Research article

Peatland Tank Model for Evaluation of Shallow Groundwater Table Data without Height Reference from Benchmark

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Abstract Long-term monitoring of shallow groundwater table (GWT) is essential for the evaluation of hydrologic conditions of peatlands, which is meaningful for their conservation and restoration, especially in certain rural areas. Although there has been research in this field, a simple and effective method for the evaluation of GWT fluctuation has not been developed. Peatland Tank Model (PTM) is a one-dimensional water balance model that represents fluctuations of shallow GWT in peatland. The model contains several parameters, i.e., *C* (coefficient of GWT increase), *Ai* (coefficient for the size of plugholes, with *i* =1, 2, 3), and *HAi* (coefficient for the height of each plughole, *i* =1, 2, 3). We used PTM with 29 years' GWT data from Ochiai, Sarobetsu Mire, northern Hokkaido, Japan. These GWT data do not have a height reference from a benchmark, so that the data have no common meaning or information in relation to the ground surface or elevation above sea level. Observation was conducted at three sites; Site D near a drainage ditch along a peat mining location; Site M at the edge of the peat mining area; and Site U in an unused area far from the drainage. A few sets of parameters were obtained on the basis of simulation results. Smaller simulation errors were attained using the PTM. The 29-year GWT fluctuations at Site D were the greatest and could be characterized by the largest parameter values. Parameter trends at three sites varied, and were able to reflect the various drainage conditions. Thus, the PTM is a promising method for the evaluation of long-term variations and site differences of hydrologic conditions in peatland.

Keywords mire, groundwater table, peatland hydrology, drainage

INTRODUCTION

In recent years, a large number of peatlands have been exploited and converted to agricultural land. Examples can be found in Canada (Bhatti and Tarnocai, 2009), Sumatra and Kalimantan in Indonesia (Page et al., 2011), and Hokkaido, northern Japan (Umeda, 1980; Fujita et al., 2009). As a unique terrestrial system, peatland requires proper means of conservation and restoration. Consequently, balancing agricultural development and peatland conservation has become a research subject. The hydrologic environment, especially shallow groundwater table (GWT) fluctuation, is the most important determinant of the formation and existence of peatland. Long-term monitoring of shallow GWT is essential for the investigation and evaluation of the hydrologic environment. Nonetheless, in the past, the majority of monitoring GWT data has been assembled in form of groundwater depth or groundwater level which are not measured with respect to certain benchmarks (sea level or ground surface). A simple and effective method for evaluating the hydrologic environment using such GWT data has not been developed. In view of this situation, this paper proposes a simple evaluation method for shallow GWT fluctuation in peatland, based on Peatland Tank Model (PTM). The model provides satisfactory simulation accuracy and flexibility.

OBJECTIVE

The objective of this study is to show how the PTM detects the spatial variability and temporal changes of GWT fluctuation patterns even if the GWT data are not measured with respect to certain benchmarks. The usefulness and effectiveness of the PTM for the shallow peatland GWT are discussed. The meaning and function of each parameter used in the PTM are also explained.

METHODOLOGY

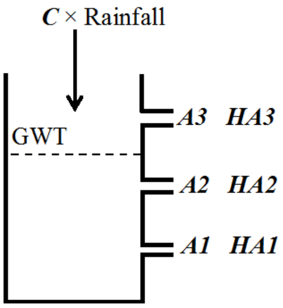

Fig. 1 Peatland Tank Model

The PTM is a water balance model for simulating the fluctuations of the shallow GWT in peatland (Umeda and Inoue, 1985). In this model, the peatland system is analogous to a water storage tank. GWT fluctuations can be represented by variations of water levels in the tank. For a bog fed by rainfall, rainwater is the sole inflow and there are almost no other water inputs from the surrounding environment. Evapotranspiration (ET) and discharge from the bog to surrounding areas are the main outflows. The PTM (Fig. 1) has three outlet plugholes on the sidewall of the tank.

