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Research Article

Assessment of the impact of climate change on the water resources in Phu Yen province, Vietnam

Nguyen Van Hong[1]*

[1] Sub Institute of Hydro–Meteorology and Climate Change; nguyenvanhong79@gmail.com

*Corresponding author: nguyenvanhong79@gmail.com; Tel.: +84–913613206

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Abstract: This study investigates the impact of climate change (CC) on water resources in Phu Yen province, Vietnam by assessing historical trends of temperature, rainfall and flood simulation scenarios from a report of Vietnam of the Ministry of Natural Resources and Environment in 2020. The method for assessing the impacts on water resources was provided in the report of the Intergovernmental Panel on Climate Change (IPCC) in 2007. Several areas in Phu Yen province could be high risk of flooding in the middle of the century, such as Son Hoa, Song Cau, Tuy An, Dong Hoa and Tuy Hoa districts, where were chosen as study areas. The analytical results indicate that the impacts of climate change significantly influence to inundation on water resources in these localities. These results could help to partially predict impacts of climate change in the future and provide useful information to plan adaptation strategies in water utilization in Phu Yen province for the policy making on sustainable management with future climatic condition.

Keywords: Impact of climate change; Water resources.

1. Introduction

Climate change has been considered as the greatest challenge of the world. It describes a change in the average climate conditions and extreme events are likely to have major impact on human and ecological systems. The water resources are amongst those severely expected affected by the changing climate [1]. In particular, the hydrological variables in terms of precipitation and temperature affect the intensity, frequency and timing of specific rainfall and potential evaporation, river runoff, surface water, groundwater, flooding, drought, saline intrusion, high tide and water demand [2–9]. The number of reports addressing both climate change and water resources [10–11]. In 2006, [12] reported that approximately 94 million people in the world will be strongly affected by, and sensitive to, variability in climate conditions with an increase around 40 cm of sea level. Among them, about 20% population is in the Southeast Asia area, particularly in the Mekong River Delta (Mekong Delta) and the Red River Delta regions in Vietnam. [13] reported that the sea level in Vietnam is rising up in the range of 1.75–2.56 mm every year. Vietnam is in the group of 5 countries most affected by the climate change, of which the Mekong Delta and the Red River Delta are the two most affected regions in Vietnam – once again the level of danger of climate change to Vietnam is affirmed. In addition, the lower Mekong Basin (Vietnam) is considered as one of three deltas in the extremely vulnerable to climate change beside the Ganges–Brahmaputra (Bangladesh) and Nile (Egypt) [15]. Several topics and projects on the assessment of climate variability relating to social economy in Vietnam were studied by many research groups in Vietnam.

For example, [16] investigated the change in nature, people and socio–economy in Ho Chi Minh City linked the variability of climate condition. In addition, [17] developed a guidance: "Assessment of the impact of climate change and identification of adaptation solutions" funded by the United Nations Development Program (UNDP).

In 2015, [18] developed the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX). [19] investigated the impact of saltwater intrusion and socio–economic factors on agricultural sector in Vung Liem district, Vinh Long province. In particular, in assessing the impact of climate change on water resources (WR), there is a project implemented by the Institute of Hydrometeorology and Environment (2010) in the Mekong Delta sponsored by the Danish Embassy in Vietnam. The vulnerability of water resources also depends on the change in intensity and frequency of extreme hazards, which have been calculated by numerical models such as: climate simulation from the AGCM/MRI (models of the Institute for Meteorology Japan), the PRECIS model of the UK Hadley Center and the CCAM model of the Commonwealth Scientific and Industry Research Organization, Australia (CSIRO), the hydraulic model simulation and the GIS modeling methods [20–21].

Phu Yen is located in the Central of Vietnam, as one of the most beautiful coastal provinces in Vietnam, with coastal islands and a complicated coastline. With the advantage of being a gateway to the sea of the Central Highlands economic region, Phu Yen province has had a strong growth rate, and marine tourism has contributed as a main sector to attract many domestic and foreign investors. So far, the increase in human activities during socio–economic development, and activities of over exploiting GHG sinks in forests and ecosystems enhance greenhouse gases emission, which could enhance the worst influence of climate change in the local area. According to the scenario RCP4.5 by the mid–century, the increase in mean surface temperature every year in Phu Yen province is around 1.5ºC [1]. As for rainfall, by mid–century, the sea level is commonly varying from 8.5–17.4% under the RCP4.5 scenarios. It has been reported that the estimated sea level increasing in Phu Yen province in the mid–century (2050) is around 22.5 cm. Consequently, it is forecasted that the risk of flooding also increases in coastal areas, and along the downstream rivers at low–lying terrain exhibit an increasing the flooding rate varies from 5.55% (in 2021) to 6.29% (RCP4.5 scenarios by mid–century), which is much higher than other areas in the whole province [22]. It is notable that the impact of climate change on the rainfall, flooding, sea level rising, and water resources in Phu Yen province could be extremely unpredictable in the future. It could be a scarcity of water resources in the dry season and flood in the rainy season, leading to the difficulties in water supply and demand in Phu Yen. Therefore, it is needed to assess the impact of climate change on the water resources in the province.

Thus, to assess the impact of climate change on water resources in Phu Yen province, The purpose of this study is used the results of data on climate change scenarios (temperature, rainfall, drought, sea level rise [2]) by using modeling method was mainly used in computing and assessing flood inundation impacts on water resources. The research result provides scientific foundation for strategic solutions and improving action plans to respond to climate change, contributing to ensure sustainable development goals in Phu Yen province.

