints for every reservoir are represented in 513 x 1025 grids measured in mm. Each value represents the local sea level change due to the impoundment of the pertinent reservoir. This value is conceptualized as the amount of sea level change (in mm) attributable to water impounded (in 10^6 m^3) at that point. To get the total sea level fingerprint due to impoundment, we scale the normalized fingerprint by total volume. After impoundment, sea level falls in areas of the world that are not near a reservoir. Sea level rises in areas proximal to a reservoir.

Control Scenario

We construct three scenarios to evaluate contribution of impoundment to local sea level in the Mekong Delta region. In the control scenario, the world's 930 largest reservoirs are used to estimate water impoundment fingerprints into the year 2100 if no dams are decommissioned or built in the Mekong Delta region or globally. The impact of global water impoundment on sea level in any given year, y, is calculated in equation 1 (Chao et al., 2008):

Equation 1: $$SL_y = \Sigma_1^{930} V_{Dam(i)}[1 + \Sigma^y_{t(i)}(0.05(y - t_i)^{-½})]F_{Dam(i)}$$

where *SL* is water impoundment's contribution to sea level, $V_{Dam(i)}$ is volume of impoundment *i* (10^6 m^3), *y* is the year of interest, t_i is the operational date of impoundment *i* in years, and $F_{Dam(i)}$ is the normalized sea level fingerprint of *Dam(i)*.

The contribution of global water impoundment to sea level in a certain year is a function of each dam's volumetric storage, sea level fingerprint, and operational date. Multiplying the volumetric storage of each dam by its associated sea level fingerprint field returns a new field, representing that dam's contribution to global sea level (in mm). The seepage term (Chao et al., 2008) describes the water that contributes to a raise in the water table surrounding the reservoir due to subsurface infiltration:

Equation 2: $$[\Sigma^y_{2018}(0.05(y - t_i)^{-½})]$$

In the first year, the seepage is 5% of total impoundment. After this initial addition, each subsequent year the total water seepage continues to grow, but at a decreasing rate represented by $(0.05/\sqrt{y-t(i)})$

Mekong Delta Removal Scenario

The second scenario estimates the change in sea over the coming century due to changes in water impoundment by removing dams and their associated fingerprints from the Mekong delta region in their 80th year of operation. 80 years was chosen as a mediary between the average age of dams being considered for decommission (Langseth et al., 2016). We calculate the impact of removal with equation 3 (Chao et al., 2008):

Equation 3:

$$\mathbf{SL_y} = \sum_{i=1}^{930} V_{Dam(i)}[1 + \Sigma_y^{t(i)}(0.05(y - t_i)^{-½})]F_{Dam(i)} - \sum_{i=2018}^{2100} V_{Dam(j)}F_{Dam(j)} - \sum_{i=1}^{930} V_{Dam(k)}[1 + \Sigma^y_{t(i)+80}(0.05(y - (t_{(k)} + 80))^{-½})]F_{Dam(k)}$$

where *i* is the dams not removed, *j* represents the dams removed in the year *y,* and *k* is dams removed prior to year *y.*

Upon removing these dams, we compared the differences in sea level field between the two scenarios by subtracting the control field from the removal field, resulting in a new field that displays the spatial variation in sea level in separate impoundment pathways.

Thailand Removal Scenario

The third scenario focuses on removing in dams in Thailand. Upon researching the political climate surrounding dams in Thailand, we were able to compile a list of dams that has either been troubled by operational inefficiencies or has been cited as inhibiting local livelihoods (Table 2). By matching these reservoirs to the objects in Hawley et al. (2019) database, we ran a scenario that decommissioned these dams in their 80th year of operation. The same equation highlighted above was used to compute annual sea level fields due to impoundment.

Table 2: List of dams removed due to current public dissent

Dam Name	Lat	Long	Operational Date	Reason for removal
Ubol Ratana	16.78	102.62	1966	Prone to cause flooding
Lam Pao Dam	16.60	103.45	1969	
Vajiralongkorn Dam	14.47	98.35	1985	Nearly exceeds or exceeds storage limit in rainy seasons
Kaeng Krachan	12.54	99.37	1966	

Implications Data

To visualize the implications of the results, we use QGIS spatial mapping to create a map of Southeast Asia that is overlaid with percentages of inhabitants facing relocation as a result of decreased access to fisheries. Ranges of potential percentages of residents affect span from 1% - 35%+. The data was sourced from The Mekong River Fisheries Commision published in 2017.

