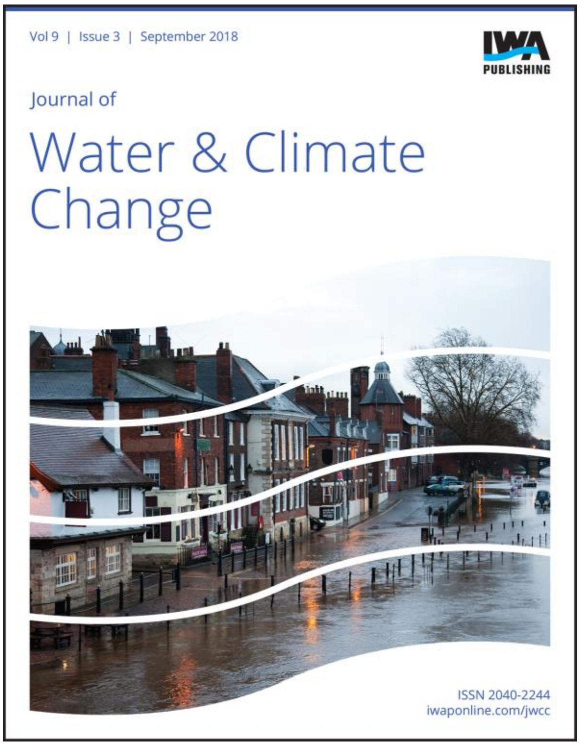
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Delimitating inland aqua-ecological zones under different climate conditions in the Mekong Delta region, Vietnam

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ABSTRACT

Climate change (CC) increases saltwater intrusion, changes water flow and alters the ecological characteristics that lead to significant impact on the farming activities in delta areas. This study defines inland aqua-ecological zones (AEZ) for CC conditions in the Mekong delta region, Vietnam. The hydraulic model Vietnam River Systems and Plains (VRSAP) was used to create maps of salinity and flood depth for three baseline scenarios (1998, 2000 and 2004) and their 2030 projection in the national CC scenarios. Zoning was then implemented in two levels. Level one delimitated the basic zone for inland aquaculture. Level two zoned for the purpose of adaptive aquaculture to CC. The results of the study identified seven sub-zones for ecological aquaculture of each baseline scenarios and their projection by 2030. In the context of CC, salinity intrusion area increases 1,442,228, 1,534,381, and 1,929,793 ha corresponded to the baseline scenarios years 2000, 2004, and 1998, respectively. The results of this study are the combination of the ecological boundary approach and hydraulic model and then AEZ for aquaculture was delimitated and spatially distributed. Thereby, their functions and structures of AEZ are identified in order to meet the demands of managers and planners for reducing the effects of salinity intrusion in Mekong Delta.

Key words | aquaculture, aqua-ecological zoning, aqua-ecological zoning scenarios, climate change, zoning

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INTRODUCTION

Aquaculture is an increasingly important food-producing sector that creates livelihoods as well as provides food for the growing global population (Larsen & Roney 2013) and for supplying the additional fish protein needed to reduce the capture of wild fish (Duarte *et al.* 2009).

The Mekong Delta lies in the south of Vietnam (Figure 1), is one of the most productive and intensively cultivated areas in Asia, and is considered to be a priority area for national economic development and food security (ADB & IMHEN 2011). The aquaculture production is approximately 3.6 million tones, with an export value of about 4.38 billion USD (MARD 2014). However, this is also one of the three most vulnerable deltas in the world to sea level rise caused by climate change (CC) (ADB & IMHEN 2011). Sea level is expected to increase by about 15 cm by 2030 (MONRE 2012) and the region is coping with three key issues: saltwater intrusion, flooding, and lack of fresh water (Carew-Reid 2007; Hideto 2012). Annual flooding of 1.9 million ha (equivalent to about 50% of the

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Figure 1 | Mekong River Basin map and water distribution (MRC 2009).

total area) occurs during a period of 3–5 months (Thai & Dung 2014) and approximately 40% of this region is affected by salinity intrusion during the dry season (Ha 2014). It was influenced by the El Niño event in 2016, which caused severe drought and salinity intrusion and serious damage to agriculture, fisheries and the livelihoods of people in Mekong River Delta (MRD) of Vietnam.

The basis for a sustainable aquaculture operation is careful planning, zoning and prioritization of sites among the different potential users (FAO 2013a). Aquaculture zoning is one of three steps in spatial planning and management (FAO 2010a) that contributes to the process of selecting suitable sites for aquaculture (FAO 2013b). Zoning is a useful tool to integrate aquaculture that controls the environment at a farm level, balances competing interests, and resolves conflicts with other users and other economic activities and exploitation of coastal resources (FAO 2013a).

Many studies on aquaculture zoning (Angell 1998; Ly 2001; Grimshaw 2009; Staple & Funge-Smith 2009) have been carried out based on FAO's approaches: agro-ecological zoning (FAO 1996) and ecosystem approaches to aquaculture (EAA) (FAO 2008) use characteristics of landform, soil, water, climate to identify zones. The most recent zoning-related study on adaptation to CC in agro-ecological zones in the Mekong Delta, Vietnam (Dinh 2014) delimitated six agro-ecological zones based on characteristics of soil, irrigation, salinity, and flooding and national CC scenarios 2030 are nested. However, these studies neglected functions of ecological transition zones where cultural models of agri-aquaculture, such as mono-, multi-, inter and rotational culture, need to be applied to prevent salinity intrusion, adapt to the impact of CC, and generally reduce the frequency of land-use conflict. The ecological characteristics of the Mekong Delta region change seasonally and depend on annual climatic characteristics with considerable variability due to the effects of water flow in rivers and tidal regimes. This creates unstable and time-changing transition zones of approximately 50–60 km (Halls & Johns 2013). Therefore, AEZ under CC impacts need to consider characteristics of water fluctuation corresponding to suitable aquaculture model in order to improve economic efficiency without ecological disruption.

In this study, based on data water flow, flood depth and salinity, intrusion layers were created by the VRSAP model. AEZ were then conducted by hierarchical approach of ecology boundary and assigned their functions. The results contribute to future aquaculture planning.

DATA AND METHODS

Approach

According to the FAO (Jhingran 1987), habitat types for aquaculture species are classified into three categories, defined by salinity: freshwater (0‰ salinity), saltwater (>35‰ salinity) and brackish water (1–2 to 35‰ salinity), which correspond to three ecological indicators in aquaculture zoning. An ecological zone is identified by a single aspect, while an ecosystem zone considers all aspects of its inclusions (rivers, mountains, forests, aquatic species, etc.). However, in spatial terms, many ecological zones may exist in many types of ecosystems and vice versa (for example, a brackish water ecological zone may exist in many types of wetland ecosystems such as estuaries, mudflats, and mangroves). Therefore, ecological zoning for aquaculture (aqua-ecological zoning-AEZ) usually considers a single environmental aspect. These zones have boundaries which, depending on the chosen level of resolution, can be conceptualized as either a zone or a fine line (László et al. 2010). According to Armand (1992), 'Any natural boundary is in reality a transition zone, which has its own two boundaries'. Consideration of the ecological zone as only the homogenous characteristics of the zone in a single environment leads to a lack of attention being paid to temporal and dynamic characteristics (changes in time) of boundary (Fagan et al. 2003). Ecologists conceptualized the ecological boundary approach to better study the various spatial structures and functions of ecological transition zones, while also accounting for temporal dynamics and multiple dimensions (Cadenasso et al. 2003; David et al. 2003; Peters et al. 2006). The application of hierarchy theory aids empirical research by classifying complex ecological systems into nested sub-levels and is therefore a suitable tool and the simplest way for studying ecological transition zones that vary in structural complexity (O'Neill et al. 1986; Matthew & Stanley 2008). The purpose of using the hierarchy approach theory on AEZ is to delimitate sub-zones with more detail for the transition zone and its function. Based on hierarchical structures defined under the ecological boundary approach (see Figure 2), the classification of ecological subzones in the MRD is proposed in Figure 3.

