Lowland Technology International 2016; 18 (3): 173-182
International Association of Lowland Technology (IALT): ISSN 1344-9656

Research Paper

Linear reservoir-based adaptive land subsidence model: Case of Sumatra peat lowland forests

Nurhamidah [1] and A. Junaidi [2]

ARTICLE INFORMATION

Article history:

Received: 17 April, 2016
Received in revised form: 15 May, 2016
Accepted: 27 June, 2016
Publish on: 28 December, 2016

Keywords:

Subsidence
Linear reservoir
Sumatra
Lowland
Delta
Peat

ABSTRACT

Any model of flood hazard assessment must account for the dynamic nature of floodplains related to the current states of topography. This article proposes a model of the spatial-temporal variability of land subsidence for predicting the land subsidence prone areas based on the concept of linear reservoir. The model is formulated based on analysis on data gathered from Hobo loggers plated along Sumatra deltas. It includes the soil characteristics, the differences in soil temperatures and the change of the groundwater level to factors that cause the land subsidence and effects of the subsidence on the floodplain facies. The validation of this model showed that the spatial-temporal variability of future land subsidence could be quantified, the future inundation depth of floodplains could be predicted, and the model could be applied on any peat land area with potential land subsidence problem.

1. Introduction

The study of modern rivers and their associated Quaternary deposits has provided knowledge into the functioning of floodplains e.g. (Schumm and Brakenridge 1987; Asselman and Middelkoop 1995; Blum and Torngvist 2000; Schumm et al., 2002). The knowledge have allowed for the development of floodplain facies models on the response of floodplains to climate and sea level change (Blum and Tornvist, 2000). These models define “the floodplain” as the relatively flat area surrounding the active river channel that floods during high discharge events – every year to every few years. Overflow and channel breaches can be caused by (Smith and Ward, 1998): (1) overtopping due to floods, extraordinary tidal fluctuations, and waves; and (2) mass failure of levee foundations as aided by subsidence, seepage, erosion, earthquake liquefaction and burrowing animals. The floods in the floodplains and their coastal deltas may also due to intense rainfall and backwater of sea level rise (Blum and Tornvist, 2000; Junk et al., 2013; Musa et al., 2014). The rainfall generates both runoff and standing pools of water on the surface of the floodplains, coincided with the tide rises.

Floodplain area varies with the height and duration of the flood wave. In the case of a levee breach, this depends on the surrounding topography. In the peat lands, the land subsidence rates range from less than 1 cm/year (Nieuwenhuis and Schokking, 1987) to more than 10 cm/year (Wosten et al., 1997). Peat can act like water reservoir that absorbs rainfall and allows it to filter gradually into soil, thereby reducing the speed and

[1] Lecturer, Civil Engineering Department, Engineering Faculty, Andalas University, Limau Manis Padang +62 (0)751 72664, INDONESIA, nurhamidah@ft.unand.ac.id
[2] Lecturer, Civil Engineering Department, Engineering Faculty, Andalas University, Limau Manis Padang +62 (0)751 72664, INDONESIA, ahmad_junaidi@ft.unand.ac.id
Note: Discussion on this paper is open until June 2017.

volume of runoff entering streams and rivers. However, the artificial drainage of peat lands, i.e. illegal logging, agriculture and land reclamation, industrial development, over-pumping groundwater resources, deforestation and fires (Armentano and Verhoeven 1988; Wosten, Hooijer et al. 2006), creates drainage channels that convey surface runoff to streams and rivers more quickly. Moreover, the shrinkage and erosion of dry peat creates numerous and wider sub-surfaces routes for water and flood wave to flow through. In the tropical areas, the process is very fast due to high temperatures. Overall, this results in increasing flood risks (Deverel and Rojstaczer, 1996)

Many studies have been done on investigating the effects of long-term land subsidence on the flood profile (Gambolati et al., 2003). However, little attempt has been conducted on developing a model of flood hazard assessment that considers the effect of the spatial-temporal variability of land subsidence (Potok, 1991; Burkett et al., 2002; Marfai and King, 2008). The present article aims at modeling the measurement of the spatial-temporal variability of future land subsidence therefore the future inundation depth of floodplains on any coastal area with potential land subsidence problem can be predicted.

Using the analogy of the peat soil as a rainfall catchment area, we propose a model of the land subsidence based on the linear reservoir concept. The model is able to calculate the conversion of the water input in the surface discharge (subsidence). 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.

Although the proposed model aims at the subsidence measurement in any area in the world, we take concrete data from the peat lands in the Sumatra areas. It was recorded by FAO in 1982 that Sumatra had 7 million hectares of peat swamp forests. However, by 1988, over 93% of the remaining swamp forest in Sumatra had been heavily degraded (Silvius and Giesen, 1992). According to local government (Much effort has been for implementing flood prevention measurements since 1996, nevertheless floods happen everywhere and even more severe (Bappeda, 2005).

