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Monitoring and Empirical Modelling for Organic Soil Subsidence Estimation in Sumatra

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Abstract*— A large area of peat swamp forests has disappeared due to either legally or illegally logging, drainage, agricultural conversion, fire, deforestation or large-scale developments for residential centers and industries. In Indonesia, less than 3% of the remaining forest is protected; the rest is available for logging and conversion to other land uses. Over 93% of the remaining swamp forests in Sumatera had been profoundly degraded. Change the land use to agriculture dramatically changes the characteristics of the peat substrate. Once drained, peat is highly flammable, and the fires can burn for month challenging to extinguish. The peat forest change to agriculture practices and other land use supposed to create short or long-term consequences. One of the consequences is surface degradation due to the oxidation process. A set of field measurements has been conducted using Hobo loggers. The measurement aimed at collecting data about the groundwater level and the soil temperature. The data was gathered within one and half year. The measurements were carried out on two conditions: during dry and wet periods. The difference of the model to other approaches into the measurement of land subsidence rate, this model adapts to the characteristics of the soil, the different temperature and the groundwater level over time as three additional factors that strongly affect to the rate of subsidence. The rate of subsidence in Sumatera varies from 2 to 13 cm per year due to the oxidation processes.

***Keywords*— peat; forest change; hobo loggers; land subsidence.**

I. INTRODUCTION

Tropical peatland forests represent approximately 60% of peat in Asia land areas, of which 80% is situated in Indonesia [1] [2]. Southeast Asian peatland forests are among the last vast tracks of rainforest in the region. They are home to many rare animal species and critical for world carbon storage. Peatlands in the coastal areas, such as on the east coast of Sumatera, act as freshwater buffers against saltwater intrusion and they protect valuable agricultural areas between the peat and the sea.

Peatlands are essential for water regulation. A volume of peat soil consists of 90% of water (Warburton, Holden, et al. 2004). Peat soils are generally meters deep, and they store and maintain large quantities of water. Therefore, the peatland forests play an essential role as a retention area for adsorbing floodwater for preventing or mitigating floods in downstream areas. A large area of peat swamp forests has disappeared due to either legally or illegally logging, drainage, agricultural conversion, fire, deforestation or large-scale developments for residential centers and industries.

By 2006, close to 45% of the remaining forests had been severely affected [3]. In Indonesia, less than 3% of the remaining forest is protected, the rest is available for logging and conversion to other land uses [4]. The original area of peat swamp forest in Sumatera was 7 million ha (FAO, 1982). By 1988, over 93% of the remaining swamp forests in Sumatera had been profoundly degraded [5] [4]. Vast areas of the forests in Indonesian have been cleared for transmigration programs. Large-scale plantation companies are now finding the swampy areas increasingly attractive for various reasons [6]. Indonesia is the largest producer of palm oil; oil palm plantation has been the core of plantation in Sumatera since the late 1990s and rapidly expanded because of their vast forests and climate conditions that are suitable for the oil palm [7] [8].

Change the land use to agriculture dramatically changes the characteristics of the peat substrate. Once drained, peat is highly flammable, and the fires can burn for month challenging to extinguish. Swamp forest fires of Kalimantan and Sumatera have been known since 1988. In 1997, due to the peatland fires in both islands, 240 people were killed, 3 million were affected, and the damage cost 8 billion US dollar [9] [10] [11]. The fires can clear layers of peat causing additional land subsidence, which follows immediately by increasing the depth of flood water, generating of floods in the river basin, and leading to an increase of downstream flood.

There appears to be no capacity to deal with this massive problem of degradation of the tropical peatland forests in Sumatera (individually) and in Indonesia [12]. Consequently, the undisturbed tropical forest areas have become extremely rare, even in the protected areas. It is argued then, in order to cope with the current conditions of the forests, the need for an integrated assessment of all indirect and direct factors that contribute to the potential impacts become apparent.

II. Material And Method

A. Description of the study area

The data of the present study was gathered from the middle of the Sumatera delta, i.e., on 100º28' - 102º 12' East longitudes and 0º20' - 1º16' North latitude. The area was covered by tropical rainforests, and approximately 40% of these rainforests grew up in lowland forests.