Study areas

Natural characteristics

The study area is downstream of the Mekong Delta. Its catchment area in Vietnam is 65,000 km^2 (Tuan et al. 2007). Its terrain is relatively flat, with the average elevation being 1.0 m above sea level. Annual rainfall varies seasonally: the rainy season, from May to November, accounts for 90–92% of the total annual rainfall in the region, with the remainder falling during the dry season from December to April. Its flow rate is dependent on the volume and intensity of rain fall in the Mekong Basin during the rainy season.

Coastal areas, where the dry season extends from January to June, are dominated by a diurnal tide from the East Sea (high amplitude from 3.5 to 4.0 m) and an irregular, semi-diurnal tide from the West Sea (high amplitude from 0.8 to 1.2 m).

Aquaculture characteristics

There are two main types of inland aquaculture in the Mekong Delta: brackish water aquaculture and freshwater aquaculture. Species that can live in both brackish and

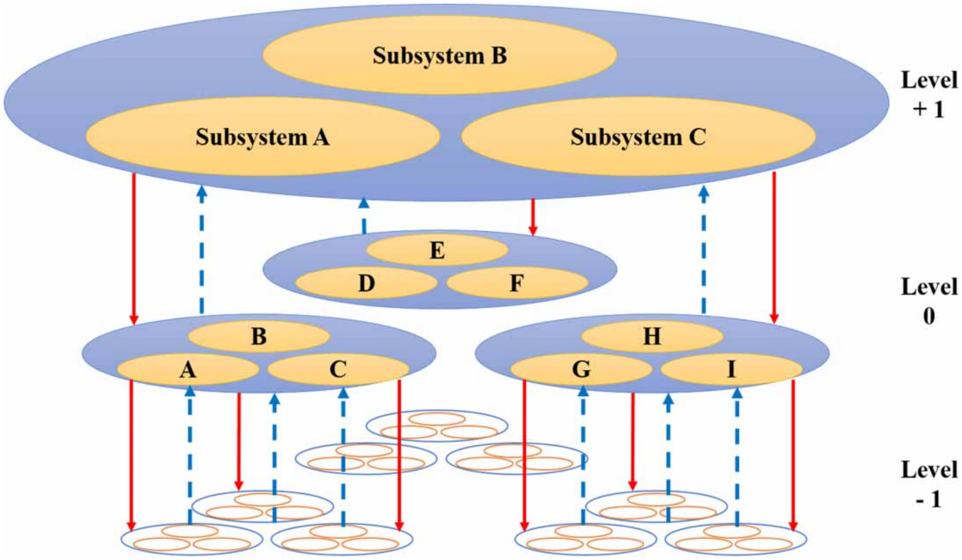

Figure 2 | Hierarchical structures – ecological boundary approach (Matthew & Stanley 2008).

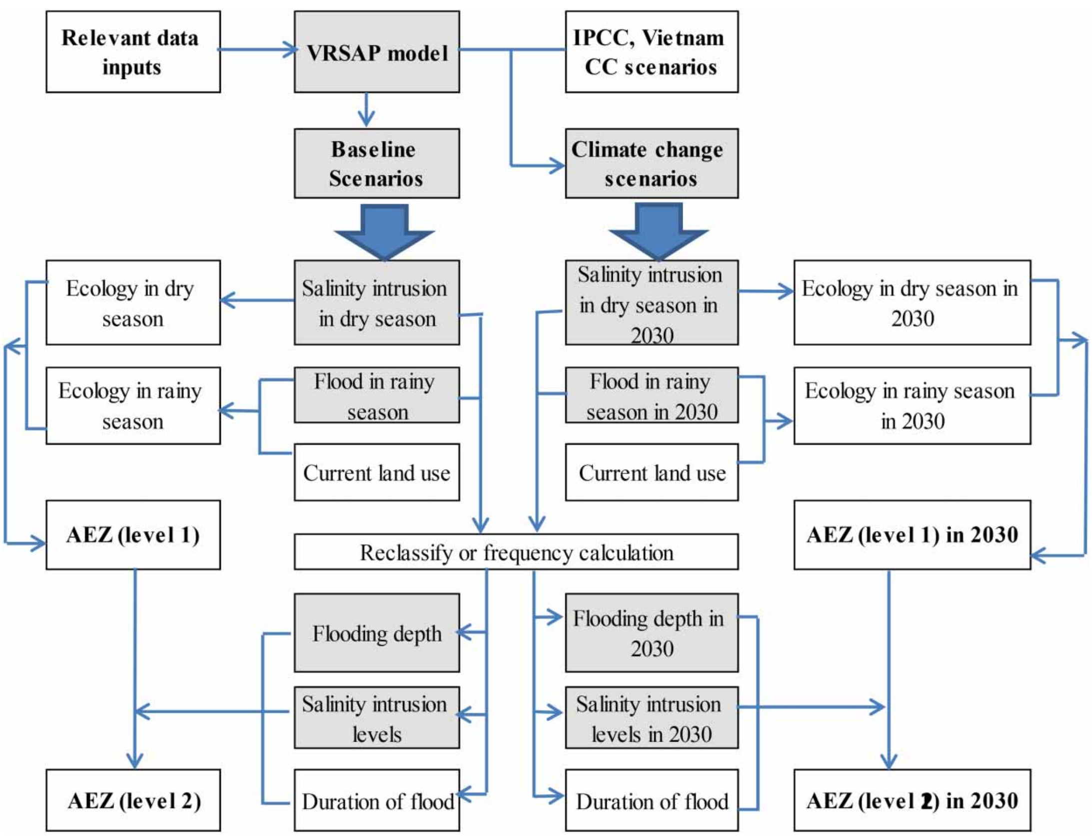

Figure 3 | Flow chart for Aqua-ecological zoning and its scenarios.

freshwater environments are also cultured in these areas. This creates diverse forms of aquaculture farming as follows:

- The inland brackish water aquaculture uses three basic methods: (1) mono-culture, which is primarily shrimp ponds that have high salinity throughout the year; (2) multi-culture, which raises mainly crustaceans and molluscs, and is associated with mangroves; and (3) rotational culture, which grows rice in the rainy (flood) season and shrimp in the dry season.
- The inland freshwater aquaculture employs a diverse range of culture model such as: (1) mono-culture (in ponds); (2) fish-orchards; (3) fish-rice and or fish-indigo forests; (4) fish in cages; and (5) fish cultured in nets during the rainy season.

Methodology

The classification of ecological subzones and their relationships in both the baseline scenarios and the CC scenario is illustrated in the flowchart in Figure 3. Baseline and CC scenarios of water variation were created by VRSAP software including salinity intrusion and flood depth layers of raster data. Based on the criteria for delimitating of AEZ level 1 and AEZ level 2, corresponding layers were conducted by classification and frequency calculation.

