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# Environmental characteristics and management challenges of brackishwater fish ponds in Cirebon Regency, West Java Province, Indonesia: a fine-scale GIS Approach

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**Abstract.** This study presents a fine-scale Geographic Information System (GIS) method to explore existing environmental and farm management constraints at extensive brackish water aquaculture ponds located in Losari District, Cirebon Regency, and West Java Province. The sampling method followed a detailed survey method, employing high-resolution satellite imagery of worldview-2 and GIS. Detailed pond unit and layout canal maps were used to guide soil and water sampling, measurement of land elevation and tide observation. The result showed that the existing pond canals were not able to supply 4,800,000 m<sup>3</sup> daily required quantity of culture water for the total 2,360 ha pond area due to high sedimentation at the mouth and along the canals. The result of spatial analysis of soil and water variables also indicated that, despite generally good soil and water quality, some existing environmental variables could potentially limit the productivity and sustainability of the existing brackishwater ponds. The soil variables such as phosphate (PO<sub>4</sub>-P) content (79.16 ± 28.34 mg / L) exceeded the optimum standard value of 35-46 mg/L, whilst total nitrogen (Total-N) content (0.07 ± 0.025 %) was lower than the optimum value of > 0.2%, for brackishwater aquaculture. Water quality variables comprising (NO<sub>2</sub>-N), total ammonia nitrogen (NH<sub>3</sub>-N) and nitrate (NO<sub>3</sub>-N) were also identified as limiting factors. Without a significant improvement in pond engineering and better understanding and management of existing environmental limiting factors, the increase in productivity and the sustainability of brackishwater fish ponds in the region seem almost impossible.

## 1. Introduction

The potential brackishwater pond areas in Indonesia are estimated at about 2.9 million ha with the total utilization of 715,846 ha (24.14%) in 2015. Of the total utilization area, 60% is under the category of traditional ponds with low productivity. Traditional pond relies mainly on natural food propagated in the pond with or without fertilization and from water supply from tidal sources. Many of these traditional ponds have been left unproductive or abandoned mainly due to <sup>20</sup> issues or environmental degradation. To maintain the fish or shrimp production, since 2012, the Ministry of Marine Affairs and Fisheries (MMAF) of Indonesia has implemented a national program called “pond revitalization program”, focusing on planning and rehabilitation of pond infrastructure (e.g. dykes and canals) and <sup>2</sup> general layout of existing ponds [1]. It should be noted that in every effort to increase



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land-based aquaculture production, it will involve an expansion of cultivated areas, increased density of aquaculture installations and increased use of feed, fertilizer and chemical inputs, including increased land and water use [2]. Inadequate aquaculture infrastructure such as pond canals will directly or indirectly lead to a decline in water quality which in turn triggers the emergence of fish or shrimp diseases [1]. Thus, land development, rehabilitation, and pond revitalization activities must pay attention to environmental characteristics and specific problems which might be the limiting factors for each location.

Most issues affecting the development and management of aquaculture, including brackishwater aquaculture are spatially referenced problems or at least have spatial components [3]. Geographic Information Systems (GIS) has various advantages compared to other conventional methods to handle processes and solve more complex spatially referenced problems in aquaculture. GIS, for examples, can provide a visual inventory of the physical, biological, and economic characteristics of the environment and also enable the generation of suitability maps for different uses [4,5]. [6] and [7] demonstrated the great advantage of GIS for brackish water aquaculture site selection by identifying land use/land cover patterns combined with 6 main group variables namely, engineering variables, water quality variables, soil quality variables, pond infrastructure facility, meteorological variables, and social restrictions. To apply spatial analysis in aquaculture [3] recommended three different *spatial scales*, comprising small farm/cluster scale; waterbody /watershed zone; global market-trade scale. A semi-detailed land suitability map can be assumed to be equivalent to the scale of watershed zones and is applicable for general aquaculture evaluation and planning purposes at provincial or regency level, whilst a detailed land suitability map of the small farm or cluster scale can be applied to help various stages in pond management, evaluation of environmental impacts and calculation of land carrying capacity [3,8,9,10].

