The 18th Biennial Conference of International Society for Ecological Modelling

Modeling the groundwater fluctuation in Sphagnum mire in northern Hokkaido, Japan

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Abstract

This research aims to investigate the role of wetland parameters in controlling the response of groundwater level (GWL) towards hydrologic condition and climate condition in Sphagnum mire of Sarobetsu Mire, northern Hokkaido, Japan. Hourly data of GWL, rainfall, and climate of summer for year 1993, 1994, 1997, 2003, 2008, and 2009 are used for modeling GWL fluctuation at point E on the observed area. The GWL modeling in this research adopts the philosophy of Sugawara's tank model, which involved c_1 as a function of soil porosity, c_2 as a function of rainfall rate, and c_3 as a function of soil hydraulic conductivity and slope. Parameter optimization of the model is undertaken by adjusting c_1, c_2, and c_3. The model is quite successful in imitating the behavior of GWL on observed area indicated by average *NS* value of about 70%. The best-fit model of each year of simulation shows that the value of c_1 and c_3 is 1.3 and 0.0, respectively. The value of 0.0 for c_3 indicates that there is no discharge coming out from the system. The value of c_2 varied and depended on the rate of rainfall and evapotranspiration. The research also found that basically c_2 is the ratio between rainfall and evapotranspiration. The model also indicates very small or almost no effect of lateral water balance such as lateral inflow from or to other sources on surrounding the observed area.

Keywords: Groundwater; Modeling; Sphagnum mire.

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1. Introduction

Wetland hydrology is the initial and key element in wetland restoration projects. Many scientists stated that wetland hydrology is the most important component of wetland ecosystems. However, dealing with wetland hydrology in wetlands restoration is not easy due to some unknown variables involved in it [1]. On the other hand, groundwater quantity and quality in wetland ecosystems is important to be investigated and studied. Although the successfulness of wetland restoration is not always depending on these aspects, groundwater quantity and quality plays an important role in maintaining the original diversity of wetland plant species [2].

Groundwater level (GWL) fluctuation in one area is affected by many factors. The fluctuation of GWL may be altered by various effects such as barometric pressure, seawater tidal fluctuation, precipitation, the change of trend component, noises, and earthquake [3-8]. In the theory of hydrological cycle, rainfall and evapotranspiration maybe the most dominant components affecting the fluctuation of ground water. In the case of shallow ground water, some parts of rainfall reach groundwater table and the rest is lost as evapotranspiration or as runoff [9]. Furthermore, the effects of hydrological aspects on GWL will also depend on the ground water system itself, its geographical location, and changes in the hydrological variables [10, 11].

Not many literatures and papers are published that focus on the application of groundwater models to wetland hydrologic systems. The existing papers have focused on the significance of hydraulic conductivity in groundwater movement in wetland areas [12, 13]. The purpose of this paper is to investigate the role of wetland parameters on controlling the response of groundwater in responding hydrologic conditions. The model involving wetland parameters and hydrological aspects has been developed for this purpose. The site chosen for this study is Sarobetsu Mire, in northern Hokkaido, Japan. The GWL and hydrological condition on this selected site had been monitored for several years therefore some amount of data has been collected there.

2. Site description

Sarobetsu Mire is one of biggest wetland areas in Japan. The mire is located in the northern part of the largest Japan northern island, Hokkaido. The mire, nowadays, is a part of Rishiri Rebun National Park. It is a coastal bog with the area of about 23,000 ha with the thickness of peat soil of 5 to 7 m. As a mire, Sarobetsu area is quite flat with slope of about 0.0003. The surface vegetation of Sarobetsu Mire is dominated by *Sphagnum papillosum*, *Sphagnum riparium*, and *Drepanocladus exannulatus*. In the shrub layer, *Rubus chamaemorus*, *Scirpus wichurae*, *Drosera anglica*, *Hemerocallis middendorffii*, and *Myrica gale* are dominantly found in the area. There are also *Sedges* of *Phragmites communis* and *Carex lasiocarpa var. occultans* in limited amount [14]. The mire contains relatively large amounts of mineral matter, as a result of Sarobetsu river flooding and the presence of volcanic ash from the mountain in surrounding area.