2. Materials and Methods

2.1. Study area

Phu Yen province is located in the South–Central Coast of Vietnam, with a drainage area of 506,057 hectares which is 1.53% of the total area of Vietnam, as shown in Figure 1. The topography of the province is quite diverse, consisting of 70% high region in the west and 30% of the fertile plain in the east such as coastal plains, low hills, coastal gentle hills, highlands and valleys [22]. Currently, water resources in Phu Yen area are come from (i) rainfall in last 3 or 4 months of the year, with the annual precipitation of 1,700–2,000 mm, and (ii) surface water sources from 17 rivers with catchment areas in range of 100–500 km^2. Among the 3 major rivers including Ky Lo, Ba and Ban Thach River, Ba River is the largest river in the Central area, with a basin area of 13,500 km^2.

Figure 1. Map of Phu Yen province.

Although the rainfall distribution over the year is significantly heterogeneous, the rivers are still the main water resource for agriculture and water supply. In particular, 65–75% of total annual rainfall is distributed from October to December in the wet season (or flood season), while January to September of the next year is the dry season, with around 25–35% of annual rainfall, as measured by volume. Additionally, there are two dry periods in April and August with only 2% of annual rainfall. Moreover, it is influenced by diurnal tide regime from 17 to 23 days every month and also by irregular semi–diurnal tide on the remaining days. Since the heavy floods at the downstream of Ba River and the tides of the East Sea are often occurred at the same time of the year, it may make an extreme danger in the downstream area during flood season, especially in the Tuy Hoa rice cultivation area of Dong Cam irrigation system. Therefore, it is necessary to have solutions for water drainage in the downstream areas and especially in the rice cultivation areas and Tuy Hoa city.

2.2. Modeling setup

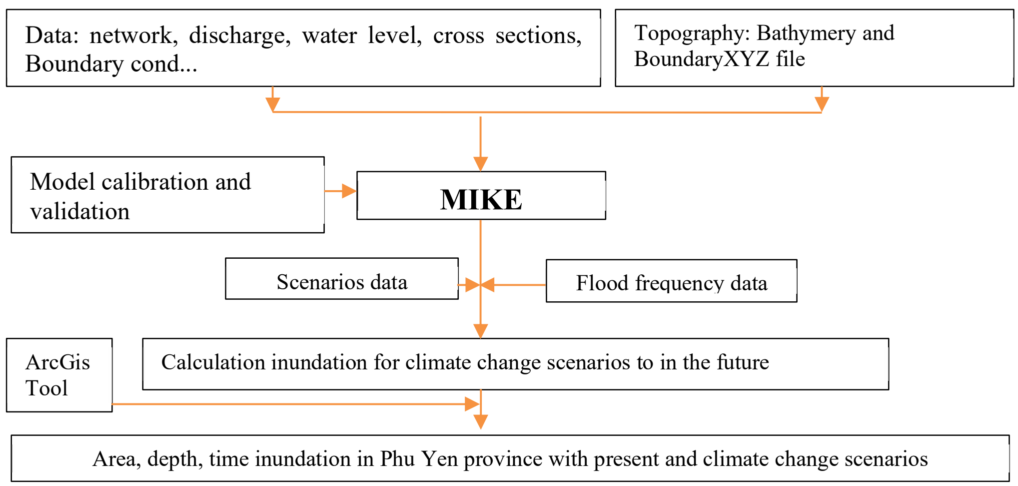


Figure 2. Oriented framework for flood calculation in Phu Yen province.

The modeling method will be mainly used in calculating and assessing flood impacts on water resources. MIKE of DHI software for the hydraulic calculation of the study area are applied in the study and the used modules consist of MIKE 11HD, MIKE 21FM and MIKE FLOOD. Models are calculated in accordance with the orientation frame, as shown in Figure 2.

2.3. Methods of assessing climate change impacts on water resources

Water resources is a sensitive sector for climate factors such as temperature, rainfall, sea level rise and the increase of the intensity and frequency of extreme climate events. Therefore, climate change has a great impact on water resources (Surface runoff water, reserves of water sources, water quality and quantity). After calculating and analyzing flood inundation levels and affected areas, the analysis of the challenges of water resources in the context of climate change is used in the methods at in the Table 1.

Table 1. Methods of assessing climate change impacts on water resources [17].

Elements of climate	Influenced objects	Risk effects	Evaluation methods and tools
Increased temperature	Surface runoff	Change the operational intensity of atmospheric circulation, water cycle, hydrological regime and other physical cycles	Mathematical model for the correlation between precipitation and temperature and runoff for the basin
Increased Precipitation	Volume of water sources	Increase water volume	Hydrological model

Elements of climate	Influenced objects	Risk effects	Evaluation methods and tools
	Water quality	Water pollution can be spread due to excessive rain causing inundation	Development of flooding maps
Sea level rise	Water source	Increase risk of inundation and soil erosion; change the flow regime in rivers and groundwater; change geomorphology in estuaries.	Models for predicting changes in surface runoff and groundwater Flood mapping method
	Water quality	The level of water pollution increases due to widespread and prolonged inundation	Flood mapping method Vulnerability and impact mapping method
Increase of the intensity and frequency of extreme climate events	Water sources	Inundation increases in some areas	Map overlapping method Vulnerability and impact mapping method

2.4. Spatial interpolation methods

Inverse Distance to a Power and Surfer 10.0 software are utilized to calculated the exposure possibilities of different areas within study scope. The distance inverse method determines values for grid cells by averaging the values of sample points in the vicinity of each grid cell. The closer the point is to the center point (being determined), and the more influence it has.