VRSAP model and the CC scenario

The VRSAP model (Khue 1986; Dong 2000; Tho 2008) has been used extensively by researchers for modeling flooding and salinity intrusion on local, zonal and nation-wide scales (Figure 4). The river and canal networks are discretized into segments, defined by their cross-sectional areas and the roughness of the representative river reach, and are connected to each other by nodes. The result of discretization was 56,611 river segments; 3,486 nodes and 2,882 parcels of data. The VRSAP model also inputs data including the recorded peak discharges at Kratie (Cambodia) and Dau Tieng, Tri An (Vietnam); conditions recorded from downstream border water levels and salinity from 11 coastal stations from the East Sea to the West Sea; and daily rainfall and evaporation observations from 24 meteorological stations. The topographic maps at a scale of 1:2000 of the main rivers, canals, road systems were used. The model results were calibrated and adjusted at 48 hydrological stations to ensure confidence of the model.

Baseline scenarios

Three years of baseline scenario data were chosen from a series of water-flow observations in Kratie (Cambodia) from 1995 to 2010 to represent a range of different water-flow conditions as follows: 1998 (low flooding/water flow and high salinity intrusion), 2000 (high flooding/water flow and low salinity intrusion) and 2004 (moderate flooding/water flow).

The CC scenario in 2030

Three scenarios were used in the Soil and Water Assessment Tool (SWAT) model to calculate upstream water flow in the Mekong Basin, rainfall, and salinity intrusion due to sea level is 15 cm higher in the study area in 2030, including: (1) the water-flow results of the baseline scenarios in Kratie from the Mekong River Committee (MRC); (2) the rainfall scenarios of Mekong River Basin from the Intergovernmental Panel on Climate Change (IPCC); and (3) B2 scenarios of Vietnam CC scenarios (IMHEN 2011).

Outputs of the model

Model outputs include flood depth and a salinity level map calculated from nodal points and interpolated by the Natural Neighbor method in a Vertical Mapper (Mapinfor Professional software by Pitney Bowes). Flood depths were defined as follows: Flood value in a nodal point = Water level value – Elevation.

The map of salinity intrusion was calculated by the interpolation method from nodal points.

Checking accuracy

The model results were tested and adjusted by observed data in 48 hydrological stations to ensure confidence of the model. Figure 5 is an example of observed and simulated water levels from July to December 2004 at My Thuan hydrological stations.

Delimitating AEZ

AEZ level 1 – Basic AEZ. Due to seasonal variations of the salinity boundary in rainy and dry seasons, AEZ level 1 is

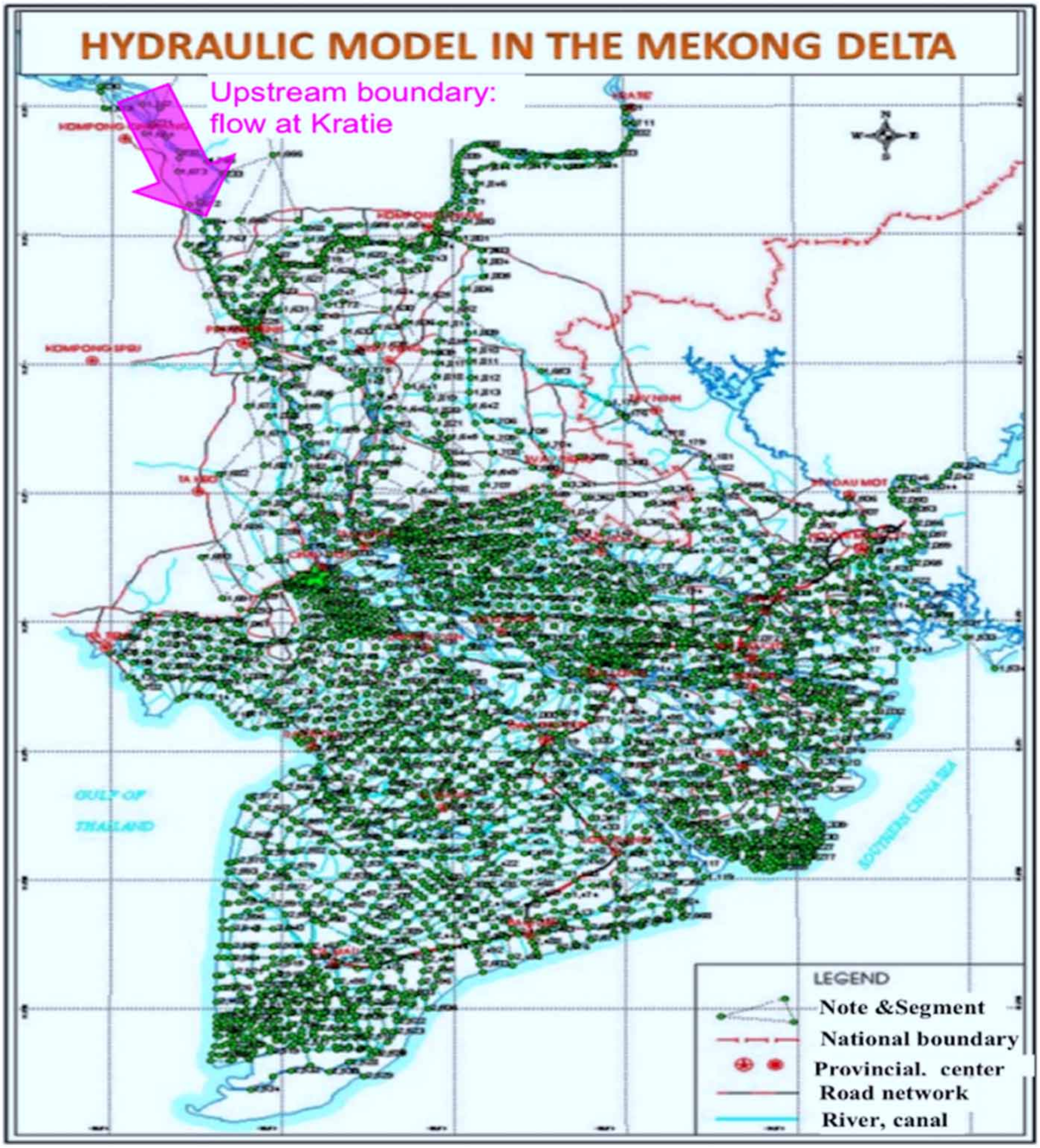

Figure 4 | Nodes and river segments for VRSAP model.

defined according to ecological conditions of the dry and rainy seasons.

- For the dry season: a map of salinity boundary and its scenarios in the dry season is created from the VRSAP model.
- For the rainy season: increased rainfall in Mekong Basin leads to floods upstream and pushes brackish water toward the coast, that is why the rice-shrimp rotated culture model is applied (shrimp culture in rainy season, rice culture in dry season) and salinity data is not

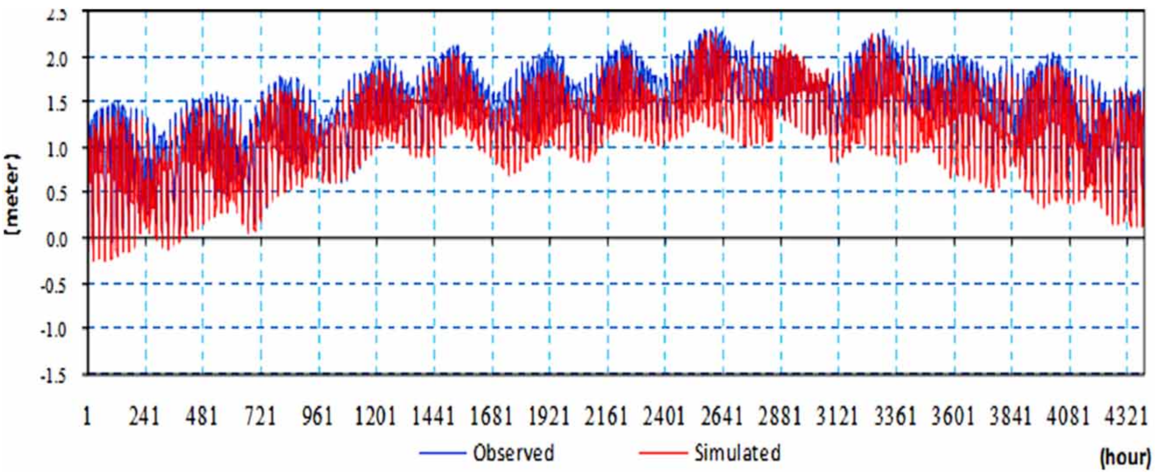

Figure 5 | Observed and simulated water level July–December/2004 at My Thuan hydrological station.