After World War II, Sarobetsu Mire was developed to be agriculture land. In 1969, a main shortcut channel was completely developed to prevent flooding that frequently happened in the area. The development of this channel has increased the productivity of the farmland. On the other hand, the structure slowly changed the characteristic of the soil and water on the mire. As a consequence, there was an invasive growth of dwarf bamboo (*Sasa*) in the area. The *Sasa* became a big concern due to its characteristic that favors dry conditions in the area. The area such as Sarobetsu Mire is ecologically valuable but very vulnerable to external impact [15]. The *Sasa* invasion, even though it happened slowly, will endanger species vegetation diversity on the area by dominating the ground surface [16-19].

Some research has been carried out in order to investigate the behavior of water in Sarobetsu Mire. In 1999, research investigating the biological and chemical environment of Sarobetsu Mire and its relation with the human activities had been carried out. The research stated that human disturbances around Sarobetsu Mire led to decrease of GWL and enabled water from the surrounding areas to flow into the mire. On the other hand, water quality and water restoration for the conservation of Sarobetsu Mire has also been investigated as well [20]. These studies have shown that there is a strong relationship between the quality and levels of the groundwater with the surrounding vegetation type in the Sarobetsu Mire.

The study site of this research is located in the Sarobetsu Mire as shown in Figure 1. There are several points of GWL measurement. The description of each point is given as follows:

- Point E is located at the eastern side of the mire. The area surrounding this point is considered as the hummock surface, which is the top of the bog with high GWL and natural bog vegetation. *Sphagnum spp.* is the dominant ground layer cover in this area.
- Point W is located about 180 m from point E on the west direction. The area of this point is transitional area between the areas of *Sasa* and *Sphagnum*. The boundary between the original area and *Sasa* invasion area exists at this point.
- Point W' is located about 150 m from point W in the west direction. In this area, the change in the hydrological condition is indicated by the gradual change in the GWL fluctuation pattern. The dominant vegetation is dwarf bamboo (*Sasa*) with the leaf area index (LAI) of 0.6.
- The other points (WW, NC, and Dam site) are the points on the relatively submerged area.
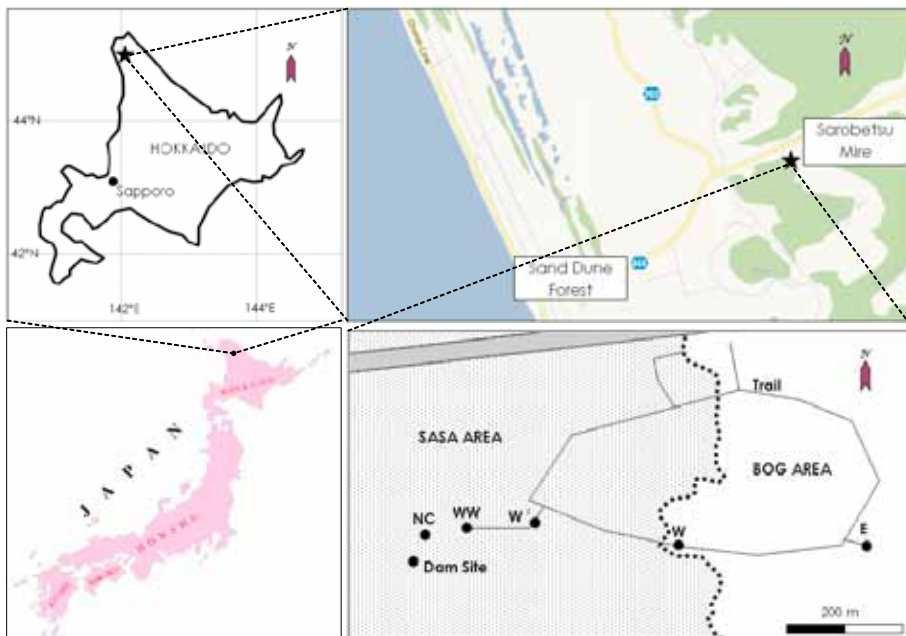

Fig.1. Location of the study and points of ground water level measurement. The bog or *Sphagnum* area, transitional area, and *Sasa* area are presented by points E, W, and W', respectively.