As over 60 million people (⅔ of nation's population) depend on freshwater fisheries to subsist in the lower Mekong basin, a decrease in catch by weight would fracture population demographics and warrant relocation. We compiled the contribution of annual gross fish weight from this area to compare to the worldly percentage. The projected fisheries yield was then calculated for 2060. The data source pre-isolated the projected data to only consider a scenario in which projected dams are constructed, blocking major migratory routes. This assumes that no other infrastructural features such as fish ladders are implemented within this timespan.

Results:

The approximate locations of dams that were considered under the two scenarios are displayed below (Fig. 3). The Mekong Delta removal scenario investigates twenty-one dams from all over Southeast Asia with differing distances from coastal regions. The second scenario focuses on four dams across the nation of Thailand who have documented dangers and negative impacts on local livelihoods. The four dams from the Thailand removal scenario are also removed in the Mekong Delta scenario, but the purpose of considering the second scenario is to account for differences in national policies regarding dams throughout the region.

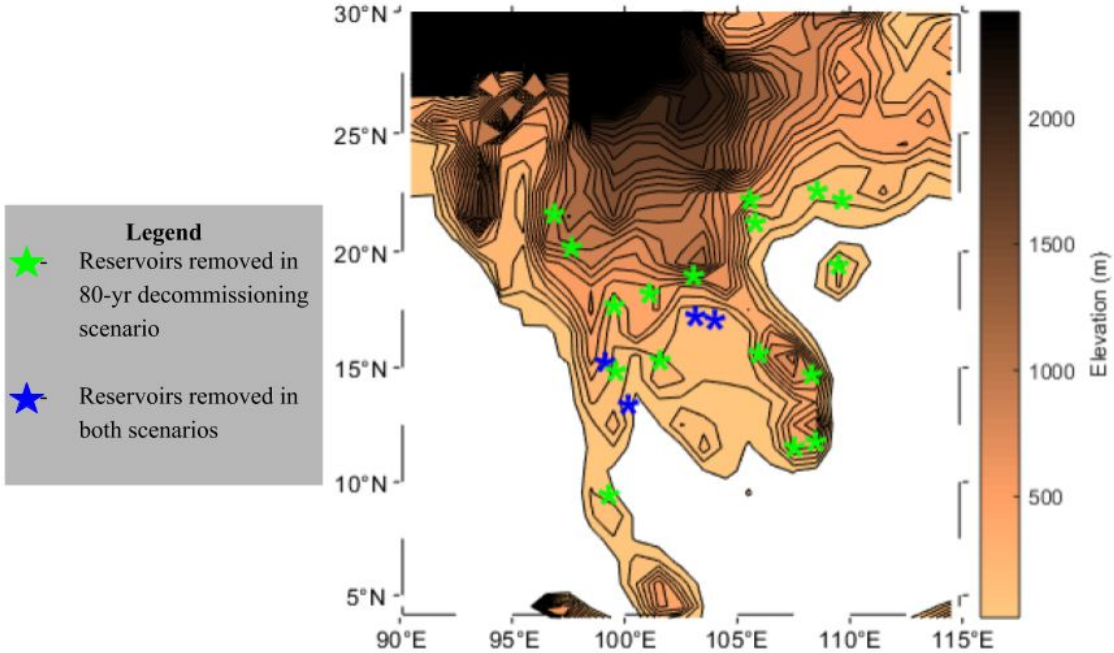

Figure 3: Location of dams in the study area of the Mekong Delta Region. Dams removed in the Mekong Delta 80-yr decommissioning scenario highlighted by a green star. Dams removed in both scenarios denoted by blue stars.

Local sea level changes from 2046, when the first dam is removed, to 2100 due to global water impoundment in the two scenarios are provided in Table 3. All values are in millimeters. The second column contains projections under the 2100 control scenario, where no impoundments are commissioned or decommissioned. Columns 4-7 contain local sea level values for each city under the Mekong Delta (MD) 80-year removal scenario. Finally, the differences between the Thailand removal scenario and the control scenario in the year 2100 are provided in column 8.

Table 3 - Summary of results for 3 different Southeast Asian coastal cities: Ho Chi Minh City, Bangkok, and Kampot. All measurements are in mm.