observed. This mean salinity only occurs in brackish aquaculture areas in the rainy season. Therefore, the maps of status of land use are collected from locals in 13 provinces and combined with information collected from fieldwork in order to build the map of aquaculture status. The salinity boundary during rainy seasons is identified by extracting zones of mangrove, mangrove-aquaculture and mono-aquaculture model in the aquaculture status map, because there are no salinity data in rainy seasons. We overlayed two data layers of salinity boundaries in the dry and rainy seasons created from VRSAP model and its corresponding scenarios for 2030. The result of this process was to create three subzones: brackish, seasonal transition and freshwater ecology.

AEZ level 2 – Goal oriented AEZ. Criteria for determining ecological subzones: Table 1 shows the criteria for AEZ level 1 and level 2. In AEZ level 2 is proposed based on characteristics of aquaculture and agriculture farming. Salinity (≤4‰ is the tolerance threshold of most crops); flooding depth, and duration of flood are criteria for suitable zones of one seasonal aquaculture (three months).

Table 1 | Criteria for determining ecological subzones

	Criteria				
No.	**AEZ level 1**	**Salinity intrusion**	**Flooding depth**	**Duration of flood**	**AEZ level 2**
1	Brackish water aquaculture ecology	During the year	No or little impact	No	Brackish water aquaculture subzone
2	Aquaculture transition ecology	In dry season >4‰	No or little impact	No	Seasonal transition aquaculture ecology
3		In dry season 0–4‰	No or little impact	No	Fresh water aquaculture ecology – salt prevention
4		In dry season >0‰	Flooding ≥ 1 m	≥90 days	Flood and salt water zone
5	Freshwater aquaculture ecology	No salinity during the year	No or flooding ≤1 m	No or <90 days	Fresh water aquaculture ecology – moderately inundated flood
6		No salinity during the year	Flooding 1–2 m	≥90 days	Fresh water aquaculture ecology – semi-inundated flood
7		No salinity during the year	≥2 m	≥120 days	Fresh water aquaculture ecology – inundated flood

The aim of the classification of these subzones was to clearly define the functions of each subzone in order to avoid unintended conflict in the process of land-use.

Input data and analysis. Ecological subzone level 2 is conducted by the following steps.

Step 1: Classifying salinity intrusion map. Salinity intrusion map from the output of the VRSAP model showing continuous values of pixels was classified into three thresholds: (1) No salinity (0‰); (2) ≤4‰; (3) >4‰; Flood depth map with three thresholds: pixel value for flood depth ≤1 m; pixel value 2 for 1–2 m and pixel value 3 for ≥2 m.

Step 2: Generating duration flood. Figure 5 and the MRC report (MRC 2008) show that the flooding usually occurs in July every year, reaching a maximum peak in September–October and minimum flood in December. This means that in the same site (at specific locations), if the value pixel =3, frequency ≥3 times in series data of average flood depth maps (six months), then these months were not interrupted. That location is suitable for one seasonal aquaculture.

Figure 6 describes the process of making the duration of the flood map, the series layers of flood depth of baseline scenarios (1998, 2000, and 2004) and their corresponding scenario in 2030 were classified to create a set of input (a) and (d) layers for frequency calculation in ArcGIS software; (b) and (e) layers are the results of frequency calculation with pixel value ≥3 and ≥2 respectively. Then the (b) layer was classified to identify the pixel with value ≥3 (flood depth >2 m, frequency ≥3) in the (c) layer; (e) layer was classified to create (f) layer: value 0 (no or flood depth <1 m), value 1 (flood depth >1 m and 1 ≤ frequency ≤2) and value 2 (flood depth >1 m, frequency ≥3).

Applying Boolean logic in ArcGIS software of raster calculation from (c) and (f) layers by using conditional operation: (g) layer = Con (c = 3, 3, f).

Step 3: Layer combination. Combination layers (1) basic ecology (level 1), (2) salinity intrusion levels, (3) flood depth and duration, will create subzone level 2 corresponding to indices in Table 1.

RESULTS AND DISCUSSION

Results of AEZ baseline scenarios

AEZ level 1 – basic AEZ

AEZ level 1 identified three types of basic AEZ based on the scenario of fluctuating seasonal water-flow. The results in Table 2 show that salt-water invasion trends enlarge eastward in the estuarial area and were significantly affected by tidal variation (4 m) in the dry season and sea level will be 15 cm higher by 2030.

AEZ level 2 – goal oriented AEZ

Based on the criteria and the hierarchical structure approach, study areas were determined with seven main AEZ subzones in level 2, of which the baseline scenarios are applied for the years 1998 (Figure 7) and 2000 (Figure 8) and are combined with downscaled factors (rainfall, sea level rise) to reflect national CC by the year 2030. The results of predicted AEZ scenarios by 2030 are shown in Figures 9–11.

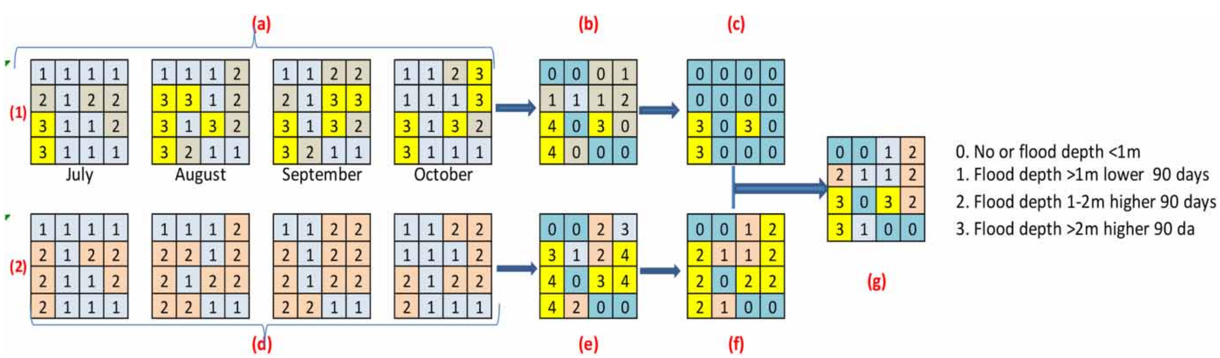

Figure 6 | Flood depth and duration of flood map.

