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Hydro-geomorphic controls on the development and distribution of acid sulfate soils in Central Java, Indonesia

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ABSTRACT

Coastal planning policies and regulations in Indonesia have not adequately considered acid sulfate soils (ASS) as a constraint on development. Aquaculture is often undertaken in unsuitable areas, and fish and shrimp culture systems, in particular, fail after a short period of production because of the impacts of ASS on pond water quality and, subsequently, on fish and shrimp health. This study describes a mapping approach based on an understanding of the hydro-geomorphic controls on the formation and the distribution of ASS in Central Java, Indonesia. The underlying approach was to identify associations between ASS development and distribution within estuarine hydro-geomorphological units (HGUs). This study utilized a multi-level methodology involving multi-resolution, remotely-sensed data and GIS analysis, coupled with field and laboratory-based data, to obtain hydro-geomorphic and soil information at different mapping scales. An estuary classification scheme for Central Java identified river, tide and wave-dominated estuaries as the dominant estuary types. HGUs were identified in each estuary type to define the relationships between landform development processes and pyrite concentration in soil layers. Thirty-nine HGUs were classified based on landforms, marine and fluvial hydrology, geomorphic processes, land use, and vegetation types. Field and laboratory assessment of soil properties were undertaken to identify the horizontal distribution of ASS in the HGUS and its vertical character in soil profiles. In contrast to previous studies, the results showed that estuaries located in low-energy environments on the north coast have low (< 0.1%) pyrite concentrations in 90% of their HGUs. Decades-old intensive aquaculture and dredging activities, that led to repeated oxidation and leaching, were identified as factors for low pyrite concentrations. On the south coast, the combination of a high river and marine energy environment created scattered landforms with soils that have very high (4–9%) pyrite concentrations. These ASS-bearing HGUs mostly developed in low-energy estuarine environments overlying former high river energy environments. The information generated for each HGU facilitated the development of an ASS mapping model that incorporates knowledge on the relationship between soil and landform formation in Central Java estuaries. Knowing where ASS occur is essential to minimize the risk of environment degradation. Using multi-resolution, remotely sensed data decreases cost and labour, compared to more traditional mapping approaches, especially to identify sampling sites for field surveys. The resulting maps and mapping methods will improve land capability assessment for brackishwater aquaculture and other coastal land use in Indonesia.

1. Introduction

Throughout Indonesia, many aquaculture ponds and coastal industries have been developed on acid sulfate soils (ASS) without an appreciation of the impacts of these soils on productivity and the environment. Acid sulfate soil is sediment containing pyrite (FeS_2) which usually forms beneath mangrove forests and other tidally-influenced environments because of bacterially-mediated reduction of sulfate to sulfides in organically-rich sediments (Dent, 1986). The pyrite remains inactive under waterlogged, oxygen-deficient conditions, which are typical of low-lying coastal environments. However, when pyrite is exposed to oxygen it oxidises and lowers soil pH (below 4) due to the release of sulfuric acid and mineral acidity associated with metal transformations. This causes severe soil acidification if the acid-neutralizing capacity of the soil is exceeded. Agriculture, drainage-related infrastructure, industry, urbanisation, and land-based aquaculture can lead to soil and water acidification in coastal lowlands (Ahern et al., 1998b; Lin et al., 1995; Sammut et al., 1996).

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Coastal resources have been exploited by aquaculture in Indonesia for the last six decades. Since the 1950s there has been progressive intensification of farming technologies as demand for shrimp has increased. Consequently, the perceived economic benefits of aquaculture in Indonesia and nearby countries has grown (Schuster, 1952, cited in Beveridge and Brooks, 2008; Beveridge, 2007) and with it increased pressure to develop coastal lowlands. The value of fish and shrimp, farmed in earthen ponds, exceeds that of many agricultural commodities in Indonesia. Accordingly, aquaculture has become the most popular livelihood for coastal communities in Indonesia, and expansive areas of ricefields and mangroves have been cleared for shrimp and fish ponds. The expansion of shrimp farming, funded and promoted under various government programs, has increased aquaculture productivity. However, in some areas aquaculture has been economically and environmentally unsustainable due to inappropriate planning decisions and a lack of understanding of environmental constraints on fish and shrimp production (Poernomo, 1992).

Many ASS-affected aquaculture ponds have been abandoned and other environments, which are susceptible to these effects, such as rivers, estuaries and possibly marine areas, have often struggled to remain commercially viable (Dieberg and Kiattisimkul, 1996; Powell and Martens, 2005; Sammut and Hanafi, 2000). Because ASS mostly occur in areas that are under development pressure and populations are high and growing, environmental decision makers and all coastal stakeholders require scientifically-based spatial information to identify the location of these problematic sediments. Mapping approaches are needed to provide efficiently-produced and comprehensive maps of ASS distribution to support economically and environmentally sustainable aquaculture development, and to more effectively manage coastal resources for other livelihoods in Indonesia.

