SEA RECLAMATION PLANNING BASED ON SUITABILITY ANALYSIS: AN EXAMPLE OF HAINAN ISLAND UNDER THE ECOLOGICAL RED LINE

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Abstract: Economic development has led to increased and expanded sea use in Hainan Province, as well as increased development and utilization of coastal and island resources. Marine reclamation land has become one of the most effective ways to solve the problem of human-land conflict and space shortage. However, without scientific planning and guidance, marine reclamation land activities can have a profound impact on marine resources and the environment. Therefore, in this study, we investigated the feasibility of sea reclamation on Hainan Island through a suitability analysis method, and optimized the design of the results based on the ecological red line plan. The results revealed that about 26.94% of the sea around Hainan Island was suitable for reclamation.

1. INTRODUCTION
In recent years, accelerated industrialization, urbanization, and population agglomeration of coastal areas have land shortages to become increasingly prominent, which has become a key factor constraining regional economic development. To meet the needs of social and economic development, large-scale marine reclamation land projects have been implemented in coastal areas to ease the tension between supply and demand in industrial and urban construction land. With the accelerated pace of construction on international tourism islands in Hainan Province and implementation of the strategies of the One Belt and One Road Initiative, the intensity of sea use in the province has been increasing annually, which has led to greater demand for marine reclamation land.

However, sea reclamation projects often have a great impact on the nature of the sea area being reclaimed (Lin et al., 2007; Zhang et al., 2013). Without scientific planning and guidance, marine reclamation land activities may have a profound impact on the sustainable use of marine resources and the environment. To protect the marine ecological environment of Hainan Province, it is imperative to compile a sea reclamation plan on a provincial scale and promote the management of sea reclamation scientifically and normatively so that shoreline and offshore sea resources can be optimal used. Also, it enables the planning of the overall layout of the sea reclamation area, implementation of control of...
the total scale of reclamation and regional sea reclamation projects, and government decisions based on scientific data and effective management methods.

We intended to assess the feasibility of sea reclamation on Hainan Island based on a suitability analysis method, and to optimize the design based on ecological red line planning results. To accomplish this, we divided the reclamation suitability into three grades: reclamation suitable areas (Grade I), reclamation restricted areas (Grade II), and reclamation prohibited areas (Grade III). We then proposed different management and control measures for these three grades.

2. METHODOLOGY

2.1 Study Area
Hainan Province is located in the northern part of the South China Sea. The province is on the second largest island of China, Hainan Island, and is the largest special economic zone and the only tropical maritime province in the country. It is located between latitude 3°20’–20°18’N and longitude 107°50’–119°10’E, with a land area of about 35,400 square kilometers and an authorized sea management area of nearly 2 million square kilometers. Taking into account the existing sea reclamation technologies and levels, the scope of suitability evaluation in this paper was 1 km offshore from Hainan Island’s main island shoreline and a depth of 30 m (Figure 1).

2.2 Method
The specific research steps were as follows:
1) The relevant data were collected, after which the main research areas were identified and digitized. 2) Correlation analysis was combined with potential-restriction models to determine indicators, establish a reclamation suitability evaluation indicator system based on the indicators, and determine each indicator weight. 3) A counter-planning approach was then used to delineate sea reclamation prohibited areas and some sea reclamation restricted areas. 4) Based on the currently available technology, the scale of the existing sea reclamation projects and the promotion of industrial clustering, we selected a grid size of 300 m×300 m within ArcGIS10.2 software (Environmental
Systems Research Institute, 2013) and limited the planning scope to the 30m isobaths. 5) Quantitative analysis was performed based on the above-mentioned selected indicators combined with related data and implemented in the GIS. 6) The GIS map was then combined with the weight values determined by the indicators, after which the sea reclamation suitability analysis chart in Hainan Province was calculated. 7) The sea reclamation suitability analysis chart was then superimposed with the restricted and prohibited areas delineated by relevant portions of the ecological red line planning of the Hainan Provincial Master Plan (defined within 30 m isobaths), and a complete reclamation suitability analysis chart in Hainan Province was built. 8) The sea reclamation suitability analysis chart developed for Hainan Province was evaluated in conjunction with relevant laws, regulations, industry plans, and actual conditions, after which the planning chart of sea reclamation suitability in Hainan Province was finalized(Yu et al.,2011; Feng et al.,2014).

2.2.1 Establishment of indicator framework
We comprehensively considered coastal natural conditions, development and utilization goals, sea reclamation status, and current problems in the evaluation area. In addition, we learned from profit and loss analysis and the ecological footprint idea. This information was then utilized to develop a potential-restriction model that was used to formulate a corresponding indicator system.