The pond revitalization program requires a robust method as well as supporting detailed spatial dataset to evaluate the suitability of local farm management policies with consideration of land characteristics. Understanding engineering suitability of canal design and networks, pond units' layout, coastal hydrology, soil, and water quality and also aquaculture production history are of important information in the implementation of the pond revitalization program. Therefore, the farm-scale approach is considered very relevant and can help the pond revitalization program succeed. This study presents a detailed scale approach of evaluating environmental characteristics and pond management challenges in Cirebon Regency which is one of the main shrimps producing area and targeted locations for pond revitalization program in Indonesia.

## 2. Materials and methods

### 2.1. The study site

The study was conducted on existing brackishwater ponds in Losari District, Cirebon Regency, West Java Province of Indonesia, which lies between 6° 44' 6" and 6° 50' 7.7" south latitude, and longitudes 108° 43' 34.8" and 108° 50' 29.1" east longitude (Figure 1). The topography in Losari District is generally low-lying coastal urban area and is facing directly the Java Sea. Land with elevation  $\leq 25$  m accounts for more than 65% of the district area [11]. Based on DKP-Cirebon report in 2012, brackishwater aquaculture ponds locates in seven coastal districts, of which the largest potential area is in Losari Subdistrict. However, despite Losari's largest potential brackish water pond area, the actual land usage for shrimp or fish farming is relatively low covering only about 1,360 of the total 4,000 ha potential areas. The existing brackishwater ponds have been utilized mainly for low-density milkfish (*Chanos chanos*) and tiger shrimp (*Penaeus monodon*) culture. Since 1993 recurrent crop losses due to white-spot disease and unfavorable environmental condition have limited production of *P. monodon* in traditional ponds throughout Indonesia. Because of this, many aquaculture ponds have fallen into disuse, or their use is limited to only milkfish production [12].

### 28. Soil and water sampling and laboratory analysis

A total of 63 for each soil and water samples was taken following a modified transect method, by which additional 27 point samples in-between the transect lines were collected to improve distribution and density of the sampling points and to capture landscape feature of the study area. The soil samples were collected from mostly fallowed pond bottoms (depths 0.1 to 0.4 m and 0.4 to 0.6 m) using a Jarret bucket auger. These soil samples were transported to the Soil and Water Laboratory of Research Institute for Coastal Aquaculture (RICA), in Maros District of South Sulawesi Province, for further analysis. Field and laboratory soil analysis was undertaken for 5 chemical and 1 physical variable. The soil physical variable was soil textural classes, whilst soil chemical analysis included  $\text{pH}_F$ ,  $\text{pH}_{\text{FOX}}$ , total nitrogen (Total-N), total and available phosphorus (P- $\text{PO}_4$ ) and Total Organic Matter (TOM) (%). Field  $\text{pH}_F$  and field  $\text{pH}$  after oxidation with 30% analytical grade hydrogen peroxide ( $\text{pH}_{\text{FOX}}$ ) were directly measured on a 'soil: water' paste [13] in the field using pH meter (Hanna-HI 8424).  $\text{N}_{\text{TOT}}$  was determined according to Kjeldahl method using Keltex apparatus [14], P- $\text{PO}_4$  analysis followed Olsen dan Bray 1 method; Olsen is applied for soil with  $\text{pH}$  higher than 5.5, whilst Bray 1 if  $\text{pH}$  lower than 5.5 [15,16]. TOM was measured using Walkley-Black's wet oxidation method using 0.5 mm soil fraction [17,18]. The baseline water quality variables that were measured covered: temperature, salinity,  $\text{pH}$ ,  $\text{NO}_2$ ,  $\text{NO}_3$ ,  $\text{NH}_3$ ,  $\text{PO}_4$ , and Fe. This suite of variables is effective as a set of indicators for the changes in water quality. Salinity and  $\text{pH}$  were measured *in situ* using an YSI Pro Plus. Nitrite ( $\text{NO}_2\text{-N}$ ), Nitrate ( $\text{NO}_3\text{-N}$ ), Ammonia ( $\text{NH}_3\text{-N}$ ), Phosphate ( $\text{PO}_4$ ) and TOM were analyzed in the Water Laboratory of RICA following the procedure of [19,20].