In terms of landscape evolution, previous studies have found that there is a relationship between landscape units with soils that contain pyrite, and the associated estuarine and catchment hydrological processes (Dent, 1986; Pons, 1988; Roy et al., 2001). Estuary types differ because of the catchment processes, geological features, tidal conditions, and marine and riverine energy that control landform evolution. ASS are known to form in low-energy environments (Dent, 1986) and their soil characteristics are likely to differ between estuary types. A low-energy estuarine environment is defined as an environment that is predominantly influenced by low marine and/or riverine energy such that sedimentation rates exceeds erosion rates; such environments facilitate landform development and mangrove growth, as well as the formation of wetlands, such as swamps. These low-energy vegetated environments, that are periodically inundated by sulfate-bearing estuarine waters, create the reducing conditions for bacterial mediation of pyrite formation (Pons and van Breemen, 1982). Under such conditions, significant fine sediments and organic matter accumulate and become anoxic, thus providing a setting for sulfur reduction; the decomposing organic material provides the necessary energy for bacteria to reduce sulfate to sulfides (Dent, 1986).

Variation in daily, annual and seasonal tides, wave conditions, and river discharge, in different estuary types, control the extent and where pyrite forms within landforms (Anda et al., 2009; Dent, 1986; Brownswijk et al., 1995). Hence, estuaries can be partitioned by landform to provide a framework for the investigation of soil forming processes and, in particular, to understand how sediments, such as ASS, are distributed and differ among estuary types.

Recent developments in ASS mapping have focused more on using high technology satellite data and sophisticated soil field measurement instruments (i.e. ground penetrating radar, LIDAR, hyperspectral sensors), and mostly conducted in developed countries such as Finland and Australia (Beucher et al., 2012; Shi et al., 2014). These studies, however, tend not to consider the estuarine evolutionary processes that are needed to understand the morpho-chronology of ASS development (Dent, 1986; Fitzpatrick et al., 2012; Roy et al., 2001). Many studies on ASS mapping have focussed on wetlands, urban areas and agricultural fields, rather than on booming industries such as aquaculture which, in countries like Indonesia, can lead to expansive areas of disturbed soils (Anda et al., 2009; Fitzpatrick et al., 2008; Madsen et al., 1985). Some studies provide very useful detailed mapping methodologies for rapid assessment of ASS distribution and soil properties, and more accurate boundary assessment (Ahmed and Dent, 1997; Bregt and Gesink, 1992; Husson et al., 2000; Tarunamulia, 2008). However, these studies usually show presence or absence of ASS and does not identify the soil profile depth and potential severity of ASS in coastal lowlands. The application of GIS and remote sensing, despite using high-end technology, are specific for a small area and for detailed mapping purposes, rather than investigating ASS mapping methods for multi-scale, multi-level, and multi-area studies. One possible reason for this may be that remotely-sensed data and GIS need to be strongly supported by local knowledge of soil properties and valid interpretations. Thus, a thorough understanding of ASS development processes, and the influence of natural and human factors on the oxidation of pyrite in ASS, is necessary when utilizing remotely sensed and GIS in ASS mapping.

Few studies, particularly in Indonesia, discuss the influence of coastal soil development processes and landscape evolution on soil pyrite concentration and its distribution in the soil profile, especially in terms of aquaculture site suitability and land capability. Most studies focus on ASS development in the context of agricultural management and land drainage (Pons, 1988; Brownswijk et al., 1995). Several studies focused more on the characteristics of coastal ASS, but there has not been much consideration given to aquaculture or coastal management planning (Dent and Pons, 1995; Anda and Subardja, 2013). The overall objective of this study is to develop an understanding of the distribution and formation of ASS based on hydro-geomorphic controls, principally sedimentary processes driven by hydrology, and the subsequent formation of pyrite-bearing coastal landforms (i.e. landforms containing ASS) in Central Java, and to incorporate this knowledge into improved mapping methods. Until today, due to the limited understanding of the relationship between estuary evolution, landform formation, and ASS formation, accurately mapping the presence or absence of ASS for aquaculture in Indonesia seems not achievable. Mapping can under or overestimate the distribution of these soils unless hydro-geomorphic controls on soil formation in different landforms are understood and applied to mapping systems. Therefore, further research is needed to improve the soil-mapping component of land capability assessment protocols and thereby increase the accuracy of the land classes in such schemes.

2. Materials and methods

2.1. Spatialization of the environmental factors for ASS formation

Five key environmental factors required for ASS to develop (Hole and Campbell, 1985; McKenzie et al., 2008; Walker, 1989), were spatialized into a mapping model. The presence of iron, which is essential for pyrite formation, is the only factor that occurs in most soils and sediments whether they are ASS or not. Therefore, existing soil maps were used for spatial data on sediments containing iron and provided other physical and chemical information. The presence of a source of sulfate is the second environmental factor for ASS development, and is related to proximity to seawater or brackishwater environments where sulfate can be delivered to sediments through tides. Estuary type identification was used to investigate the past and present tide dynamic and distribution.

Abundant organic material (the third key environmental factor for ASS development) in brackishwater environments can be determined from the presence of brackishwater vegetation. Mangrove clearance for land use, or for a source of wood for charcoal production, has stripped mangroves in many areas of Indonesia. Nevertheless, such areas still contain relict soil organic matter and were likely to have had sufficient organic matter in the past for pyrite to form. Therefore, this study