Table 2 | The areas of subzones according to the scenarios (Unit: ha)

			Baseline scenario 1998		Baseline scenario 2004		Baseline scenario 2000	
No.	**Type of AEZ level 1**	**Type of AEZ level 2**	**1998**	**2030**	**2004**	**2030**	**2000**	**2030**
1	Brackish water AEZ	Brackish water	799,210	799,210	799,210	799,210	799,210	799,210
2	Transitional AEZ	Seasonal brackish-water	615,962	762,990	485,292	547,025	390,868	423,010
3		Salt prevention	512,024	777,364	249,290	675,744	244,133	307,215
4		Seasonal flood and salt water	2,596	12,114	589	7,533	8,017	20,580
		Sum	1,929,793	2,351,678	1,534,381	2,029,513	1,442,228	1,550,015
5	Freshwater AEZ	No or moderately inundated flood	1,916,394	1,467,954	1,923,517	1,324,510	1,599,731	1,173,496
6		Semi-inundated flood	163,461	189,586	272,247	340,484	365,379	632,774
7		Inundated flood	4,935	5,365	284,439	320,077	607,245	658,298
		Sum	2,084,791	1,662,906	2,480,203	1,985,071	2,572,355	2,464,568
Total area			4,014,584	4,014,584	4,014,584	4,014,584	4,014,584	4,014,584

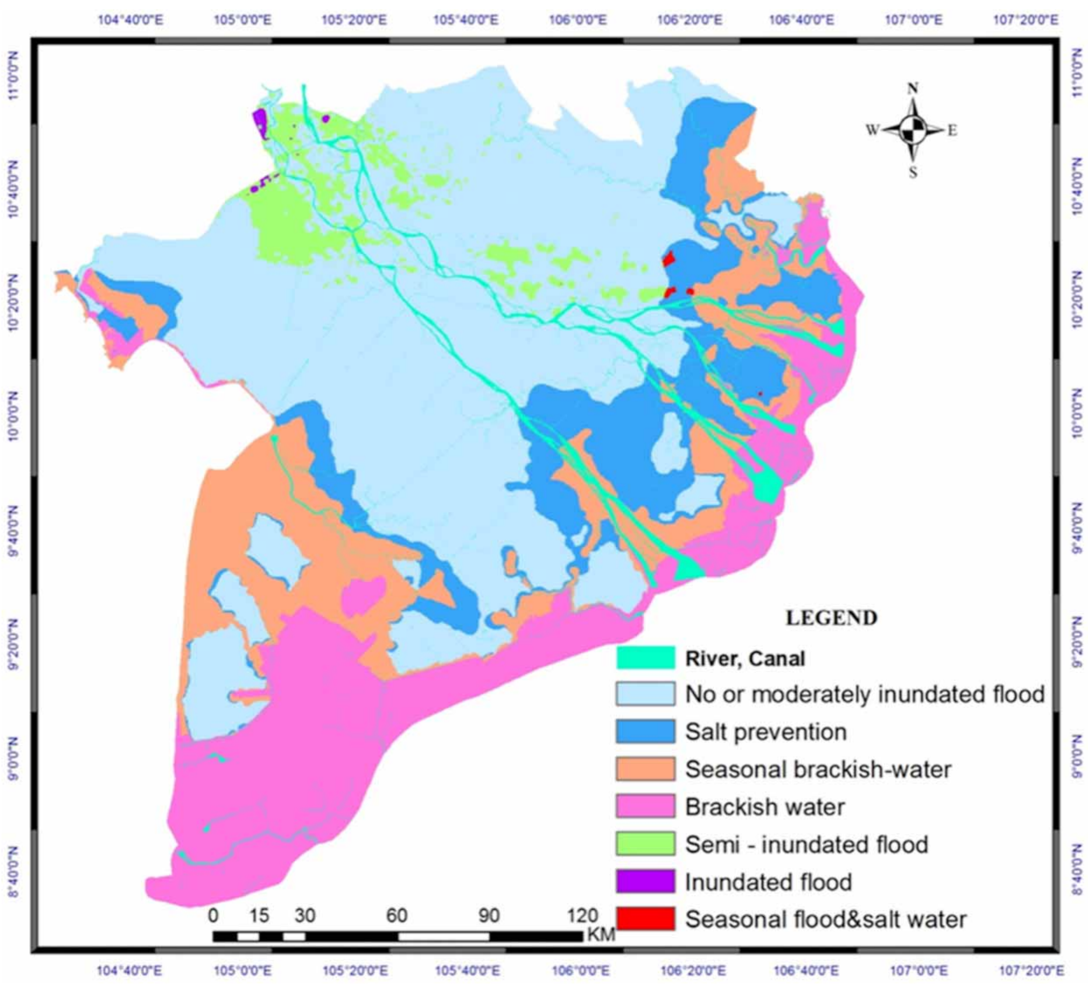

Figure 7 | AEZ according to the baseline scenario in 1998.

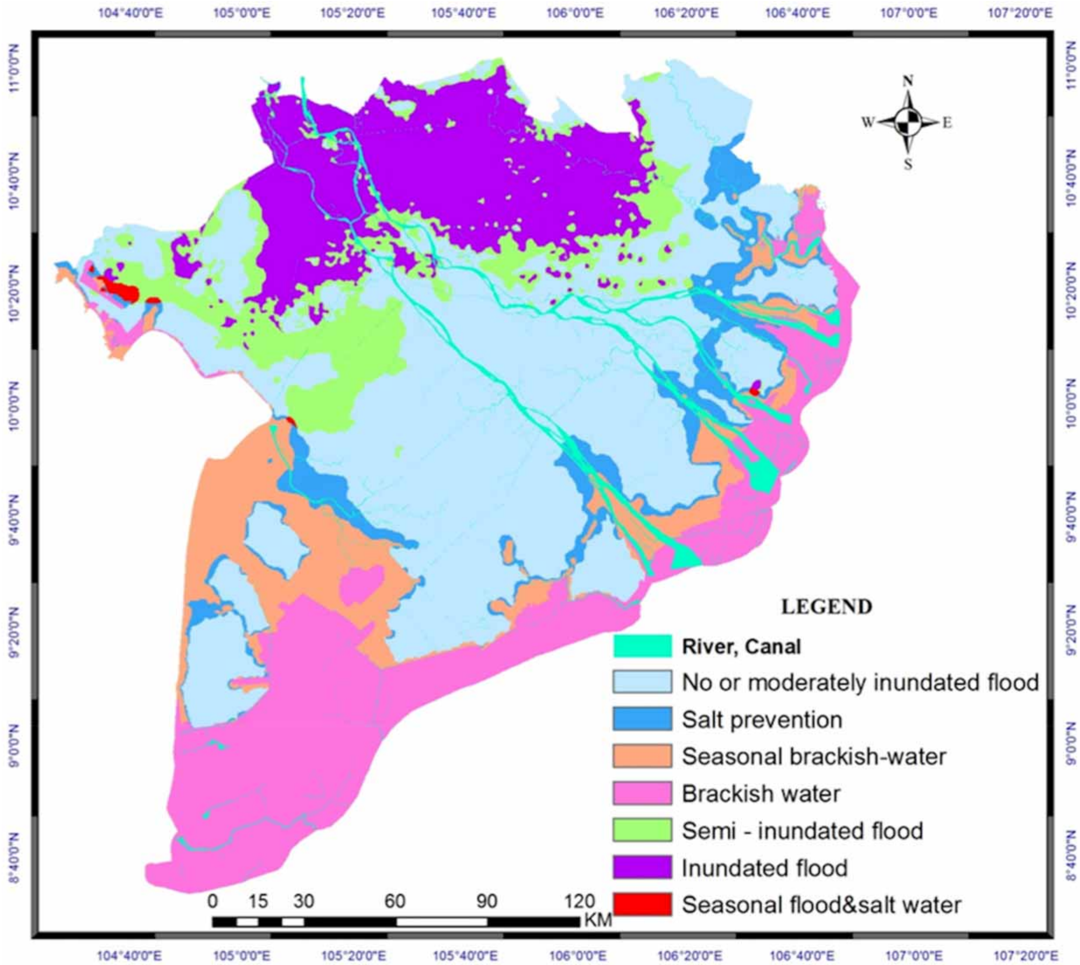

Figure 8 | AEZ according to the baseline scenario in 2000.