This article is organized as follows. Based on literatures, in section 2, we explore the state of art of approaches from amount of references which resembles to the land characteristics into land subsidence in the peat land areas and its measurement. The analysis of these approaches leads to the design of the adaptive land subsidence model based on the linear reservoir concept that is described in section 3. The section includes the description of the data that is gathered from Sumatra deltas and the validation of the model. Finally, in section 4 we conclude our contributions.

2. State of the art

2.1 Cause of land subsidence

Research by Schothorst (1977) in the Netherlands found that 35% land subsidence could be due to physical process, while the rests were caused by a result of biochemical process. These processes mainly depend on type of peat, decomposition rate, density and thickness of the peat layer, the depth of drainage, and climate (Schothorst, 1977; Schothorst, 1982; Reddy et al., 2007; Leifeld et al., 2011). Once organic soils have been drained, the irreversible process of subsidence starts (Stephens et al., 1984), which can only be blocked by re-saturating the peat (salmah et al., 1991).

The physical process on land subsidence or so-called consolidation is a permanent compaction on saturated peat layer that lies below the ground water level. Drained depth, peat thickness and density of soil can influence the consolidation. This process occurs rapidly in the first 5 to 10 years. A study in Malaysia by Wosten et al. (2003) found that the initial subsidence rates ranged between 2 to 4.6 cm per year. The worst could be as high as 20 – 50 cm per year (Welch and Nor, 1989), as it happened to the soils under pasture in New Zealand (Armentano and Menges, 1986). The consolidation rate can be calculated using the change in bulk density (Salmah et al., 1994). The change is approached using the following equation:

$$x = 0.005665y - 3.52 \quad [1]$$

Where x is the depth below ground level and y is the bulk density

Two types of the biochemical process that can cause land subsidence are: 1. Oxidation and 2. Shrinkage, Oxidation occurs due to the influence of oxygen on the physical layer of peat. The increase of the level of decomposition results in loss of organic matter. At least 75% of long-term subsidence is estimated due to this type of the biochemical process (Stephens and Speir, 1970). Shrinkage is the reduction in volume due to drying peat. Desiccation and the evaporation of water result in the shrinkage of peat layer upon the groundwater table.

Due to their dry circumstances, oxidation is a major cause peat soil subsidence in both tropical and subtropical regions (Andriesse 1988; Deverel and Rojstaczer, 1996; Fornasiero et al., 2003). It is expected that this process in the equator areas, because of their latitude, will exceed the percentage over the other parts of the world. Meanwhile, nearly 70% of the world's tropical peat lands are located the Southeast Asia at altitude from 0 to about 50 m above seak-level with their thickness varying from 0.3 m to 20 m (Anderson, 1983; Wosten et al., 2008); an example of these tropical peat lands is located in Sumatra, Indonesia.

The total land subsidence is usually described as a series of phases. It starts with the consolidation, followed by the slower process of oxidation and shrinkage. However, a study on the land subsidence over 21 years has found that such a linear subsidence model provided a poor prediction of subsidence over time (Wosten et al., 2008). Doels (1995) improved the model by approaching the three subsidence factors (i.e. consolidation, oxidation and shrinkage) individually. Other research has included other significant factors that influence land subsidence besides the three factors mentioned above, such as fire (Maltby and Imirzi, 1993), excessive groundwater withdrawal and intensification of agriculture (Wosten et al. 1997; Dradjad et al., 2003). The latest caused 30 cm of peat land subsidence (cumulated in the period of 1960-1997) in Peninsular Malaysia due to the large-scale agriculture reclamation of tropical peat in tidal swamplands areas through the installation of irrigation-drainage system.

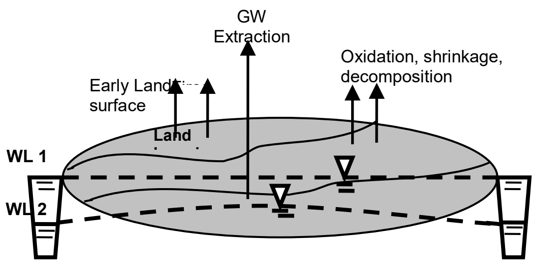

Fig. 1. The peat subsidence process influenced by fire, groundwater extraction, oxidation, shrinkage and decomposition.

Figure 1 illustrates the land subsidence condition during the peat subsidence process. Peat layer can be loss quickly by fires and slowly by the oxidation, shrinkage, and decomposition without rewetting all peat layers above drainage base on river level. Different attempts have been done in minimizing the subsidence. For example, by maintaining ideal conditions for a particular crop yet minimizing oxidation (Berglund, 1995; Morris et al., 2014).