In theory, the PTM can be characterized by Eqs. 1 and 2.

$$GWT_n = GWT_{n-1} + C \times R_n - \left(\sum_{i=1}^{3} QAi_{n-1} \right) \tag{1}$$

$$QAi_{n-1} = Ai \times \left(GWT_{n-1} - HAi \right) \tag{2}$$

Here, GWT_n and GWT_{n-1} represent the GWT at times n and $n-1$, respectively. C is the coefficient of GWT increase owing to rain. R_n is the amount of rainfall during time period $(n-1)$ to n. QAi_{n-1} is the amount of groundwater drawdown from the each plughole (i =1, 2, 3) during the same period. Coefficients Ai ($0 \leq Ai \leq 1$) and HAi are the size and height of each plughole, respectively. The time unit (data sampling interval) of 2 hours was used for estimating GWT by the PTM.

Constant discharge of the peatland and ET were incorporated into water loss from the bottom plughole. Based on such concept, parameter *A1* represents the basic discharge (constant discharge and ET) from the peat layer above height *HA1*. Similarly, parameters *A2* and *A3* are introduced to represent water losses of the layer above heights *HA2* and *HA3*, respectively. These two parameters are used to characterize more rapid water losses in the shallow surface layer of the peat (Fig. 1). Parameter *C* shows the magnitude of GWT increase in response to rainfall in the peatland.

Two simulation methods were implemented (Table 1). Because it is difficult to adjust simultaneously all seven parameters and this may make the contribution of each parameter ambiguous, we did not manipulate all seven. Without an explicit principle, determining the parameters is meaningless. Therefore, several rules (mentioned in the footnote of Table 1) were established. Based on these rules, the number of parameters in the PTM was reduced from the original seven to three (Method 1) or two (Method 2).

Table 1 Simulation methods

Method	Manipulated Parameters	Fixed or Automatically Determined Parameters	Remarks
1	*C*, *A1*, *A2*	*A3*, *HA1*, *HA2*, *HA3*	*1, *2
2	*C*, *HA1*	*A1*, *A2*, *A3*, *HA2*, *HA3*	*2, *3
			In all cases, *A3* = 1.

*1: *HA1* = *HA2*−40 cm, *HA3* = *HA2*+10 cm or *HA3* = GWTm (if (*HA2*+10 cm) > GWTm).
*2: *HA2* is equal to the value of upper tertile of GWT data calculated via the following steps. In the first step, all observed GWT data within the calculation period at each site were sorted numerically, in descending order. This set should include every datum, even if there are overlaps. Then, the value found one third of the way down from the maximum in the organized dataset is defined as the upper tertile.
*3: *A1* = 0.0003, *A2* = 0.03, *HA3* = *HA2*+10 cm or *HA3* = GWTm (if (*HA2*+10 cm) > GWTm). GWTm: the maximum GWT.

We adopted PTM with 29 years of GWT data recorded (1983–2012, except for 1998) at Ochiai, Sarobetsu Mire, northern Hokkaido (approximately 45°8′N, 141°44′E). GWT was observed at three sites: Site D near a drainage ditch along the peat mining location; Site M at the edge of the peat mining area; and Site U in an unused area far from the drainage (from 2006 onwards, the measurement of Site U could not be continued due to the problems of instrument). Annual average temperature in this area is ~6.1 °C, varying from −6.5 °C in February to 19.6 °C in August. Annual average precipitation is 1,073 mm (Japan Meteorological Agency). On average, the warm period without snow cover lasts from mid-April through late October. All calculations were performed for July through September. Due to the limitation of equipment and manpower, the observed GWT data were measured without reference height such as ground surface or elevation above sea level. Compared with the absolute ground water tables, GWT without reference height are more difficult to evaluate, because the data have no common meaning.

In PTM computations, the parameters were adjusted repeatedly until the optimum simulation result was attained, where the chi-square value of GWT was minimized and the Nash-Sutcliffe efficiency coefficient and correlation coefficient (*r*) were maximized. Values of each parameter were compared by site and examined by one-way analysis of variance (ANOVA). ANOVA significance levels were set to 0.05 and 0.01. Based on 29 years' GWT observations at each site, long-term trends of each parameter were evaluated by the coefficient of determination (R^2). All statistical tests were conducted using SPSS 16.0 statistical software (SPSS Inc., Chicago, IL, USA).