3. Methodology

3.1. Data

The point of observation for this research is the bog or *Sphagnum* area presented by point E in Figure 1. Ground water level data were obtained by installing water level loggers in the ground water sampling pipes. The data used for this research is continuously recorded water levels in the intervals of 1 h at 0.5 m depth from the ground surface. We used hourly data for the analysis. The GWL data in summer season, from 1 June to 30 September, are used to analyze the trend of the GWL for every year. The GWL data were collected for the years 1993, 1994, 1997, 2003, 2008 and 2009. Hourly rainfall, air temperature, wind speed and sunshine hours were obtained from the AMeDAS station of Toyotomi City (45–06.4' 141–45.9'), which were measured by the Japan Meteorological Agency.

3.2. The estimation of evaporation

The Penman-Monteith method used to estimate reference evapotranspiration (ET_0) in this research is the one modified by FAO and given as follows [21, 22].

$$ET_0=[0.408\Delta(Rn-G) + \gamma(900/T)u_2(e_s-e_a)]/[\Delta + \gamma(1+0.34u_2) \qquad (1)$$

where ET_0 is the reference evapotranspiration (mm day^{-1}), R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1}), G is the soil heat flux density (MJ m^{-2} day^{-1}), T is mean daily air temperature at 2 m height (°K), u_2 is the wind speed at 2 m height (m s^{-1}), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), Δ is the slope of the saturation vapor pressure curve (kPa °C^{-1}), and γ is the psychrometric constant (kPa °C^{-1}). The reference evapotranspiration will be estimated as a daily value. However, for the purpose of the simulation in groundwater modelling in this research, the data will be averaged into hourly bases.

3.3. GWL modeling

Groundwater modeling in this research adopts the philosophy of tank model [23, 24] with the parameters of h, R, ET_0, c_1, c_2, and c_3 as defined in Figure 2.
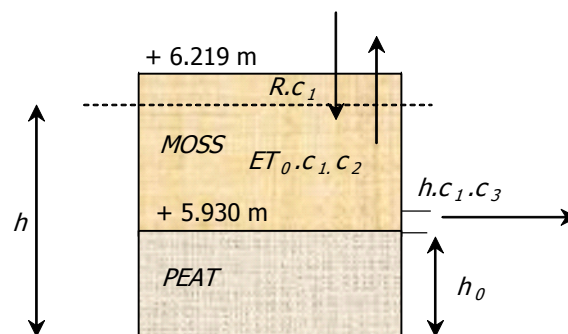

Fig. 2. Tank Model of GWL modeling in the Sphagnum mosspeat system.

The mechanism of daily water balance on the system is defined as follows:
If $h > h_0$, then:

$$\Delta h = c_1.R - c_1.c_2.ET_0 - c_1.c_3(h-h_0) \tag{2}$$

If $h < h_0$, then:

$$\Delta h = c_1.R - c_1.c_2.ET_0 \tag{3}$$

where, h is the GWL (m), Δh is the change of GWL (m), h_0 is the highest elevation of the water in peat zone (m), R is the rainfall (mm/h), ET_0 is the reference evapotranspiration (mm/h), c_1 is specific yield, c_2 is the crop coefficient for sphagnum moss and c_3 is the coefficient for the groundwater discharge. From field observation, the elevation of the border between moss and peat (h_0) is estimated to be situated around +5.930 m.