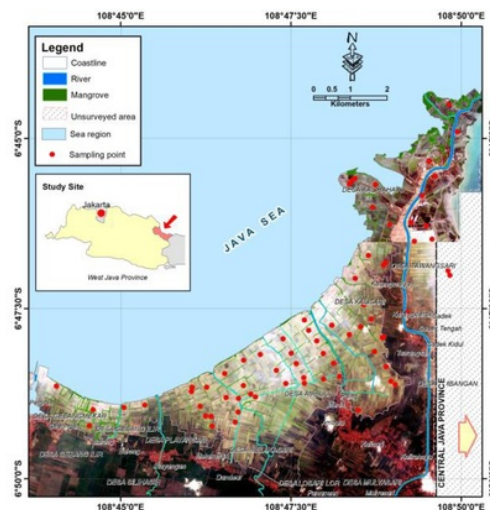


Figure 1. North coast of Cirebon Regency and location of sampling sites in Losari District.

Detailed mapping of pond bed elevation was carried out using Nikon® Digital Theodolite NE-102 on 55 main control points and 212 survey points which were distributed throughout study areas. At the same time as pond bed elevation measurement, a 15-day tidal observation was conducted using an automatic tide gauge of Keller Water Level Logger and calculated using least square method to predict average high tidal surface [21]. Seven primary tidal constituents including the principal lunar semi-diurnal components (M2), Principal solar semi-diurnal components (S2), lunar elliptic semi-diurnal constituents (N2), lunar declination semi-diurnal constituents (K2), Luni-solar diurnal component (K1), Principal lunar diurnal component (O1) and solar declination diurnal constituents (P1) were obtained from this analysis. The output of the tidal analysis of local mean sea level was used as a reference datum for elevation data to generate a detailed mapping of the pond bottom.

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Key soil and water variables considered as key limiting factors for the production of brackishwater ponds in the study area were selected and spatially analyzed using *ordinary kriging* (OK) method [22,23]. The output of kriging maps of key soil and water variables were used to explain spatial variability and context of the environmental and management challenges in the study area. All statistical analysis was performed by SPSS software version 17. The descriptive statistics analysis (e.g., mean and standard deviation) was first done to gain insight into the distribution values of soil data. Spatial analysis that includes vectorization, spatial interpolation, and combination of thematic maps was analyzed using ArcGIS 10.3, Map Info 9.0 and SURFER 8.0 software.

### 3. Results and Discussion

#### 3.1. Layout, topography, and hydrology of brackishwater ponds area

The map of pond layout which was manually extracted and vectorized from the WorldView-2 imagery was presented in Figure 2. As shown in the detailed map, there was an estimate of 3000 existing pond units covering the total area of 2.360 ha and stretching 20.7 km coastline of the survey area in Losari District. Fish or shrimp pond units generally were range in size from 0.2 to 3 ha (average 0.8 ha). The existing ponds were generally converted from mangrove and rice fields, which were located 1 to 10 meters from the primary or secondary canals. The analysis also indicated that pond units received seawater from 20 main canals during high tide, and used the same canals to discharge effluent at low tide. Canal length varied from 400 to 3000 m with an average width of 5 m. Water used for fish culture come from sea canals, brackish water rivers, or a mixture of the two which were then spread to pond units through secondary or tertiary canals. Mangroves (mainly *Rizophora sp*) can now only be observed in several spots along primary canals or edge of the pond units nearby coastline.