2.2.1.1 Development potential analysis
The development potential analysis is mainly reflected in the socio-economic conditions. Here, we combined relevant experiences (such as break-even analysis and ecological footprint) and selected the following two indicators:

1) Government sea reclamation promotion policy is a positive indicator. According to the view of resource economics, the fundamental factor driving consumption of natural resources is population growth and economic development, and the relevant policies introduced by the government comprise the most direct manifestation of these two driving factors. Therefore, selection of the government’s sea reclamation promotion policy in counties (cities, districts) in which the study area is located as an evaluation indicator can reflect the demand for sea reclamation.

2) Fixed asset investment intensity is a positive indicator that determines the sea reclamation construction scale. A greater intensity of social investment results in a greater scale of sea reclamation.

2.2.1.2 Restrictive conditions
The restrictive conditions were divided into the following six categories:

1) Water depth conditions serve as a negative indicator, in which a shallower water depth is associated with a lower cost of sea reclamation.

2) Distance to major development activities. Considering that sea reclamation activities change the natural environment, major development activities should be taken into consideration, especially for coastal tourism areas, port dock areas, areas with public welfare activities in the sea (such as installation of waterways, anchorages, submarine cables, and pipelines), and artificial islands.

3) Distance to natural shoreline is a positive indicator. Hainan Province has the longest natural coastline in China. When planning for sea reclamation, full consideration should be given to the impact that implementation of the project may have on the natural shoreline.

4) Marine ecological conditions serve as a negative indicator. In the sea reclamation site selection, ecologically sensitive areas should be avoided and fishery resources should be protected. Therefore, we considered the following elements in this project: fish eggs, larvae, and benthic biomass.

5) Hydrodynamic conditions. In the sea reclamation site selection, full consideration should be given to changes in hydrodynamic conditions before and after implementation of the project, as well as to the sensitivity of the area’s hydrodynamic forces. To accomplish this, we utilized the following three indicators:
Scouring and silting conditions. This is a neutral indicator. The state of scouring and silting after reclamation will reflect the degree of impact on the surrounding environment. Balanced scouring and silting results in a better situation.

Typhoons, storm surges and other natural disasters are negative indicators. Project site selection should try to avoid areas subjected to frequent natural disasters, which are mainly located in the eastern coastal areas of Hainan Province.

Hydrodynamically sensitive areas such as estuaries and bays are positive indicators. Estuaries and bays are sensitive to hydrodynamic forces and vulnerable to changes in the environment. When implementing sea reclamation projects, the selection of sites in these areas should be minimized.

6) Distance to protected areas and areas in which legal regulations prohibit development is a prohibition indicator. If in such regions, the indicator value is 0.

2.2.2 Suitability evaluation model
The evaluation model for sea reclamation suitability used in the study is as follows (Wang et al., 2015):

\[ S = \sum_{i=1}^{n} B_i W_i \]

where \( S \) is the comprehensive evaluation indicator of sea reclamation suitability; \( B_i \) is the score of the \( i \)-th evaluation factor (dimensionless), \( W_i \) is the weight of the \( i \)-th evaluation factor and \( n \) is the number of factors participating in the evaluation.

2.2.3 Quantification of indicators
The quantification of each evaluation factor was based on influence degree of each evaluation factor on sea reclamation, and the evaluation indicator was divided into three levels according to the determined classification conditions of the evaluation factors. The evaluation scores were 3, 2, and 1 (see Table 1). The classification conditions and the evaluation scores were determined using expert consultation.

| Influencing factor                  | Evaluation indicator                        | Classification condition                        | Evaluation score |
|------------------------------------|--------------------------------------------|------------------------------------------------|------------------|
| Social and economic conditions     | Government’s sea reclamation promotion policies | Relevant plans of provincial government or above | 3                |
|                                    |                                            | Relevant plans of the provincial management department, counties, and cities | 2                |
|                                    |                                            | Relevant plans at other levels | 1                |
| Investment intensity of fixed asset|                                            | Ranked in the top 1/3 of the 12 counties and cities | 3                |
|                                    |                                            | Ranked in the middle of the 12 counties and cities | 2                |
|                                    |                                            | Ranked in the bottom 1/3 of the 12 counties and cities | 1                |
| Water depth                        | Water depth                                | 0–10 m | 3 |
|                                    |                                            | 10 m–20 m | 2 |
|                                    |                                            | 20–30 m | 1 |
| Distance to major development activities | Coastal tourism area, port dock area         | More than 3000 m | 3 |
|                                    |                                            | 1000–3000 m | 2 |
|                                    |                                            | 0–1000 m | 1 |
|                                    | Public welfare activities in the sea (e.g. fairways, anchorages, submarine cables, and pipelines) | Over 1500 m | 3 |
|                                    |                                            | 500–1500 m | 2 |
|                                    |                                            | 0–500 m | 1 |
|                                    | Construction of artificial islands         | 3B>G | 3 |
|                                    |                                            | B<G≤3B | 2 |
|                                    |                                            | 0<G<3B | 1 |
| Marine ecological                 | Fish eggs                                  | 0–100 ind/m³ | 3 |
Conditions

