Policy Research Working Paper 9352

Resilient Shores: Vietnam's Coastal Development between Opportunity and Disaster Risk

Background Paper

Coastal Development between Opportunity and Disaster Risk

A Multisectoral Risk Assessment for Vietnam

Johannes Braese
Sophie Anne de Vries Robbé
Jun Rentschler

WORLD BANK GROUP
Global Facility for Disaster Reduction and Recovery
&
Urban, Disaster Risk Management, Resilience and Land Global Practice
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Abstract

This paper presents a multisectoral risk assessment, analyzing natural risks faced by key drivers of socioeconomic development in coastal Vietnam. The analysis quantifies the exposure of assets and economic activity to the following natural hazards: riverine flooding, coastal flooding, typhoon winds, coastal erosion, and saline intrusion. These hazards are analyzed according to their impact on agricultural production, aquaculture, human settlements, industrial zones, tourism, health care facilities, schools, and the electricity transmission network. Overall, the results show the complex nature of natural risk in Vietnam, with significant exposure of key economic sectors, public services and assets. The estimates suggest that exposure varies greatly between hazards, sectors, and provinces. This paper provides detailed technical descriptions of the methodologies, data sources, and analytical assumptions employed to obtain the estimates, and acts as a technical background paper to *Resilient Shores: Vietnam's Coastal Development between Opportunity and Disaster Risk* (Rentschler et al., 2020).

This paper is a product of the Global Facility for Disaster Reduction and Recovery and the Urban, Disaster Risk Management, Resilience and Land Global Practice. It is part of a larger effort by the World Bank to provide open access to its research and make a contribution to development policy discussions around the world. Policy Research Working Papers are also posted on the Web at http://www.worldbank.org/prwp. The authors may be contacted at jbraese@worldbank.org; sdevriesrobbe@worldbank.org; and jrentschler@worldbank.org.

Coastal development between opportunity and disaster risk: A multisectoral risk assessment for Vietnam

Johannes Braese[1,2], Sophie Anne de Vries Robbé[1], Jun Rentschler[1]

[1]Global Facility for Disaster Reduction and Recovery, World Bank, Washington DC, USA
[2]Technical University Berlin, Faculty of Electrical Engineering and Computer Science
Contacts: jbraese@worldbank.org; sdevriesrobbe@worldbank.org; jrentschler@worldbank.org

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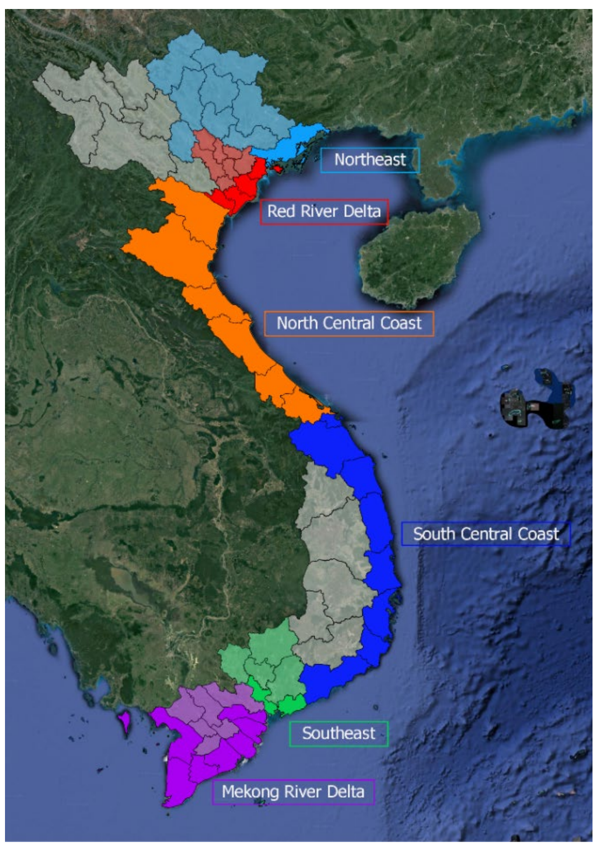
Contents

1. Introduction

This paper serves as an analytical background paper to the 'Resilient Shores' report (Rentschler et al. 2020. Specifically, it describes the methodologies and data sources employed to provide a quantitative assessment of the exposure of coastal provinces in Vietnam to various natural hazards. All analyses conducted here build on a review of the current state of the literature as summarized in the report. As methodologies are described, this paper also presents some analysis outcomes. For a full overview over the results and for policy implications of these findings, readers are referred to the main report and the technical annex to the report.

Geographically, the scope of this work covers all 28 coastal provinces in Vietnam (figure 1.1). As it is aimed at providing an overview over the effects of natural hazards on the Vietnamese people, the thematic scope is wide. Natural shocks can directly affect people (like a roof being blown off by a typhoon), they can affect their livelihoods (like the destruction of a field of crops), or they can disrupt infrastructure services that people rely on for work and life. Specifically, this paper considers four categories of natural hazards: flooding, typhoon winds, coastal erosion, and droughts and saline intrusion. The impacts of these hazards are estimated on various types of agriculture and aquaculture production; on existing and fast-growing human settlements; on health care facilities and schools; on industrial zones; on hotels; on power generation plants; and on the electricity distribution grid. As a detailed analysis of the exposure of the national transportation network was published recently (Pant et al. 2019), roads and railways are not analyzed here.

Figure 1.1: Overview of the 28 coastal provinces and the regions included in the analysis



Source: Google Maps (background image).

Since this is the quantitative part of a larger report describing the Vietnamese natural hazard environment, its main constraint is the availability of data. If a hazard or an impact channel cannot be described quantitatively, it cannot be analyzed here, but will still be discussed in the main report. For several relevant assets exposed to natural hazards, no official catalogues of geolocated assets exist or could be found. To still provide estimates of hazard exposure where possible, this work assembles some datasets from openly available sources. While these datasets should not be regarded as complete, they provide the best possible estimates, and hopefully as such are useful to policymakers.

In locating assets affected by hazards, data compiled from satellite imagery is especially important. Rather than simply using the raw output from the sensor, this analysis combines multiple types of such data and algorithmically detects specific objects, such as aquaculture ponds or rice paddies. While no such datasets were created originally for this analysis, several developed in other contexts were applied here. The employment of such datasets opens analyses of hazards at spatial granularities and geographic ranges that were not possible before, covering very large areas at very fine resolutions.

Sections two and three of this paper describe the hazard and sectoral data employed in the analyses, respectively. Section four details the methodology through which exposure estimates were computed for all relevant hazard/sector combination. Section five describes an approach to approximate the impact of such exposure in economic terms. Section six finally discusses the methodologies employed and concludes.

2. Hazard data

This analysis quantitatively considers four types of natural hazards affecting coastal Vietnam: flooding, typhoon winds, coastal erosion, and drought and saline intrusion. These hazards were selected based on discussions with experts and insights from existing literature describing the risk landscape in Vietnam (Rentschler et. al 2020, chapter 3). In this section, the data employed to model each hazard are described.

2.1. Flooding

This analysis uses one dataset modelling fluvial and pluvial flooding and a second one modelling coastal flooding. For sake of simplicity the combination of fluvial and pluvial flooding is addressed as riverine flooding in the main report. Fluvial flooding occurs when excessive rainfall over an extended period of time causes a river to exceed its capacity. A pluvial, or surface water flood, is caused when heavy rainfall creates a flood event independent of an overflowing water body. A coastal flood occurs in areas that lie on the coast of a sea, ocean, or other large body of open water, and is typically the result of extreme tidal conditions caused by severe weather (World Meteorological Organization, 2011).

The first dataset combines information on flood extent and flood depth from pluvial and fluvial flooding into one flood map. It was developed by the company Fathom, formerly known as SSBN. The map covers all of Vietnam at a resolution of about 90 by 90 meters. Flood events with return periods of 5, 20, 50, 100, 250, and 500 years are modelled. A 100-year event, for example, is expected to occur once every 100 years, on average (figure 2.1.a). As with most large-scale flood maps, the effects of man-made flood protection structures like dikes are not incorporated. The dataset is in raster format (Bangalore et al. 2017).

Existing coastal flood maps covering Vietnam, most prominently the Global Tide and Surge Reanalysis (GTSR) data set (Muis et al. 2016), are expected to underestimate coastal flood risk in Vietnam. Resulting from coarse resolution in modelling elevation, bathymetry and meteorological forcing, the dataset underestimates extreme sea levels. In addition, the largest tropical cyclone-induced surges are not all

included in the available observations after which storm surges were modelled due to the limited period of the available records (Muis et al. 2016). In Vietnam, the GTSR dataset shows barely any flooding along the North and South Central coast which does not accurately reflect actual flooding experienced in these regions. This can likely be explained by the absence of wave setup in the GTSR approach in combination with a topography characterized by relatively steep slopes on this coastline section (Bunya et al. 2010).

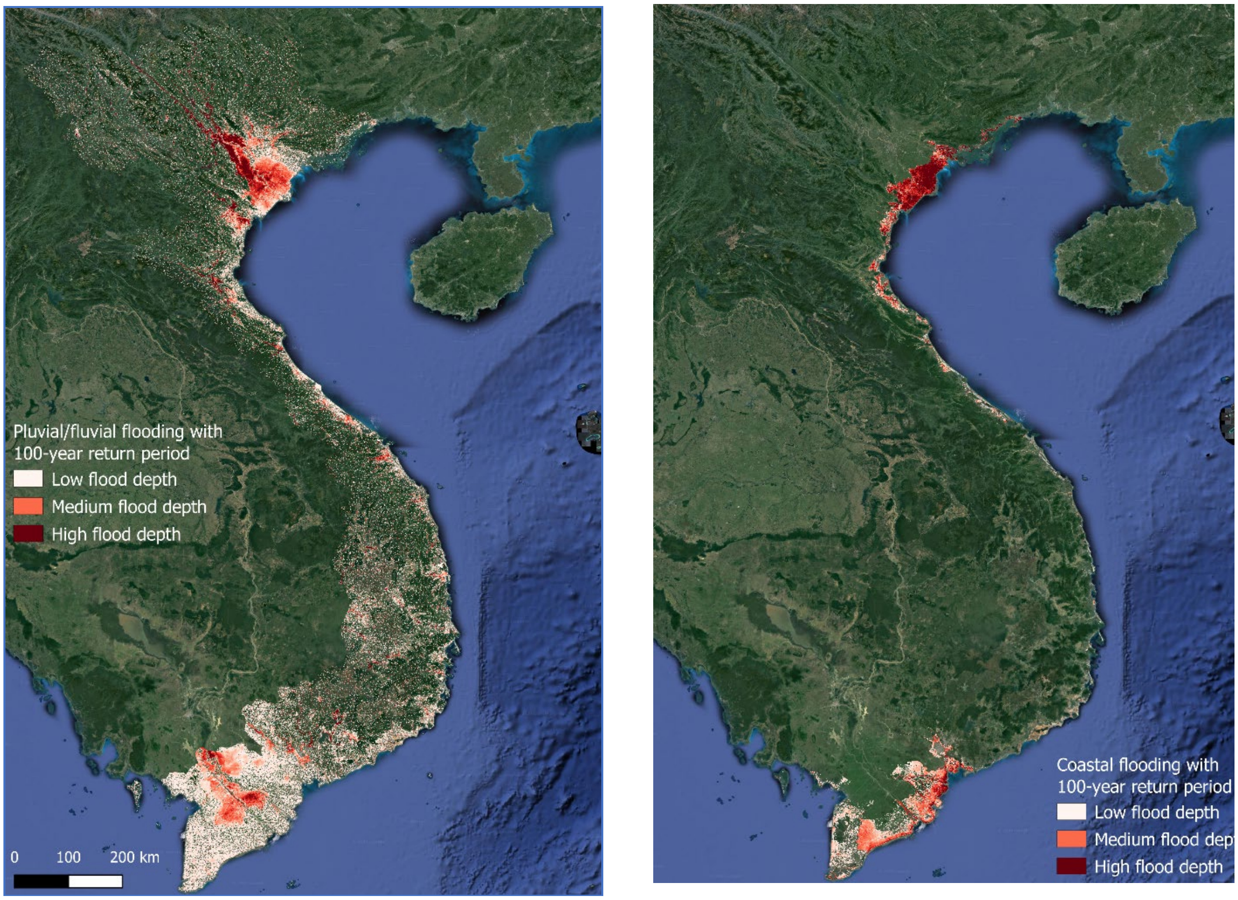
For this report, a new set of coastal flood maps for Vietnam has been created that tries to reflect flood risk more accurately. It is based on a global digital elevation map with a resolution of 90 meters at the equator that has been corrected for several errors typically present in spaceborn elevation models (Yamazaki et al. 2017). In order to arrive at predictions for flood extent and depth, digital elevation data is combined with averaged provincial surge levels. For each province and each return period, an average surge level is calculated based on modeled frequency curves. These curves have been generated by statistically postprocessing the results from storm surge modeling with a wide range of possible typhoons (Ministry of Agriculture and Rural Development, 2012). The flood depth in the new coastal flood map is then calculated following $ss_{i,t} - dem_j$, in which $ss_{i,t}$ reflects the average storm surge level in province i for return period t, and dem_j reflects the average altitude in grid cell j of the digital elevation map used. Whenever $ss_{i,t} - dem_j \leq 0$ the corresponding grid cell value is set to 0, indicating no flooding. The output has a raster format with a resolution of about 3” resolution (~90 m at the equator). Following this simple methodology, flooding depth for the 28 coastal provinces are calculated for events with return periods of 5, 25, 50, 100, 250, and 500 years (figure 2.1.b). Just as with the pluvial and fluvial flooding maps no information on existing flood protection measures has been incorporated into this modelling.