3.4. The estimation of specific yield of the groundwater

A simple field test of wetting and draining for peat moss was applied to get the specific yield of groundwater at point E on September 2010. The undisturbed peat moss samples with size of 6 cm diameter and 7 cm height were taken and filled into beakers that had the inside diameter of 6 cm. After that, distilled water was gradually added to the beakers. The weight and water table height were measured simultaneously. Figure 3 shows the result of the test. The specific yield of the surface peat moss layer (6.20 – 6.13 m) is 1.32 and that of the subsurface moss layer (6.13 – 6.08 m) is 2.29.
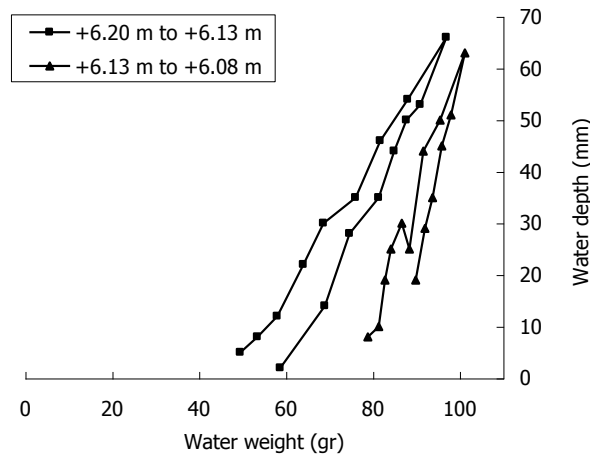

Fig. 3. Specific yield of groundwater (c_1) of the surface peat moss layer (6.20 – 6.13 m) and that of the subsurface moss layer (6.13 – 6.08 m) is 1.32 and 2.29, respectively.

3.5. Model efficiency measurement

In order to assess the predictive power of the model in this research, the Nash–Sutcliffe model efficiency coefficient (*NS* value) has been used. The coefficient is defined as:

$$NS = 1 - [\Sigma(h_o - h_m)^2 / [\Sigma(h_o - h_{\bar{o}})^2]$$

where h_0 is observed GWL value at time *t*, h_m is the calculated GWL value at time *t*, and $h_{\bar{o}}$ is the average of observed GWL values [25]. The method is usually used for discharge modeling. However, in its application, the *NS* value is also applicable for measuring the accuracy of model outputs other than discharge [26]. Like other information criterion values, the *NS* maximum value is 1.0, which means a perfect match of modeled data with the observed data. If the *NS* value is equal to 0.0, the model predictions will be as accurate as the mean of the observed data.

4. Result

4.1. Data description

Figure 4 shows hourly summer rainfall and calculated evapotranspiration rate used in the research. Simple statistical analysis is applied in the data in order to describe the characteristic of the data. The analysis indicates the existence of significant fluctuations on the summer rainfall data. The average of the data is 0.111 mm/h with a standard deviation of 0.031 mm/h. The years of rainfall on the figure can be classified into wet years and dry years. The years 1993, 2003, and 2008 are included in the dry years with the average rainfall rate of 0.085 mm/h. On the other hand, the years 1994, 1997, and 2009 are included in the wet year with the average rainfall rate of 0.138 mm/h. There is no specific trend in the rainfall data.

Evapotranspiration rate is calculated using the FAO Penman-Monteith equation. The result is daily evapotranspiration rate. The daily rate is further divided by 24 h in order to find the hourly data. The graph in Figure 4 indicates that there is no significant fluctuation in the evaporation rate. The average summer evapotranspiration data is 0.049 mm/h with a standard deviation of 0.009 mm/h. Dynamic trend with positive slope is detected in the data indicating the dynamic increase of the evapotranspiration rate in the observed area. However, the increase is not significant.

Table 1. Hourly average of GWL in Sarobetsu Mire

Year	GWL (m)
1993	6.009
1994	6.029
1997	6.018
2003	5.990
2008	5.910
2009	5.925

Figure 5 shows the hourly data of GWL for summer (June–September) of years 1993, 1994, 1997, 2003, 2008, and 2009 of Sarobetsu Mire. Figure 5 also indicates a significant negative slope in the average of GWL between 1993 and 2009. The trend of GWL tends to be stable between 1993 and 1997. However, a significant decrease of GWL happened in 2008 and 2009. The year 2003 seems to be the