AEZ level 2 is established in order to assign functions for application of a suitable aquaculture model. This model could provide support for decision-makers to prevent salt-water invasion by delimiting the salt prevention zone and provide solutions to develop aquaculture models for future flooding in the context of CC.

Brackish water AEZ

The brackish water zone is determined as existing mono-aquaculture farming and shrimp-forest models where salinity is present year-round. This research assumed that a rise in sea level would cause salinity intrusion to invade further inland during the dry season but would not affect other regions, such as the shrimp-rice rotational model, in the rainy season.

Distribution: Brackish water AEZ is distributed along coastal areas. Brackish water aquaculture zones are influenced by salinity levels throughout the year.

Functional recommendation: To develop brackish water aquaculture farms following the mono-aquaculture model or forest-brackish water aquaculture combination model. This zone should not be expanded to prevent salinity intrusion and adverse effects of sea level rise.

Transitional zone

The transitional zone is divided into three subzones as follows:

1. Seasonal brackish water AEZ: Brackish water AEZ is determined as salinity level with >4‰ in the dry

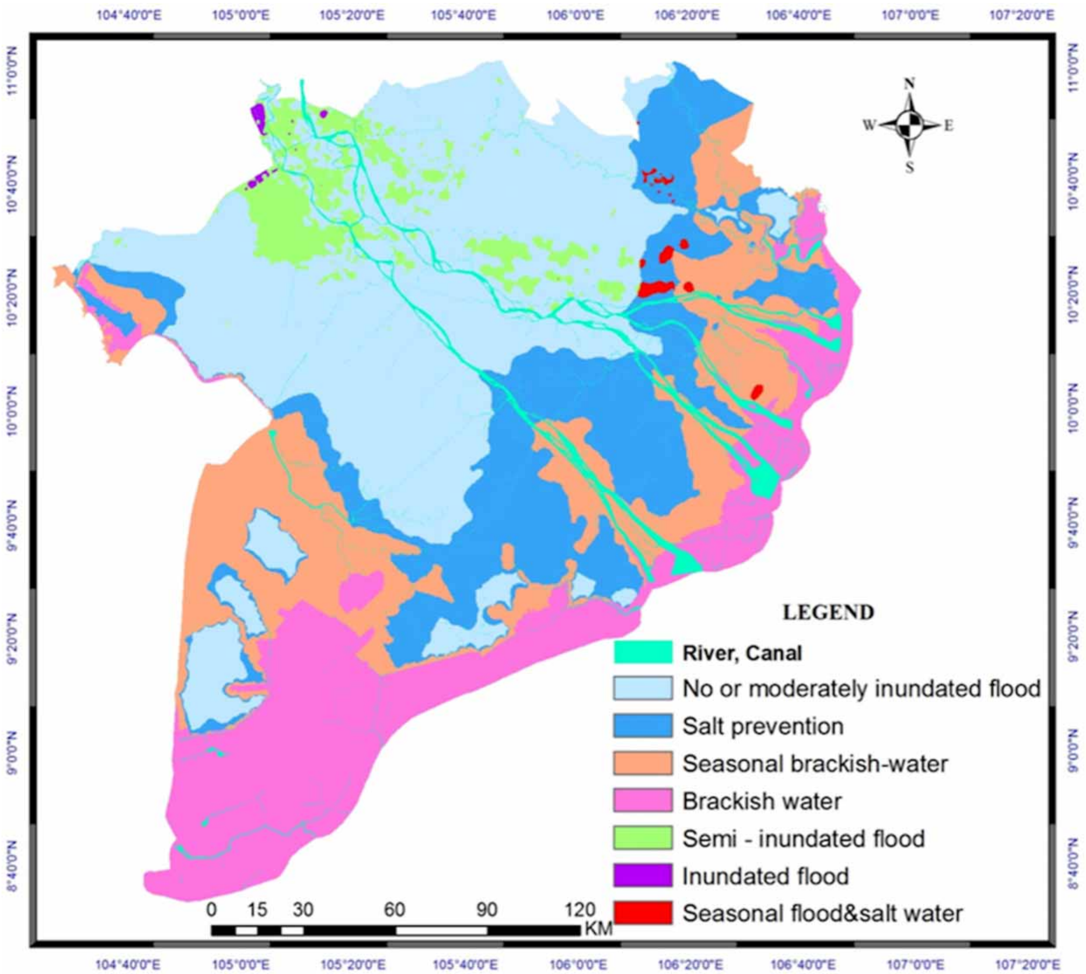

Figure 9 | AEZ projection 2030 according to the baseline scenario in 1998.

season. If the aquaculture status and salinity intrusion maps are overlaid, most brackish water aquaculture–rice rotational models are in regions with salinity of 4–15‰. The area of this zone in the baseline 1998 (615,962 ha) scenario is larger than 1.5 times of that in the baseline in 2000 (390,868 ha) and 2004 (485,292 ha).

Distribution: This zone is adjacent to brackish water AEZ and tends to invade inland. The seasonal aquaculture zone is distributed in some districts of Ca Mau, Kien Giang and along the banks of the river, which is affected by the sea tide.

Functional recommendation: In the rainy season, these areas should be used for agriculture and aquaculture rotation (rice-white leg shrimp). In the dry season brackish water aquaculture rotation models should be applied in order to adapt to the higher rates of salinity intrusion anticipated due to CC. Mono-aquaculture should be limited to avoid salinity intrusion toward agriculture areas. For all scenarios, our results show that the ecological transition zone will expand inland by 2030 due to the impacts of CC.

2. Salt prevention AEZ: This is an important zone, with 1–4‰ salinity in the dry season. The area of this zone in the baseline 1998 (512,024 ha) scenario is greater than 1.8 times of the ones in baseline 2000 (244,133 ha) and 2004 (249,290 ha).

Distribution: These areas also tend to invade inland due to the increase of salinity intrusion due to sea level rise and tidal level from the East Sea. The estuaries of Soc