However, extensive public protection infrastructure such as dikes exist in many provinces in Vietnam, aimed the mitigation of both at riverine and at coastal flooding. Given the absence of flood protection modelling in the flood maps described above, using them as they are would result in an overestimation of flood exposure. Unfortunately, incorporating flood protection infrastructure into flood models at a national scale is still prohibitively difficult. This analysis thus uses a novel approach based on knowledge collected for the main report combined with qualitative expert assessment to estimate the flood risk, while accounting for existing protection infrastructure (section 4.1).

Figure 2.1: Riverine and coastal flood risk in Vietnam

a) Riverine (fluvial and pluvial) flooding

b) Coastal flooding

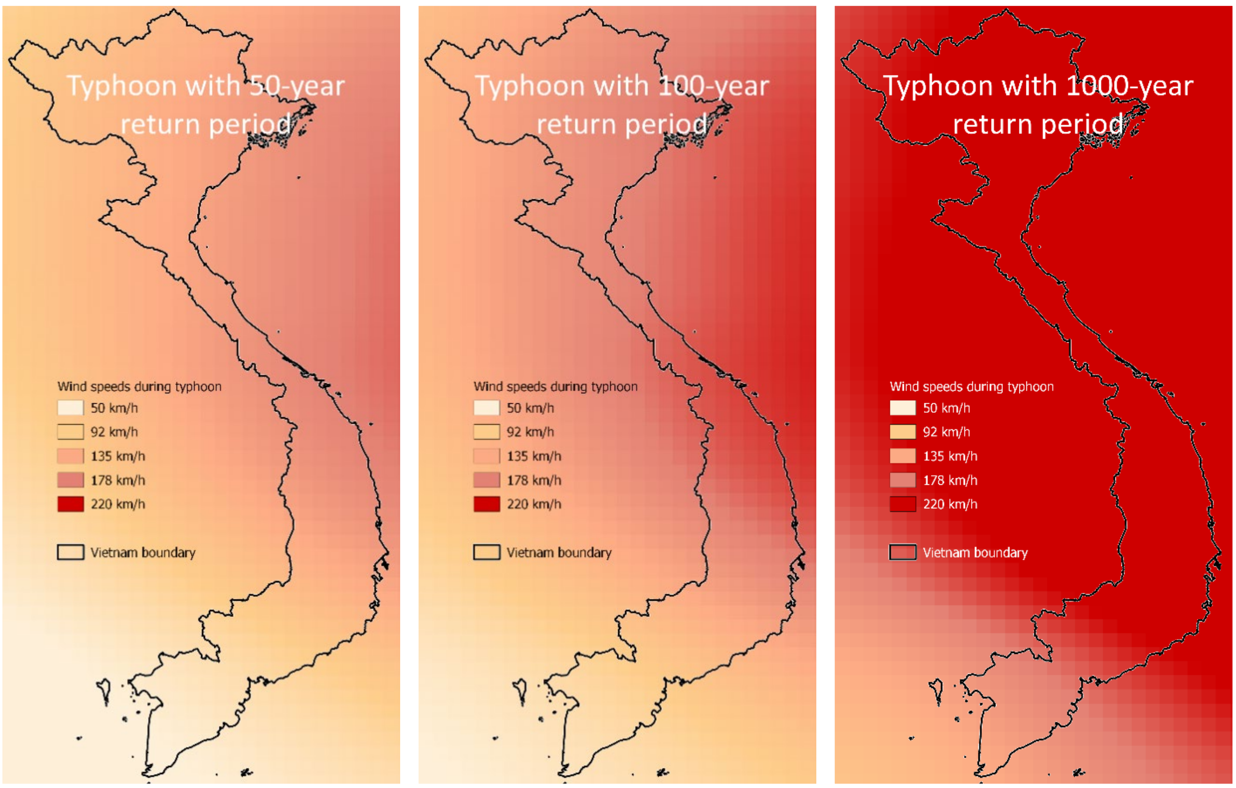


Source: Fathom[1] (riverine flood map), Braese et al. 2020 (coastal flood map)(Bangalore et al., 2017), Google Maps (background satellite image).
Note: Both flood exposure maps indicate flooding for an event with a 100-year return period without accounting for protection infrastructure. For coastal flooding, flood extent is shown only in the 28 coastal provinces.

2.2. Typhoon winds

Typhoon wind speeds used in this analysis were produced by a global model of cyclone winds calibrated on over 2,500 past cyclones, terrain composure, and ocean depth. It contains the modelled maximum wind speed at every location in Vietnam for typhoons occurring, on average, every 50, 100, and 1000 years (figure 2.2). The data is in raster format has a grid resolution of roughly 30 by 30 kilometers (UNDRR, 2015).

Figure 2.2: Wind speeds over Vietnam in typhoons of varying severity



Source: UNDRR, 2015.

2.3. Coastal erosion

In order to quantify sediment changes on the coast in the form of coastal erosion or accretion, two datasets were used. The first roughly covers the Mekong River Delta, while the second covers the remaining provinces in North and Central Vietnam.

Coastline changes in the Mekong Delta, including Ho Chi Minh City and Bà Rịa-Vũng Tàu, were evaluated based on data provided by the Viet Nam Disaster Management Authority in vector format[2]. By analyzing the coastline in 1988 and 2015 in imagery from Landsat satellites, sediment changes in this period could be quantified.

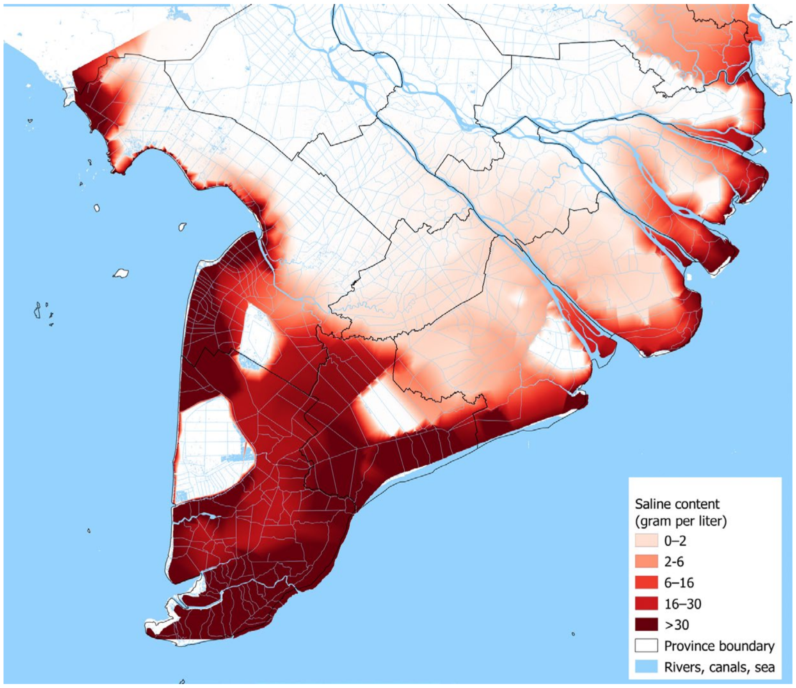
Similarly, coastal erosion data in the provinces further north were developed by companies Deltares and Royal Haskoning DHV (Deltares at al. 2017). Coastline changes in the period between 1990 and 2015 were detected automatically based on imagery from Landsat and Sentinel satellites. In this vector format dataset, average erosion or accretion is available by coastline segments with a length of 500 meters.

2.4. Drought and saline intrusion

Saline intrusion describes a natural phenomenon where low water levels in freshwater aquifers lead to a flow of sea water with high concentrations of salt inland into the aquifers. This makes these water sources unusable for human consumption or for irrigation, potentially disturbing aquaculture production.

In Vietnam, saline intrusion particularly affects the Mekong River Delta. To analyze this hazard, a dataset in raster format describing the worst saline intrusion event in 2016 was provided by the (Southern Institute of Water Resources Research (SWIRR). With a resolution of about 50 by 50 meters, it shows the salinity level at each point in the delta during the 2016 event (figure 2.3).

Figure 2.3: Saline intrusion in the Mekong River Delta in 2016



Source: SWIRR[3] (saline intrusion data).

3. Sectoral data

In this section, the various types of socioeconomic and asset data used to represent human and economic activity for the exposure analysis are described.

3.1. Detection of human settlements and different types of agricultural production with high-resolution land use data

The exposure of various types of agricultural production and urban areas is estimated based on land use data with a very high spatial resolution. This dataset was developed by the Japanese Aerospace Exploration Agency and is openly and freely available online (JAXA EORC, 2018).

The land use map provides a fine-grained overview of land use for all of Vietnam for 2015, for northern regions and for central and south Vietnam in 2017. Developed specifically for Vietnam, the map distinguishes between the nine predominant land use categories in the country, which are explained in detail in Table 3.1. The raster dataset has a resolution of 15 x 15 meters in the northern region and 10 x 10 meters in the central and southern regions (figure 3.1).

The dataset was created using an algorithm combining satellite and other data of various resolutions. The algorithm is fed with 24 different satellite bands, measuring surface reflectance in the visible and infrared spectra, topographical data from the Shuttle Radar Topography Mission (SRTM), and road network data from the OpenStreetMap project. It also exploits temporal variation in satellite imagery within a year, which enables classification based on land cover change, such as a change from crop cover to bare soil after harvest (Hashimoto at al. 2014).