transitional year of GWL decreasing process. However, GWL data around 2003 was not obtained, and therefore, it is difficult to say that there is any decreasing process of GWL on the area observed. The complete presentation of hourly average of GWL is given in table 1.
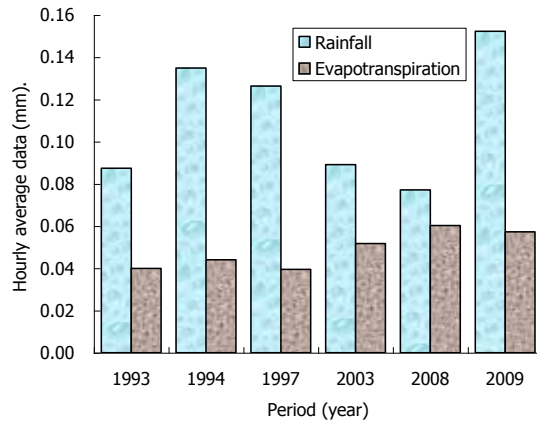

Fig.4. Hourly summer rainfall data and hourly summer evapotranspiration data of Sarobetsu Mire calculated using FAO modified Penman-Monteith equation. Data were obtained from the AMeDAS station of Toyotomi City (45–06.4' 141–45.9'), which were measured by the Japan Meteorological Agency.
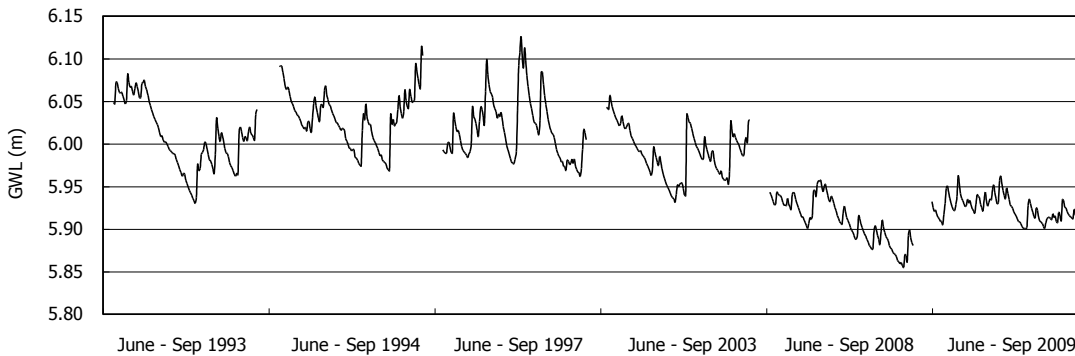

Fig.5. Hourly summer GWL data for year 1993, 1994, 1997, 2003, 2008, and 2009 of Sarobetsu Mire.

4.2. Correlation analysis

The dominant hydrological factor affecting the GWL fluctuation is investigated using correlation analysis. Pearson's correlation method is used to describe the relationship between rainfall–GWL and evapotranspiration–GWL. The result of the analysis indicates a strong relationship between the average evapotranspiration–average GWL and the value of correlation coefficient equal to -0.93. This value states that evapotranspiration significantly affects the decrease of GWL. On the other hand, the relationship between average rainfall and average GWL is not quite significant. The value of correlation coefficient for this relationship is equal to 0.12, this means that there is negligible effect of rainfall on the fluctuation

of GWL in the area. The illustration of the relationship between rainfall–GWL and evapotranspiration–GWL is given in the graphs shown in Figure 6.
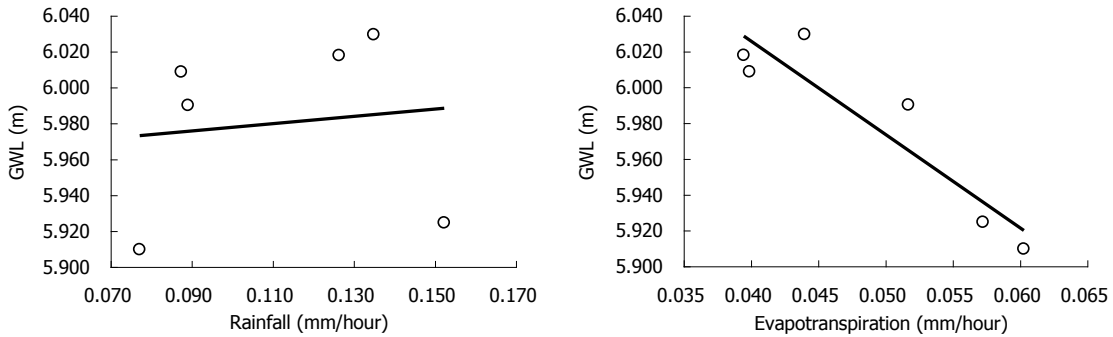