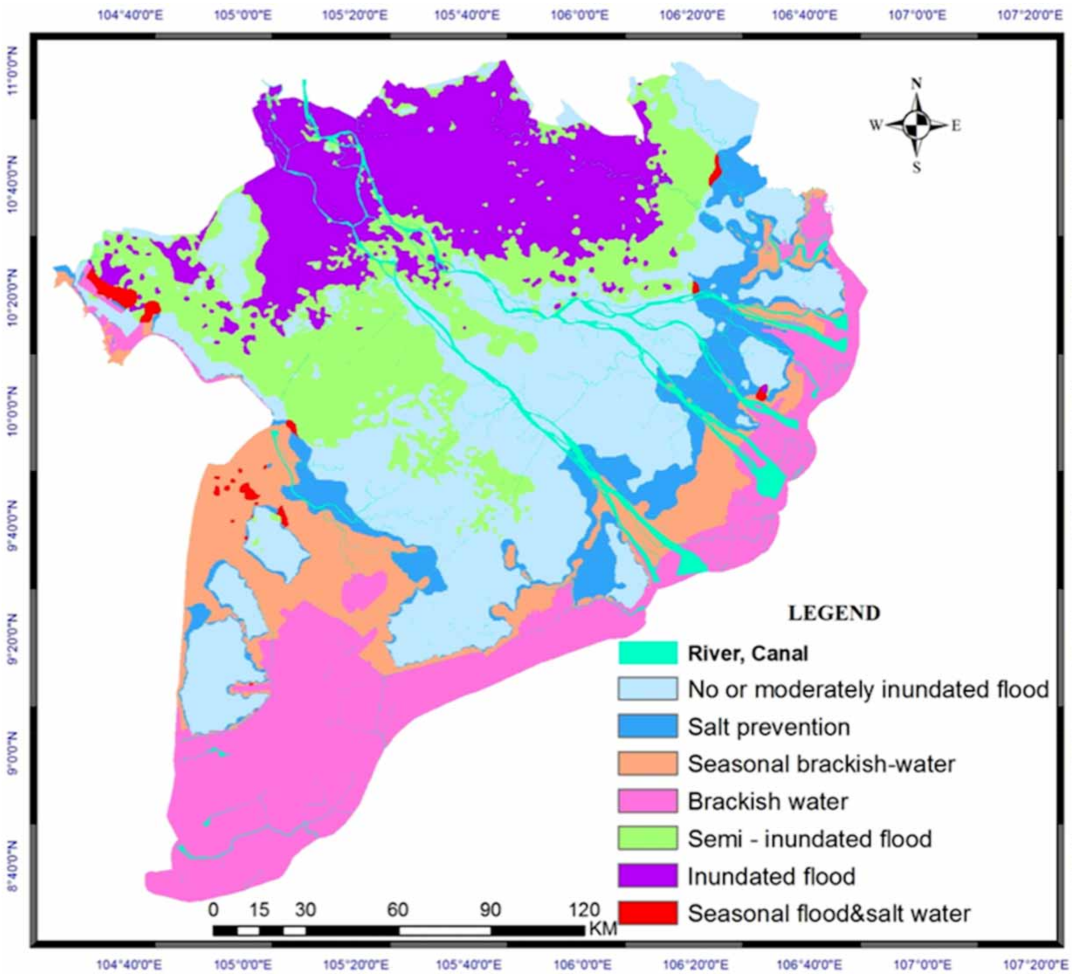

Figure 10 | AEZ projection 2030 according to the baseline scenario in 2000.

Trang, Tra Vinh, Ben Tre, Tien Giang and Long An provinces are the areas most affected by tidal fluctuation and river flow in the dry season.

Functional recommendation: It is difficult to prevent salt-water in MRD because of the high density of canals and the river system. Therefore, in order to adapt to the effects of salt-water intrusion, suitable cultivation models for improvement of production efficiency proposed to apply: intercropping farming models and rotational agriculture-fisheries for species that are able to live in both freshwater and brackish water environments, such as tilapia, red tilapia and giant shrimp.

3. Seasonal flood and salt water AEZ: This zone is formed in areas of salt-water (dry season) and flood (rainy season) by intensively effected sea level rise and rainy variation of CC and extreme events (Table 2).

   Distribution: This is mainly distributed in lowland, interference of semi-inundated induce (in the rainy season) and salty level ≤4‰ (in the dry season).

   Functional recommendation: Aquaculture models recommend the same salt prevention zone.

Freshwater AEZ

The freshwater AEZ is divided into three subzones in level 2, including the following:

1. No or moderately inundated flood AEZ

   This subzone is defined as any inland area uninfluenced by the rainy season or which have a flood

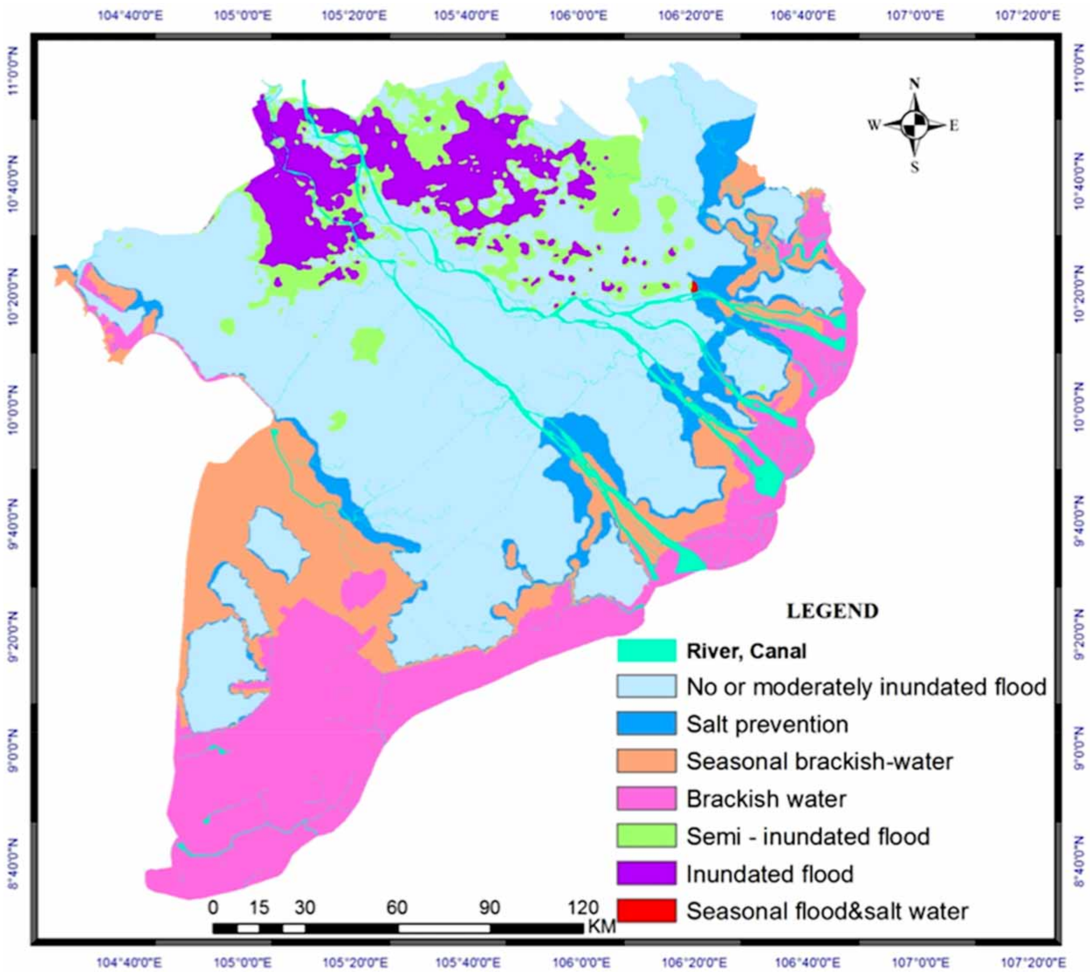

Figure 11 | AEZ projection 2030 according to the baseline scenario in 2004.

depth of less than 1 m over a period of under 90 days. The results of three scenarios were: 1998 (1,916,394 ha), 2000 (1,599,731 ha) and 2004 (1,923,517 ha).

Distribution: This ecological zone is mainly distributed in the central provinces (Can Tho, Hau Giang, Vinh Long, Dong Thap) of Mekong Delta areas and some forest areas in U Minh Thuong and U Minh Ha of the Ca Mau and Kien Giang provinces.

Functional recommendation: Moderately inundated flood areas are suitable for traditional models of fresh water aquaculture that include culture models such as: rice-fishing in lowlands, fish culture in orchard ditches, forest-fish and intensive aquaculture (catfish) in place along the Tien and Hau rivers.