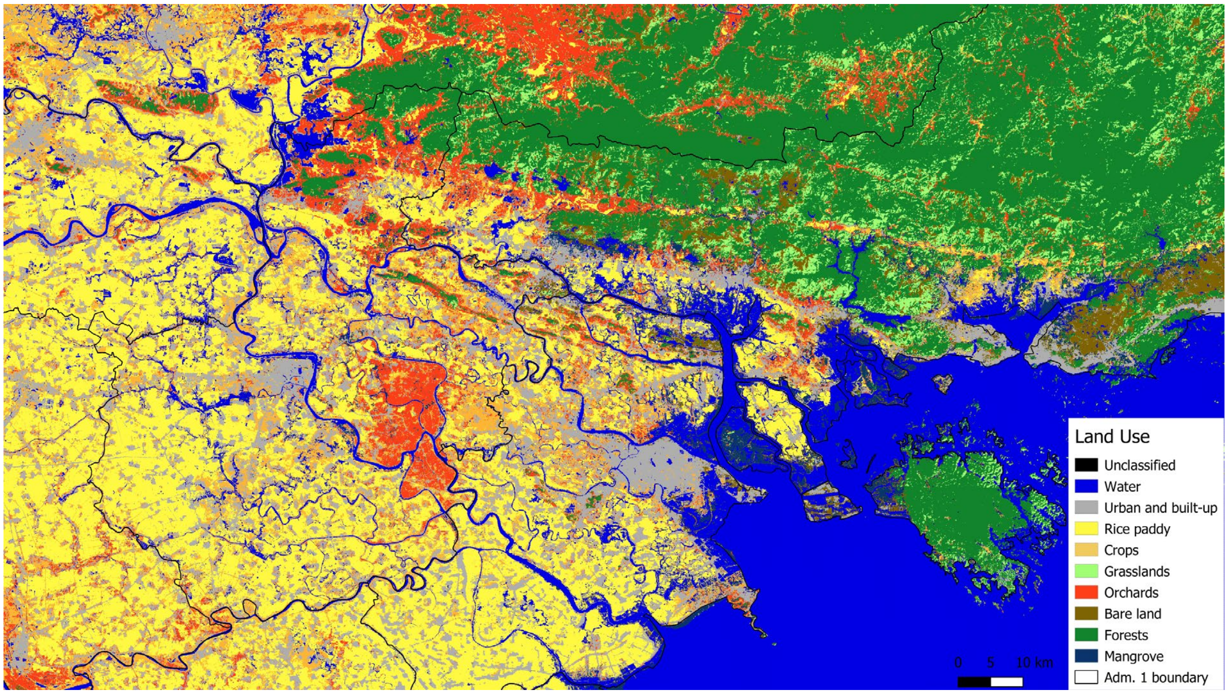
Table 3.1: Description of categories in land use data

Category	*Definition*
Water	Oceans, seas, lakes, reservoirs, and rivers. They can be either fresh or saltwater bodies.
Urban	Land covered by buildings and other man-made structures.
Paddy	A flooded parcel of arable land used for growing semiaquatic crops, most notably rice.
Crop	Lands covered with temporary crops followed by harvest and a bare soil period. These may include single and multiple cropping systems. Note that perennial woody crops will be classified as the appropriate forest or shrub land cover type.
Grass	Lands with herbaceous types of cover. Tree and shrub cover is less than 10 percent.
Orchard	An orchard is an intentional planting of trees or shrubs that is maintained for food production.
Bare land	Lands with exposed soil, sand, rocks, or snow, that have never had more than 10 percent vegetated cover during any time of the year.
Forest	Lands dominated by woody vegetation with a percent cover of over 60 percent and height exceeding 2 m. Almost all trees and shrubs remain green year-round. The canopy is never without green foliage.
Mangrove	Mangroves are a group of trees and shrubs that live in the coastal intertidal zone.

Others	The other land cover categories

Source: JAXA EORC, 2018

Figure 3.1: Land use in a section of the Red River Delta

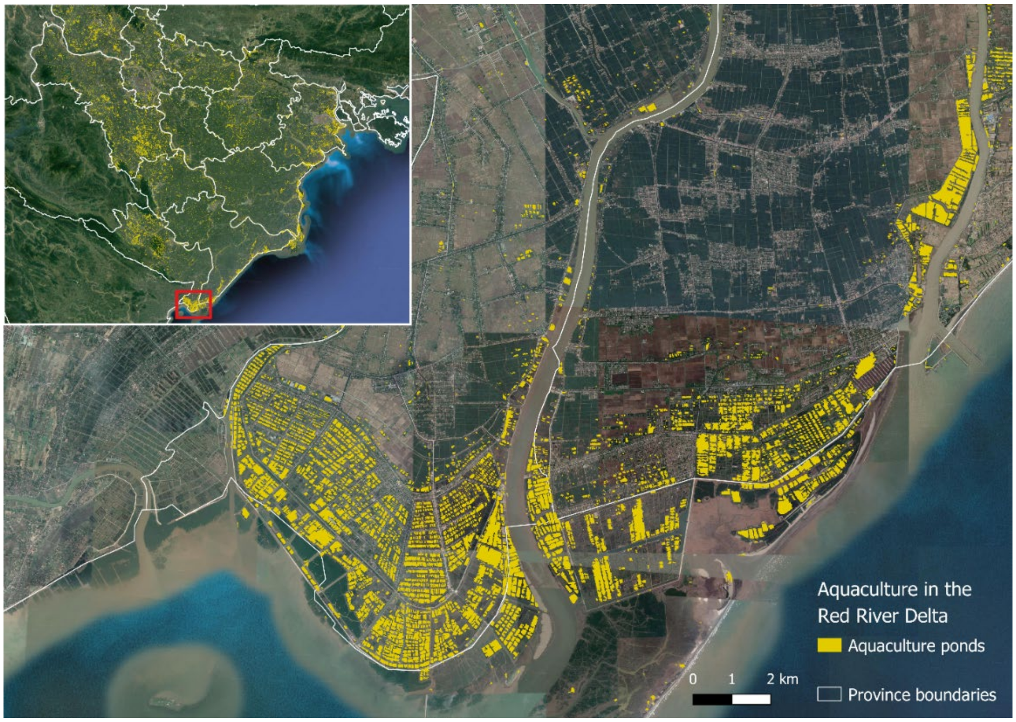


Source: JAXA EORC, 2018

3.2. Aquaculture

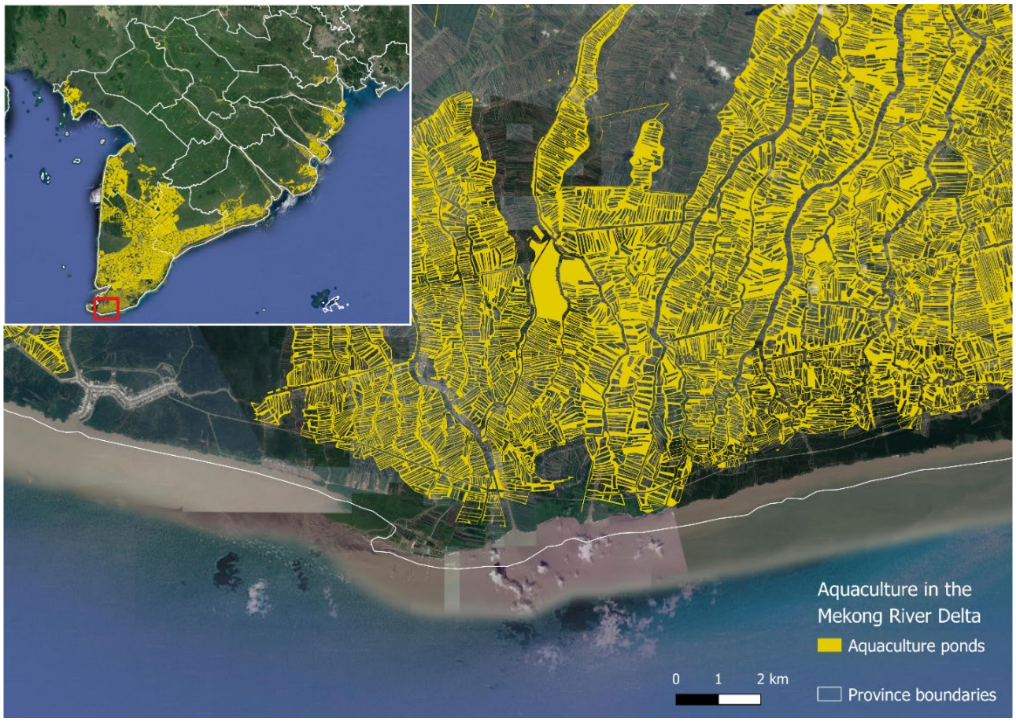
Information on aquaculture production in Vietnam's two main river deltas was obtained from two data sources. In the Red River Delta, a vector dataset of the locations of individual aquaculture ponds was used. It was created and provided by researchers of the German Aerospace Center (DLR). As part of their methodology, an algorithm extracted individual ponds from time series of radar satellite data. Specifically, 83 Sentinel-1 scenes from between 2014 and 2016 were processed. Radar data, such as the observations from the Sentinel-1 series of satellites, enables the detection of water-covered surfaces irrespective of daylight and clouds. Through the exploitation of time series data, aquaculture ponds can be distinguished from other water-covered bodies such as rice fields which are not submerged year-round. Overall, an accuracy of 0.84 is reported for pond detection in the Red River Delta (Ottinger et al. 2018). In the Mekong Delta, a vector dataset containing the locations of individual aquaculture ponds was provided by SWIRR.

Figure 3.2: Aquaculture ponds in the Red River Delta



Source: Ottinger et al. 2018 (aquaculture ponds Red River Delta), Google Maps (background satellite image).

Figure 3.3: Aquaculture ponds in the Mekong River Delta



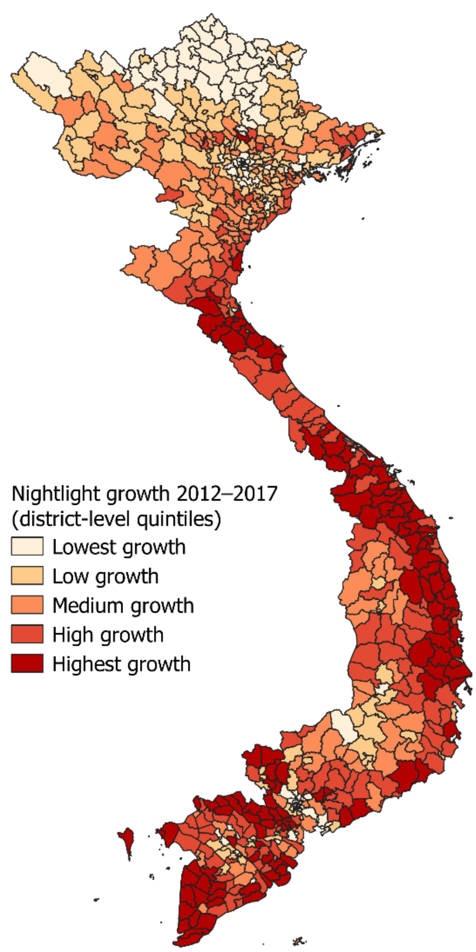
Source: SWIRR[2] (aquaculture ponds Mekong River Delta), Google Maps (background satellite image).

3.3. Nightlights

Satellite images taken during nighttime can provide insights into the ongoing processes of urbanization. Increasing brightness in a particular area over time indicates growth in industrial or residential developments or an increase in the number of streetlights. These provide useful proxies for urbanization and emerging industrial activity. This study uses so-called 'nightlight' data to assess urban and industrial growth in Vietnam (World Bank, 2020).

At a resolution of about 900 meters, the raster data describes the increase of nightlight growth between 2012 and 2017 for every point in Vietnam. The raw data has been sourced from Visible Infrared Imaging Radiometer Suite (VIIRS) sensors mounted on US satellites, and has been cleaned to remove irregularities, such as lighting used for the year-round growing of dragon fruit. To allow easier interpretability, the data has been classified into five categories of nightlight growth.

Figure 3.4: Urban and economic nightlight growth in coastal regions is among the fastest in Vietnam
Night light growth between 2012 and 201 (district-level quintiles)



Source: World Bank, 2020.

3.4. Industrial

In order to analyze the exposure of industrial activity to natural hazards, a dataset of 372 industrial zones in Vietnam was obtained (World Bank, 2020). Of these industrial zones, 15 percent are within 10 kilometers of the coast, and 127 industrial zones are located within coastal provinces.