Interpolation:

$$\hat{Z}(S_0) = \sum_{i=1}^{n} \lambda_i Z(S_i);\ \ \lambda_i = \frac{d_{ij}^{-p}}{\sum_{i=1}^{n} d_{ij}^{-p}} \quad (1)$$

where d_{ij} is the spatial distance between the two points i and j. The higher the exponent p is, the lower the influence of the distant points is and some consider insignificant, normally p = 2. However, in some cases the input data density is high, p must be correspondingly high. In this study, it is expected to apply p = 5.

Search Radius: The characteristic of the interpolated surface is also influenced by the search radius that limits the number of sample points used to calculate the interpolated grid cells.

Barrier: A barrier is a set of polylines as an interruption limiting the area to seek sample points. A polyline can be a cliff, a mountain, or some other barriers in the landscape. When this element appears, only the sample points on the same side and the grid under survey are considered. In the case of interpolation for inundation and saline intrusion, the barrier is the boundary of the rivers.

2.5. Mapping method

Techniques of information integration were used for mapping, overlapping layers of weighted information, synthesizing, calculating for main and sub–indexes through ArcGIS 10.1 software on the map, as coordinate system VN_2000.

2.6. Data

In this study, data used in the method for collecting, synthesizing, inheriting are documents of natural, socio–economic and environmental conditions; data on climate change scenarios (temperature, rainfall, drought) (as shown in figures 3–5), topographical data including 119 of cross – sections, the computation mesh of the main river bed, more than 20 river banks of Ba and Ky Lo river systems and sea level rise in Phu Yen province to develop the inundation maps from which to assess the impacts of climate change on the water resources in Phu Yen province. 270 survey questionnaires of people in 8 cities, towns and districts of Phu Yen province are used to assess which floods have serious impacts in the locality. Inundation and data of climate change and sea level rise scenario are built according to the average emission scenario RCP4.5 in 2030 and 2050 [22].

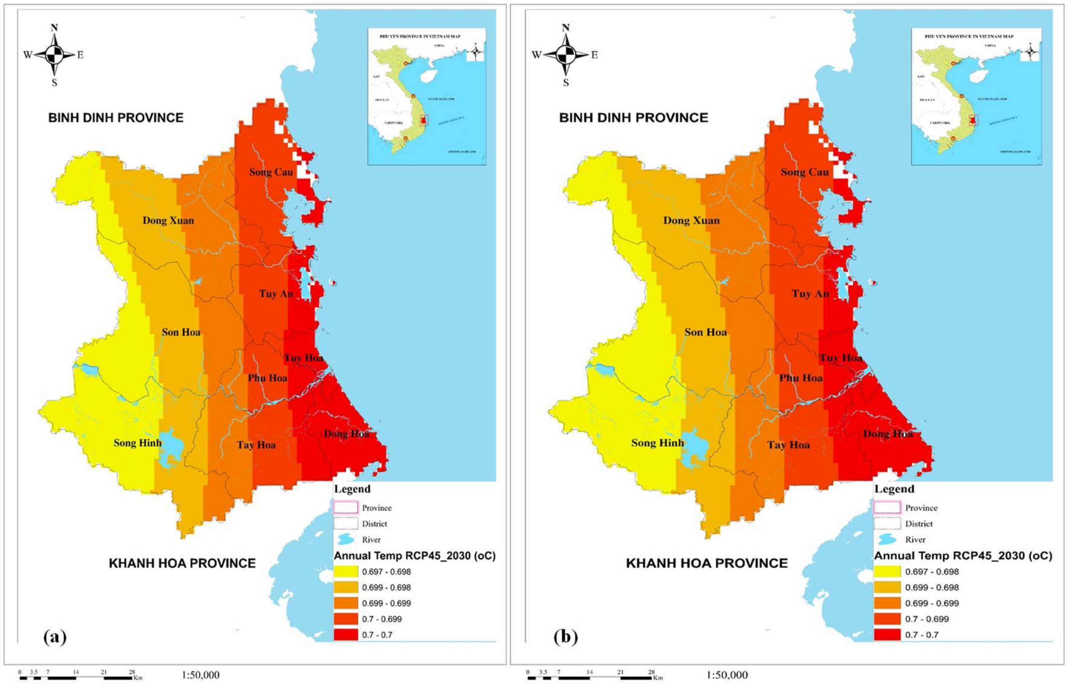


Figure 3. Scenario of annual average temperature change in Phu Yen province: (a) RCP4.5 năm 2030; (b) RCP4.5 năm 2050.