RESULTS AND DISCUSSION

Throughout the results from 1983 to 2012, parameter *C* was in the order Site D > Site M > Site U, from both methods (Fig. 2). This indicates that the magnitude of GWT increase in response to rain events was maximum at Site D and minimum at Site U. A larger value of *C* means less effective porosity for water storage in peat (Umeda and Inoue, 1985). Therefore, it is concluded that the effective porosity of peat at the three sites was in the order Site D < Site M < Site U. At the three sites, changes of parameter *C* over the last 29 years do not show clear trends ($P > 0.05$) (Fig. 2). However, there is a strong negative regression relationship between *C* and total amount of rainfall from July through September at all sites (Fig. 3). From Method 1, R^2 at Site D exceeded 0.80 ($P < 0.01$). This relationship can be explained by the fact that effective porosity increases in peat near the ground surface. When the amount of rainfall increases, the GWT may spend more time in the upper part of peat layer, where the effective porosity of peat is relatively large and the ratio of water table increase (*C*) becomes small.

In Method 1, GWT fluctuations can be characterized by variations of parameters *C*, *A1*, and *A2*. The difference of *A1* between Sites M and U was not obvious (n=21, $P > 0.05$); however, this difference was significant between Site D and the other two sites (n=28 for Site D and M, n=21 for Sites D and U, $P < 0.01$) (Fig. 4). Differences of *A2* among the three sites were not obvious ($P > 0.05$). The average *A2* at site U (n=21, average = 0.03) is smaller than those at the other two sites (n=28 for Site D, n=29 for Site M, average of both sites = 0.04). Parameters *A1* and *A2* at all sites over the last 29 years do not show clear trends ($P > 0.05$). The fact that the value of *A1* at Site M was similar to that at Site U means that characteristics of basic and constant water losses from the peat layer (mainly from the catotelm) were similar at those two sites. In contrast, a larger *A1* at Site D means that the amount of water loss was greater than at the other two sites. Similarly, *A2* at the three sites was nearly identical, which indicates that water losses from the upper peat layer (part of the acrotelm) at the three sites were similar. In conclusion, Site D had greater water loss compared with the other two sites, but water loss of the upper peat layer at all three sites were similar.