3.5. Hotels

In recent years, the importance of the tourism sector for the Vietnamese economy has increased steadily, with coastal tourism contributing an important share. However, reliable spatial data is sparse: regional breakdowns of visitor numbers are difficult to source and must be approximated (World Bank, 2019). For a detailed risk analysis, such data is insufficient.

This analysis circumvents the lack of available data sources by using data from the OpenStreetMap (OSM) project. OSM is an open and free initiative that aims to create and continuously update a map of the world that is created entirely from user-contributed data. Next to detailed street networks, the locations of various points of interests are published by community volunteers. From this source, a dataset of 5,658 hotels, hostels, guest houses, and motels was downloaded in early 2019 (OpenStreetMap, 2019). Each datapoint includes an exact point location. Of the hotels, 3,309 are located in coastal provinces and 1,531 are located within 5 kilometers of the coastline.

This dataset is not a complete dataset of all hotels in the country. Considering that there were about 25,600 accommodations in Vietnam in 2017, the OSM dataset used here contains between a fifth and a quarter of the complete set of hotels in the country (Vietnam National Administration of Tourism, 2019). This incompleteness is not a problem per se for the validity of the hazard analysis, as the OSM set could be a randomly drawn subsample of the total population of hotels. Unfortunately, in the absence of a "true" dataset of all hotels, it is impossible to know which hotels are present in the OSM subset and which are not. Some biases might arise from the fact that the data is crowd-sourced; if the contributors are mostly Europeans, for example, the dataset could overrepresent hotels frequented by international tourists. Another potential bias might arise from differing spatial distributions in ground data and the OSM subset. Between provinces, the distribution of hotels seems to be fairly accurate; the correlation coefficient of the provincial tourism GDP in 2016 and the number of hotels per province from OSM is 0.77. However, the spatial representativeness of hotels within a province cannot be tested without more granular data.

Despite these caveats, the OSM hotel dataset remains the only large and geolocated dataset of tourist hospitality locations in Vietnam. Using it as the basis for the assessment of the exposure of the tourism sector to hazards such as flooding and coastal erosion can provide new insights into the natural risk environment of the Vietnamese economy.

3.6. Health care facilities and schools

Insights into the exposure of health care facilities are based on a dataset provided by a collaboration between the Government of Vietnam, the World Bank, and the World Health Organization. The dataset contains 1,583 geocoded public hospitals and district health centers. Not included are regional polyclinics, commune health centers, and private sector facilities (Government of Vietnam, WHO, & World Bank, 2019).

Schools are vital to every community, enabling the future prosperity of its members. If they are destroyed by a natural disaster, the impact on the livelihoods of the children inhibited in their education can persist

for years. As no official datasets of school locations could be obtained for this analysis, just as with hotels, volunteer-contributed geolocations of schools were sourced from the OSM project (OpenStreetMap, 2019). Consequently, all the caveats mentioned in section 3.5 for the hotel dataset also apply here. The OSM school dataset contains 1,546 schools, 864 of which are located in coastal provinces. According to 2017 data from GSO, these 864 schools represent about 12 percent of all schools in coastal provinces (General Statistics Office of Vietnam, n.d.).

Importantly, the schools in the dataset do not seem to represent a random subsample of all schools, as some provinces contain only very few school, and three provinces have no schools at all in the dataset. Table 3.2 gives an overview over the provincial distribution of the geolocated dataset from OSM and compares it to the number of schools in each district according to the official statistics.

Table 3.2: School numbers comparison across datasets

Coastal province	Number of schools (GSO)	Number of school locations (OSM)	Coverage rate (%)
Ba Ria-Vung Tau	167	27	16
Bac Lieu	88	0	0
Ben Tre	178	13	7
Binh Dinh	338	31	9
Binh Thuan	193	33	17
Ca Mau	132	4	3
Da Nang City	199	38	19
Ha Tinh	273	7	3
Hai Phong City	311	58	19
Ho Chi Minh City	1208	505	42
Khanh Hoa	199	32	16
Kien Giang	155	10	6
Nam Dinh	266	10	4
Nghe An	541	6	1
Ninh Binh	152	9	6
Ninh Thuan	92	20	22
Phu Yen	138	7	5
Quang Binh	182	3	2
Quang Nam	260	10	4
Quang Ngai	214	5	2
Quang Ninh	216	2	1
Quang Tri	167	0	0
Soc Trang	135	3	2
Thai Binh	229	7	3
Thanh Hoa	669	1	0
Thua Thien-Hue	207	17	8
Tien Giang	228	6	3
Tra Vinh	122	0	0

Sources: General Statistics Office of Vietnam, 2019, OpenStreetMap, 2019.

Note: First column represents the number of schools in coastal provinces according to official figures from the General Statistics Office of Viet Nam (GSO), second column reflects the number of school locations per province sourced from OpenStreetMap. Third column represents the coverage rate of the OSM dataset with respect to the GSO dataset.

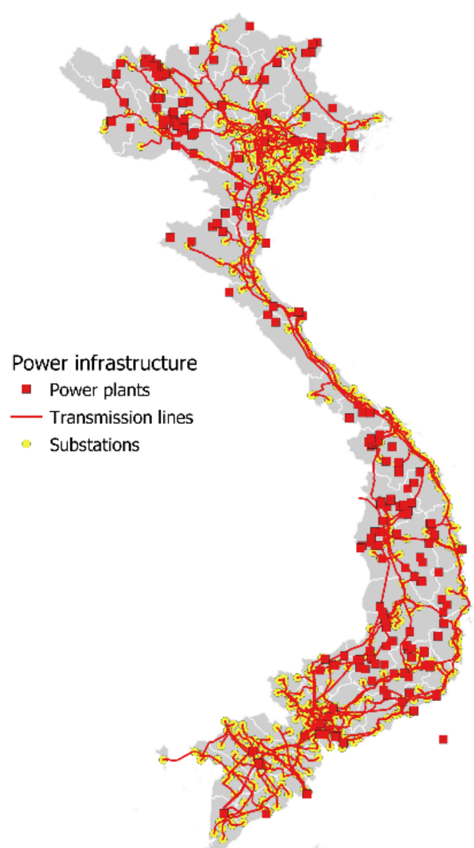
3.7. Energy

The exposure of the energy sector is analyzed with data on power plants and the transmission network, including transmission lines and electrical substations.

Data on power plants was sourced from the free and open Global Power Plant Database created and maintained by the World Resources Institute (WRI) (Global Energy Observatory et al. 2019). As of early 2019, this data covers 219 power plant locations in Vietnam, 73 of which are located in coastal provinces.

A digital spatial representation of Vietnam's electricity transmission network in vector format was prepared by a team at the World Bank and is freely and openly available online (World Bank, 2017). It contains the locations of transmission lines, with a total length of over 23,000 kilometers and over 800 substations. In the digitization process inaccuracies in the order of 2 to 10 kilometers deviation from the exact locations of the electricity infrastructure could have occurred. Resulting implications for the validity of the analysis are discussed below.

Figure 3.5: Power plants and electricity transmission network in Vietnam.



Source: Global Energy Observatory et al., 2019 (powerplants); World Bank, 2017 (transmission lines and substations).

3.8. Data for the approximation of economic impacts

This section describes non-spatial aggregate statistics used to convert exposure shares into economic figures in the sectors tourism, aquaculture, and agriculture.

To approximate the economic impact of hazards on the tourism sector, macroeconomic estimates were sourced from World Bank open data[4] and publications. National tourism GDP was obtained by applying the contribution of tourism to GDP in 2017 (WTTC, 2018) to the national GDP in 2017 (World Bank, 2019). The number of direct jobs in the tourism industry in 2017 are obtained from numbers published by the World Travel and Tourism Council (WTTC, 2018).

In the fisheries sector, aquaculture output in tons per province in 2017 was sourced from the General Statistics Office of Vietnam (GSO, 2019). Total country export value of aquaculture production for 2017 (Danh, 2016; VietNam News, 2019) has been estimated after applying a 65 percent contribution of aquaculture to the total fisheries sector 2020 (Dinh, 2017a). The number of jobs in the aquaculture sector is estimated using the number of jobs created per ton of output from the National Fisheries Development Strategy to 2020 (Dinh, 2017a). Assuming no significant change in productivity from the 2020 outlook in 2017, this number has been used to estimate the amount of jobs in the aquaculture sector using actual production for 2017.

Vietnam's combined agriculture, forestry and fishing GDP for 2017 and the combined employment in agriculture (that is, from agriculture, forestry and fishery) for 2017 has been sourced from World Bank macroeconomic indicators (World Bank, n.d.). To estimate the contribution of the cultivated crops sector to the combined agriculture-forestry-fisheries sector, contributions of these individual sectors to the combined agriculture sector have been sourced from different World Bank publications (Dinh, 2017a, 2017b, 2017c; World Bank, 2010). For aggregated cultivated crops the provincial area used for cultivation is derived from the researchers' own calculations, retrospectively aligned with national estimates for 2017 from the General Statistics Office of Vietnam (General Statistics Office of Vietnam, n.d.). For rice, provincial production area and provincial yields for 2017 have both been sourced from the General Statistics Office of Vietnam(General Statistics Office of Vietnam, n.d.). Export values for rice for 2014 and the contribution of rice to the aggregated export value of cultivated crops for 2014 have been derived from World Bank publications (Dinh, 2017b). From this, the aggregated export value of cultivated crops for the same year has been estimated. Employment in the rice sector has been estimated using a labor intensity of rice production of 0.6 workers per hectare (Nolte and Ostermeier, 2017).

4. Methodology and exposure results

This section explains the methodological details of how exposure was modelled based on the data sources described in the previous sections. Results will be presented only selectively as overview figures. For full results and a discussion of their significance, please refer to the main report (Rentschler et al. 2020).

The quantitative analyses described in this section were conducted using the programming language Python, and relied extensively on the free and open-source libraries Rasterio, Shapely, and GeoPandas.

4.1. Accounting for flood protection measures

As described in section 2.1, the flood maps used in this analysis do not incorporate information about existing flood protection infrastructure. In the event of heavy rain or a coastal surge, the underlying simulations assume that water flows freely in the natural terrain without being obstructed by any man-made structures such as dikes. However, in many provinces this is not the case as the Vietnamese government has invested significantly in flood protection infrastructure. Ignoring the existing protection systems and using the flood maps as they are would thus lead to an overestimation of flood exposure.

As part of the main report to which this paper contributes, a team of experts conducted a comprehensive assessment of flood protection measures in Vietnam. For all coastal provinces, the flood protection system was divided into stretches that were classified according to the flood events the infrastructure would be able to withstand, based on characteristics such as the type of the structure or its height.[5] For each province, the current state of existing flood protection measures is assessed. Based on these results, the share of modelled flood extent that existing flood protection infrastructure would stop has been determined per province, return period and flood type. The results hereof are shown in table 3.3 and 3.4, where the numbers represent the share of modelled flood area that would be flooded considering the existing protection infrastructure. Therefore, it decreases the flood extent in those places where dike systems and other protection infrastructure are in place. With this, knowledge based on a detailed qualitative protection infrastructure assessment is converted into a numerical offset. To illustrate this, consider 100 square kilometers of rice paddy in the province of Nghe An that are marked as flooded by a 5-year coastal flood according to the original flood maps that do not take into account protection infrastructure. The expert assessment here states that only 20 percent of the modelled coastal 5-year flood extent in this province would occur due to the protection offered by a dike along one part of the coast, reducing the actual area flooded to 20 square km. In the asset exposure analysis of this report, exposure estimates derived from the unprotected flood maps are treated this way to incorporate flood protection measures.

These protection offsets are applied uniformly per province and event after the flood exposure is estimated. The strongest assumption in the methodology lies in this uniformity – it assumes that the existing protection infrastructure protects all assets to the same degree, irrespective of their location within the province. Given this assumption this methodology cannot be used to identify affected areas within a province. At the national level, however, the methodology produces estimates that hold considerable advantages over the absence of any estimates, as well as over unprotected figures that dramatically overestimate the existing risk.