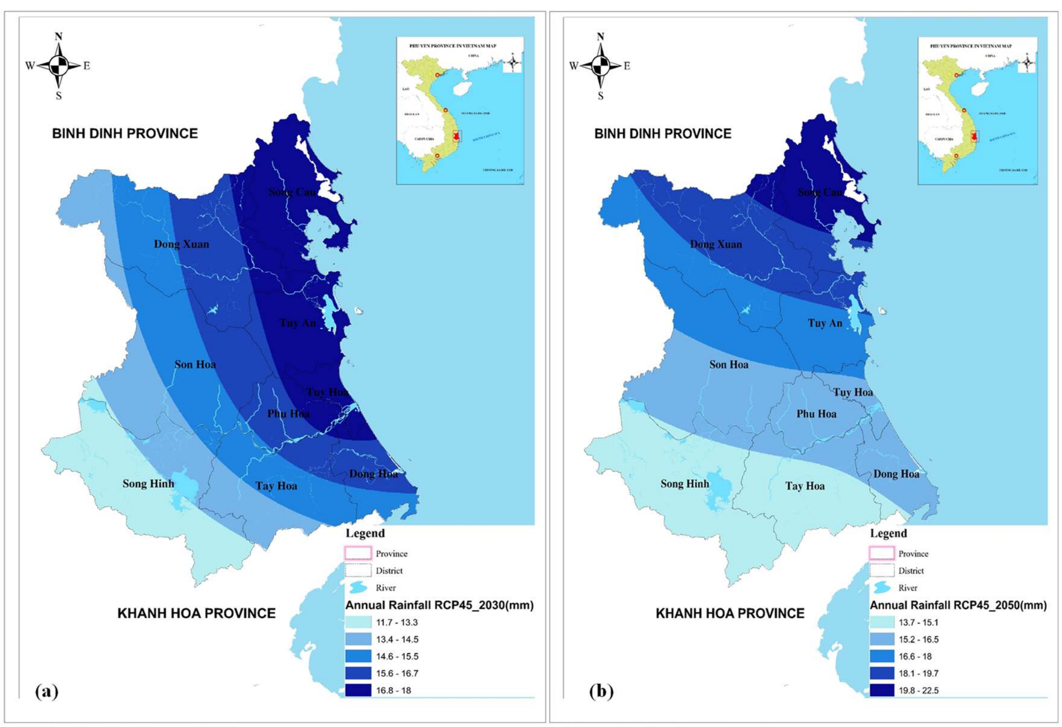


Figure 4. Scenario of annual rainfall change in Phu Yen province: (a) RCP4.5 in 2030; (b) RCP4.5 in 2050.

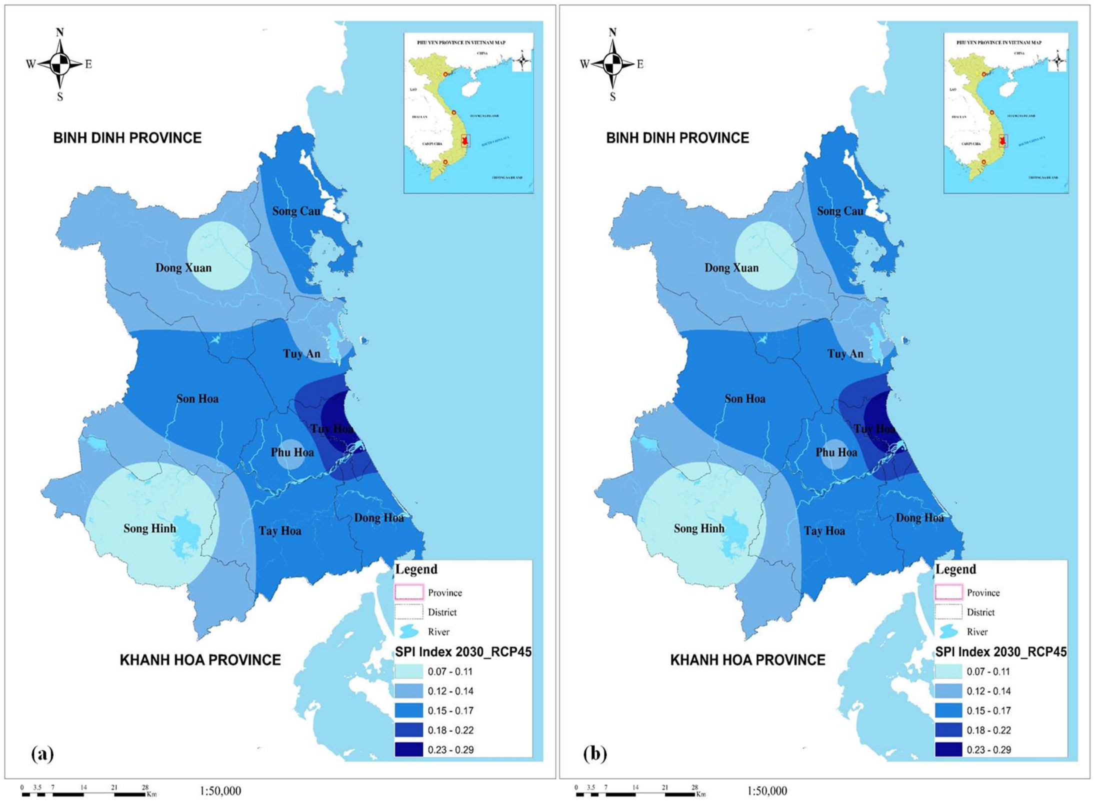


Figure 5. Scenario of changes in the yearly standardized precipitation index (SPI) in Phu Yen province: (a) RCP4.5 in 2030; (b) RCP4.5 in 2050. (Note: SPI Index range: ≥ 2: extremely wet; 1.5 ÷ 1.99: very wet; 1.0 ÷1.49: moderately wet; -0.99 ÷ 0.99: near normal; -1.0 ÷ -1.49: moderately dry; -1.50 ÷ -1.99: severely dry; ≤ -2.0 extremely dry).

3. Results and Discussion

3.1. Model calibration and validationof MIKE 11HD model

Calibration and validation of MIKE 11HD model used the past floods to find the suitable parameters for the simulation scenarios. The calibration and validation process used an observed water level at Phu Lam station during from Feb to July, 2016 and from Feb to July, 2013, respectively. In this study, Nash–Sutcliffe efficient (NSE) and Coefficient of determination (R^2) were used to evaluate the observed and simulated water levels. The results of the calculated and observed water levels are in good agreement in terms of the vibration amplitude, absolute value, and phases during both the calibration and validation processes. The values R^2 ranged from 0.89 to 0.92 for calibration and validation, respectively. It indicates that model results produced for the flow are very good for both periods. The NSE value for calibration and validation of water level at Phu Lam ranged from 0.79–0.80. The simulation results for the hydrodynamic regime using MIKE11HD model were very good in term of performance ratings as revealed by NSE and R^2. The calibration parameters used in the model validation process were bed resistance Manning coefficients which varied from 0.03 to 0.033 ($m^{1/3}$/s). The calibration characteristic parameters such as Manning coefficients (M), time, and time–step is performed by means of gradually.