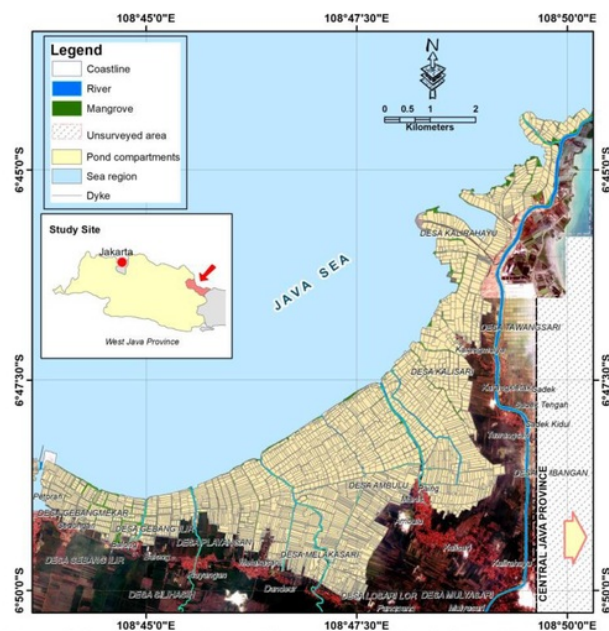


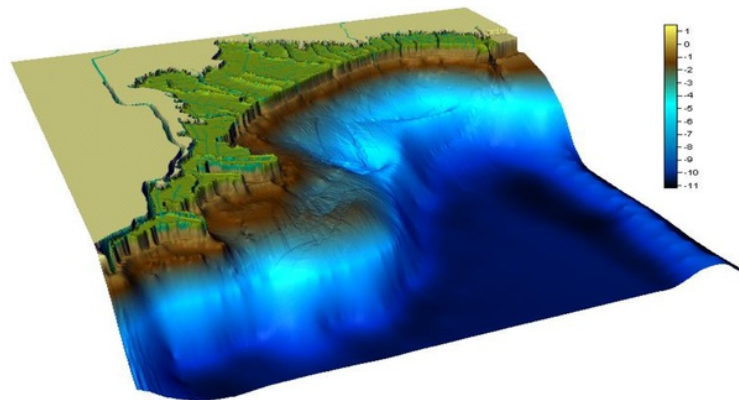
Figure 2. Map of the pond and canal layout vectorized from WorldView-2 imagery

Based on the analysis of local tide data, it was known that the tidal type for the study region was a mixed-type with semi-diurnal dominance (formzhal numbers/F = 0.95). With this mixed tidal cycle, water exchange in pond culture can only be effectively done twice daily, with the average 5 hours

water intake period in every high tide. With amplitude values of major harmonic constituents (M2=3; S2=42, N2=3; K2=47; K1=39; O1=4 and P1=26), a relatively small ( $\leq 1$  m) were very likely to occur in the study region even at average high tides.

The detailed topographic maps of sea bed and pond areas were shown in Figure 3. The general topography of the sea bed was gently sloping (slope  $< 2\%$ ) within a distance of 300 m from the coastline, but subsequently changes to  $> 10\%$  seaward. This indicated that a fairly strong wave often occurred in this region. Sediment from bank or pond wall erosion and sludge was removed during harvest and pond preparation, transported to the rivers or pond canals when high waves will be pushed and deposited along the beach and around the mouth of rivers or canals. The deposited sediments form arising coastal land overgrown with mangroves. Unfortunately, most of the newly growing land has been converted into fish ponds, by which creating more problems in management.