City	2100 control	MD Residuals	Projections by year MD removal				Thailand residuals
			2030	2050	2070	2100	
Ho Chi Minh City	-24.23	-6.98	-20.40	-22.03	-28.03	-31.21	-0.38
Bangkok	-16.95	-15.50	-14.35	-16.87	-26.79	-32.45	-2.70
Kampot	-25.61	-3.87	-21.47	-23.32	-26.82	-29.49	-0.54

The 2100 control scenario demonstrates how the current landscape of global water impoundment will impact Southeast Asia's above-water geography to sea level rise (Fig. 4). Localities displayed with brighter colors represent sites of impoundment. Sea level fingerprints refer to changes in sea level due to gravitational attraction and loading effects of changing masses. High-volume impoundments scale the sea level fingerprint of that locality into significantly more positive values. This scenario provides a standard from which the two removal scenarios can be compared to measure the significance of impoundment removal as a method for combating sea level rise.

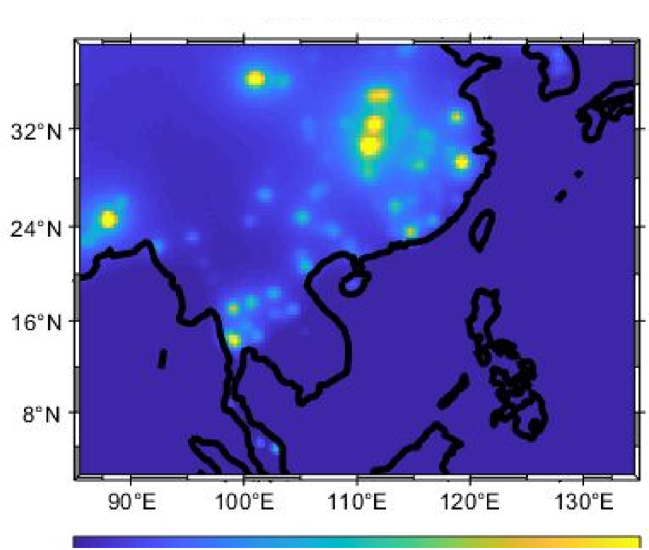

Figure 4: Sea Level Due to Impoundment in the year 2100 without any removal or construction of reservoirs. Continuous storage of water by current reservoirs is factored in through the seepage term.

The Mekong Delta removal scenario is important to consider in a future reality where reservoir improvements and maintenance are seen as too costly, and removal becomes a viable option for impoundments all over Southeast Asia. Sea levels in the year 2100 under the Mekong Delta scenario are shown in Figure 5.

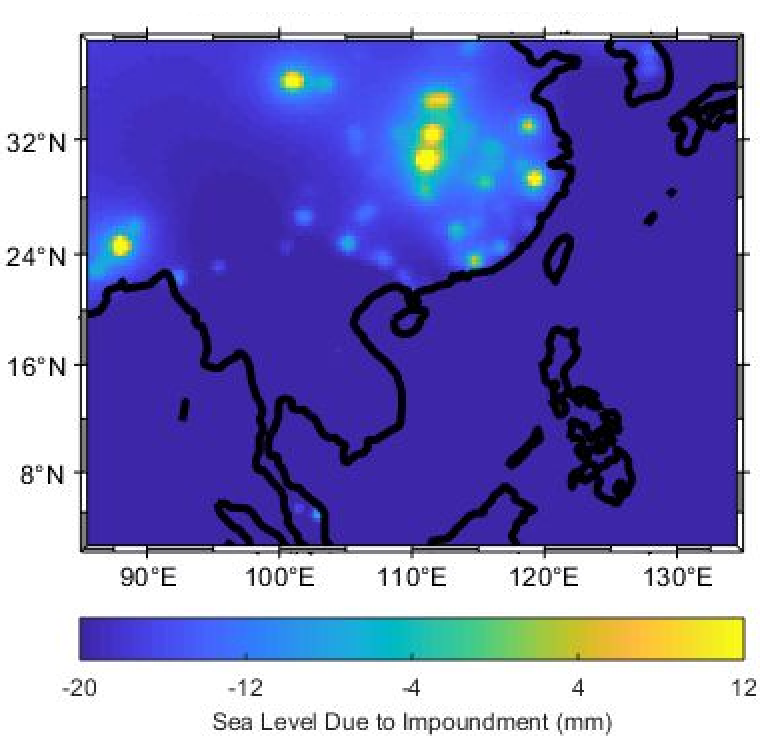

Figure 5: Sea Level Due to Impoundment in the year 2100 under the 80-year Mekong Delta Removal scenario. A total of 21 dams are removed in this scenario.