Fig.6. The illustration of the relationship between the averaged rainfall–averaged GWL and the averaged evapotranspiration–averaged GWL for the observed year

4.3. Sensitivity analysis

Sensitivity analysis is carried out in order to investigate the effect of adjusted parameters to the GWL fluctuation on the model. Parameters tested in the sensitivity analysis are c_1, c_2, and c_3. Sensitivity analysis is conducted by observing the increment of hourly average GWL on the basis of the growth of each parameter value. On this sensitivity analysis of c_1 parameter, the values of c_2 and c_3 are set to 1.0 and 0.0, respectively. For the sensitivity analysis of c_2 parameter, the values of c_1 and c_3 are set to 1.0 and 0.0, respectively. On the other hand, in the sensitivity analysis of c_3 parameter, the values of c_1 and c_2 are set to 1.0. The setting of parameter value and the results of the analysis is described in table 2 and Figure 7.

4.4. Model calibration

The method of groundwater modeling in this research follows a classical way of modeling watershed hydrology, for example, by assessing groundwater discharge and recharge as a residual of soil water balance equation [27-30]. In this kind of modeling philosophy, water draining below the soil zone is considered to be immediately transferred to the groundwater as recharge [31] and the water evaporated from the soil zone is considered as discharge.

Table 2. The setting of parameter value and the results of the sensitivity analysis.

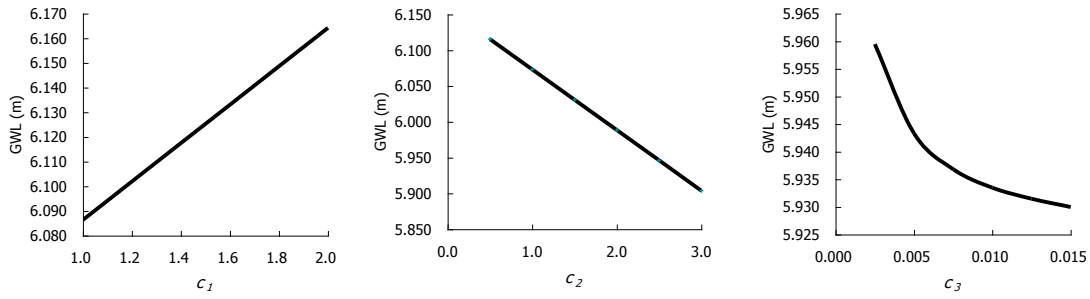| c_1 increment	GWL increment	c_2 increment	GWL increment	c_3 increment	GWL increment
1.0	-	0.5	-	0.0025	-
1.2	0.012	1.0	-0.042	0.0050	-0.014
1.4	0.012	1.5	-0.042	0.0075	-0.006
1.6	0.012	2.0	-0.042	0.0100	-0.003
1.8	0.012	2.5	-0.042	0.0125	-0.002
2.0	0.012	3.0	-0.042	0.0150	-0.002

Fig.7. Graphical illustration of the results of the sensitivity analysis. The relationship between increment of c_3 and GWL indicates c_3 is a very sensitive parameter if compared to the other parameters

On the basis of sensitivity analysis, groundwater model is calibrated to fit the measured GWL of point E for the years of 1993, 1994, 1997, 2003, 2008, and 2009. The calibration process is undertaken by adjusting c_1, c_2, and c_3 parameter values into the best fit of the observed and calculated GWL. The best fit of the model is indicated by the highest value of the *NS* value for all the years of simulation. The best-fit model of each year of simulation is given in table 3 and illustrated in Appendix A-1. On the best model, the values of c_1 and c_2 are 1.30 and 0.00, respectively. The value of 0.0 for c_3 indicates that no discharge comes out of the system. The values of c_2 varied on the basis of the rate of rainfall and evapotranspiration.