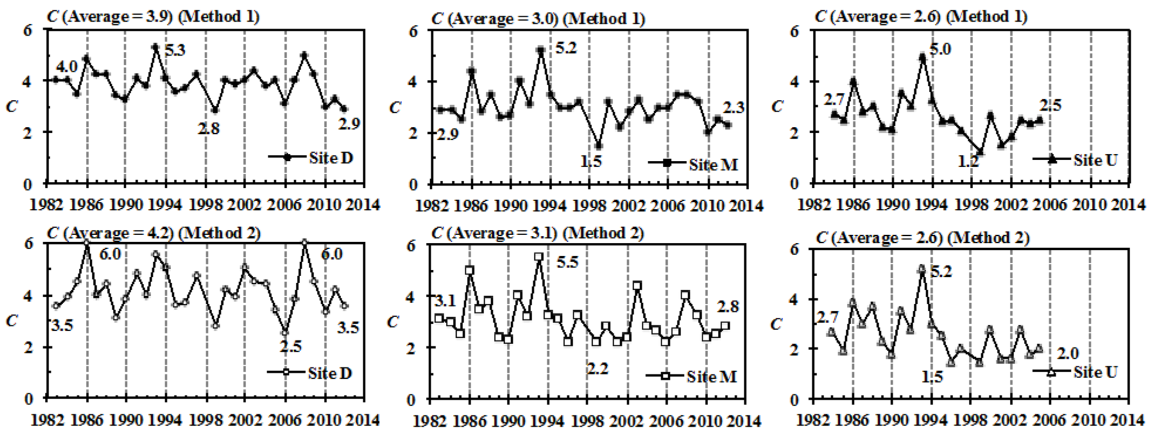

Fig. 2 Variation of parameter *C* at three sites from 1983 to 2012

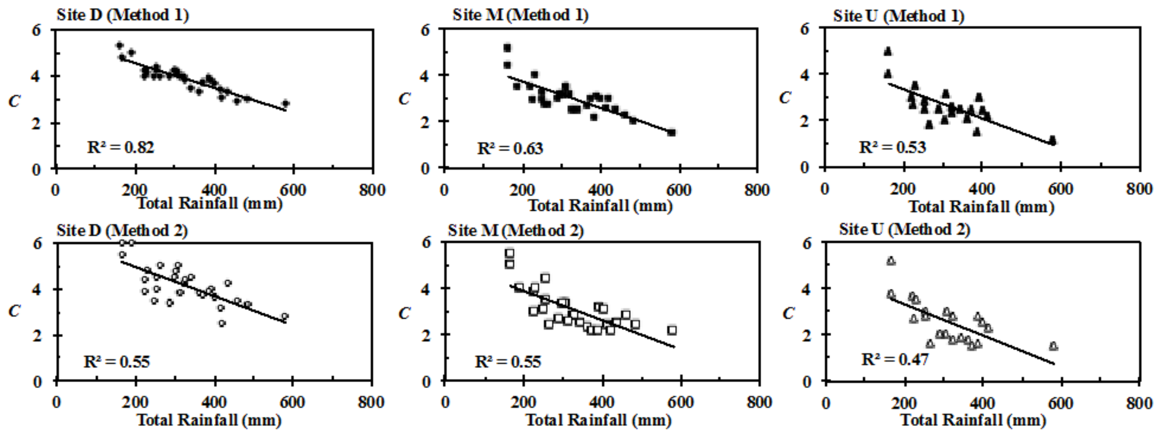

Fig. 3 Relationship between parameter *C* and total rainfall (July through September) at three sites from 1983 to 2012

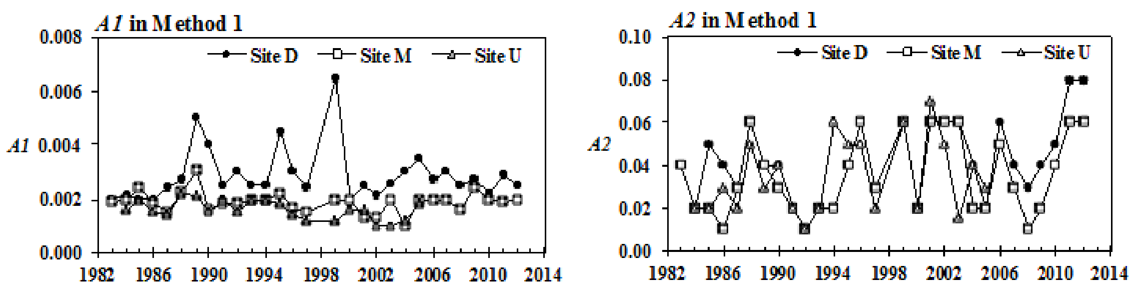

Fig. 4 Variation of *A1* and *A2* in Method 1 at three sites from 1983 to 2012

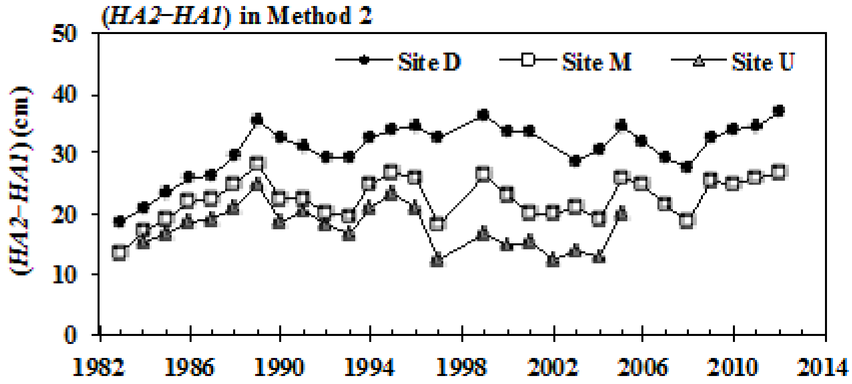

Fig. 5 Trends of (*HA2–HA1*) over 1983–2012 at three sites, from Method 2

In Method 2, GWT fluctuations are represented by parameter *C* and (*HA2–HA1*). Figure 5 shows variations of vertical distances between the lower two outlet plugholes (*HA2–HA1*) at the three sites. Under the same condition of *A1* = 0.0003, *A2* = 0.03, and *A3* = 1 for the three plugholes, there were significant differences in (*HA2–HA1*) among the three sites. Average values of (*HA2–HA1*) during the last 29 years at sites D, M, and U were 30.7 cm, 22.5 cm, and 17.9 cm, respectively. The greater vertical distance (i.e., depth of bottom plughole) at Site D means that the unit-time GWT drawdown from the bottom plughole *QA1* (cf. Eq. 2) at Site D was larger than those at sites M or U. Thus, the larger value of (*HA2–HA1*) indicates more rapid discharge. Over the same period, (*HA2–HA1*) at site D increased, with slope 0.29 cm/year ($P < 0.01$). (*HA2–HA1*) at Site M increased by 0.14 cm/year and decreased by –0.22 cm/year at Site U, but the trend was not significant for either ($P > 0.05$) (Fig. 5).