To measure the impact of a dam removal scenario, we calculated the residuals between the control and both removal scenarios (Figs. 6 and 7). The residuals displayed across Southeast Asia are represented in the year 2100. There is a sea level fall surrounding dams that are removed. This is the ground rebounding and water migrating away because the dam's gravitational pull is gone. This causes sea level to rise farther away, from the water that was once surrounding and impounded in the dam.

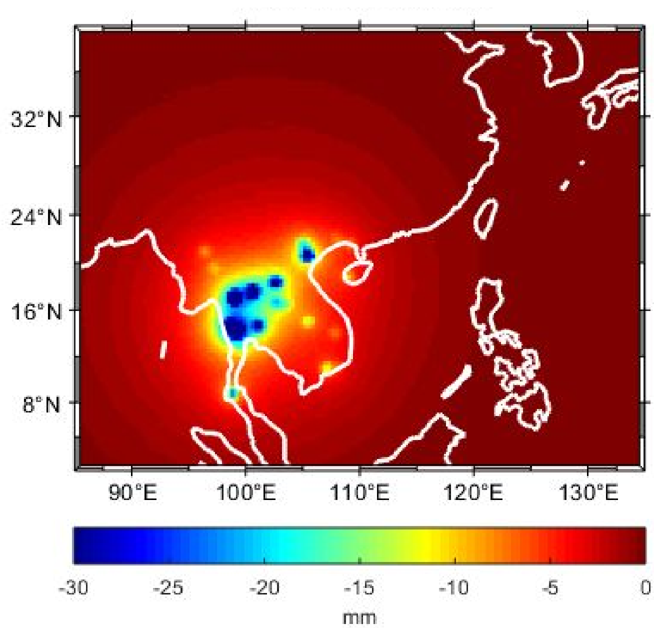

Figure 6: Residuals (mm) between the 2100 80-year Mekong Delta Removal scenario and the 2100 control scenario.

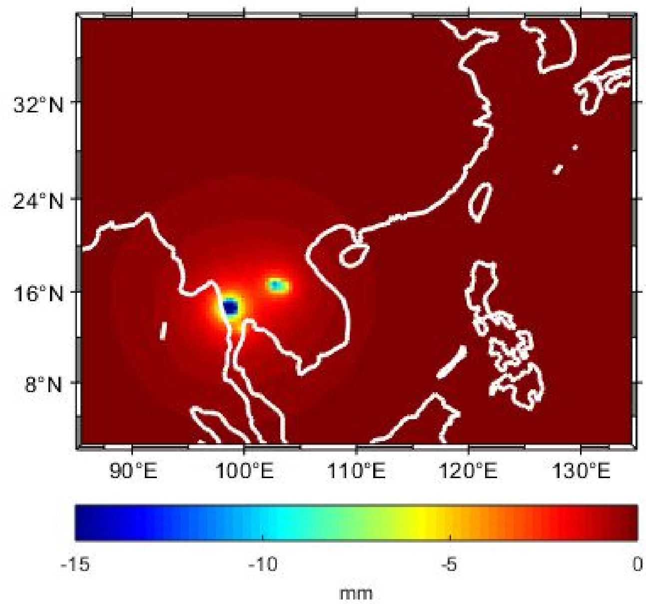

Figure 7: Residuals (mm) between the 2100 80-year Thailand Removal scenario and the 2100 control scenario.

To demonstrate how sea level changed due to water impoundment removal in Bangkok and Ho Chi Minh, Figure 8 shows a time series for both of these localities. The control scenario is displayed in both plots with a blue line. Similarly, the Mekong Delta removal scenario result is represented by a dashed red line. In Figure 8a, a heavy black line represents the result from the Thailand removal scenario. Sea level is gradually falling because additional impoundment from global seepage. The sharp decreases in sea level are from when a local dam is removed.