- **Juvenile fish**
  - 100–500 ind/m³: 2
  - 500 ind/m³ or more: 1
  - 0–100 ind/m³: 3
  - 100–500 ind/m³: 2
  - 500 ind/m³ or more: 1

- **Benthic biomass**
  - 0–6 ind/m³: 3
  - 6–60 ind/m³: 2
  - 60 ind/m³ or more: 1

Distance from natural shoreline

- 5000 m or more: 3
- 3000–5000 m: 2
- 1000–3000 m: 1

Hydrodynamics

- **Scouring and silting conditions**
  - Scouring and silting balance: 3
  - Silting status: 2
  - Scouring status: 1

- **Natural disasters (e.g., typhoons and storm surges)**
  - Low frequency of natural disasters: 3
  - Average frequency of natural disasters: 2
  - High frequency of natural disasters: 1

- **Hydrodynamically sensitive areas (e.g., estuaries and bays)**
  - 6000 m: 3
  - 2000–6000 m: 2
  - 0–2000 m: 1

Distance from protected areas and areas in which legal regulations prohibit development

- Adopting “counter-planning” to remove areas that are prohibited from sea reclamation in related plans in advance

Note: Some indicators are explained below:

**Government policy on reclamation promotion:** The suitability was mainly determined according to different levels of plans. The relevant plans formulated by the state council and provincial government were assigned a value of 3, while relevant plans formulated by provincial management department and county/city-level government were assigned a value of 2 and relevant plans formulated by the county/city management department and other levels were assigned a value of 1.

**Investment intensity of fixed assets:** The degree of suitability was mainly determined based on relevant items in the statistical yearbook of Hainan Province in 2015. The investment intensity of fixed assets of four counties and cities, namely Ledong County, Changjiang County, and the cities of Dongfang and Quzhou, were ranked in the bottom 1/3 of the 12 counties and cities, so the assigned value was 1. The investment intensity of the fixed assets of four counties and cities, namely Lingao County, Chengmai County and the cities of Wanning and Wenchang, were ranked in the middle of the 12 counties and cities; therefore, the assigned value was 2. The investment intensity of fixed assets of four counties and cities, namely Lingshui County and the cities of Qionghai, Sanya, and Haikou, were ranked in the top 1/3 of 12 counties and cities; therefore, the assigned value was 3.

**Water depth conditions:** As water depth increases, the technology and cost of sea reclamation increase rapidly. In light of the existing situation, the current plan (2016–2020) selected a water depth within 30 m and divided it into three levels, 0–10 m, 20–20 m, and 20–30 m.

**Artificial islands have been built:** According to relevant research, \(L \leq G \leq B\) indicates that it is easy to form a connecting island dam (\(G\) is the interval between artificial islands, \(L\) is wave wavelength where the artificial island is located, and \(B\) is the length of the existing artificial island). Therefore, when \(0 < G \leq B\), the risk is the highest, and the suitability value is a minimum of 1. In combination with related experience, when \(B < G \leq 3B\), two artificial islands have a reduced mutual influence, and the assigned value was 2. For \(3B < G\), the influence of the islands can be ignored.

**Scouring and silting conditions** were mainly based on the surveyed coastline (State Oceanic Administration, 2012).

**Natural disasters such as typhoons and storm surge:** Based on statistical analysis of related data, the frequency of natural disasters such as typhoons and storm surges was determined and graded. A total of 22 typhoons landed in Hainan from 2000 to 2014, of which 11 landed at Wenchang, four at Wanning, three at Sanya, two at Qionghai, one at Ledong, and one at Lingshui. The suitability value of...
Wenchang, Sanya, and Wanning was selected as 1, while that of Lingshi, Ledong, and Qionghai was 2, and that of other areas was 3.

2.2.4 Determination of indicator weights

The analytic hierarchy process was used to determine the weight of each indicator (Feng et al., 2014; Richard et al., 2018).