Water availability or good water supply is one of key environmental factors affecting the productivity of small-scale pond-based aquaculture. Water in the pond must be kept at certain level and the quality must be kept high to ensure optimal growth of cultured organisms. If it is assumed that the average depth of pond canals is 1 m, the total surface area of the (primary, secondary and tertiary) canal is 2,400,000 m<sup>2</sup>, and the tidal type of semi-diurnal (tidal range = 0.9 m); then daily water available is approximately 4,800,000 m<sup>3</sup>. The available volume of water is expected to supply 3000 pond units having a total area of 2360,21 (23,600,000 m<sup>2</sup>) with water requirements 8,850,000 m<sup>3</sup> (50% of the total needs of the pond units with an average water depth of 0.75 m). If existing canals can effectively function as expected, the available volume of water could technically meet the water requirements for fish pond culture. According to [24] water availability is considered sufficient if it can be obtained within a period of 5 high tides. The result of calculations seemed to exceed the real capacity of existing canals in providing water because with an average maximum flow rate of 0.5 m / sec, high tide water could only reach a maximum distance of  $\pm 1$  km (high tide time period = 5 hours). The shape of curved and shallow canals also inhibits the flow of water into fish ponds. Additionally, primary canals required times to distribute available water into secondary and tertiary canals. Some of the ponds in this study area also obtained water from rivers and freshwater canals of which the seawater supply was only possible with the help of pumps, especially those that are further away from the coastline.



**Figure 3.** The topography of brackishwater ponds area and pond bed (water depth and elevation in meter)

Under these circumstances, maintaining the required volume and optimum quality of water for pond aquaculture in this location seemed very difficult due to the limited number and improper design of primary canals. The accumulated organic matter as results of dead benthic algae, fish feces, and

uneaten feed along with hazardous pesticide residues was usually washed and discharged by farmers through primary canals with the hopes that it will be wasted and neutralized when reaching the sea as receiving the body. Unfortunately, the pond effluents very often before reaching the sea were pushed back by high tide and incoming wave and deposited at the canals' mouth. This inefficient effluent treatment could create environmental conditions that are not suitable and even dangerous not only for cultured organisms but also other coastal habitats.

### 3.2. Soil and Water Quality

The result of the physicochemical analysis (pH, salinity, temperature, DO, nitrate, ammonia, nitrite, phosphate, and TOM) was summarized in Table 1. The result of in-situ measurements of water quality showed that salinity, temperature, pH and DO of pond water were still in the tolerable level and safe for brackishwater aquaculture. However, the result of the spatial analysis revealed temperature values ranged from 29.7°C to 38.0°C, of which some have exceeded the optimum value for shrimp culture, particularly for tiger shrimp (*Penaeus monodon*). The spatial distribution of pond water temperature values was described in Figure 4. Lying in the tropical region, Indonesia does not experience large seasonal temperature fluctuations, only daily temperature fluctuations that were observed to cause problems in pond culture. Variations in temperature and high values of water temperature measured in some spots were mainly due to differences in measurement time and the difference in pond water depth. According to [24], water temperature for the growth of tiger shrimp ranges from 26°C to 32°C, but the optimum temperature for increased productions is between 29 °C and 30°C [24]. [25] reported the optimum temperature to support the growth of whiteleg shrimp (*Litopenaeus vannamei*) ranges from 25 °C to 35°C. Given this, the kriging map does not only describe the spatial distribution of key variables values but also explains the reason for the spatial variability.

**Table 1.** Descriptive statistics of pond water variables (n=65)

Variables	Value (mean ± standard of deviation)	Suitable value*
Salinity (ppt)	25.44 ± 7.08	5-34
Temperature (°C)	32.97 ± 1.67	21-32
pH	8.25 ± 0.27	6.5-8.3
DO (mg/L)	5.62 ± 1.18	4-10
Nitrite, NO <sub>2</sub> -N (mg/L)	0.09 ± 0.16	<0.05
Ammonia, NH <sub>3</sub> -N (mg/L)	0.32 ± 0.16	<0.10
Nitrate, NO <sub>3</sub> -N (mg/L)	0.64 ± 0.67	<0.30
Phosphate, PO <sub>4</sub> -P (mg/L)	0.04 ± 0.07	0.01-0.10
TOM (mg/L)	50.50 ± 7.42	26 - 60

\*[24, 6]