Table 3. The best fit model of each year of simulation

Year	*NS* Value	c_1	c_2	c_3
1993	0.77	1.30	2.13	0.00
1994	0.65	1.30	2.84	0.00
1997	0.60	1.30	3.33	0.00
2003	0.82	1.30	1.85	0.00
2008	0.80	1.30	1.69	0.00
2009	0.50	1.30	2.94	0.00

The research found that the value of c_2 is actually the ratio of the annual average value of rainfall and annual average value rate. The relationship is formulated as follows:

$$c_2 = R_{ave}/ET_{0-ave} \qquad (4)$$

where R_{ave} is the annual average value of rainfall of the observed year and ET_{0-ave} is the annual average value of evapotranspiration of the observed year. On the other hand, due to the stable water balance in the system, the volume of rainfall is about equal to the volume of evapotranspiration. The relationship is illustrated in Figure 9.
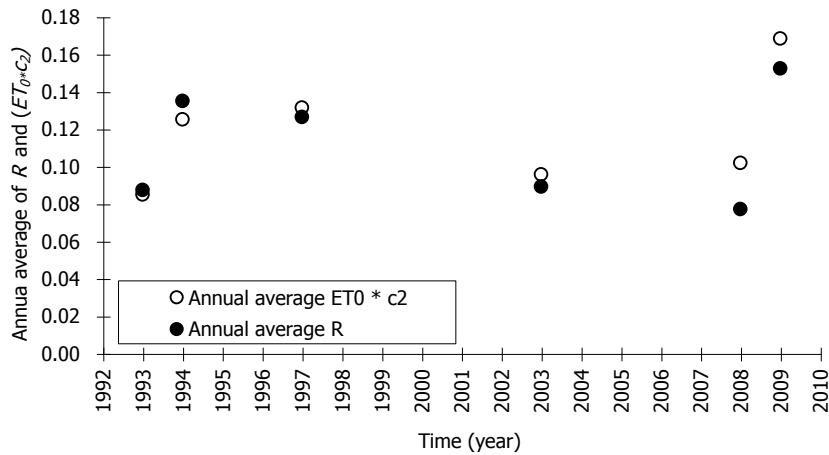
Fig. 9. The relationship between annual average rainfall and annual average evapotranspiration on the system

The effect of rainfall on evapotranspiration rate is not a surprising fact. In some evapotranspiration calculation methods such as Turc–Langbein method [32], rainfall is considered as a factor for calculating evapotranspiration rate. In this research, the effect of rainfall to evapotranspiration can be detected from the relationship between rainfall and c_2. The graph in Figure 10 shows that rainfall and c_2 have strong a relationship, as indicated by the value of correlation coefficient equal to 0.77.
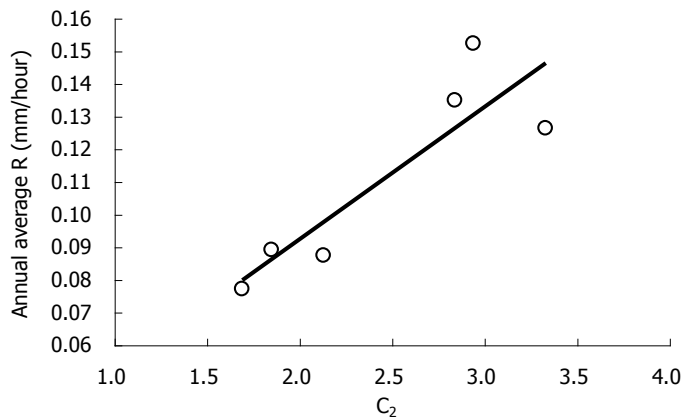

Fig. 10. The relationship between annual average rainfall and c_2.

5. Discussions

In Sarobetsu Mire, the fluctuation of GWL is varied due to the fluctuation of rainfall and evapotranspiration. However, evapotranspiration is found as a dominant factor affecting GWL fluctuation in the area rather than rainfall. The result of correlation analysis indicates a strong relationship between evapotranspiration–GWL and the value of r equal to -0.93. This fact shows that evapotranspiration drives

the fluctuation of GWL by reducing groundwater storage and decreasing GWL in the system. This is very understandable because there are not so many rain events during summer and on the other hand, evapotranspiration happens every day.