2.2 Land subsidence measurement methods

Current approaches into the land subsidence measurement fall into two categories: (a) technical measurement, comprising mainly using Global Positioning System surveys, subsidence poles and leveling surveys; and (b) empirical modeling, such as *Arrhenius law*, *linear regression*, and *Stephen equation*.

Arrhenius law views that 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. The subsidence can be realized in the short and long term since densification leads to subsidence within a short duration; while the biochemical oxidation causes the long-term subsidence. The law uses the Q_{10} concept where each reaction has a Q_{10} value that range between 1.5 and 2.5 and averages approximately 2.0. A study in Everglades had used this law to calculate a continuation of their organic soil subsidence, which was recognized by as the lowering of the ground water level.

The law also recognizes temperature as a key factor in determining whether or not there will be a continuation of subsidence on peat soils. The higher temperature, the higher is the chemical reaction by the peat soils. The consequence of the temperature level is expressed by the term Q_{10}, i.e. with every change of 10° C there is a subsequence chemical reaction:

$$S_2 = S_1 (Q_{10})^x \quad [2]$$

S_1 is the known the oxidative subsidence rate at a known soil temperature T_1, S_2 is the corresponding oxidative subsidence rate at a soil temperature T_2. Q_{10} represents the change on the reaction rate for each 10° C temperature changes:

$$x = \frac{T_2 - T_1}{10} = \frac{\Delta T}{10} \quad [3]$$

The *linear regression* method was developed to measure the long-term effect of land subsidence with limited data using the following equation:

Subsidence rate = 0.04 * GW_level [4]

Where the Subsidence rate is calculated as cm/year and the groundwater level is cm. According to Wösten et al. (1997, 2008), the increasing of the land subsidence rate at the initial phase was 0.9 cm per year and experienced a decrease to 0.4 cm per year. The Equation [2] was admitted as the best prediction for long-term effect of groundwater level changes as the consequences of the land use change in Malaysia Peninsular. To validate the model, Wosten et al. (2008) used the data of Stephens and Stewart (1976) and Schothorst (1977). Climate related differences in environmental parameters, i.e. soil temperature and seasonal periodicity resulted in the different the differences seen between the Florida's and Malay's soils, described in this study and compared with Indiana and the Netherlands (Hoogland et al., 2012).

Stephens and Stewart (1976) used the Arrhenius law to evaluate the biochemical subsidence rate for low moor organic soul at each location using the annual average soil temperature at the 10 cm depth. The basic subsidence formula of the *Stephen Equation* is:

$$S_T = (a + bD)Q_{10}^{(T-T_o)/10} \quad [5]$$

S_T is the biochemical subsidence rate at temperature T, D is the depth of the water table, *T* is the annual average soil temperature at the 10 cm depth, T_0 is the base soil temperature, and a and b are constants. Q_{10} refers to the equation [2], which represents the change on reaction rate for each 10°C temperature change. Stephen and Steward (1976) assumed that the biochemical reactions responsible for the decomposition of peat had a Q_{10} value of 2.0 and the base temperature T_0 at which decomposition become significant was 5°C. Therefore, based on this assumption, the equation [5] is written as:

$$S_T = (a + bD)(2)^{(Tx-5)/10} \quad [6]$$

In the case of the Lullymore Experimental Station in the Irish Republic (Stephens and Stewart, 1976), the Equation [3] has been used to estimate the annual subsidence rate for the arable low more soils with *T* is 8.5°C and D is held at 90 cm. Thus, the Equation [5] for this region is:

$$S_L = (-0.1035 + 0.0169 * 90)(2)^{(8.5-5)/10} \quad [7]$$

Stephen and Steward (1976) argued that for a similar type of peat soils in the tropical countries, which have degree temperatures around 30°C. They adjusted the Equation [5] to be:

$$S_X = (-0.1035 + 0.0169 * 90)(2)^{(30-5)/10} \quad [8]$$

Hence, to measure the land subsidence rate in Florida, (Stephens and Stewart, 1976) used the following formula:

$$S_X = (0.0169D - 0.1035) * 2^{(T-5)/10} \quad [9]$$

Meanwhile, the formula applied for measuring the land subsidence rate in Malaysia (Wosten et al., 1997; Wosten et al., 2008) is the following:

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

The Equations [5] to [10] have been applied in the areas that are positioned on different latitudes. We found the similarity of the assumptions taken: the T_0 is equal to 5°C, and the Q_{10} is equal to 2. These values were used to measure their land subsidence rate without taking into account the difference of the climate and the type of peat soils of the respected areas.

3. Adaptive land subsidence measurement

The previous overview from literatures shows that oxidation is the major 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 greatly on the long-term subsidence rates from one climatic region to the other. However, we found that the current approaches into 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. This step results 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 satellite imaginary 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 for the field monitoring. Based on this comparison, we presented the validation and the analysis of the proposed model.

The following subsections describe the design of the model: the proposed model, the data acquisition work and the validation of the model.