The result of the laboratory analysis of pond water quality in Table 1 generally indicated that phosphate and BOT values of pond water were still within a suitable range for aquaculture. However, the concentrations of NO<sub>2</sub>-N, NH<sub>3</sub>-N, and NO<sub>3</sub>-N must be monitored because most of it exceeded the acceptable concentration for fish culture. NH<sub>3</sub>-N concentration obtained in this study ranged from 0.0013 - 0.762 mg/L (0.32 ± 0.163), that were mostly higher than the standard water quality for the growth of marine biota, which was less than 0.10 mg / L [26]. Ammonia can be in the form of NH<sub>3</sub> molecules or NH<sub>4</sub> ions, of which NH<sub>3</sub> was more toxic than NH<sub>4</sub> [24]. NH<sub>3</sub> can penetrate into cell membranes faster than NH<sub>4</sub> [27]. The NH<sub>3</sub> concentration of 0.05 to 0.20 mg/L could inhibit the growth of aquatic organisms in general. If NH<sub>3</sub> concentration was more than 0.2 mg/L, it was toxic for some fish species [28]. [29] reported the acceptable concentration of ammonia for tiger shrimp culture was less than 0.1 mg / L. Fish cannot adapt with high concentrations of NH<sub>3</sub>, because it can affect the oxygen binding by blood and eventually leads to suffocation. The high concentration of ammonia and nitrite was also an indication of polluted environmental which was usually attributed to domestic

waste, industrial waste and fertilizer run-off from agriculture activities. In addition, the high level of ammonia concentration in pond water was a good description of the anaerobic condition of pond bottom due to high decomposition of organic matter and problems of pond waters exchange. The nitrate concentration obtained in this study ranged from 0.001 mg/L to 0.640 mg/L, with the average concentration was higher than the acceptable seawater standard for marine organisms (0.008 mg/L) [26].

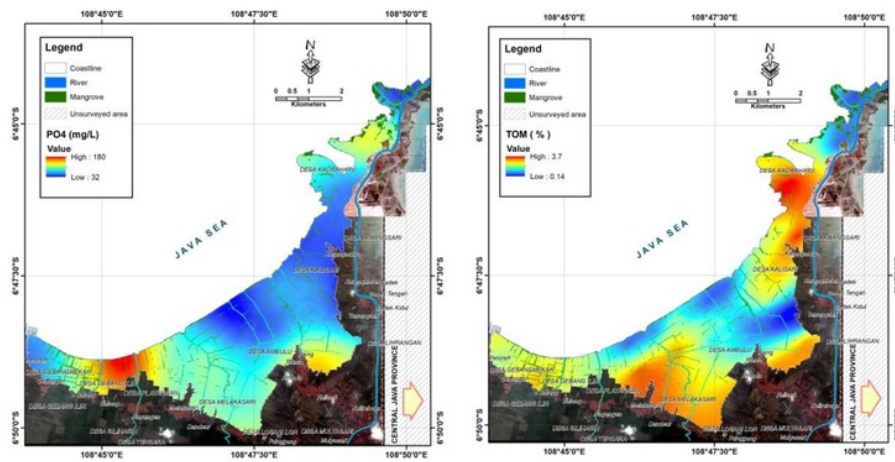
Table 2 summarizes the result of descriptive statistical analysis of soil variables. The result indicated that most soil variables under consideration were generally acceptable for aquaculture standard. The  $pH_F$  values ranged from 6.16 to 7.98 and were still within the acceptable criteria and will not be a limiting factor for aquatic organisms. According to [6], pond soil with a  $pH_F$  ranging from 6.5 to 8.5 was good because the limiting factor can be very easily managed. The difference between  $pH_F$  and  $pH_{FOX}$  ( $pH_F - pH_{FOX}$ ) of soil samples which was a good indicator for potential acidity ranging from 0.0 to 1.23 ( $0.41 \pm 0.35$ ) was also still in the suitable category for aquaculture. The greater  $pH_F - pH_{FOX}$  value indicated the greater the potential for acidity in acid sulfate soils (ASSs). The soil quality variable observed to be a limiting factor for aquaculture was the concentration of phosphate. As can be seen in Table 2, phosphate values of soil samples obtained from the study area ranged from 31.99 - 180.88 ( $79.16 \pm 28.34$ ). Although the result, in general, showed a high level of soil fertility, in some locations the concentrations have exceeded the optimum standard for aquaculture activities. Spatial distribution of  $PO_4$  values as shown in Figure 4 indicated that the highest phosphate content values were concentrated at the location around the intensive ponds and in the ponds neighboring rice fields. The high phosphate content around intensive ponds could be attributed to effluents such as water, sediment and uneaten feed released to nearby environments. Excessive application of phosphate fertilizers on agriculture farms will also eventually be drained through canals that interconnected with aquaculture ponds.