To determine the quantitative scale, a scale of importance 1–9 was used. For $a_{ij}$, 1 indicates the two elements have the same importance, 3 indicates the former is slightly more important, 5 indicates the former is obviously more important, 7 indicates the former is very important, and 9 indicates the former is extremely important, while 2, 4, 6, and 8 are intermediate values of the above judgment.

$$A = \begin{bmatrix}
a_{11} & a_{12} & \cdots & a_{1n} \\
\vdots & \vdots & \ddots & \vdots \\
a_{m1} & a_{m2} & \cdots & a_{mn}
\end{bmatrix}$$

The judgment matrix must satisfy the following:

$$a_{ij} = 1/a_{ij} = w_i/w_j$$

$$a_{ij} = 1$$

For the judgment matrix $A$, the calculation satisfies $A \cdot W = \lambda_{max} \cdot W$, where $\lambda_{max}$ is the maximum eigenvalue of $A$, and $W$ is the normalized eigenvector corresponding to $\lambda_{max}$. $W$ is the weight of the corresponding element’s single order. The square root method was used to solve the normalized characteristic eigenvectors and eigenvalues. Specifically, the $n$-th square root $\bar{W}_i = \sqrt[n]{M_i} (M_i = \prod_{j=1}^{n} a_{ij}$ of each row of the judgment matrix was calculated as the value of each row element of the judgment matrix, after which the square root vector was normalized to obtain the $i$-th component of the eigenvector $W$. $\bar{W}_i = \bar{W}_i / \sum_{i=1}^{n} \bar{W}_i$ $(i = 1, 2, \cdots, n)$. The square root vector was then normalized to obtain the $i$-th component of the eigenvector and the maximum eigenvalue of the judgment matrix was finally calculated $\lambda_{max} = \sum_{i=1}^{n} (AW)_i / (nW_i)$, $(AW)_i$ as the $i$-th component of vector $AW$.

To check the consistency of the judgment matrix, the consistency indicator must be calculated: $CI = (\lambda_{max} - n)/(n-1)$. The CI value is then compared with that of the average random consistency indicator, $RI$, and recorded as $CR$. When $CR = CI/CR < 0.10$, the judgment matrix is considered to have satisfactory consistency.

The weights of the indicators obtained were as follows: government’s sea reclamation promotion policy = 0.2381; investment intensity of fixed assets = 0.0952; water depth condition = 0.0741; coastal tourism area and port (dock) area = 0.0768; public welfare activities in the sea (such as fairways, anchorages, submarine cables, and pipelines) = 0.0385; construction of artificial island = 0.0513; fish eggs = 0.0278; larvae and juveniles = 0.0278; benthic biomass = 0.0556; distance from the natural shoreline = 0.1481; scouring and silting conditions = 0.0513; typhoons, storm surges, and other natural disasters = 0.0513; hydro dynamically sensitive areas such as estuaries and bays = 0.0641.

Note: The consistency ratio of the judgment matrix was 0.0000; the weight of the main goal was 1.0000.

3. RESULTS

3.1 Evaluation of Sea Reclamation Suitability Grades

According to the suitability degree of sea reclamation, we divided the region into three grades: reclamation suitable area (Grade I); reclamation restricted area (Grade II); reclamation prohibited area (Grade III) (see Table 2 for the division of suitability grades). Any evaluation factor with a score of 0 has a one-vote veto decision, any form of sea reclamation development activities in the area is prohibited. The rest of the area was evaluated based on the reclamation suitability evaluation model. Determination of the reclamation suitability score standard was based on a combination of the total score frequency curve method and expert consultation to check the score and adjust it as necessary. First, frequency statistics were made based on the total score value, after which a frequency histogram
was plotted. The frequency was then selected according to actual degree of suitability. Next, the boundary of the curve distribution was demarcated, and the rationality of the boundary was fine-tuned through expert consultation and scoring. Table 3 shows the criteria for suitability grading.