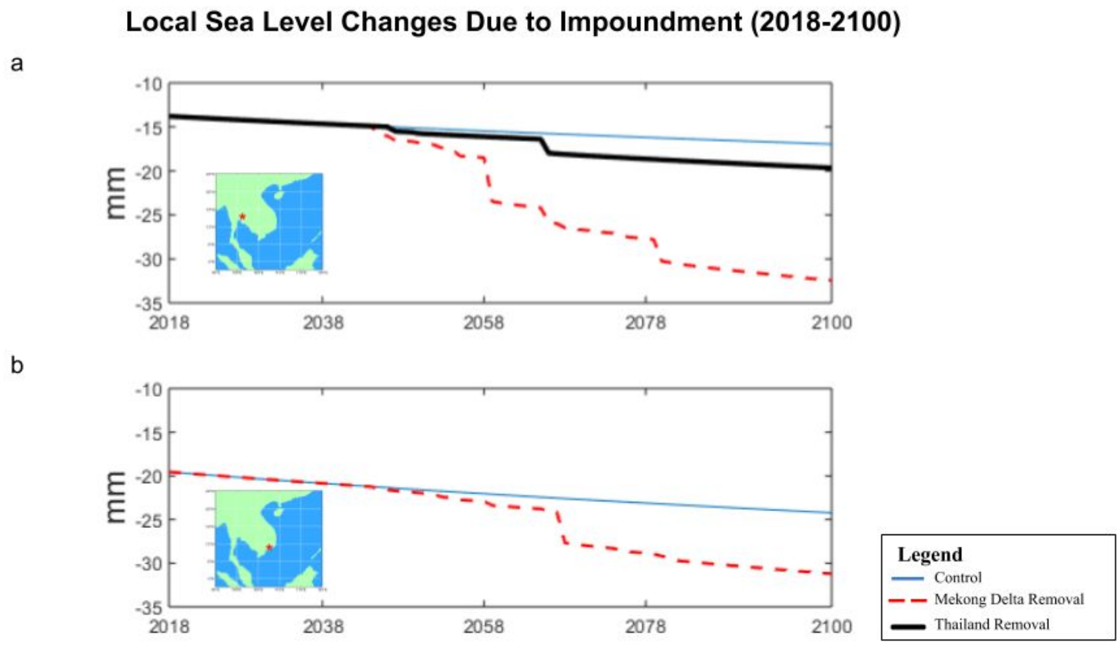

Figure 8: Time series of dam impoundment contributions to local sea level near (a) Bangkok, Thailand and (b) Ho Chi Minh City, Vietnam.

Discussion

We highlight Ho Chi Minh City, Bangkok, and Kompat in Table 1 because they are densely-populated coastal cities in three different nations. Measuring the sensitivity of sea level changes due to water impoundment near these cities can serve as a guide to how dam removal might impact different regions in Southeast Asia.

Regarding the control scenario, high-volume water impoundments are sufficiently far away that they produce a local sea level fall in all 3 locations, due to regional impoundment's location on inland river systems. If you were to examine cities closer to dams, you would expect to see a positive relationship between sea level and global water impoundment.

Thailand has the highest density of locations that will experience sea level rise when water is impounded in dams. The potential for dam removal as a defense against sea level rise is expected to be more impactful in Thailand than Vietnam. Under the Mekong Delta Removal scenario,sea level rises around Thailand and falls in the area immediately north. Additionally, the sea level fall along the coastal regions of Vietnam and Cambodia increase in magnitude. In accordance with the distribution of impoundments, Thailand observes the largest difference in sea level between the control and Mekong Delta removal scenarios. Portions of Thailand experience sea level fall of over 30 mm due to the removal of dams (Fig. 4). This is also revealed in Figure 6, as Bangkok experiences a much sharper sea level fall due to impoundment than Ho Chi Minh City. This region of sea level fall due to removal extends eastward into the South China Sea and down into the Gulf of Thailand. The non-uniform sea level changes due to dam removal are felt by countries not involved in the dam removal process, demonstrating that a mass dam removal movement does not solely produce localized effects.

The timing of decommissioning events creates an uneven progression of sea level change in the coming century. On a 20-year time-scale, 2050-2070 experiences the largest fall in sea level. The majority of dam building in these nations occurred during the 1970's and 80's, and under an 80-year decommissioning assumption the water impounded in these dams must be released in the 2050's and 60's. Whether or not these governments decide to restore dams or decommission them, by the midpoint of the 21st century governments will need to contemplate the need for dams in terms of energy production, agriculture, and flood prevention.

Under the Thailand removal scenario the effects on sea level are much smaller and localized to Thailand (Table 1). Even in this scenario, Vietnam and Cambodia experience a very small sea level fall compared to the control scenario (Fig. 5). Similar to the Mekong Delta scenario, the major sea level fall occurs around the mid-2060's (Fig. 6a), a period of significant climate insecurity due to flooding in a low-emissions scenario (Pillai, xiv).