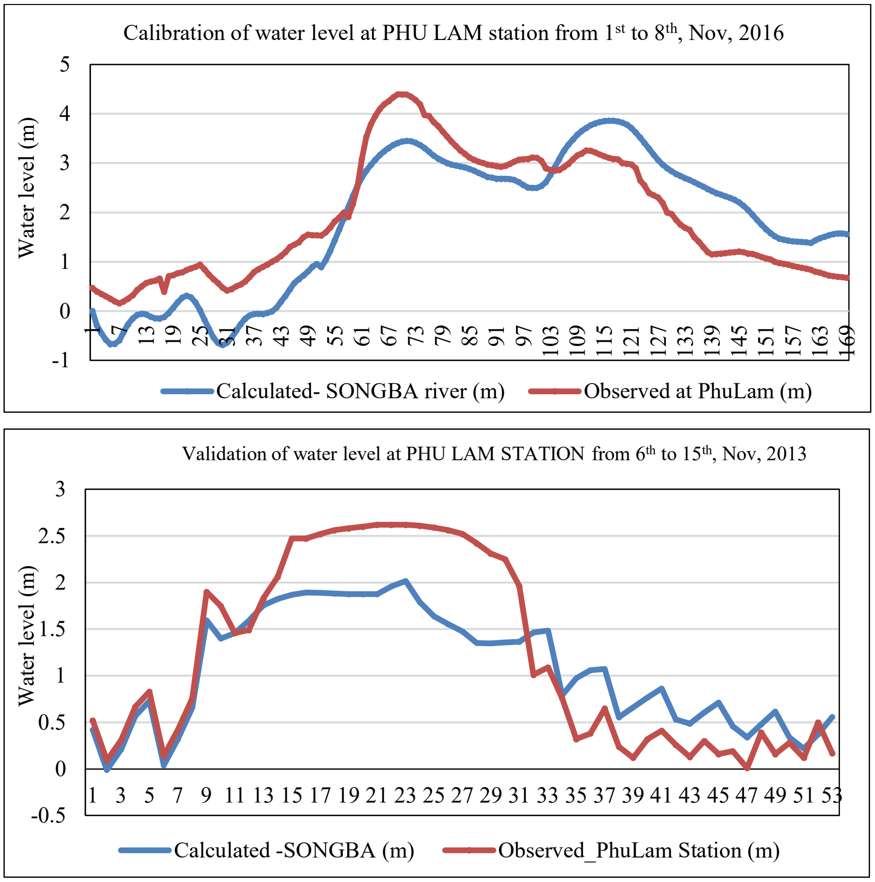
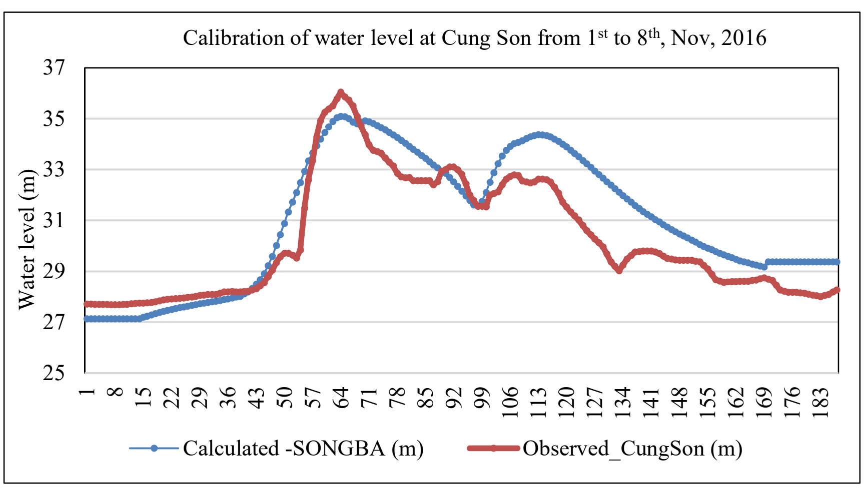


Figure 6. The calibration and validation process used an observed water level at Phu Lam station.

3.2. Model calibration and validation of MIKE FLOOD model

Calibration of MIKE FLOOD model used an observed floods in downstream at Cung Son site, Ba River and Ha Bang site, Ky Lo river. The values R^2 ranged from 0.92 to 0.93 for calibration, respectively (Cung Son site (R^2 = 0.92) and Ha Bang site (R^2 = 0.93)). The NSE value for calibration of water level at these sites ranged from 0.63–0.71 (Cung Son (NSE = 0.71) and Ha Bang (NSE = 0.32)), from 01st to 06th, December, 2016.



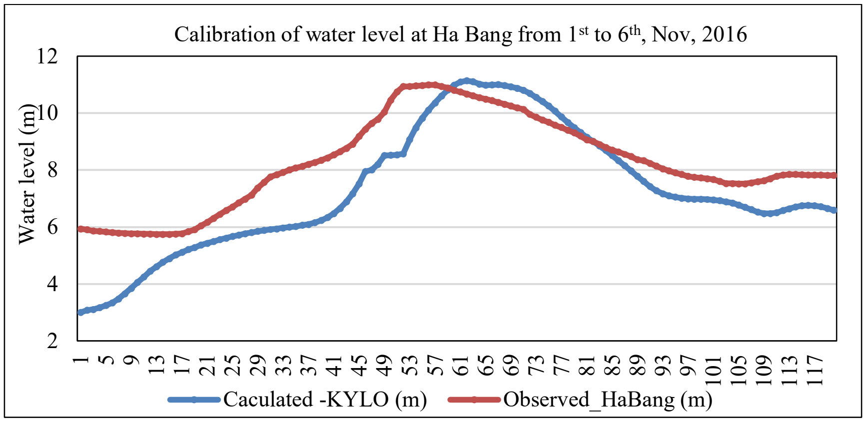


Figure 7. The calibration process used an observed water level at Cung Son and Ha Bang site from 01st to 06th, December, 2016.