3.1 Linear Reservoir for measuring land subsidence rate

The linear reservoir concept is based on analysis of the recession limbs of the drainage hydrographs, and has already been used extensively for description of catchment responses (Linsley et al., 1988; Hornberger et al., 1991; Dingman, 1994; Sivapalan et al., 2002; Buytaert et al., 2004). We use the analogy to this concept to model the peat soil subsidence. Here, the water and peat soils are considered as one volume. The concept can be described as:

$$S = kD \quad [11]$$

$$I - O = \frac{dS}{dT} \quad [12]$$

I is the inflow, O is the outflow, S is the stored amount of the water and peat soils, T is the soil temperature and k is a rate constant. We consider that the groundwater level at the soil temperature T is $D_{(T)}$, which can be described as:

$$D_{(T)} = \frac{S_{(T)}}{k} \quad [13]$$

Where $S_{(T)}$ is the land subsidence at the soil temperature T.

Figure 2 the water balance concept shows the change of volume due to the input I, the output O and the annual rate subsidence S. The volume of the combination of the water and peat soils can shrink as a result of water evaporation and peat oxidation.

If we ignore the inflow, the Equation [12] becomes:

$$0 = S_{(T)} + \frac{dD_{(T)}}{dT}$$

$$0 = S_{(T)} + \frac{dD_{(T)}}{dT}$$

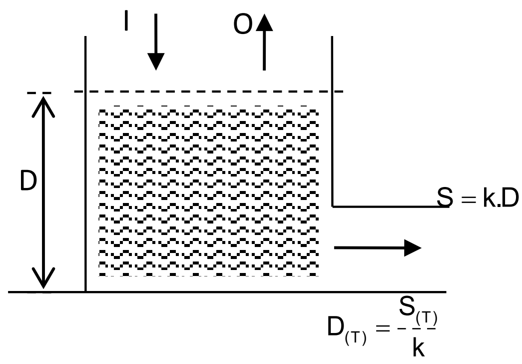

Fig. 2. The water balance concept.

$$\frac{d}{dT}\left[\frac{S_{(T)}}{k}\right] = -S_{(T)}\text{, multiplied by } \frac{1}{S_{(T)}}$$

$$\frac{1}{S_{(T)}}\frac{d}{dT}\left[\frac{S_{(T)}}{k}\right] = -1$$

$$\frac{d\left[\frac{S_{(T)}}{k}\right]}{S_{(T)}} = -dT$$

$$\int \frac{d\left[\frac{S_{(T)}}{k}\right]}{S_{(T)}} = -\int dT$$

With T_0 as the initial soil temperature and by considering the change of temperature $T - T_0$, $S_{(T)}$ can be determined by:

$$\frac{1}{k}\ln S_{(T)} = -\left[T - T_o\right] + C$$

$$\ln S_{(T)} = -k\left[T - T_o\right] + C$$

$$S_{(T)} = e^{-k[T - T_o] + C}$$

The initial land subsidence at the initial soil temperature *T₀* is:

$$S_{[T_o]} = e^{-k[T_o - T_o] + C} = e^{C}$$

Based on the Arrhenius law, i.e. the Equation [2], the land subsidence at the soil temperature T becomes:

$$S_{(T)} = e^{C}.e^{k[T_o - T]} \text{ or } S_{(T)} = S_{(T_o)}.e^{k[T_o - T]}$$

Here, we consider the initial land subsidence as function of the groundwater level D that is written as:

$$S_{T_O} = (a + bD)$$

Where a and b are constants. Therefore, the land subsidence at the soil temperature T can be combined in:

$$S_{(T)} = (a + bD).e^{k[T_O - T]} \quad [14]$$

Where $S_{(T)}$ is the annual rate subsidence (cm) at the soil temperature T (°C) and groundwater level D (cm).

ΔT = To-T is taken from the difference between the highest and lowest hourly soil temperature data at 10 cm depth for a year and the coefficient *k* is adjusted from **Table 1**, a and b are constants.

Furthermore, to take into account of the different characteristics of peat soils, we take the values of *k* from the research of Ho and McKay (2000). The values of *k* in **Table 1** are listed for certain peat soil doses (gram/liter).

3.2 Data acquisition

The data of the present study was gathered from the middle of the Sumatra 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 at lowland forests (see **Fig. 3**).

These forests are mostly located on the eastern coast of Sumatra. 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 eastern cost of Sumatra function as a retention area by absorbing floodwater. Thereby, they prevent or mitigate flood in 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 3 shows that Histosols are used 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 a more rapid subsidence due to the oxidation biochemical process and the drained Histosols are vulnerable to fires.

We conducted a set of field measurements using Hobo loggers located on the middle stream areas of the river.