In light of these results, the original question of whether the fall in sea level due to dam removal will significantly combat the current trend of sea level rise must be addressed. Sea level rise caused by climate change impacts the Mekong River delta region disproportionately, specifically in Vietnam and Thailand (MRC). The mouth of the Mekong River is one of two primary lowland environments in the Mekong River basin, alongside the broad river valleys that reach seaward from the northern uplands. The delta lies less than 2m above sea level. The depressions and lowlands caused by ancient tectonic forces create possibly dangerous societal consequences if sea level continues to rise (MRC).

In Vietnam, the Mekong River Delta region is home to 22% of the country's population. Under a 1 m sea level rise scenario, an estimated 7 million people will be displaced, and 28% of highways and 27% of provincial roads will be affected. It also puts 39% of the region at risk of flooding. The delta region is home to half of all Vietnam food production, making it a vital area for the country's future security (Khanh et al., 2012). The average purchasing power per capita in the 11 coastal provinces neighboring the Mekong drainage area is the U.S. equivalent of $1,084.56, placing it 30% lower than the national average of $1,553.96. On average, 39% of the population in the area are not educated past primary school. This lack of available funds and lower education limits the local population's options if they are displaced due to sea level rise, putting them at a disproportionate risk. Climate change also adds the additional problems of increased storm events, accelerated erosion along the coast, increased salinity of estuaries, saltwater intrusion into freshwater, and an overall degradation of water quality.

Vietnam isn't the sole country at risk if sea level continues to rise. In Thailand, the total area of water inundation may increase up to 26% in 2050 and 81% in 2100 under an aggressive sea level rise scenario. This rise leads to an increase in flood affected buildings by a factor of 1.5 from 2025 to 2100 (Dutta, 2011). Sea level rise in Thailand is partially due to climate change, but is further exacerbated by land subsidence. Mainly stemming from drainage and groundwater withdrawal, over the 20th century coasts in Bangkok have subsided up to 2 m. The subsidence has caused shorelines directly south of Bangkok to retreat over 1 km (Nicholls et al., 2010). Under a high emissions climate change scenario, there will be a 30% increase in flood-prone area in Bangkok in 2050 from an extreme event, causing the percentage of Bangkok residents affected by inundations to rise by 75%. Increased costs caused by climate change for damage from an extreme event in Bangkok is an estimated 1,558,714,500 USD. Land subsidence coupled with sea level rise puts Bangkok at risk of disappearing into the sea in 15 to 20 years . Bangkok is home to over 8 million people, putting them all at risk of displacement. The same climate change scenario will increase Ho Chi Minh City's area inundated from from 54% to 61% for regular events in 2050, and from 68% to 71% inundation for extreme events, creating a rise in the affected population of 62%. (Pillai xiv).

Because the areas of interest is particularly at risk if sea level continues to rise, we explored if the fall in sea level due to dam removal would be enough to significantly offset sea level rise. Although we found dam removal does cause a local decrease, it only partially negates the current trend of rising sea level. The area with the largest fall in sea level due to dam removal saw a drop of 30 mm; however, the IPCC projects that for 1.5 ℃ of global warming, sea level will rise between 260 to 770 mm by 2100 (IPCC, 2018). Additionally, the average level of sea level rise expected in the Mekong region by 2050 puts over 1.9 million people at risk of displacement (Ericson, 78). The overall fall in sea level due to dam removal is not enough to significantly offset the rise is sea level due to factors including climate change and land subsidence. In the future, a new strategy will need to be found to successfully negate sea level rise if the Mekong River delta region is to continue existing under its present circumstances.

Aside from sea level concerns, dam removal is still a pragmatic approach to sustaining fisheries along the Mekong River Basin. Freshwater fisheries in Southeast Asia are among the most expansive worldwide, feeding settlements and residents of the region. Annually yielding approximately 1.5 billion US dollars and 3.9 million tons of various key species, some countries, especially Cambodia, value this natural resource more than national rice production (Baran, 2007). As the population of the Lower Mekong Basin is projected to exceed 100 million permanent residents by 2025, the demand for harvests will proportionately escalate (Baran, 2007). Although the Mekong currently makes up approximately 25% of the world's freshwater fishery harvest, a 2060 projection indicates that the contribution will decrease to relatively 10% (Fig. 9). If the influx of available catches declines, the ramifications to the greater communities could include malnutrition or even relocation. Although aquaculture (farmed fishing) has been historically efficient, the yield is still auxiliary to that of wild capture fisheries (Baran, 2007).