Validation of MIKE FLOOD model used an observed floods in downstream at Cung Son site, Ba River and Ha Bang site, Ky Lo river. The values R^2 ranged from 0.92 to 0.96 for validation, respectively (Cung Son site (R^2 = 0.92) and Ha Bang site (R^2 = 0.96)). The NSE value for validation of water level at these sites ranged from 0.72–0.75 (Cung Son (NSE = 0.75) and Ha Bang (NSE = 0.72)), from 04th to 08th, December, 2013.

The validation model results in the flood from 04th to 08th, December, 2013 showed that the MIKE FLOOD model was well–simulated between observed flood and calculated water level at sites. It could be concluded that the MIKE FLOOD hydraulic model was reliable enough to simulate and calculate the flood scenarios and establishing inundation maps.

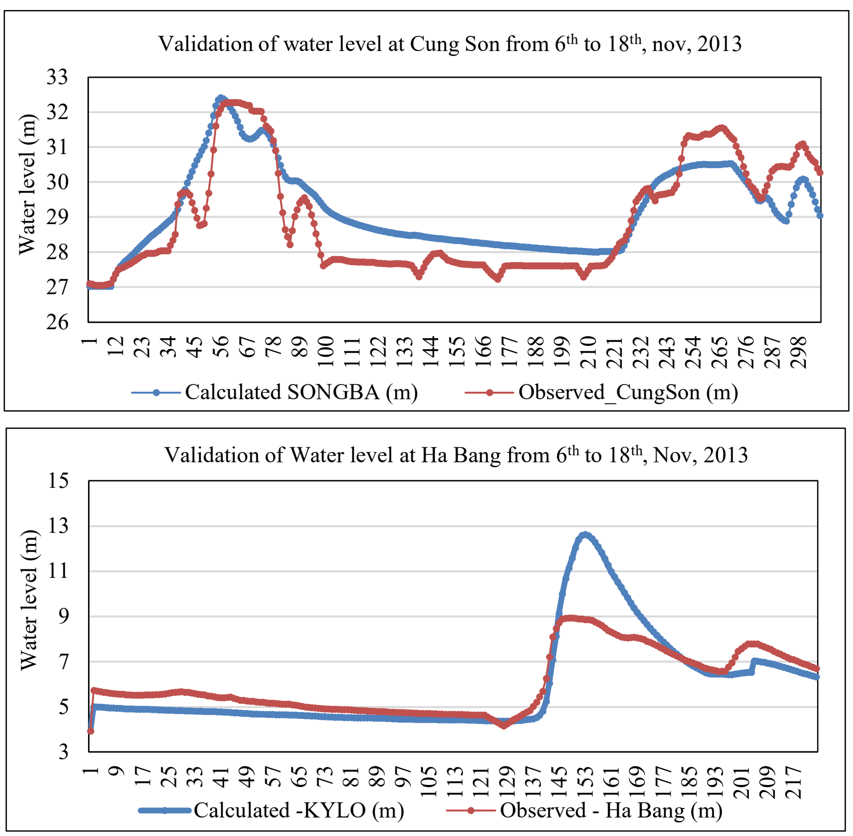


Figure 8. The validation process used an observed water level at Cung Son and Ha Bang site from 04th to 08th, December, 2013.

3.3. Computating flood inundation results

The results of flood inundation in the area are evidenced by the simulation time shown in figure and application of ArcGIS 10.1 software and data layers including flooded layer depths simulated by MIKE FLOOD model, terrain data, administrative boundary data, flood survey data, situational data and so on to establish the inundation map according to the scenarios. The inundation map that illustrates flooding inundation according to the scenario given is shown in Figure 9. Because the territory stretches along the coastline and the river system flows in the West–East direction. The riverbed is steep and narrow at the upstream and wider at the downstream toward the sea. Therefore, the lower coastal area in Phu Yen province is heavily affected by floods. The scenario of climate change (rainfall changes with the seasons), sea level rise is used calculated as the RCP4.5 with scenarios corresponding to the periods 2030, 2050. The results of the calculation flood according to the scenarios represented in Figure 9. The calculated flood inundation results of the scenarios have a relative increase compared to the current flood status, by the rainfall volume in the upstream, sea level rise in downstream of the rivers. The higher the sea level rise scenarios, the greater the flood inundation level and the area of flooding. The areas affected by flood inundation are mainly in Tuy Hoa City, Tuy An District, Cau River Town, Hinh River District and Dong Xuan District.

- Regarding the flood level: the lowest is 0.1 m, the highest is 4.0 m and the maximum flood level is in range of 1.0–3.0 m. Specifically, the flooded area of the whole Phu Yen province with the flooding level of 1.0–2.0 m could be 6,560 and 6,624 ha as predicted in 2030 and 2050, respectively. If the flooding level is from 2.0–3.0 m, the flooded area of the whole province might become to be 7,692 ha (in 2030) and 7,700 ha (in 2050), as shown in Table 2.