The measurement aimed at collecting data about the groundwater level and the soil temperature. The data was gathered within one and half year, from 10th of June 2009 until 28th of December 2010. The measurements were carried out on two conditions: during dry and wet periods. According to **Fig. 4**, based on the results of monitoring in the field, soil temperature varies inversely with groundwater level. The soil temperature increase at the time of level the groundwater level down, and increasing groundwater level have 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 land surface. The rate of declining depends on the characteristics of peat soil. We also took into account three different peat soil characteristics. These characteristics were based on the first three of the peat soil doses in **Table 1**, i.e. 4 gr/lt, 8 gr/lt, and 16 gr/lt.

Table 1. The effect of peat dose on lead ion sorption data (Ho and McKay, 2000).

Peat Soil Doses (g/lt)	Correlation Coefficient	Metal Ion Removal Capacity at Equilibrium (mg/g)	*k*(g/mg*min)	Initial Sorption Rate (mg/g*min)
4	1.00	24.9	8.88×10^{-3}	5.13
8	1.00	12.2	6.82×10^{-2}	10.2
16	1.00	6.15	0.359	13.6
24	1.00	4.09	1.03	17.2
32	1.00	3.07	2.17	20.4

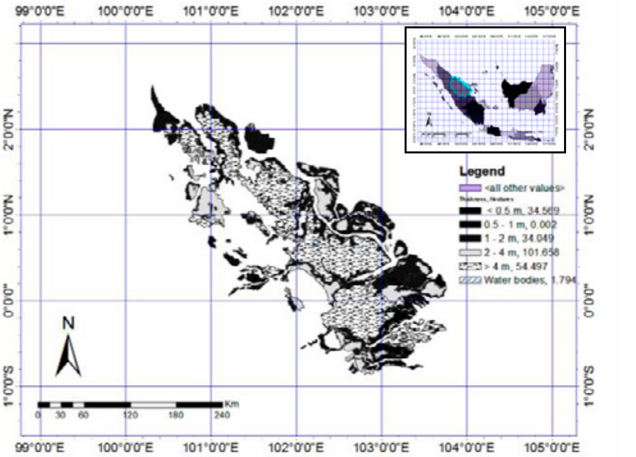

Fig. 3. The peat thickness around the eastern coast of Sumatra (Riau Forestry Management and Research, 2008).

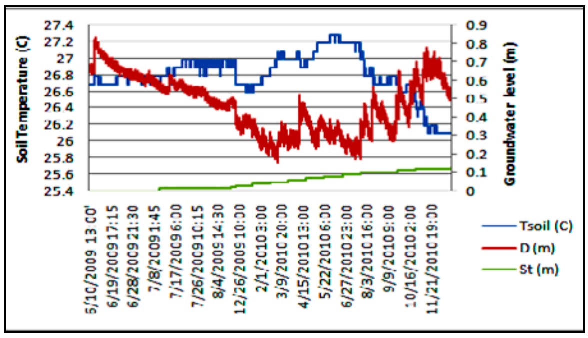

Fig. 4. The soil temperature, groundwater level and in situ settlement gauge measurement were under observation for 18 months.

3.3 Validation of the model

The 18-month-field measurement resulted in and the equation [14] based on the linear reservoir concept were employed to validate the model. Equation [14] was used to estimate the rate of land subsidence by taking into account three different reaction rate constants *k* of the peat soil. The difference between the highest and lowest soil temperature in the area of interest is 20ºC. Using these numbers, Equation [14] can be derived as follows:

St = 1.092a+1.092bD

Trend field measurements in **Fig. 5** were generated by assuming; with St = 10 cm/year, D=80 cm and k1 =8.88 x 10^{-3} (see table 1), equation [14] resulted in 1.092a+95.4b=10. Whereas with St = 5 cm/year, D=40 cm and k1= 8.88 x 10^{-3}, the equation above mentioned will resulted in 1.092a+47.7b=5. By substituting the first equation into the second equation, the variables a and b can be obtained being -0.42 and 0.105 respectively. The similar procedure was also applied for k2, k3, k4 and k5 values. However as representation of Sumatra, it was decided to apply k1, k2 dan k3 only. Having these values, the relation between the subsidence rate and the average of the groundwater depth can be developed and shown in **Fig. 5**. The results of the field monitoring are presented in the following figure. Linear regressions relationships were applied to show the correlation between the rates of subsidence and the ground water table changes. The monitoring had been carried out for 18 months, and these measurement results were compared and used to validate the result of modeling. Based on the variation of different peat soil composition, for k1 value of 8.88 x 10^{-3} then acquired land decreasing trend as depicted by brown dots (k1 marked). For instance, when the groundwater depth is 80 cm, the potential impairment of land (land subsidence) would be 9.5 cm per year. Modeling results using k2 of 6.82 x 10^{-2}, are showed in green points (k2 marked). The potential of land subsidence for groundwater at a depth of about 80 cm is obtained by the potential decrease of 8 cm per year. The red dots (k3 marked) show a potential reduction of land of k3 with a value of 0.359.