Table 3.3: Protection offset share for coastal flooding for each coastal province and return period

	Return period in years					
Province	**5**	**25**	**50**	**100**	**250**	**500**
Quang Ninh	10	80	100	100	100	100
Hai Phong City	0	30	100	100	100	100
Thai Binh	0	10	100	100	100	100
Nam Dinh	0	30	100	100	100	100
Ninh Binh	10	50	100	100	100	100
Thanh Hoa	10	50	100	100	100	100
Nghe An	20	100	100	100	100	100
Ha Tinh	10	80	100	100	100	100
Quang Binh	10	80	100	100	100	100
Quang Tri	5	50	100	100	100	100
Thua Thien - Hue	20	100	100	100	100	100
Da Nang City	20	100	100	100	100	100
Quang Nam	20	100	100	100	100	100
Quang Ngai	20	100	100	100	100	100
Binh Dinh	20	80	100	100	100	100
Phu Yen	20	80	100	100	100	100
Khanh Hoa	20	80	100	100	100	100
Ninh Thuan	5	50	100	100	100	100
Binh Thuan	20	100	100	100	100	100
Ba Ria-Vung Tau	10	80	100	100	100	100
Ho Chi Minh City	5	50	100	100	100	100
Tien Giang	0	30	50	100	100	100
Ben Tre	20	100	100	100	100	100
Tra Vinh	10	80	100	100	100	100
Soc Trang	5	50	100	100	100	100
Bac Lieu	5	50	100	100	100	100
Ca Mau	5	50	100	100	100	100
Kien Giang	5	50	100	100	100	100

Source: Van Ledden et al. 2020.
Note: Each number represents the share of modelled coastal flood extent that is actually expected to occur in a given province for a specific return period taking into account the current state of the existing flood protection infrastructure. These offsets are designed to be used specifically with the flood maps described in section 2.1 and should not be used in combination with other flood maps or for other applications.

Table 3.4: Protection offset share for riverine flooding for each coastal province and return period

	Return period in years					
Province	**5**	**25**	**50**	**100**	**250**	**500**
Quang Ninh	0	50	1	1	1	100
Hai Phong City	0	0	0	0	5	100
Thai Binh	0	0	0	0	5	100
Nam Dinh	0	0	0	0	5	100
Ninh Binh	0	0	0	0	5	100
Thanh Hoa	0	0	5	100	100	100
Nghe An	0	0	5	100	100	100
Ha Tinh	0	0	5	100	100	100
Quang Binh	0	100	100	100	100	100
Quang Tri	0	100	100	100	100	100
Thua Thien - Hue	0	100	100	100	100	100
Da Nang City	0	100	100	100	100	100
Quang Nam	0	100	100	100	100	100
Quang Ngai	0	100	100	100	100	100
Binh Dinh	0	100	100	100	100	100
Phu Yen	0	100	100	100	100	100
Khanh Hoa	0	100	100	100	100	100
Ninh Thuan	0	100	100	100	100	100
Binh Thuan	0	100	100	100	100	100
Ba Ria-Vung Tau	0	100	100	100	100	100
Ho Chi Minh City	0	0	0	5	100	100
Tien Giang	0	5	100	100	100	100
Ben Tre	0	5	100	100	100	100
Tra Vinh	0	5	100	100	100	100
Soc Trang	0	5	100	100	100	100
Bac Lieu	0	5	100	100	100	100
Ca Mau	0	5	100	100	100	100
Kien Giang	0	5	100	100	100	100

Source: Van Ledden et al. 2020.
Note: Each number represents the share of modelled riverine flood extent that is actually expected to occur in a given province for a specific return period taking into account the current state of the existing flood protection infrastructure. These offsets are designed to be used specifically with the flood maps described in section 2.1 and should not be used in combination with other flood maps or for other applications.

This newly created body of flood protection infrastructure knowledge allows for refinement of the flood exposure analysis in Vietnam. Ideally, it would be used to rerun the flood modelling. However, this is very difficult for several reasons. First, it would require manual modelling of all the categorized flood protection measures and their effectiveness. Furthermore, in order to incorporate structures as small as an individual dike, the resolution of the flood model would need to be increased drastically. Given the country-level scope of this analysis, this would result in large increases in the computational power required. Finally, and most crucially, re-implementing the flood model at a higher resolution requires a digital terrain model (DTM) of equally high or higher resolution (Rentschler et al. 2019a for an example of the creation of a detailed flood map which incorporates man-made structures at the city level in Kampala). In the

future, high-resolution DTMs based on technologies such as LIDAR might enable such an approach even at the country-level, but this is beyond the scope of this work.

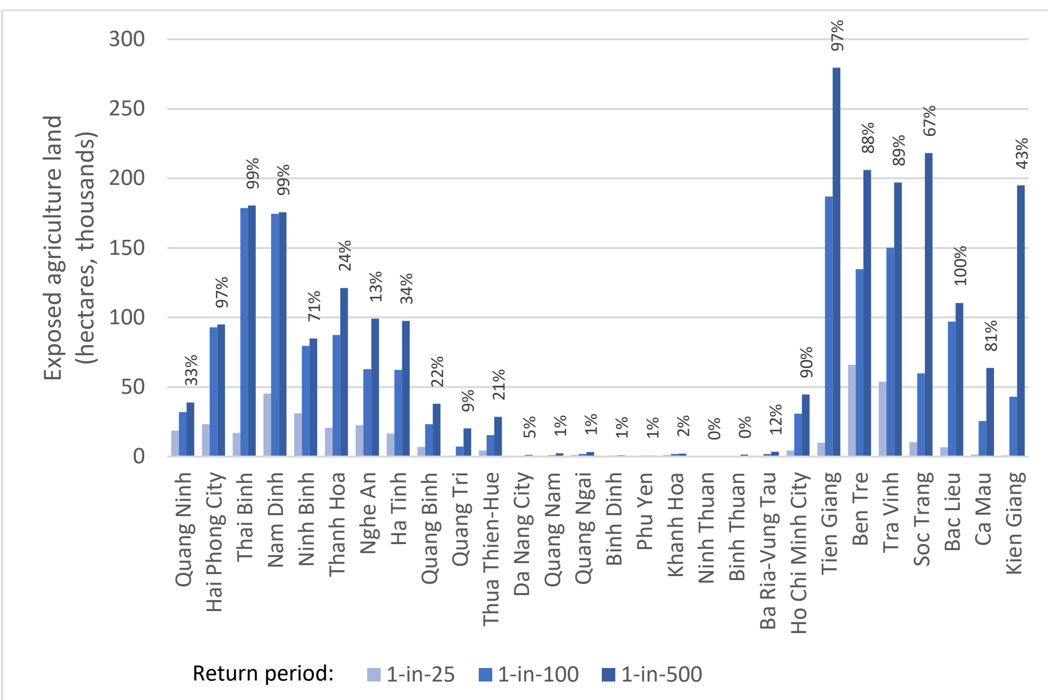
4.2. Flood exposure of agriculture and aquaculture production

The exposure of agricultural production to flooding is estimated based on the land-use maps described in section 3.1. Specifically, a distinction is made between areas where there is farming of rice, orchards and other crops. As the resolution of the datasets differs, the flood maps are scaled up to match the detailed resolution of the land use data. This can be conceptualized by dividing a square into four new squares that occupy the same area. For each agricultural land use type and each flood return period, the amount of flooded agricultural area per province is extracted using a spatial overlay. This is done separately for coastal flooding and for riverine flooding. Agricultural area is considered to be flooded if it is affected by flooding to a depth of at least 25cm, a threshold chosen as most plants cannot withstand flooding above this height. Finally, the results of flood-exposed agricultural area are corrected to account for existing flood protection infrastructure in each province, as described in section 4.1.

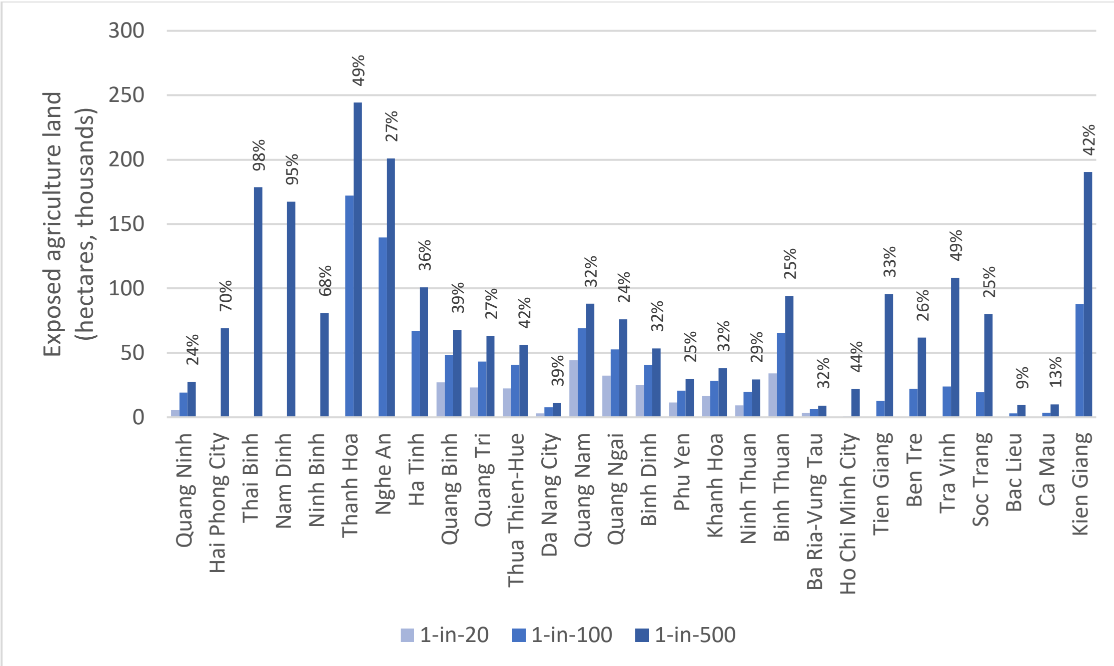
Figure 4.1 and Figure 4.2 give an overview over the exposure of crop and rice production to flooding of three different return periods while accounting for protection infrastructure.

Figure 4.1: Agricultural crop production is particularly exposed in the Red river and Mekong delta, especially for coastal flooding

a) Coastal flood risk: exposure of all agricultural land (sum of rice, crops and orchards)



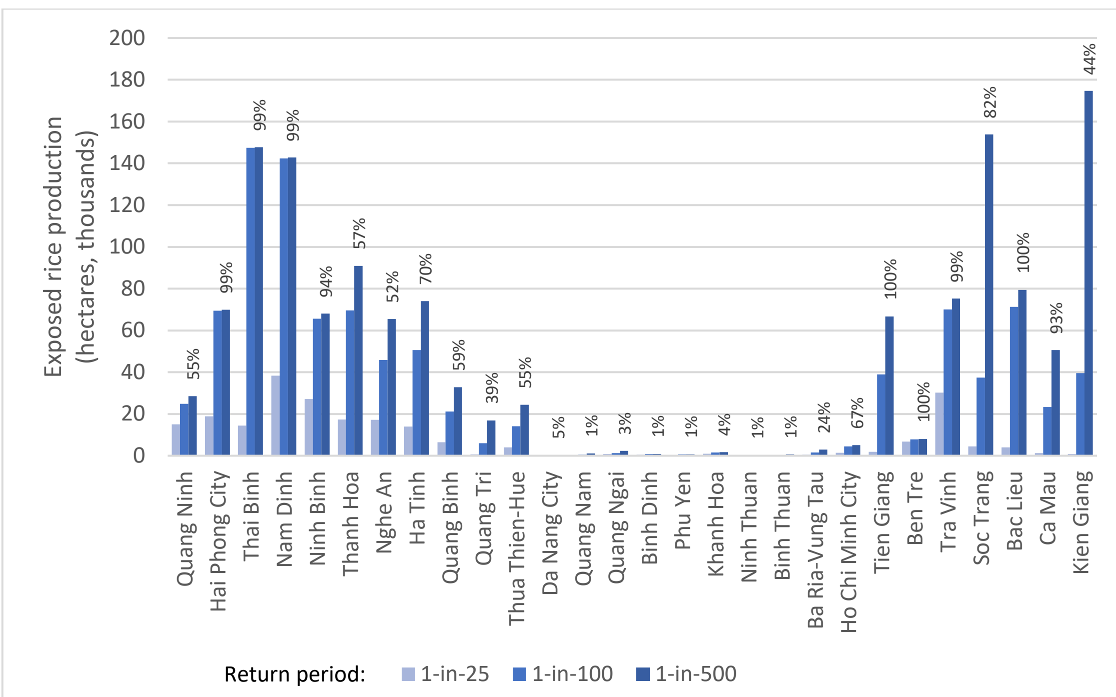
b) Riverine flood risk: exposure of all agricultural land (sum of rice, crops and orchards)