In many studies, the potential impact of the change of land-use on groundwater resources may reduce or increase groundwater recharge and ultimately exacerbate future water shortages or surplus due to the extra water demand or water recharge of surface vegetation [33]. In the case of Sarobetsu Mire, the impact of the change of land-use on groundwater fluctuation is not exactly found. The surface vegetation of Sarobetsu Mire is relatively stable along the years due to conservation program by the government. Field observation and literature studies also show that the area surrounding point E in Sarobetsu Mire is relatively unchanged. In the model, the value of c_3 equal to 0.0 indicates that the system experiences pure vertical water balance system with very small or almost no effect of lateral water balance such as lateral inflow from or to other sources in surrounding areas. In peatland moss, the transitional peat soils exhibit remarkable anisotropy of permeability. Previous research in the mire of Bibai area of Central Hokkaido indicated that the vertically saturated hydraulic conductivity was about 400 times more than its horizontally saturated hydraulic conductivity. This condition is probably due to the effect of horizontal sedimentation of plant fiber [34].

The balance between the inflow of rainfall and the outflow of evaporation indicates that there is no significant effect of flow from or to other areas surrounding the mire. This statement is opposite to the hypothesis from previous research. The research stated that originally, the natural channel flowed into Sarobetsu River, but human disturbances around this area led the GWL to decline and enabled water from the surrounding areas to flow into the mire. As a consequence, the decreased water level may also drain the mire. The model indicates that the decrease of GWL in Sarobetsu Mire is more related to the fluctuation of water budget (rainfall–evapotranspiration) rather than human factors. This fact is shown by the Spearman's correlation value between the average water budget (rainfall–evapotranspiration) and the average GWL. Spearman's correlation value for both data is -0.91. Even if there are any human activities such agriculture in the surrounding area, the effect to the GWL fluctuation is not quite significant.

It is important to note that the average GWL in wetland in sub-tropic areas like Sarobetsu Mire is also affected by the GWL at the beginning of summer. At this moment, snowmelt is a dominant source of groundwater recharge in the area instead of summer rainfall. Furthermore, the snowmelt is a result of climatic condition such as temperature, wind, and sunshine in the beginning of the summer season. In short, the average GWL in summer season in Sarobetsu Mire is the function of summer GWL fluctuation with the spring GWL condition as an initial reference. The summer average GWL tends to be uncertain for every year following the uncertainty of climate and hydrologic condition.

6. Conclusions

The model investigating the role of wetland parameters on controlling the response of GWL according to hydrologic condition and climate condition in Sarobetsu Mire has been analyzed. The model represents vertical water balance that drives the GWL fluctuation in Sarobetsu Mire. The model also explains the role of each hydrological factor in the groundwater flow mechanism in the observed area. The best model of each year of simulation shows that the value of c_1 is 1.3 while the value of c_3 is 0.00. The value of 0.0 for c_3 indicates that no discharge comes out from the system. The variation only happens in the values of c_2. The value of c_2 varied on the basis of the average value of rainfall and evapotranspiration rate. In fact, c_2 is the ratio between rainfall and evapotranspiration.

Hydrologic models such as the model in this research will be a potentially valuable instrument in predicting potential hydrological events in wetland areas. GWL model applied in this research can be used as a reference in the research on groundwater resource in the wetland areas, especially the peatland

areas. A similar approach can possibly be applied to other peatland areas with climate, hydrology, and hydro-geological data that are relevant. This quantitative model can also be used as a consideration in investigating the hydraulic parameters of specific peatland areas; furthermore, the parameters can be employed in more complex groundwater modeling using sophisticated groundwater software. Finally, by following the previous research statement, we believe that the GWL model in this research can be a useful input for wetland analysis, especially peatlands in the scheme of remediation and restoration efforts anywhere in the world.

Acknowledgement

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Appendix A. The fit of model for every year of simulation