With a depth of groundwater 80 cm, the acquiring land reduction potential value for k3 is 3.5 cm per year.

The difference of the soil temperature in a year is in the range of 20 to 40ºC. With the groundwater level D equal to 20, 30, 40, 50, 60, 70, and 80 cm, we can simulate the annual subsidence rate of the organic soils using the Equation [14]. **Figure 6** shows the results of this simulation.

This **Fig. 6** shows that for D equal to 80 cm, which usually occurs during the dry season based on the

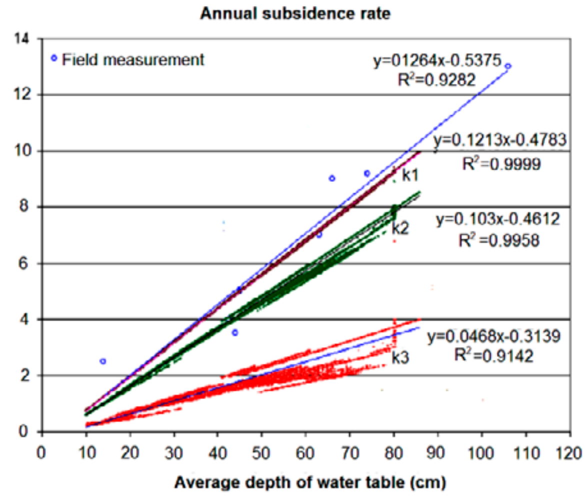

Fig. 5. The annual subsidence rate calculated based on the Adaptive Land Subsidence Model for three different values of k.

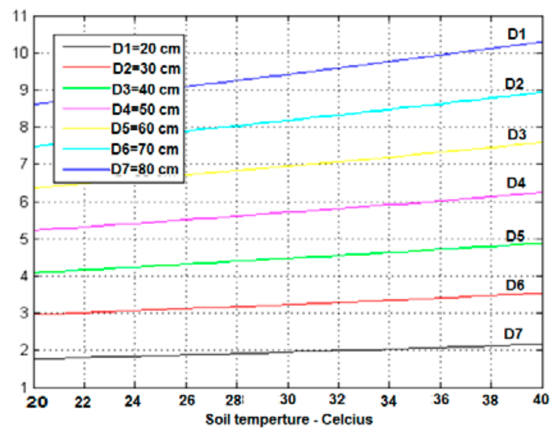

Fig. 6. The Annual subsidence rate of organic soil Sumatra peat areas based on the Adaptive Land Subsidence Model at different soil temperatures and the groundwater levels.

proposed model, the annual subsidence rate in Sumatra peat areas is more than 10 cm/year. In the dry season, the soil temperature of the areas can be higher than 40ºC. During this season, the dryness can cause fire and the fire results to the rapid land subsidence.

This model can be used for any location worldwide with the adjustment of parameters; T and k. Calibration need to be performed on other regions, among others; measurement of land surface temperatures (high and low) and adjustment of the gram per liter content of the peat soils. Regarding the soil characteristic, land subsidence of peat tends to be linear. This model is suitable to predict land subsidence of an area which has few monitoring data.

4. Conclusion

To strengthen the evidence supporting the hypothesis about the correlation between land subsiding and the high occurrence of floods in the Sumatra regions, besides the rainfall-runoff modeling, the research has collected measurement data of ground level, groundwater level, and soil temperature during both dry and wet session with distinctive peat soil characteristics. Using the data, an adaptive land subsidence model has been developed. The model takes an assumption that water component and peat soil are integrated in a volume and the both of them will react to evaporation and oxidation due to year-round temperature change.

Using an analogy of water reservoir for the integration of water and peat soils, the adaptive land subsidence model applies the linear reservoir concept adopted from the field of hydrology for calculating the capacity rate of peat soils in wetland. In this case, the peat soils act as a vast water reservoir. The concept follows the water balance concept for assessing the current status and trends in water resource availability in a reservoir over a specific period of time. To illustrate this concept, consider a reservoir with the water inflow (input) for this reservoir is precipitation and the water outflow (output) is evaporation outflow, any exploitation of water resource from the reservoir will change in the water volume in the reservoir. The model applies a similar approach for wetlands, where the inflow is rainfall and stream flow, and the outflow is evaporation, groundwater extraction and oxidation. The evaporation and the groundwater extraction are factors that cause the initial groundwater level reduction, while the oxidation causes the subsidence of peat soils.

To see the correlation between the groundwater level reduction and the temperature, the present research has compared and analyzed the model using conditions: evaporation and oxidation are treated as one parameter. The results show that the lower groundwater level and the higher temperature will create the higher annual amount of the subsidence rate (see **Figs. 5** and **6**).