These forests are mostly located on the eastern coast of Sumatera. 56.6% of the areas are layered with peat soils. 30 % of these layers have more than 4 m depth. In natural conditions, the swamp areas of the east coast of Sumatera function as a retention area by absorbing floodwater. Thereby, they prevent or mitigate flood in the downstream area. The areas along the rivers in the area of interest serve as overflow areas during flood periods in the wet season, while in the dry season the stored water is slowly released.

Figure 1 and 2 present that peat soils are functioned around the eastern coast of Sumatra for crop production and forestry, as well as wildlife and recreation. The organic material can be harvested for horticultural potting soil and for heating and electricity. If the soils are used for crop production, extensive drainage is required. As a rule of thumb, the subsidence should have occurred at a rate of 1 inch of soil per year. However, the drainage leads to more rapid subsidence due to the biochemical oxidation process and the drained Peat soils are vulnerable to fires.

Fig. 1 Peat land distribution and peat thickness on Sumatera island

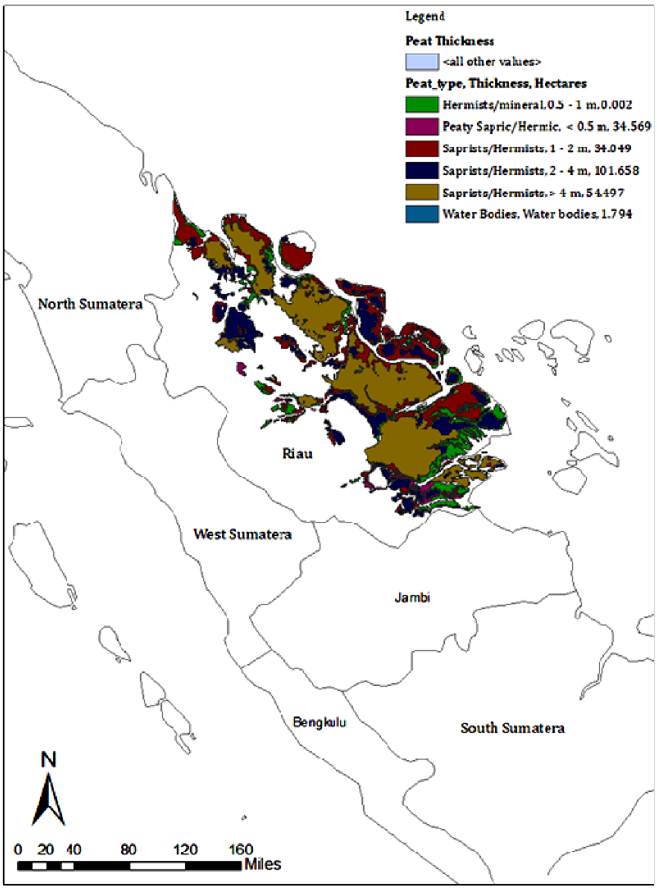

Fig. 2 Peat land distribution and peat thickness on Riau province

B. Data acquisition

We conducted a set of field measurements using Hobo loggers. The measurement aimed at collecting data about the groundwater level and the soil temperature. The data was gathered within one and half year. The measurements were carried out on two conditions: during dry and wet periods. According to Figure 3, based on the results of monitoring in the field, soil temperature varies inversely with groundwater level. The soil temperature increases at the time of level the groundwater level down, and increasing groundwater level has the potential to the soil temperature declined. The process of the rise and down of soil temperature and groundwater level led to a decline of the land surface. The rate of decline depends on the characteristics of peat soil. We also took into account three different peat soil characteristics. These characteristics were based on the three of the peat soil characteristics in doses.

C. Adaptive land subsidence measurement

The previous overview from the literature shows that oxidation is the primary cause of peat soil subsidence in many countries in the world. The overview also shows that other factors besides extreme rainfall, such as the latitude of the area, the soil temperature rate and the groundwater level, affect significantly on the long-term subsidence rates from one climatic region to the other. However, we found that the current approaches to the measurement of land subsidence rates do not take into account these factors. Here, we aim to develop a model of land subsidence that adapts to the type of peat soils, the soil temperature and the changes of groundwater level.

The linear reservoir concept is used to design the proposed model. We consider the concept mainly because it takes into account parameters used in the Arrhenius law, linear regression and the Stephen equation. To develop the model, we followed the following procedures. Firstly, we designed the adaptive land subsidence model based on the linear reservoir concept.