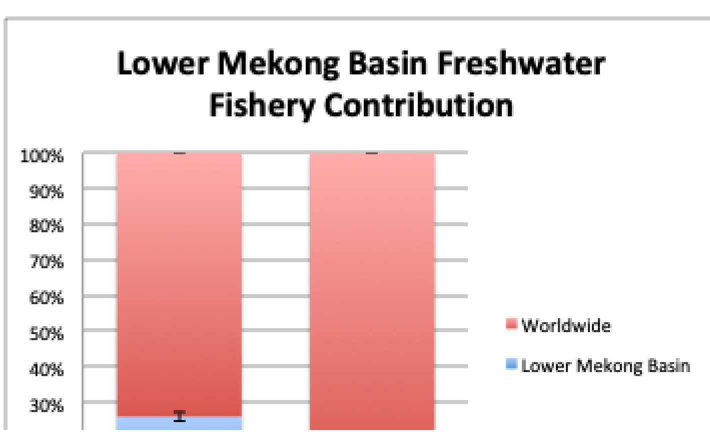

Figure 9: Projected Lower Mekong Basin and global freshwater fishery proportions based on waterway obstructions and inland flood plain reductions (Mekong River Fisheries Commision, 2017).

One of the most significant threats to freshwater fisheries in the Lower Mekong is the reduction of flood plains. Once a year after the dry season, regions along the Mekong experience monsoon flooding, not uncommonly releasing up to 54 times the minimum mean discharge (Welcomme, 1985). The periodic floods create vast expanses of approximately 84,000 km^2 of plains (Scott, 1989), establishing crucial breeding and hatching environments for numerous native fish species. Furthermore, flood plains allow fish to complete migratory routes among various waterways oftentimes traversing national boundaries. Dams reduce local flooding extents as they impound large portions of precipitation in a contained reservoir (Baran, 2007). Obstructing necessary fish migration routes, dams inhibit efficient reproduction and ultimately prevent fish from reaching key fishing areas. With increasingly less viable harvests, many residents along the Mekong are susceptible to relocation. The Lower Mekong Basin is especially vulnerable as the increasing number of dams downstream continuously hinders fish passage toward the river mouth (Fig. 10). While communities closest to the Mekong River Delta face severe consequences due to fish reallocation, the residents in the north of the basin are less affected. In accordance to the dam removal scenario in which deconstruction occurs, both inland flood plains and fish migration will remain unhindered and will relieve the strain on access to fisheries for communities along the river.