The variant of peat soils is also a key factor that causes rapid subsidence of peat soils. The deeper groundwater resources from the surface discharge and the higher soil temperature will accelerate the annual rate of land subsidence. The present research projects the annual rate of land subsidence along East Sumatra's deltas, which will be 12.5 cm per year (see **Fig. 3**). The proposed adaptive land subsidence model can be applied in all areas by entering the relevant variables, namely: (a) the lowest and the highest temperature values in a year, (b) the soil sample, and (c) the soil characteristic, i.e. chemical reaction of peat. Based on the simulation result of the model, to avoid the rapid acceleration of land subsidence, it is recommended to maintain the groundwater level about 10 cm deep from the soil surface.

Acknowledgements

The research of this paper was financially supported by Andalas University Padang, Indonesia, grant no. 030/UN16/PL/AKS/2015. I would like to express my deep gratitude to Prof. Dr. Ir. Nick van de Giesen for his encouragement and useful critiques of this research work. I would also like to thank Dr. Hatma Suryatmojo, for his support in the site measurement.

References

Anderson, J., 1983. The tropical peat swamps of western Malesia. In: Gore AJP (ed) Mires: Swamp, bog, fen and moor. New York: 181-199.

Andriesse, J. P., 1988. Nature and Management of Tropical Peat Soils. Food and Agriculture Organization (FAO) of the United Nations Soils Bulletin no. 59.

Armentano, T. and Menges, E., 1986. Patterns of change in the carbon balance of organic soil-wetlands of the temperate zone. The Journal of Ecology: 755-774.

Armentano, T.V. and Verhoeven, J.T.A., 1988. The contribution of freshwater wetlands to the global biogeochemical cycles of carbon, nitrogen and sulphur. Wetlands and Shallow Water Bodies 1 SPB Academic Publishing, The Hague: 1-34.

Asselman, N.E. and Middelkoop, H., 1995. Floodplain sedimentation: Quantities, patterns and processes. Earth Surface Processes and Landforms, **20** (6): 481-499.

Bappeda, 2005. Feasibility study "pengendalian banjir sungai Siak di kota Pekanbaru propinsi Riau". Final Report, CV. Sigma Momen ENG.

Blum, M.D. and Tornqvist, T.E., 2000. Fluvial responses to climate and sea-level change: A review and look forward. Sedimentology, **47**: 2-48.

Burkett, V.R., Zilkoski D.B. and Hart, D.A., 2002. Sea-level rise and subsidence: Implications for flooding in New Orleans, Louisiana. US Geological Survey Subsidence Interest Group Conference: Proc. the Technical Meeting, Galveston, Texas November 2001: 27-29.

Buytaert, W., B. Bievre, D., Wyseure, G. and Deckers, J., 2004. The use of the linear reservoir concept to quantify the impact of changes in land use on the hydrology of catchments in the Andes. Hydrology and Earth System Sciences, **8** (1): 108-114.

Deverel, S.J. and Rojstaczer, S., 1996. Subsidence of agricultural lands in the Sacramento San Joaquin Delta, California: Role of aqueous and gaseous carbon fluxes. Water Resources Research, **32** (8): 2359-2367.

Dingman, S.L., 1994. Physical hydrology. Englewood cliffs, N.J, Prentice hall: pp 575.

Doels, D., 1995. The Peat oxidation and permanent shrinkage (POXAPS) model. DLO Winand staring centre for integrated land. Soil and Water Research, Wageningen.

Dradjad, M., Soekodarmodjo, S., Hidayat, M.S. and Nitisapto, M., 2003. Subsidence of peat soils the tidal swamplands of Barambai, South Kalimantan. Journal Ilmu Tanah dan Lingkungan, **4** (1): 32-40.

Fornasiero, A., Putti, M., Teatini, P., Ferraris, S., Rizzetto, F. and Tosi, L., 2003. Monitoring of hydrological parameters related to peat oxidation in a subsiding coastal basin south of Venice, Italy. Hydrology of Mediterranean and Semiarid Regions: 458-462.

Gambolati, G., Putti, M., Teatini, P. and Stori, G.G., 2003. Subsidence due to peat oxidation and its impact on drainage infrastructures in a farmland catchment south of the Venice Lagoon. Materials and Geoenvironment, **50**: 125-128.

Hoogland, T., van den Akker, J.J.H. and Brus, D.J., 2012. Modeling the subsidence of peat soils in the Dutch coastal area. Geoderma, **171**: 92-97.

Hornberger, G.M., Germann P.F. and Beven, K.J., 1991. Throughflow and solute transport in an isolated sloping soil block in a forested catchment. J. Hydrology, **124**: 81-99.

Junk, W.J., An, S., Finlaysom, C.M., Gopal, B., Kvet, J., Mitchell, S.A., Mitsch, W.J. and Robarts, R.D., 2013. Current state of knowledge regarding the world's wetlands and their future under global climate change: A synthesis. Aquatic Sciences, **75** (1): 151-167.