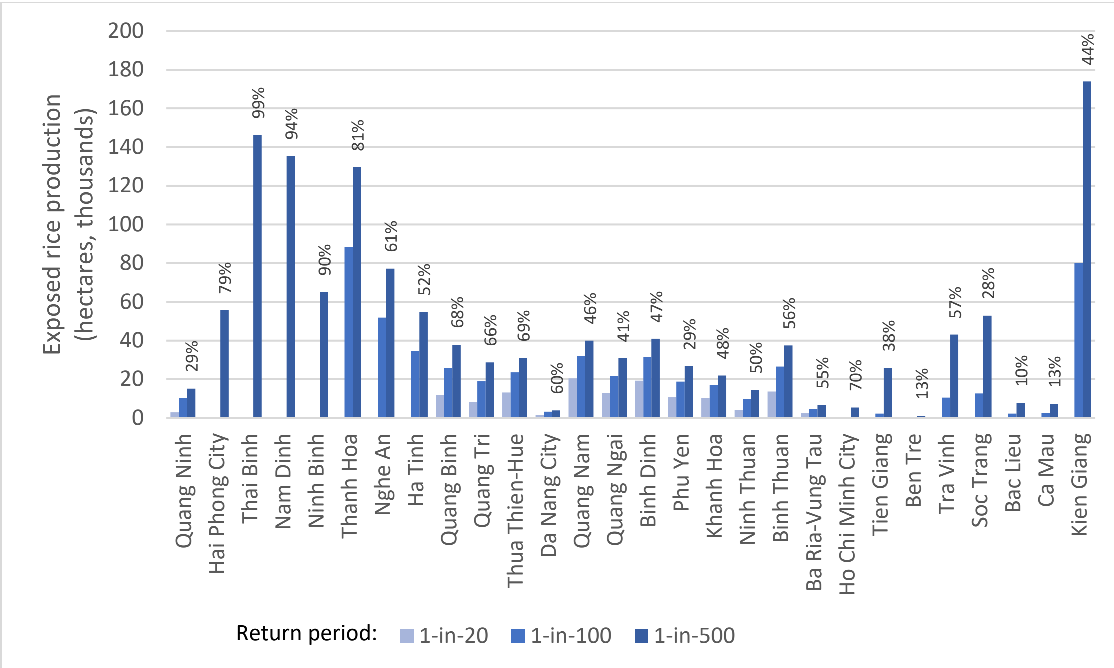
Data: JAXA EORC, 2018 (land use maps), Braese et al. 2020 (costal flood maps), Fathom[1] (riverine flood maps).
Note: Shown percentages are percentages of flooded crop area for a 1-in-500-year flood. A flood threshold of 25cm has been applied,

Figure 4.2: Rice production in the Red River and Mekong Deltas are particularly exposed to flood risks, especially for coastal flooding.

a) Rice production area exposed to coastal flood risk



b) Rice production are exposed to riverine flood risk

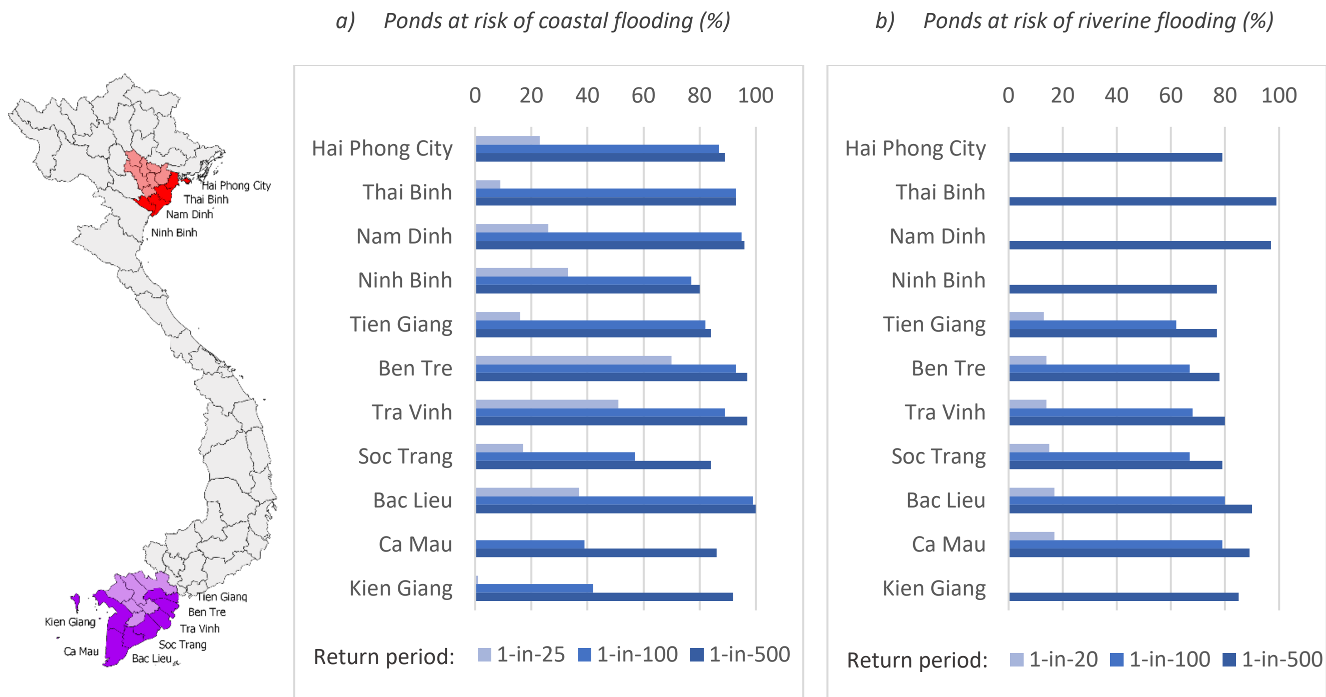


Sources: Based on data from JAXA EORC 2018 (land use maps), Braese et al. 2020 (coastal flood data) and Fathom[1] (riverine flood data).

Note: Shown percentages are percentages exposed rice area for a 1in500 year flood. A flood threshold of 25cm has been applied.

The exposure of aquaculture production in the two big deltas is based on the two datasets of aquaculture ponds described in section 3.2, provided in vector format. In order to overlay these with flood maps, the pond datasets are converted into high-resolution raster data. This reduces the accuracy of the data, as ponds are not square and thus do not exactly match the raster grid. To increase robustness of the analysis, two different rasterization strategies are employed that yield an under and overestimation of the actual pond area. [6] The averaged result of the two strategies is used in further calculations. As the resolution of the flood maps is coarser than the ponds map, the impact of the information lost in the pond rasterization on the result is small. The remaining methodology for aquaculture exposure estimates is equivalent to that for agriculture. It involves downscaling of the flood raster, computing overlays per province, averaging the results from the two-pond rasterization strategies, and applying the flood extent offsets to account for flood protection infrastructure. This is repeated for all return periods in each of the two sets of flood maps – coastal and riverine – and each coastal province in the two deltas. The results for a 20-, 25-, 100- and 500-year return period are shown in figure 4.3.

Figure 4.3: Aquaculture is severely threatened by coastal flooding, but the protection system means the risk of river flooding is lower



Sources: Based on data from JAXA EORC 2018 (land use maps), Braese et al. 2020 (coastal flood data) and Fathom[1] (riverine flood data).

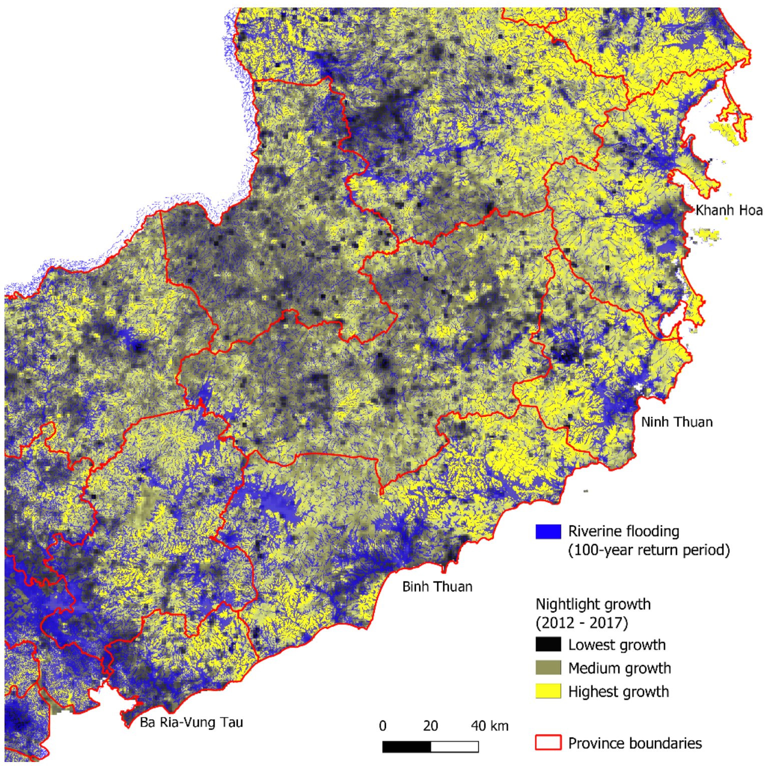
4.3. Flood exposure of socioeconomic and electricity infrastructure assets

Based on land use data described in section 3.1 flood exposure in built-up areas has been analyzed (figure 4.4). Using the nightlight data described in section 3.3 the same has been done for fast-growing regions (figure 4.5). As both datasets are provided in raster data formats, the methodology employed is equivalent to that for agriculture.

Figure 4.4: Urban and built-up areas around Phan Thiet exposed to a 100-year riverine flood

Source: Fathom[1] (flood map), JAXA EORC, 2018 (land use map), Google Maps (background satellite image).

Figure 4.5: Urban and economic growth is concentrated in some of Vietnam's areas most exposed to natural hazards



Source: Fathom[1] (flood map), World Bank, 2020 (nightlight data).

The other socioeconomic assets described earlier (industrial zones, hotels, health care facilities, schools, powerplants and electrical substations) are in point formats. A hotel, for example, is represented by a latitude-longitude pair located at its center. However, it is not only at this center point at which danger of flooding is relevant, but also at the surrounding hotel buildings and recreational facilities. In order to take this into account, a circular buffer of a fixed length is defined for each asset type described by a point location. This buffer is chosen to approximate the typical size of each analyzed asset class. Flood exposure is then checked not only at the center point, but also at the buffered area around the point. The buffers assigned to assets are 100 meters in radius for hospitals, schools, electrical substations, and industrial areas, and 200 meters in radius for hotels and power plants. Flood exposure is determined as in the previous analyses, with the results computed and protection offsets applied for each province, return period, and set of flood maps.