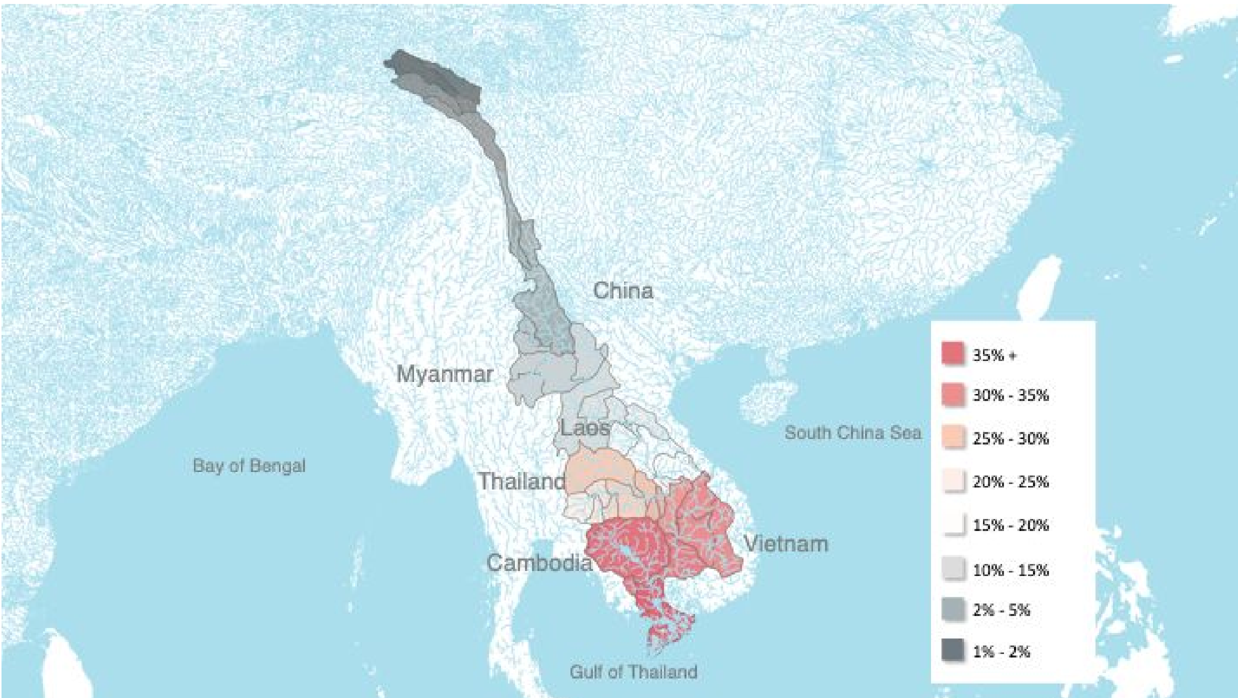

Figure 10: Projection of population percentage facing relocation due to fishery harvest projections for 2060 (Mekong River Fisheries Commission, 2017).

Assumptions

Our study relies heavily on many assumptions, the central one being the assignment of an 80-year operational lifetime to dams that were removed. This assumption was made using the Glines Canyon and Elwha River dam removals in Washington state as proxies for average age of dam decommission (NPS, 2015). However, it must be acknowledged that dam construction practices and standards vary per country, and assuming each dam will be removed exactly 80 years after commission is an oversimplification.

In our calculation of each dam's volumetrically-scaled sea level fingerprint, we assume a capacity of 100%. Since we did not explore patterns in reservoir capacity, we were not able to justifiably add a scalar to represent a more feasible reservoir capacity.

Lastly, our model does not factor in future impoundment around the world. Hydroelectric power potential in the Mekong River region is estimated to be between 175-250 gigawatts, leading many countries in the region to see the river as a relatively untapped source of power. Between China, Myanmar, Laos, Thailand, Cambodia, and Vietnam, 71 hydroelectric dams are pending construction on the Mekong River between 2010 and 2030. Vietnam alone plans to add four additional gigawatts of electricity from hydropower between 2017 to 2030 (EIA, 2015). This trend is not limited to just the Mekong River region; as of 2014, at least 3,700 major dams are planned or under construction, leading to a predicted rise in global hydroelectricity capacity of 73% (Zarfl, 2015).

Conclusion

It is difficult to predict what the water impoundment landscape will look like in the mid-21st century, but it is useful to begin pondering how the aging infrastructure will be dealt with, especially when considering the linkages to local sea level. We examined this topic in the context of Southeast Asia due to its climate-sensitivity as a densely-populated region with numerous coastal megacities and a heavy reliance on impoundment infrastructure. Upon applying two separate impoundment removal scenarios, one concerning the entire Mekong Delta region and the other Thailand, it is apparent that removing dams should not be the only climate resiliency measure taken to avoid the severe implications of sea level rise in the region. All three localities of interest, Bangkok, Kampot, and Ho Chi Minh City, experience centimeter-level reductions in local sea level depending upon the volume of water removed. However, it is not nearly enough to counteract the meter-level sea level rise projections for the region.

The sea level changes we estimated provide a springboard for future contemplation of this issue, and the hope is that through more realistic impoundment projections, a clearer estimate can be derived. As policy around dams becomes actualized in the coming century, it will be less difficult to craft realistic impoundment scenarios. At this stage, however, our scenarios are exploratory and should only be valued for their fundamental conclusions, that being dam removal can entail small reductions in local sea level.

In addition, this same methodology can be extended to other regions as research into local sea level dynamics grows. Dam removal should be considered a minor but relevant component of local sea level dynamics as projections for constrained regions are refined. The first step to incorporating dam removal into local sea level projections is defining which impoundment policies should be pursued in the coming century. To do this, interdisciplinary research must be conducted between sea level modelers and specialists in impoundment infrastructure to explore the role impoundment will play in local sea level relative to other forcings.

Public impact on fisheries and food resources, however, are well projected and better understood than that of sea level. A region contributing approximately a quarter of the world's freshwater fish yield is facing consequential deterioration partially caused by dam presence. Within 40 years, there is a significant likelihood that over 35% of permanent residents in the Mekong Delta region will be forced to relocate due to fisheries becoming unavailable. As more dam construction projects are being proposed, the severity of this issue continues to rise. Although the degree of influence is reduced in the northern regions of the drainage, the actions of communities upstream can inhibit fish harvests along the entire waterway. Although it is apparent that dams alone do not cause fish stocks to deplete, they are a major contributor to the downturn. If not for sea level, public policy should contemplate the region's food supply as an aftereffect to dam construction.

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