Table 2 Grading system of sea reclamation suitability evaluation

| Suitability grade                      | Grade description                                                                 |
|---------------------------------------|------------------------------------------------------------------------------------|
| Sea reclamation suitable (Grade I)    | The sea areas in which the Hainan master plan or related divisions allow changes in the nature of the sea and the corresponding functional areas are available |
|                                       | There is a strong and reasonable demand for engineering construction that changes the nature of the sea |
|                                       | Local resources and environmental conditions are suitable for implementation of projects that change the nature of the sea |
| Sea reclamation restricted (Grade II) | Marine functional division only allows project implementation in sea areas that have no effect on the functional area and induce little change in the nature of the sea |
|                                       | There is a need for engineering construction that changes the nature of the sea |
|                                       | Local resources and environmental conditions permit project implementation that changes the nature of the sea locally or to some extent |
| Sea reclamation prohibited (Grade III)| Sea areas in which Hainan Province’s master plan or marine functional divisions seriously exclude projects that change the nature of the sea |
|                                       | Sea areas in which local resources and environmental conditions seriously exclude projects that change the nature of the sea |
|                                       | Sea areas in which relevant decree clearly stipulates the prohibition of reclamation or sea areas with important protection targets |

Table 3 Division criteria for sea reclamation suitability evaluation

| Sea reclamation suitability indicator | Evaluation criteria |
|--------------------------------------|----------------------|
| Reclamation suitable (Grade I)       | 0.000–1.8053         |
| Reclamation restricted (Grade II)    | 1.8053–2.5262        |
| Reclamation prohibited (Grade III)   | 2.404–3.000          |

3.2 Sea reclamation Suitability in Hainan Province
According to the results, about 26.94% of the total sea area in Hainan Province is suitable for reclamation, while about 52.04% of the area is characterized as sea reclamation restricted, and the sea reclamation prohibited area is about 21.02% of the total sea area (Figure 2 and 3).
Figure 2  GIS map of sea reclamation suitability
(red = sea reclamation prohibited area, yellow = sea reclamation restricted area, green = sea reclamation suitable area)

Figure 3  GIS map of sea reclamation suitability after the ecological red line is superimposed
(red = sea reclamation prohibited area, yellow = sea reclamation restricted area, green = sea reclamation suitable area)
3.3 Management Requirements for Sea Reclamation

3.3.1 Management requirements for sea reclamation suitable areas
Sea reclamation suitable areas refer to areas in which sea reclamation activities can be conducted in accordance with the needs of the natural environment and socio-economic development of the region. In this round of sea reclamation planning, a total of 10 reclamation suitable areas with a total area of 257,319 hectares were identified.

Sea reclamation suitable areas allow for appropriate sea reclamation development activities based on the needs of surrounding port dock areas, urban construction, or other major construction projects. However, strict control requirements must be applied. Rationales of sea reclamation activities should be strictly demonstrated to ensure reasonable sea reclamation requirements. Accordingly, the scale of sea reclamation shall be subject to the control of the national and provincial marine departments. In addition, in order to protect the natural shoreline as much as possible, prolong artificial shorelines, various measures must be taken, such as rationally optimize the layout of the reclamation sea level, implement artificial islands, multi-jet banks, and block group reclamation.

3.3.2 Management requirements for sea reclamation restricted areas
In this round of sea reclamation planning, there were 23 restricted areas of sea reclamation with a total area of 500,625 hectares.

Sea reclamation restricted areas shall strictly limit the development activities of sea reclamation. With the exception for construction of port dock areas in which moderate reclamation can be conducted along the shoreline, sea reclamation should not be conducted within 1 km of the shore. If reclamation activities are truly required after rigorous discussion, multiple plans should be compared regarding project site selection, impacts of changes in hydrodynamics and scouring/silting, graphic design schemes, sea use scale, and reclamation methods. Measures shall be implemented to prevent unreasonable site selection, excessive use of the sea, abuse of shoreline resources, and severe damage to the environment, as well as to achieve scientific use of the sea to protect marine biodiversity and protect the natural environment.

3.3.3 Management requirements for sea reclamation prohibited areas
In this round of reclamation planning, there were a total of 24 sea reclamation prohibited areas with a total area of 200,994 hectares.

No form of sea reclamation is allowed in sea reclamation prohibited areas.

4. CONCLUSIONS
(1) We analyzed the area 1 km offshore from Hainan Island to a depth of 30 m through suitability analysis combined with the ecological red line method. The results showed that the sea reclamation suitable area accounts for about 26.94% of the entire sea area, while the sea reclamation restricted area accounts for about 52.04%, and the sea reclamation prohibited area accounts for about 21.02% of the entire sea area.

(2) Combining relevant planning and actual conditions, different management requirements for sea reclamation suitable areas, sea reclamation restricted areas, and sea reclamation prohibited areas were proposed.

(3) It should be noted that the sea reclamation suitable area defined in this paper does not mean that all sea reclamation projects can be conducted within the area. Rather, proposed projects should include site selection analysis within the suitable area, and their impact on the ecological environment should be discussed.
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