4.4. Typhoon wind exposure of electricity transmission infrastructure

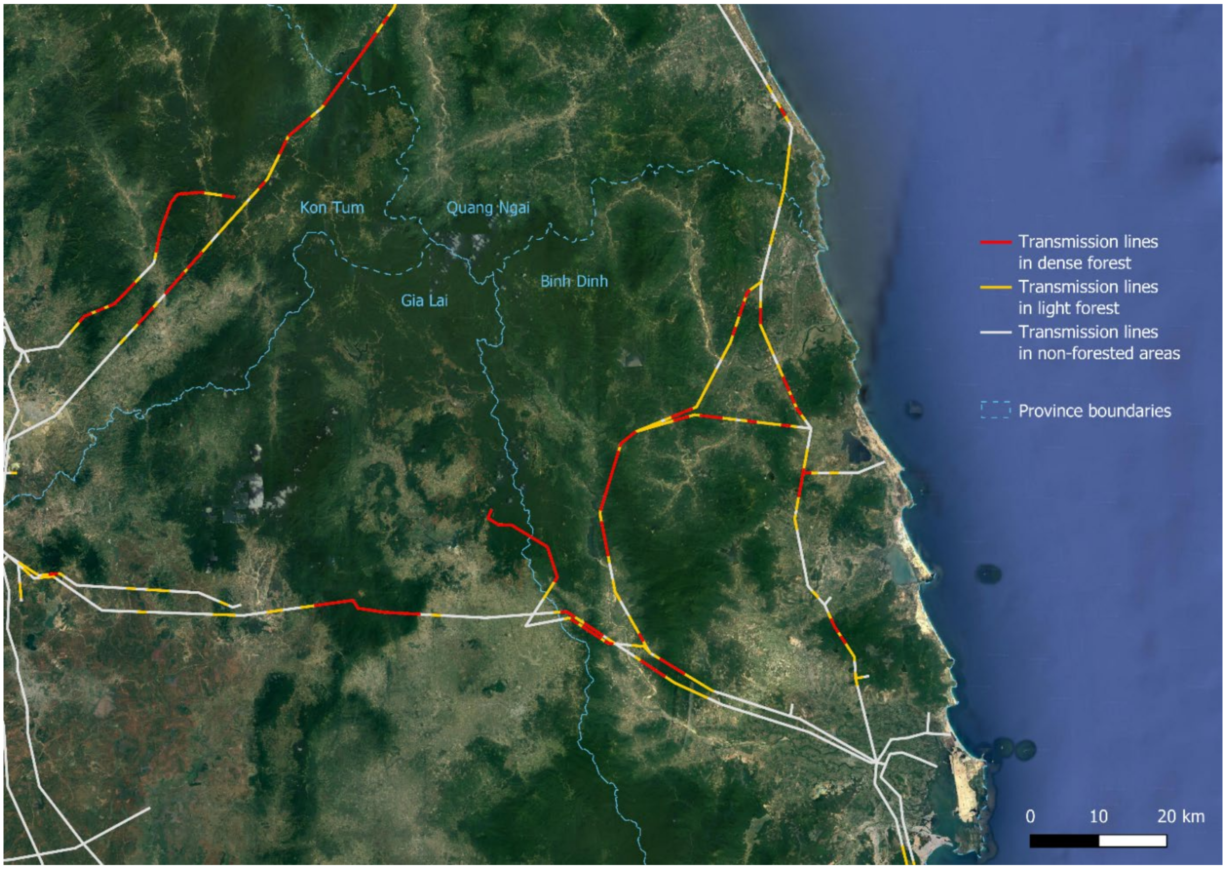
The exposure of electricity transmission infrastructure to cyclones is computed similarly to the flood exposure analysis. For each cyclone return period, an overlay between the cyclone raster and the transmission lines in polygon form determine which parts of the network are affected by which wind speed.

But high wind speeds do not have the same effect everywhere. In fact, their disruptive impact on the power grid is mediated by forests. Outages during storms are often caused by trees that fall onto transmission lines and take out a section of the grid (Rentschler et al. 2019b). In order to identify sections of the power grid that are particularly threatened in this way, the land use data described in section 3.1 is incorporated into the analysis. Specifically, the area surrounding the transmission lines (within 100 meters on either side) is probed on whether it is forested or not. Then, each 1 kilometer section of the grid is classified as either located in a dense forest (at least 75 percent tree cover), located in a light forest (tree cover between 25 and 75 percent), or located in a non-forested area (figure 4.6).

According to this approach, 36 percent of the Vietnamese transmission grid is located in forests, and 15 percent is located in dense forests. The exposure to typhoon wind speeds is then determined individually for the sections of the transmission network located in heavy, light, and non-forested areas.

As mentioned in section 3.7, the digitization process of the power lines could have resulted in errors in the locations of certain sections of the grid. Given the resolution of the wind speed data of about 30km, this should not have a major effect on the overlay with the wind speed data. However, the classification of transmission line segments according to the forest cover in the surrounding area is more sensitive to such errors. Here, the vertical displacement of a power line section could lead to it being classified as non-forested when it is located in a forest or vice versa. Although this inaccuracy is somewhat reduced by looking not only at the area directly underneath a power line but also the area surrounding it, this caveat should be kept in mind when interpreting the results.

Figure 4.6: Transmission lines classified according to forest cover in surrounding area in central Vietnam



Source: World Bank, 2017 (transmission lines), Google Maps (background image).

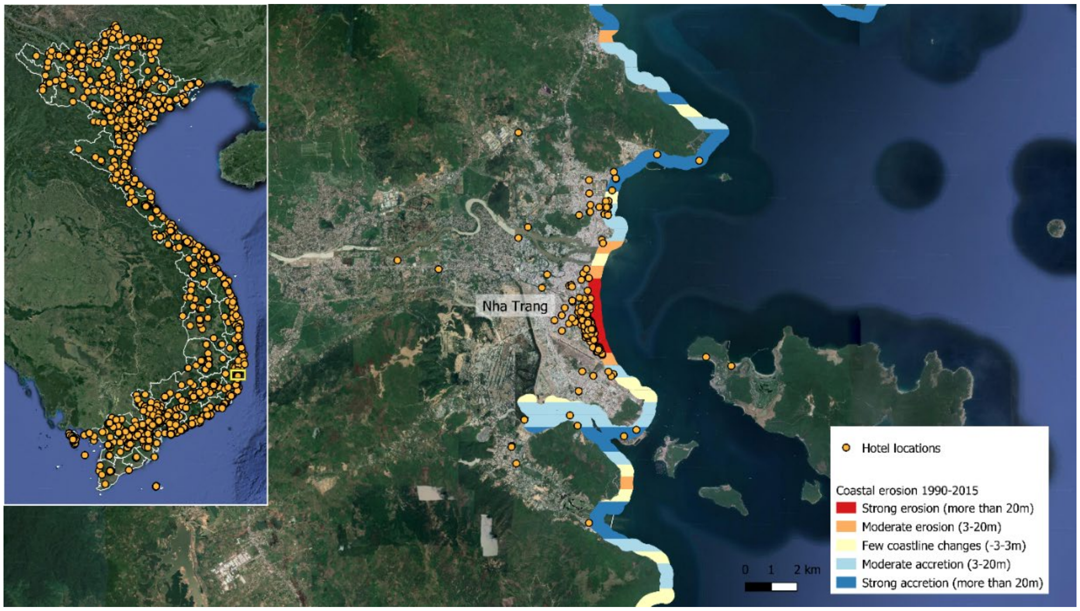
4.5. Coastal erosion exposure

This analysis uses coastal erosion data introduced in section 2.3 to assess the overall exposure of coastal hotels in Vietnam to changes in coastal sediment. Coastal hotels are defined as lying within 5 kilometers of the shoreline. For these, the nature and state of the coastline are assumed to be significant factors in their attractiveness to tourists. In the 28 coastal provinces, the hotel dataset described in section 3.5 contains 3,309 hotels, of these 1,531 are located within 5 kilometers of the coast (figure 4.7).

The exposure of hotels to erosion is computed at the nearest point of the seashore for each coastal hotel. Almost a fifth experienced coastal erosion of more than 20m between 1988/1990[7] and 2015 on the nearest section of the coast. In contrast, accretion of more than 20m affected the coastline near more than a fifth of these hotels.

An analogous analysis is conducted to get an estimate of the exposure of built-up coastal areas. Based on the land use maps described in section 3.1, coastal settlements are defined as built-up areas within 250 meters of the coastline. Erosion is evaluated at the closest shoreline point for each of these built-up areas. The results show that only 19 percent of settlements in Vietnam's northern and central shores are near stable coastlines, more than one-third are near moderately or severely eroding shores, and almost half experience moderate or severe accretion. In the Mekong Delta's coastline is among the most dynamic, with more than two-thirds of built-up areas experiencing severe coastline changes — more than 20 meters of accretion or erosion — between 1988 and 2015.

Figure 4.7: Right panel: Hotels and coastal erosion in Nha Trang. Left panel: Locations of hotels sourced from OpenStreetMap in Vietnam



Source: Deltares et al., 2017 (erosion data), OpenStreetMap, 2019 (hotel locations), Google Maps (background image).

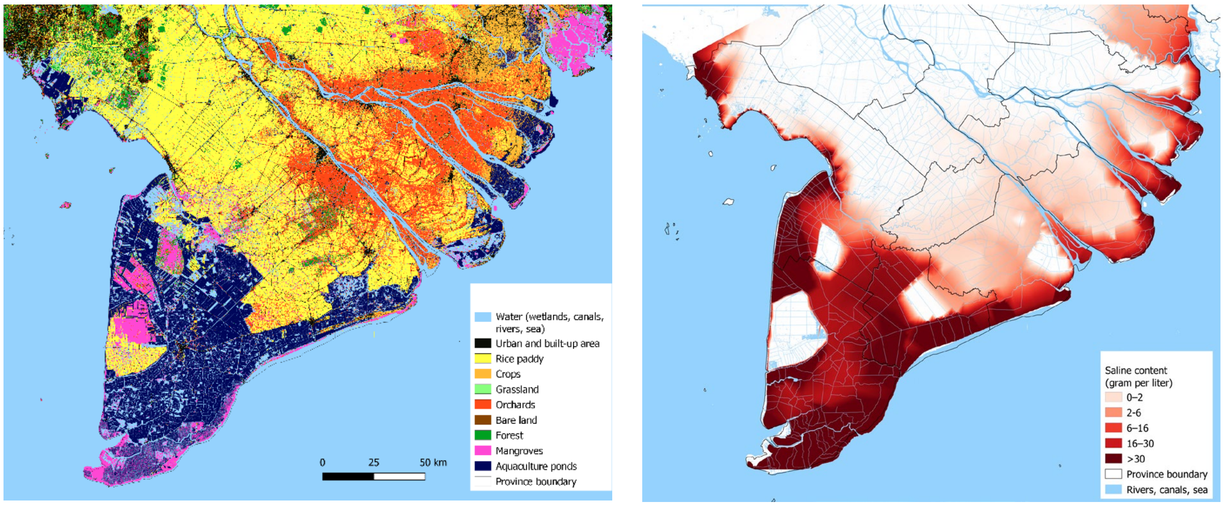
4.6. Saline intrusion and agricultural production

In the Mekong River Delta, saline intrusion harms agricultural production in dry years. This analysis quantifies the extent to which production of rice, other crops, and orchards were affected by saline intrusion in 2016. The location of agricultural production is based on the land-use maps described in section 3.1 (figure 4.8.a), while hazard information is extracted from the saline intrusion maps introduced in section 2.4 (figure 4.8.b). Overlaying these two datasets allows quantification of the production area affected by different levels of salinity per province and agriculture product. A brief overview over the results is given in figure 4.9.