2. The semi-inundated flood AEZ

This zone is defined as any area with a flooding depth of 1–2 m during a period of over 90 days in the rainy season.

Distribution: This ecological zone distributes mainly on two sides of Tien and Hau rivers and is more vulnerable to the effects of flooding.

Functional recommendation: To develop freshwater aquaculture models adapted to semi-flood conditions such as agriculture-fish and orchard-fish in places of low elevation.

3. Inundated flood AEZ

This subzone is an area with a flooding depth of more than 2 m during a period of over 120 days and is significantly affected due to flood.

Distribution: In the rainy season, water in canals, river systems and upstream flows over the Cambodian border and creates inundated areas along both sides of the Tien and Hau river branches. The results of three baseline scenarios show areas in 1998 (4,935 ha), 2000 (607,245 ha), and 2004 (284,439 ha). Inundated flood AEZ largely expand to the upstream area of the Vietnamese part of Mekong River.

Functional recommendation: This zone is suitable for farming models using nets, especially in the rainy season in order to adapt the impacts of CC, such as increased flooding.

AEZ scenarios 2030

According to the three baseline scenarios in 1998, 2000 and 2004, the results of the AEZ scenarios 2030 show significant differences between the aqua-ecological transition and freshwater ecological zones in the rainy season. In all three scenarios, by 2030, the area of the ecological transition zone increases significantly due to the impact of salinity intrusion, which shows the highest increase of 10.5% of the total area using the 1998 baseline scenario while the increases in the 2000 and 2004 baseline scenarios were 2 and 12% of the total area.

For the freshwater AEZ, the area of the semi-flooding, inundated flood subzone tends to increase in all 2030 scenarios. At the same time, moderately inundated flood AEZ decreases (Table 2).

One of the driest years in the region was 1998, so the AEZ of this scenario shows the ecological transition zone invading deep inland by 2030; the year 2000 had the highest flood, so in 2030 the flooding freshwater aquaculture ecology shows expansion by 2030, especially in the areas around the upper Tien and Hau rivers.

The year with medium/average flood was 2004. We propose using this baseline scenario as the basis for aquaculture development planning according to ecological zones at the local level.

Comparison between approaches

Figure 12 shows that criteria-based approach is conventionally used for zoning and planning aquaculture. In the analyzing process, the weight of criteria is subjectively applied and the results showed that suitable sites of sparse aquaculture were not ecologically structured and the function of zones is not considered. For that reason, land-use conflicts usually occur.

For a hierarchical approach, basic zones (level 1) for aquaculture including (brackish water, freshwater and transitional zones) are identified to provide salt and flood boundaries for decision makers as to where to expand or not.

In level 2, goal oriented zoning for aquaculture is to nest aquaculture models corresponding to their ecological characteristics, in order to adapt for climate-smart aquaculture.

CONCLUSIONS

In this study, the hydrological VRSAP model was conducted by input data of river networks in 1998, 2000 and 2004 that represent three baseline scenarios of water flow (high, average and low). The national scenario of the rainfall and sea level rise by 2030 (national CC scenarios) were integrated and nested to create flood depth and salinity levels of the baseline scenarios and their projection by 2030. Flood duration layers were then processed by frequency calculation of monthly flood depth data. Thereby, seasonal water scenarios of baseline and their projection by 2030 were generated for AEZ fluctuation.

Aqua-ecological hierarchy in this study was considered based on the structures and functions of ecological categories in conformity with the principle of four basic zoning characteristics (ecological origin, spatial structure, function and temporal change; Fagan *et al.* 2003). This is a new approach by nesting ecological and aquaculture characteristics for Aqua-ecological zoning.

The results of AEZ level 1 expressed significantly widespread flood and salinity of invasion in the case of extreme events and CC influences. More concretely, the salinity area is about 38% in ordinary conditions of water flow (2004); and about 48% in extreme conditions of drought (1998); the flooded area over than three months accounts for 14% in the 2004 scenario, and 24% of extreme conditions of flood in the 2000 scenario.

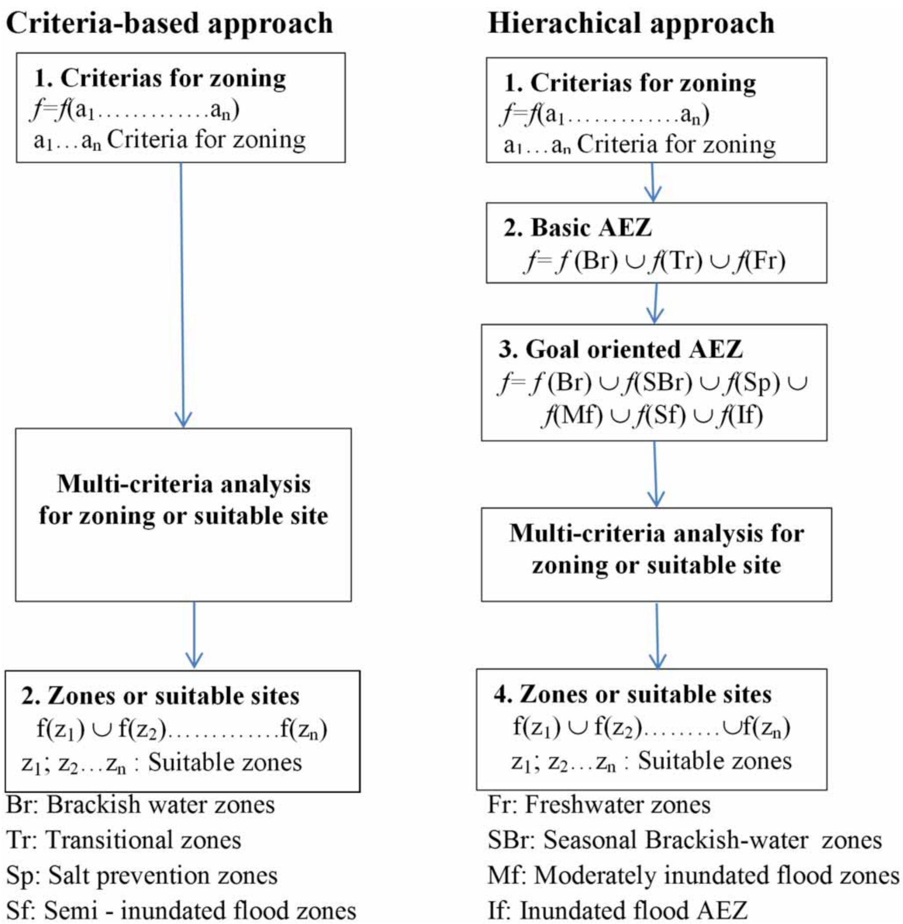

Figure 12 | Approaches comparison.

AEZ in level 2 was divided into seven sub-zones by correspondence between water variation and aquaculture in one season. Aqua-ecological characteristics were recognized in a time frame of three months. The results show that the tendency of the salt-prevention zone ($\leq$4‰) severely expands to inland due to the impacts of CC and extreme events. Seven sub-zones were recommended for their corresponding aquaculture models. The results of the study provide policy implications to the decision maker so that they may propose the aquaculture models and fishery species which can best adapt to CC and limit salinity intrusion into the Mekong Delta areas of Vietnam.

In this research, some kinds of aquaculture have been suggested according to the functions and ecological characters of the subzones. However, the data of water flow in the year 2016 (seriously extreme events of drought in Me Kong Delta area) should be updated, and AEZ should be in higher resolution, such as a suitable site assessment for aquaculture models in each ecological zone needs to be done in order to downscale these results for further study.

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