- Regarding the flooding scope and flooding rate: the two districts Dong Hoa and Phu Hoa could be largest flooded areas, and highest the flood rates with 11.05% and 13.18% compared to the total natural area of the two districts, respectively (Table 3). On the other hand, the districts Son Hoa, Song Hinh, and Song Cau town have the smaller flooded areas.

Table 2. The flood rea corresponds to flooding levels in Phu Yen province under the RCP4.5 scenario (Unit: hectare).

Time	**2030**					**2050**				
Flood (m)	0.1 – 0.5	0.5 – 1	1 – 2	2 – 3	3–4	0.1 – 0.5	0.5 – 1	1 – 2	2 – 3	3–4
City/ District										
Tuy Hoa City	28	84	604	1084	2468	28	80	676	1024	2528
Song Cau Town	76	212	284	48	88	76	212	284	48	88
Dong Xuan District	12	64	260	372	884	12	64	248	376	892
Dong Hoa District	76	464	1580	2428	6428	76	468	1588	2472	6476
Phu Hoa District	48	600	2288	2352	1600	44	560	2224	2368	1696
Son Hoa District	36	12	112	116	388	36	0	112	112	404
Song Hinh District	92	68	152	120	512	92	44	164	108	536
Tay Hoa District	420	564	708	428	424	720	576	784	476	464
Tuy An District	480	460	572	744	1864	480	460	544	716	1920
Province	1,268	2,528	6,560	7,692	14,656	1,564	2,464	6,624	7,700	15,004

Table 3. Flooded area and flooding rate in Phu Yen province under the RCP4.5 scenario (Unit: hectare).

City, district, town	**Natural area**	**Flood area (ha)**		**The rate of flooded area over the natural area (%)**	
		2030	**2050**	**2030**	**2050**
Tuy Hoa City	110,336.04	4,268	4,336	3.87	3.93
Song Cau Town	28,302.83	708	708	2.50	2.50

City, district, town	Natural area	Flood area (ha)		The rate of flooded area over the natural area (%)	
		2030	2050	2030	2050
Dong Xuan District	26,981.64	1,592	1,592	5.90	5.90
Dong Hoa District	99,289.37	10,976	11,080	11.05	11.16
Phu Hoa District	52,292.90	6,888	6,892	13.17	13.18
Son Hoa District	94,737.44	664	664	0.70	0.70
Song Hinh District	66,611.95	944	944	1.42	1.42
Tay Hoa District	43,283.54	2,544	3,020	5.88	6.98
Tuy An District	11,843.62	4,120	4,120	34.79	34.79
Province	**533,679.32[(a)]**	32,704[(a)]	33,356[(a)]	6.13[(b)]	6.25[(b)]

Note: (a) = Total area, (b)= Rate of flooded area over the province

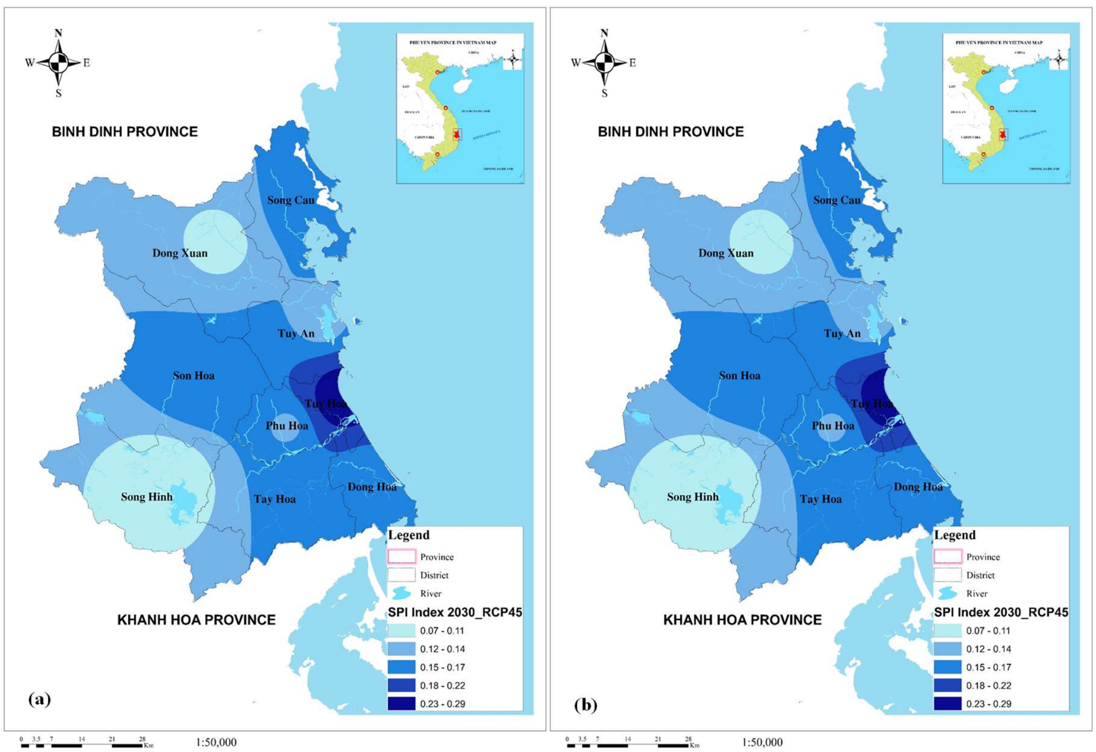


Figure 9. Map of climate change impact indicators in Phu Yen province according to the RCP4.5 scenario: (a) RCP4.5 in 2030; (b) RCP4.5 in 2050.

Regarding the popular flooding depth (0.1–0.5 m) and serious flooding depth (> 2.0 m): It can be observed that the inundation rate in 2030 and 2050 are 3.88 and 4.69 %, respectively, in total flooded area of the whole province, as presented in Table 5.