The reason for such a change may be inferred as follows. In summer 1983, the drainage ditch near these three sites was dredged and deepened. In the following few years (1983–1989), leakage of water by piping from the adjacent mining pool to the ditch was observed. In terms of parameter variation, (*HA2–HA1*) increased yearly in this period. In the last 29 years, drainage intensity at Site D clearly increased. However, at sites M and U, variations of drainage intensity were not as significant. This fact indicates that drainage changed the water loss characteristics of peat and its influence persisted in the following years.

The three observation sites have different drainage conditions. However, it is difficult to distinguish the difference of GWT fluctuations visually, so these fluctuations appeared similar. Using the PTM, various characteristics of GWT increase could be represented by parameter *C*, and GWT decrease could be described by parameters *Ai* and (*HA2–HA1*). Large values of parameters *C*, *Ai* and (*HA2–HA1*) indicate that GWT may response to rain and dry events greatly. Moreover, differences of *Ai* among observed sites were able to reflect site differences of drainage characteristics in various peat layers (Method 1). Variations of (*HA2–HA1*) could depict long-term trends of drainage characteristics at each site (Method 2). In addition, the parameters could also represent peat properties. A larger *C* value indicates less effective porosity and less water storage of peat. Larger *Ai* and (*HA2–HA1*) values indicate that the GWT decreases rapidly so that the peat becomes drier during rain-free periods.

There is a strong regression relationship between parameter *C* and total amount of rainfall. Therefore, this amount during the simulation period gives hint to the determination of *C*. For instance, the value of *C* in a year with greater rainfall would be smaller. In the case of greatly changed drainage conditions, simulation by Method 1 was unable to match actual GWT fluctuations, because the distance between *HA1* and *HA2* was fixed at 40cm. For instance, if a drainage channel was renewed or newly excavated near the observation site, drainage may have intensified and the drop of GWT from the height of *HA2* may have exceeded 40cm. Under such circumstances, Method 2 is considered more suitable than Method 1. In practical use of the PTM, the vertical distance and size of each plughole could be adjusted according to peatland conditions at individual sites. Additionally, the principle of computation, such as simulation rules and methods, could be adjusted to meet specific peatland conditions.

Average simulation errors of all calculations are shown in Table 2. By applying the rules in the footnote of Table 1, Method 2 could simplify the computation by decreasing the number of parameters to be fit, but simulation error might become slightly larger than that of Method 1. Moreover, through Method 2, site differences were shown more clearly by the obvious differences of (*HA2–HA1*) at the three sites, and the trend of long-term drainage effects also became apparent through yearly decline of the depth of the bottom plughole at Site D.

Table 2 Average errors of all simulations by site for each method

Method	Site D (n=28)			Site M (n=29)			Site U (n=21)		
	r	CHI	NSE	*r*	CHI	NSE	*r*	CHI	NSE
1	0.91	9.2	0.84	0.93	5.5	0.86	0.93	5.1	0.86
2	0.89	12.6	0.83	0.92	6.0	0.84	0.93	5.9	0.85

r: *correlation coefficient; CHI: chi-square value; NSE: Nash-Sutcliffe efficiency coefficient*
n*: number of observed years*

CONCLUSSIONS

The present study proposed a PTM-based evaluation method for shallow GWT fluctuations of peatland, especially bogs. This method can simulate the GWT with accuracy of a few centimeters. Further, subtle differences in fluctuation patterns can be distinguished by model parameters for different locations or time series.

The observed GWT data used herein were not measured with respect to certain elevation references or benchmarks (i.e., sea level or ground surface). In this study, we provide a solution to evaluate the changes in GWT fluctuation patterns or site differences of GWT conditions of peatland, when the ground water table data were measured without height reference. Through use of the PTM, such observed GWT data were effectively used for evaluating such changes and differences. Especially via Method 2, variations and trends of parameters revealed the site differences and long-term changes of GWT condition.

The seasonal response of ET and amount of soil moisture in the unsaturated peat surface layer were not considered in the current version of the model. Hence, improvement could be made in the near future to achieve more accurate simulation results.

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