Fig. 3 Field Measurement using Hobo Logger

This step results in a formula to measure the land subsidence, which takes into account the characteristics of the soils, the different of the temperature soils, and the change of the groundwater level. Here, we also identified necessary parameters that were needed to be collected from the field.

Secondly, we used the imaginary satellite maps for selecting locations where the monitoring devices were placed.

Thirdly, we conducted a set of field measurements on the selected locations within a year following the two seasons that occurred in the area. This activity measured the identified necessary parameters, i.e., the temperature soils and the groundwater level. During this field measurement, we also monitored the land subsidence from the selected locations within a year. These data were used to compare the results of the measurement using the adaptive land subsidence model with the actual data.

Finally, we simulated the land subsidence in the selected location by plotting the parameters into the adaptive land subsidence model. Then, we compared the simulation with the results of the field monitoring. Based on this comparison, we presented the validation and analysis of the proposed model.

III. Results and Discussion

A. Land subsidence modeling

1) Arrhenius equation

According to Arrhenius law, oxidation and densification are a consequence of draining peat soils. Alternatively, when the density of peat soils is increased, this results in compaction, desiccation, and loss of groundwater buoyant force. Arrhenius also provides that subsidence can be realized in the short and long term. Densification leads to subsidence within a short duration. Subsidence is realized after a long duration, due to biochemical oxidation. This is especially the case in warm climatic conditions. Arrhenius law uses the Q_{10} concept where most of these reactions have a Q_{10} value that ranges between 1.5 and 2.5 and averages approximately 2.0. It has been applied to calculate organic soil subsidence in Everglades, and it was recognized that as the groundwater level lowered it resulted in the continuation of subsidence on peat soils.

Beside the groundwater level, the temperature is also a critical factor in determining whether there will be a continuation of subsidence on peat soils. The higher of the temperature will create the higher the chemical reaction of peat soils. This change in the reaction is as a consequence of increased or reduced temperature and is expressed by the term Q_{10}. With every temperature change of 10 C, there is a subsequent chemical reaction, according to the Arrhenius law.

$$S_2 = S_1 (Q_{10})^x$$

S_1 = The known oxidative subsidence rate at a known soil temperature T_1

S_2 = Corresponding oxidative subsidence rate at a soil temperature T_2

Q_{10} = represents the change in reaction rate for each 10^oC temperature change

$$x = \frac{T_2 - T_1}{10} = \frac{\Delta T}{10}$$

From the evidence explained that we have assumed that the biochemical reactions responsible for the decomposition of peat have a Q_{10} value of 2.0 and that the base temperature at which decomposition becomes significant is +5°C

[13] suggested that although equation (1) can be used to evaluate the soil temperature effects on the rate of organic soil decomposition, however algebraic equations for evaluation is probably much better to use.

2) Linear regression

The long-term effect of land subsidence on limited data was developed by Wosten as the following formula:

*Subsidence rate (cm/year) = 0.04 * groundwater level (cm)*

According to [14, 15], increasing of subsidence rate at initial phase was 0.9 cm per year and experienced a decrease to 0.4 cm per year. The formula was admitted as the best prediction for the long-term effect of groundwater level changes as consequences of land use change in Malaysia peninsular. Regarding prove it, the formula compared with the empirical model which has developed by Stephens and Stewart (1976). The result of application which is used for Florida and peninsular Malaysia.

3) Stephen equation

Stephen and Stewart determined the Arrhenius law to evaluate the biochemical subsidence rate for low moor organic soil at each location using the annual average soil temperature at the 10 cm depth.

The basic subsidence equation is:

$$S_T = (a + bD) Q_{10}^{(T \;\; T_o)/10} \tag{1}$$

ST = biochemical subsidence rate at temperature, T. D = depth of water table. T = annual average soil temperature at the 10 cm depth. To = base soil temperature, by assuming as 5°C. a and b are constants.