In the range of popular flooding depth: Tuy An and Tay Hoa district reveal highly proportion of flooded areas with 1.47, 1.28 % (2030) and 1.44, 2.16% (2050), as calculated in the total flooded area of the province, respectively.

In the range of serious flooding depth: Tuy Hoa city, Dong Xuan district and Dong Hoa are localities with higher flooding rates compared to other urban districts in the same depth range. In the years of 2030 and 2050, the above localities have the rate of flooded area over 78% in comparison with the total flooded area of the whole province. In addition, Son Hoa district has flooded areas in 2030 and 2050 accounting for 75.90% and 77.71%, respectively.

Table 4. Flooding rates in Phu Yen province classified by popular and severe flooding depth, RCP4.5 scenario (Unit: %).

City/ District	Popular Flooding Depth (0.1–0.5 m)		Serious Flooding Depth (>2.0 m)	
	2030	2050	2030	2050
Tuy Hoa City	0.09	0.08	81.92	83.22
Song Cau Town	0.23	0.23	19.21	19.21
Dong Xuan District	0.04	0.04	78.89	79.65
Dong Hoa District	0.23	0.23	80.69	80.76
Phu Hoa District	0.15	0.13	57.38	58.97
Son Hoa District	0.11	0.11	75.90	77.71
Song Hinh District	0.28	0.28	66.95	68.22
Tay Hoa District	1.28	2.16	33.49	31.13
Tuy An District	1.47	1.44	63.30	63.98
Province	3.88	4.69	68.33	68.07

Water resources are an important factor in the socio–economic development of each locality, but urbanization and population growth have led to a series of consequences such as water pollution, decrease in water quantity. In addition, climate change factors also contribute to changes in the quality and quantity of water resources. Climate change impacts the water environment through the following aspects:

Rainfall changes, increases in the rainy season and decreases in the dry season, along with an increase in temperature leads to a change in the evaporation factor, which is potential to change the flow of rivers as well as underground water flows. Flood and drought have serious impacts on water environment through both water reserve and quality.

Due to the high risk of flooding in 2030 and 2050, the water resources management in Phu Yen province should be careful considered. The high level of inundation will lead to riverside areas in the Ba River basin from Ha Bang station (Dong Xuan district) to Phu Lam station (Tuy Hoa city) being heavily flooded, with the popular flooding levels in range of 0.6–1.15 m.

- Dams on the river such as Lo Gom, Thach Khe, Dong Kho (Song Cau town) is in the flooded area from 0.65 to 1.25 m. In addition, dams namely Dong Lau, Bau Da, Tan Giang Huong, Dinh Ba are also affected in the popular flooding level of 0.15 to 0.25 m.
- The dyke sections of Xuan Hai, Xuan Loc, Xuan Canh (in Song Cau town), Binh Thanh dyke, An Hiep dyke – Phu My and Ngo Ham Thuy dyke (in Tuy An district) are also in the flooded area due to sea level rise, increasing the risk of bank erosion by the dyke in 2030 and 2050 if there is no response approach for climate change.

In addition to analyzing flooding levels and affected areas, the analysis of the strengths, weaknesses, opportunities and challenges of water resources in the context of climate change is the basis for planning adaptation solutions, integrating into water exploitation and use planning in Phu Yen (Table 5).

Table 5. Analysis on the pros and cons, opportunities and challenges of water resources in the context of climate change in Phu Yen province.

Pros	Cons
Hydropower works and irrigation lakes are capable of storing a huge amount of water, supplementing surface water for many areas Ba River – Ky Lo River flow from the Central Highlands, bringing a relatively large amount of fresh water to the locality.	Irrigation infrastructure is incomplete, many areas are in lack of water in the dry season, especially the mountainous areas affected by salt water intrusion and drought.

Pros	**Cons**
Opportunities	**Challenges**
Heavy rain is an important source of replenishment of surface and groundwater, especially in the rainy season. Irrigation systems are being built to meet the demand of water for production in many different areas.	The dry season is getting more and more severe, leading to a local drought. The water level of the lakes is low in several times, reducing the water supply capacity for production and salinity downstream areas. Flooding caused by tides affects surface water quality, especially in coastal areas such as Tuy Hoa, Song Cau, ... Heavy rains change water quality, water sources containing a lot of pollutants and suspended solid.

4. Conclusion

MIKE software (MIKE11, MIKE 21 and MIKE FLOOD) have been used in this study with rainfall and air temperature data under climate change scenariors. The result shows that: (i) water resources distribution in Phu Yen provice will be potentially affected by the flood due to the sea level rise in some concerned areas including districts with major rivers flowing through and high risk of inundation in the middle of the century such as Son Hoa, Song Cau, Tuy An, Dong Hoa and Tuy Hoa districts; (ii) inundation due to floods will be a source of significant amounts of surface water and groundwater to reduce water pressure during dry times; (iii) inundation caused by the sea level rise will increase the spread of salinity in the surface water, potentially leading to the deterioration of groundwater quality in the coastal areas of the province such as Song Cau, Tuy An, Tuy Hoa and Dong Hoa, etc.

MIKE software is a very useful tool for flood inundation simulation in Phu Yen provice even lack of investigated data on flood traces and MIKE 21 model has not been verified and calibrated. It can be applied effectively to assess impact of climate change on the water resources in other provinces / cities / river basins in Vietnam if measured data on topography, water level and flood traces with high reliability are available.

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Author Commitment Statement: The paper submitted with the full knowledge and consent of the author (if any), without any prior publishment or copy from other previous studies; There is no dispute of interest in the authors group.

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