**Table 2.** Descriptive statistics of soil variables (mean  $\pm$  standard of deviation; n=65)

Variables	Value	Suitable Value*
$pH_F$	$7.06 \pm 0.32$	6.5 – 8.5
$pH_F - pH_{FOX}$	$0.41 \pm 0.35$	< 1.0
Phosphate (P- $PO_4$ ) (mg/L)	$79.16 \pm 28.34$	35 - 46
Total-N (%)	$0.07 \pm 0.025$	> 0.21
TOM (%)	$1.73 \pm 0.876$	3.5 – 6.0
Textural classes	clay, sandy clay, clay loam, loam, sandy loam, and sandy clay loam	clay, clay loam, silty clay loam, silty loam, loam, and sandy clay loam

\*[30,31,32]

The results in Figure 4 further showed that the average total nitrogen (Total-N) concentration was lower than the optimum value required for aquaculture, with concentrations of 0.02 - 0.18%. Nitrogen (N) plays important role in the dynamics of the aquaculture system; however, using only the total N level, it was still difficult to determine the role of various derivative N compounds at the study location. This was due to dual roles of N compounds as nutrients and as poisons [33]. As with the total N-content, TOM of the soil was also lower than the required for growth of aquatic organisms. TOM content of soils samples obtained from the study area ranged from 0.14% to 3.78%, which were lower than suitable values for aquaculture [34]. Low TOM content of the pond soil, efforts were needed to increase the level through the application of organic fertilizers in order to increase the biomass of natural feed. However, the high content of organic matter in soils can cause an increase in the population of bacteria,  $CO_2$ ,  $H_2S$ , and  $CH_4$  that potentially inhibit the growth of vannamei shrimp. It also required a high oxygen demand and causes severe oxygen depletion, which in turn affected fish yields [35]. Since most fish and shrimp ponds in the study area were managed following traditional plus (improved extensive) and semi-intensive technologies, it was necessary to provide natural food to support the growth of cultured organisms.



**Figure 4.** Kriging map of PO<sub>4</sub> and TOM of pond bed soil

As with other traditional aquaculture practices in Indonesia, the management of brackishwater ponds in this location is carried out with rudimentary methods including sub-surface soil removal, use of chemicals (lime, fertilizers and pesticides), regular water exchanges to improve water quality and enhance nutrient recycling in pond, removal of accumulated organic materials, and repairing of cracked dykes. Bearing in mind that lime and fertilizer requirements, for example, might not be longer suitable with the current conditions of pond environmental quality. Based on field observation, it was very clear that most farmers did not fully take into account the aforementioned key soil and water variables during site election, pond preparation, and pond management. These pond management methods have been practiced from generation to generation. Therefore, the brackish water aquaculture management practices must be (re)evaluated regarding significant changes in the quality of the pond environment and specific characteristics of pond clusters or pond units.

#### 4. Conclusion

The present study has shown that the fine-scale spatial analysis approach provided a very useful information that was applicable to the farm level of aquaculture management in general. The fine-scale spatial analysis approach accurately maps and gives insight into environmental and pond engineering constraints in the study site. Given its appropriate soil quality, water quality and climate conditions; there was a continuous shrimp or fish loss that causes the total production from brackishwater aquaculture below target. The present aquaculture practices in the study site have not fully adopted or complied with good aquaculture practices and farmers have not properly managed the existing limiting factors. The environmental limiting factors identified must be handled appropriately to ensure the increased production and sustainability of brackishwater aquaculture in the study area.

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