Q10 refers to equation (1), represents the change in reaction rate for each 10^oC temperature change assumed as 2, therefore equation (1) is written as:

$$S_T = (a + bD)(2)^{(Tx-5)/10} \tag{2}$$

This equation has been used to estimate the annual subsidence rate at the Lullymore Experimental Station in the Irish Republic for the arable low moor soils, where the average annual soil temperature is 8.5 °C, and the water table depth is held at 90 cm. Therefore, the equation to represent this region is:

$$S_L = (-0.1035 + 0.0169 * 90)(2)^{(8.5-5)/10} \quad (3)$$

Steven and Steward argued, for a similar type of peat soil in tropical countries which have degree temperatures around 30 °C , the equation can be adjusted as :

$$S_x = (-0.1035 + 0.0169 * 90)(2)^{(30 \quad 5)/10} \quad (4)$$

Therefore, the formula of land subsidence which used at Florida can be derived as follows:

$$S_x = (0.0169D - 0.1035) * 2^{(T-5)/10} \quad (5)$$

Meanwhile, subsidence formula that applied for Malaysia, as shown as following [14, 15]:

$$S_x = (0.093 + 0.00524 * GL) * 2^{(T-5)/10} \quad (6)$$

From those formulas which have been applied in different latitude, it appears that there are similarities to the assumptions for the value of base soil temperature (To), i.e., at 5°C and the value f Q_{10} equal to 2, even though located at difference climate and consisted of a different type of peat soils.

4) The long-term effect of climate on organic soil subsidence

In natural conditions, swamp areas function as a retention area by adsorbing floodwater, thereby preventing or mitigation flood in downstream areas. Swamp areas along the river serve as overflow areas during flood periods, while in the dry season the stored water is slowly released.

Data from field measurements are used in order to determine the value *a* and *b*. Field measurement was taken for a year and carried out on soil temperature and the groundwater level. The reaction of land surface caused a decrease due to changes in temperature and soil water table depth.

(6)

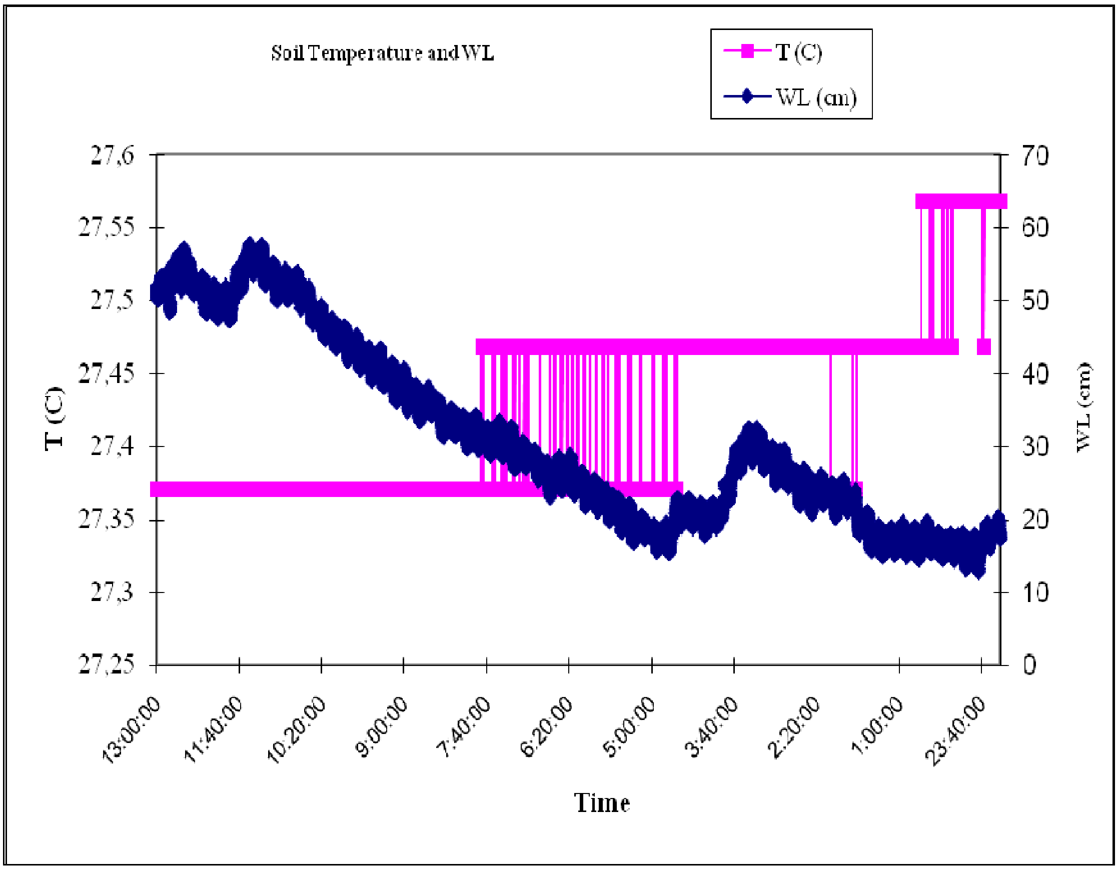

Fig. 4 Soil temperature and groundwater level measurement during the dry and wet season