Leifeld, J., Muller, M. and Fuhrer, J., 2011. Peatland subsidence and carbon loss from drained temperate fens. Soil Use and Management, **27** (2): 170-176.

Linsley, R.K., Kohler, M.A. and Paulhus, J.L.H., 1988. Hydrology for engineers. London, UK, McGraw-Hill: pp 340.

MacDicken, K., 2002. Cash for tropical peat: land use change and forestry projects for climate change mitigation. Jakarta, Indonesia, Agency for the Assessment and Application of Technology (BPPT) and Indonesian Peat Association (IPA): pp 272.

Marfai, M.A. and King, L., 2008. Tidal inundation mapping under enhanced land subsidence in Semarang, Central Java Indonesia. Natural Hazards, **44** (1): 93-109.

Musa, Z.N., Popescu, I. and Mynett, A., 2014. Modeling the effects sea level rise on flooding in the lower Niger River. Proc. 11th Intl. Conf. on Hydro informatics: 17-22.

Nieuwenhuis, H.S. and Schokking, F., 1997. Land subsidence in drained peat areas of the Province of Friesland, The Netherlands. Quarterly Journal of Engineering Geology, **30**: 37-48.

Potok, A.J., 1991. A Study of the relationship between subsidence and flooding. The 4th Intl. Symp. on Land Subsidence, Houston, Texas, International Association Hydrological Sciences (IAHS) : 389-397.

Reddy, K.R., Osborne, T.Z., Inglett, K.S. and Corstanje, R., 2007. Influence of water levels on subsidence of organic soils in the upper St. Hohns river basin. Special Publication SJ2007-SP5. St. Johns River Water Management District.

Salmah, Z., Spoor, G., Zahari, A.B. and Welch, D.N., 1991. Importance of water management in peat soil at farm level. Tropical Peat. Proc. Intl. Symp. on Tropical Peatland : 6-10.

Schothorst, C., 1977. Subsidence of low moor peat soils in the western Netherlands. Geoderma, **17** (4): 265-291.

Schothorst, C.J., 1977. Subsidence of low moor peat soils in the western Netherlands. Geoderma (Elsevier Scientific Publishing Company, Amsterdam-Printed in The Netherlands), **17**: 265-291.

Schothorst, C.J., 1982. Drainage and behaviour of peat soils. Proc. Symp. on Peat Lands Below Sea Level: Intl. Institute for Land Reclamation and Improvement: 130-163.

Schumm, S. and Brakenridge, G., 1987. River responses. North America and adjacent oceans during the last deglaciation, **3**: 221-240.

Schumm, S.A., Schumm, S.A. and Dumont, J.F., Holbrook, J.M., 2002. Active tectonics and alluvial rivers, Cambridge Univ. Press: pp 276.

Silvius, M. and Giesen, W., 1992. Integration of conservation and land-use development of swamp sorest of East Sumatra. Proc. Workshop on Sumatra, Environment and Development: its past, present and future. Bogor: 16-18.

Sivapalan, M., Jothityangkoon, C. and Menabde, M., 2002. Linearity and nonlinearity of basin response as a function of scale: discussion of alternative definitions. Water resources research, **38** (2): 4-1-4-5.

Stephens, J.C., Allen, L.H. and Chen, E., 1984. Organic soil subsidence. Reviews in Engineering Geology, **6**: 107-122.

Stephens, J.C. and Speir, W.H., 1970. Subsidence of organic soils in the USA. Publ. int. Ass. sci. Hydrol., Symp. Tokyo: 523-534.

Stephens, J.C. and Stewart, E.H., 1976. Effect of climate on organic soil subsidence. Proc. of the 2nd Symp. on land subsidence, Anaheim, California: 647-655.

Wosten, H., Hooijer, A., Siderius, C., Rais, D.S., Idris, A. and Rieley, J., 2006. Tropical peatland water management modelling of the Air Hitam Laut catchment in Indonesia. Intl. J. River Basin Management, **4** (4): 233-244.

Wosten, J.H.M, Ismail, A.B. and van Wijk, A.L.M., 1997. Peat subsidence and its practical implications: a case study in Malaysia. Geoderma, **78** (1-2): 25-36.

Wösten, J., Ritzema, H., Chong, Tom K.F. and Liong, T.Y., 2003. Potentials for peatland development. Integrated Peatland Management for sustainable development. A Compilation of Seminar Papers. Sarawak Development Institute, Sarawak, Malaysia: 233-242.

Wosten, J.H.M., Clymans, E., Page, S.E., Rieley, J.O. and Limin, S.H., 2008. Peat-water interrelationships in a tropical peatland ecosystem in Southeast Asia. Catena, **73** (2): 212-224.