Figure 4.8. Saline intrusion poses a significant risk to rice production in the Mekong Delta

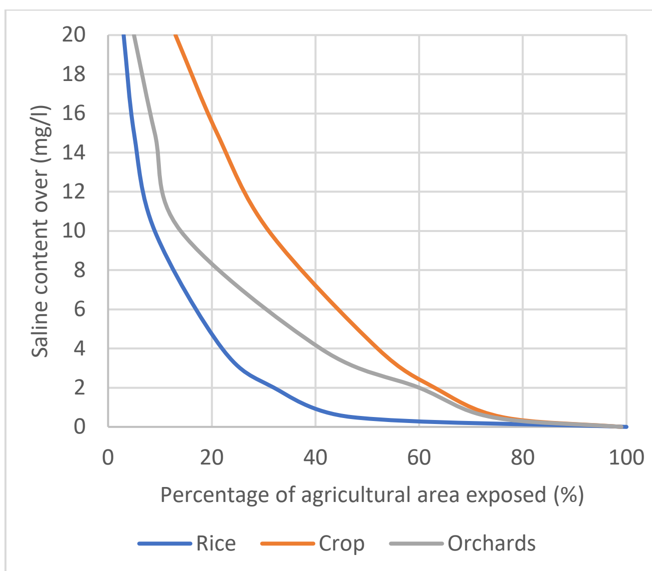
Agricultural production area affected by saline intrusion in the Mekong Delta, 2016

a) Land use *b) Saline intrusion in 2016*



Source: JAXA EORC, 2018 (land use map), SWIRR[2] (saline intrusion data).

Figure 4.9: Agricultural production in the Mekong River Delta affected by saline intrusion with varying severity in 2016



Data: JAXA EORC, 2018 (land use map), SWIRR[2] (saline intrusion data).

5. An approximation of economic impacts

The analyses in this work so far describe exposure in terms of the percentage of a certain asset affected by a natural hazard. This section aims to transform these estimates into figures that might be considered more tangible and easily interpretable. Specifically, it approximates economic impacts in monetary terms and in jobs affected.

5.1. General approach and assumptions

To transform exposure estimates derived in section 4 to economic figures, province-level economic data, such as contribution to GDP, export and employment data, obtained in section 3.8, are combined with asset exposure estimates from section 4. This translates flood exposure estimates into economic exposure estimates providing an approximation of the economic impact of the natural shock. To illustrate this, assume a 100-year coastal flood exposes 40 percent of the rice paddy fields in coastal provinces. Total yearly export value of rice derived from coastal provinces is $1.2 billion, providing jobs to 2.2 million people. Following the employed methodology, given flood would put at risk $480 million worth of exports and some 880,000 jobs. Following this methodology, impact estimates are produced under two simplifying assumptions.

First, sectoral output must be evenly distributed across all assets of that sector within each province. For hotels, as an example, this assumes that all hotels contribute equal revenue to GDP. For agriculture this means that there are no differences in yield and productivity across provinces, implying that X percent of crop fields in a certain province contribute exactly X percent of national crop production, and therefore also contribute X percent to agriculture GDP, agricultural export and job creation. In reality there are many factors affecting agricultural yield, such as different soil resources, water resources, availability of irrigation systems, input, and so forth. For rice, due to data availability, calculations take differential provincial yields into account. Due to data limitations, for other crops and orchards, this is not possible.

Secondly, the analysis is simplified considerably by assuming equal damage from all kinds of exposure to one natural hazard. It is assumed that if a certain asset is exposed to a certain shock, all annual output from that asset is exposed. In reality, damages to the business of a hotel experiencing flooding to a depth of 20cm will be different to one affected by 80cm of flooding. However, linking the amount of exposure to a degree of damage requires empirical damage curves which are not available in Vietnam, and hence would require considerable assumptions as well. The scope of this analysis assumes constant damages resulting from a binary exposure criterion.

Considering the simplifying assumptions made in the hazard assessment and in the conversion to economic estimates, the figures estimated here should not be treated as forecasts or certain facts. Instead, they represent an estimate of the extent of economic activity endangered by a natural shock of a certain return period. As such, they aim to serve as an easily interpretable and comparable approximation of the impacts of natural hazards that form the basis for policy discussions.

5.1. Economic impacts of flooding in the agriculture sector

For agriculture, an economic assessment is made separately for the aggregated cultivated crops sector and for rice. The economic impact for this sector is estimated using the exposure estimations from section 4. For both coastal and riverine flooding a inundation threshold of 25cm is applied. For aggregated corps total area per province used for cultivated crops is used to disaggregate national export value and

cultivated crops contribution to GDP at provincial level. The same holds for employment. It is thus assumed here that there are no significant differences in productivity or yield among different provinces. For rice, a slightly different methodology has been applied. Export value and jobs are disaggregated based on provincial share of area used for rice production. To arrive at provincial rice output (in ton), provincial rice area (in hectare) and provincial rice yield (ton/ha) are used. Then, jobs or monetary value at risk is calculated multiplying the provincial level estimates with the provincial level exposure for the different return periods. Detailed province-level results for each return period and type of flooding are summarized in the technical annex to the main report (De Vries Robbé et al. 2020).

5.2. Economic impacts of flooding in the aquaculture sector

The economic impact of flooding on aquaculture production is estimated based on the exposure calculated in section 4. For each coastal province in the Red River and the Mekong Deltas, the analysis of section 4 gives the share of aquaculture production affected by any flooding of a certain return period. Multiplying the affected share with the provincial aquaculture output in tons, aquaculture contribution to GDP in $ or number of aquaculture jobs at the province level gives an estimate of the economic impact of each flood event in each province. To arrive a provincial disaggregation of export, GDP and jobs, the national values are distributed among the provinces using provincial aquaculture production numbers. Here assumption is made of that factors as yield and productivity are uniform across provinces. Put differently, a province creating X percent of national aquaculture production is assumed to produce X percent of national aquaculture exports. Detailed province-level results for each return period and type of flooding are summarized in the technical annex to the main report (De Vries Robbé et al. 2020).

5.3. Economic impacts of flooding in the tourism sector

For tourism, economic estimations are conducted for flooding and coastal erosion. The share of hotels exposed to each of the two hazards in each coastal province is sourced from the exposure analysis in section 4. For flooding, this consists of the share of exposed hotels by 25cm flooding for each flood return period. For erosion, this is the share of coastal hotels affected by strong or moderate coastal erosion. The methodology then proceeds in two steps. First, each province’s contribution to tourism GDP is calculated by dividing national tourism GDP by the share of hotels in each province. Analogously, the number of jobs in the tourism industry is distributed among provinces. In the second step, the share of hazard-affected hotels is applied to the amount of GDP or jobs affected for each province, each hazard, and each hazard return period. This results in a province-level estimate of affected GDP and jobs, once for coastal erosion and once for each flood return period. Detailed province-level results for each return period and type of flooding are summarized in the technical annex to the main report (De Vries Robbé et al., 2020).

6. Discussion and conclusion

In conducting a quantitative analysis, this paper relies on the quality of the underlying hazard and sectoral data. The spatial hazard data used to model coastal flooding and typhoon wind exposure are extracted from global hazard models. Such global models require global datasets as input and incur significant computational complexity. Consequently, they have a coarse spatial resolution, like a grid cell size of about 900x900m for coastal flooding in Vietnam. In reality flood depth is not uniform within each 900x900m block of land, but heterogeneous due to the elevation profile within that block. Consequently,

their use results in a loss of information when applied at a local scale. The distorting effect of this is somewhat reduced by using spatial buffers around asset location points. Conceptually, these buffers could be imagined as reducing the asset location point resolution and thus counteracting some of the distorting effects of low-resolution hazard data. In addition, the underestimation of flood extent for extreme coastal flooding in tropical regions, together with the absence of wave setup in the coastal data, will probably result in an underestimation of the effect of flooding, especially in regions where the coast is relatively steep. In future, the development of localized natural hazard models at the national scale could add significant value to risk assessments, especially in the case of coastal flooding.

As the flood maps used here are modelled without information on flood protection, this paper uses an unconventional approach to incorporate flood protection infrastructure into the exposure estimates (section 4.1). The flood exposure offset determined for each province, every return period, and every flood type requires some limiting assumptions – for example, that protection infrastructure protects all assets within a province uniformly. This assumption might be violated for assets like industrial zones, which might be more likely to be situated in places with more advanced protection infrastructure. For other assets such as rice fields, this assumption seems more likely to hold. Still, to avoid severely overestimating exposure when not accounting for protection systems in place, this approach seems reasonable for the scale of the analysis conducted. While it prohibits exposure estimates at the sub-provincial level, it proves useful for estimates at the provincial and national level. Future research aimed at incorporating protection infrastructure into large-scale flood modelling could help make such work-arounds redundant.

As exposure is derived from the combination of hazard and asset information, the results produced hinge on the quality of the asset data to the same degree. The geolocated datasets of hotels and schools are sourced from volunteer contributions, and do not represent all hotels and schools in Vietnam (sections 3.6 and 3.5). It is possible that the nature of crowd-contribution leads to biases in the representation of subgroups of each asset class. For example, as crowdsourcing is unpaid and requires an internet connection, contributions made could overrepresent more easily accessible areas, and lead to the underrepresentation of installations from poorer or otherwise less accessible villages. This is especially true for the results for schools, where the provincial distribution does not match the distribution from the General Statistics Office of Vietnam, and should be interpreted with great care. Still, in data-sparse environments, openly available data can provide second-best options for approximating hazard exposure. Despite their imperfection, such estimates can be valuable in disproving the absence of risk which may be suggested by the absence of information. Results relying on crowd-sourced data thus do not represent hard facts, but best estimates forming the basis for discussion.

In other sectors, asset and socioeconomic data is more reliable, and this leads to greater certainty in the results regarding their exposure. In particular, the analysis uses datasets leveraging new developments in the processing of remote sensing data. These datasets provide highly granular estimates of the locations of specific assets like aquaculture ponds, data which would be prohibitively expensive to collect by other means. Due to the cheapness of computing power and the ease of automated spatial analysis, information about exposure can be created at higher resolutions than ever before. As methodologies to extract specific asset locations from various types of remote sensing data become more established and the barriers to implement these algorithms become lower, the translation of such methodologies to different settings can be expected to produce insights into distributions of natural hazard risk in new regions.

Overall, this paper shows that the exposure of Vietnam's people and their economy is significant, but that this exposure varies greatly. It varies across space as some provinces are more exposed than others. It

varies across time as some provinces are well protected for hazard events with low return periods, but would be seriously exposed in rare shocks. Finally, exposure varies across sectors, as some are more subjected to and affected by natural forces than others, and the contributions provinces make to the aggregated economy differ as well. Such complexity in exposure calls for sophisticated policy measures. Fortunately, the Vietnamese government is aware of these risks, and is actively trying to minimize them. An overview of existing policies and recommendations on how these can be extended to deal specifically with the hazards revealed here can be found in the main report, part 3.

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[1] Information from Fathom Global, https://tinyurl.com/sfzgo7z

[2] Based on data provided by the Vietnam National Disaster Management Authority (VNDMA).

[3] Data on aquaculture ponds and saline intrusion in the Mekong River Delta where obtained from Southern Institute of Water Resources Research (SWIRR) in Hanoi, Vietnam.

[4] Information from World Bank Open Data available at https://data.worldbank.org/

[5] For a more detailed explanation of assessment of the coastal protection system in Vietnam, see the technical background paper by Van Ledden et al. (2020).

[6] The process can be imagined as laying a raster grid consisting only of squares on top of the pond data in polygon format, which consist of many irregular shapes. Due to the fixed grid structure of the raster, not all information from the irregular polygons can be retained. For each square in the raster grid, the rasterization algorithm decides whether to classify the square as “pond” or “non-pond”. In the first approach, only squares in which a pond is located in the square’s center are classified as “pond”. In the second approach, all squares that contain ponds anywhere are classified as “pond”. Overall, the first approach can be expected to underestimate the total pond area while the second approach is more likely to overestimate. Thus, this analysis uses both approaches, determines flood exposure for both scenarios, and then averages the results.

[7] Erosion data is available between 1990 and 2015 for Vietnam’s northern and central shores and between 1988 and 2015 for the coastal provinces in the Mekong River delta including Ho Chi Minh City and Ba Ria-Vung Tau province

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