Equation (6) can be used to estimate the biochemical subsidence rate for organic soils at Sumatra delta where the data of soil temperature at the 10-cm depth is as shown in figure 4. In Sumatra, the study of land subsidence was conducting by installing Hobo logger. Measurements are taken for one and half year form 2012-2013 for every ten minutes as shown in figure 4. It gives information about groundwater and soil temperature measurements. Measurements have been formulated on two conditions; during the dry and wet period. At first installation, data is recorded every ten minutes each 3 months during the wet and dry season. Based on these measurements, land subsidence due to peat oxidation is analyzed by developing algebraic Stephen equation 6 .

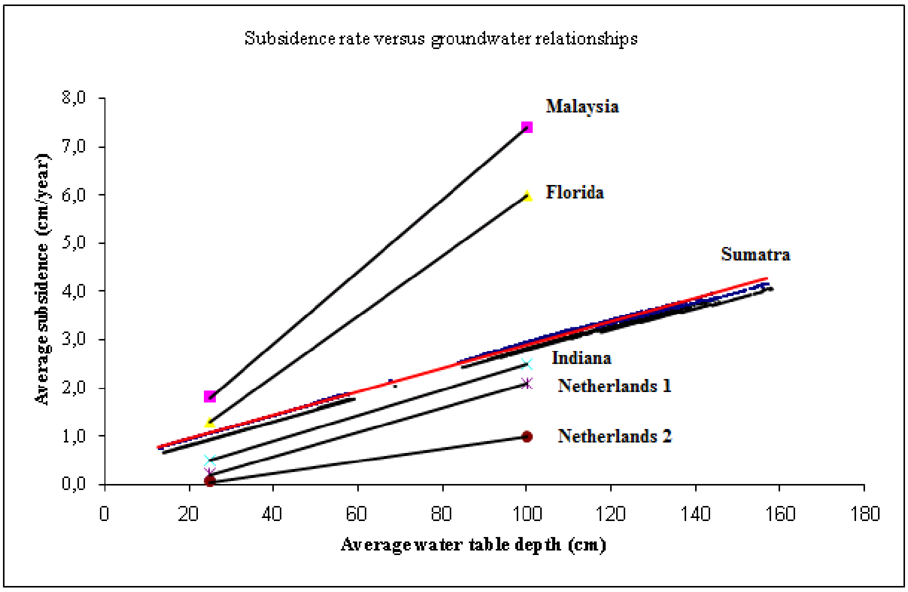

Fig.5 Land subsidence in Sumatra and around the world using Stephen equation

Histosols are used for crop production and forestry, as well as wildlife and recreation. The organic material can also be harvested for horticultural potting soil and for heating and electricity. They can be production crop soils; however extensive drainage is required.

Unfortunately, drainage trigger to subsidence. Subsidence is the loss of soil depth. Subsidence happens when water is drained from the profile. The organic materials “float” in wet conditions and become more compact when drained. Once drained, the soil begins to oxidize and microbes consume the organic matter and slowly turn it into carbon dioxide with time. Subsidence, as a rule of thumb, occurs at a rate of 1 inch of soil per year. This creates problems for drainage ditch maintenance and long-term uses of agricultural soils. Histosols, when drained, are also vulnerable to fires.

IV. Conclusions

The state-of-the-art in land-subsidence analysis progresses unevenly because the degree of understanding of various subsidence mechanisms varies. The most study has been directed to subsidence related to man’s engineering activities. This is facilitated by the availability of data on quantities of subsurface material removed (or injected), on rates and duration of extraction operations, and on changes in ground-water levels. Natural processes are not as easily quantified.

A case of land subsidence is necessarily the integrated surface expression of whatever processes may be active at that site, whether natural or manmade or both. A working hypothesis as to the mechanism or combination of mechanisms operative at the specific site is requisite for designing control measures. The complexity of subsidence mechanisms and their interaction requires a cooperative effort among different disciplines, both in collecting physical evidence and in developing the rationale for the processes involved. The hydrologic sciences have been and will continue to be, significant contributors to land subsidence investigations.

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