Effect of Reed Vegetation on Evapotranspiration and Treatment Performance with Vertical Subsurface Flow Constructed Wetlands in the Treatment of Landfill Leachate

Tokuo Yano[1,*], Masatomo Nakayama[2], Kazuhiro Yamada[1], Akiko Inoue-Kohama[1], Shinya Sato[3], Keijiro Enari[1]

[1]Department of Environment and Applied Chemistry, Tohoku Institute of Technology 35-1 Yagiyama-kasumicho Taihaku-ku, Sendai, 982-8577, Japan
[2]Department of Civil Engineering and Management, Tohoku Institute of Technology 35-1 Yagiyama-kasumicho Taihaku-ku, Sendai, 982-8577, Japan
[3]Sendai Kankyo Kaihatsu Co., Ltd, 460-1 Aonogi-Imozawa Aoba-ku, Sendai 989-3212, Japan

Abstract In this study, the effect of reed vegetation on evapotranspiration (ET) and treatment performance was estimated, and a commonly used meteorological estimate of potential evapotranspiration (PET) was compared with ET with vertical subsurface flow constructed wetlands (VSSFs) in the treatment of the high salinity of landfill leachates. The experimental approaches consisted of three runs: Run A was a poor reed vegetation bed, Run B was a dense reed vegetation bed, and Run C was a bed without reeds. The results of this study are as follows: The salinities of the leachate inflow in Run A and Run B were 15.8 ± 1.9g Cl⁻/L and 15.5 ± 2.8g Cl⁻/L, respectively. The average ETs of Run A, Run B and Run C were 4.2mm/d, 7.4mm/d and 3mm/d, respectively. The annual ET rates of Run A, Run B and Run C were 1535mm, 2702mm and 1101mm, respectively. On the other hand, those of PET estimated on the basis of the Hamon equation of 2017and 2018 were 741mm and 791mm, respectively. The PET rate was much less compared to the ET rate in the dense vegetation bed. It was necessary to consider site-specific factors such as growth of plants in the evaluation of the water budget. The water loss by evapotranspiration in Run B was much more than those in Run A and Run C. Although the removal rates calculated from the concentration between inflow and outflow did not differ between the dense vegetation bed and the poor vegetation bed, the load reduction rates calculated from the water budget differed between dense vegetation and poor vegetation.

Keywords Reed Vegetation, VSSF, Evapotranspiration, Water Budget, Treatment Performance

1. Introduction

Constructed wetlands (CWs) are widely known to save energy, to be low cost, to have environmental friendliness and to provide sustainability for the wastewater treatment system. They have been used for treating various types of

wastewater around the world including domestic, agricultural, industrial wastewaters and various runoff waters [1, 2].

CWs also have been frequently used for the treatment of landfill leachates in many countries [3]. In spite of different views on leachate treatment, many experts agreed that an on-site treatment facility was needed, since it was easy to operate, and ecological in terms of costs and energy [4].

Various kinds of plants are planted in CWs: cattail (*Typha latifolia* L.), reed (*Phagmites australis* Trin ex Steudel), rush (*Juncus effusus* L.), yellow flag (*Iris pseudacorus* L.), managrass (*Glyceria maxima*), giant reed (*Arundo donax* L.), and willow (*Salix sp.*)[5, 6].

There are several roles for each of the wetland plants on the CWs [7-9], which are: (1) Prevention of clogging by the rhizomes of plants (2) Oxygen release from the rhizome (3) The offer of a habitat of a rhizosphere (4) Uptake of nutrients, and (5) The offer of a natural landscape. Vymazal and Kropfelva published a thorough literature review on the role of plants in CWs [10]. However, the mechanisms by which macrophytes perform water treatment in CWs are under debate. Evapotranspiration (ET) is one of the most important roles of plant [11]. CWs receive water through inflow and precipitation, and lose water to outflow, evaporation and transpiration, i.e., evapotranspiration. Plants have a critical role in determining the dynamics of water loss, mainly through ET. The ET of emergent macrophytes is a significant process in CWs. Difficulties in accurately calculating ET in CWs can lead to inaccurate water balance [12].

Simple meteorological methods or off-site ET data are often used to estimate ET, but these approaches do not include potentially important site specific factors such as plant communities, root zone, water level, and soil property. Chazarenc showed the importance of evapotranspiration during hot periods in natural wetlands and also in CWs [13]. It is of particular importance that leachate volume decreases as a result of ET in CWs [14]. ET therefore might be used in CWs for landfill leachate treatment. Such CWs are planted with macrophytes like willows, poplars and reeds, as the plants that are recommended for landfill leachate ET [15]. Many researchers reported CWs for landfill leachate treatment with willows [16-21]. Landfill leachates contain various quantities of undesirable, and even toxic, organic and inorganic substances [3]. Bialowiec et. al. have showed that the common reed is the most suitable plant for landfill leachates, because of their very high ET rates, high biomass yield and high resistance to pollutant load [15]. Its degree of success has varied but not exceeded a 50% removal efficiency of such pollutants as COD, BOD, and nitrogen [22]. Most of landfill leachate in Japan contain a high salinity which is close to that of sea water [23-25]. Many kinds of plants are difficult to grow under high salinity conditions. It is commonly assumed, however, that reeds can tolerate salinity to a high degree. Matoh demonstrated that reeds were successfully grown at chloride concentrations of up to17.8gCl⁻/L [26], and reeds could grow normally until 10.7gCl⁻/L. Barr reported that *P. australis* could tolerate salinity to quite a high degree of up to 7.3gCl⁻/L for normal growth, surviving at up to 12.7gCl⁻/L [27]. Mauchamp demonstrated that reed growth decreased as salinity increased (50% decrease at 4.6g・Cl⁻/L when compared to freshwater) and a 7-100% mortality depending on population, occurred at 9.1gCl⁻/ L and 12.1gCl⁻/L[28]. Although, there were few studies concerning the treatment of high salinity landfill leachate with constructed wetlands, several reports concerning horizontal subsurface constructed wetlands (HSFs) were given during past several years [23-25]. The ET capacity of reeds in VSSFs in different type of reed vegetation and the effect of reed vegetation on the treatment performance in the treatment of high salinity landfill leachate have not been thoroughly investigated.

The objectives of this study were to estimate the effect of reed vegetation on ET and the treatment performance, and to compare a commonly used meteorological estimate of potential evapotranspiration (PET) with the ET which was estimated on the basis of a water balance method.

2. Materials and Methods

The pilot-scale VSSFs were located in the Miyagi prefecture in Japan. The three pilot-scale constructed wetlands were identical in size and construction (2m long × 1m wide with a 0.55m water depth).

The experimental approaches consisted of three runs: Run A contained a poor reed vegetation, Run B contained a dense reed vegetation and Run C was without reeds (Figure1). The reeds in Run A were two-year old specimens and the reeds in Run B were seven-year old specimens under the condition of high salinity landfill leachate. Inflow, outflow and precipitation were measured in order to evaluate the water budget of the VSSFs. The flow rate was 70 L per day, and 14 L of the inflow was intermittently introduced five times a day. The measured parameters were pH, COD, TN, NH_4-N, NO_2-N, NO_3-N, TP, air temperature, EC, and Chloride. The air temperature every 30 min and the amount of dairy precipitation were measured. An investigation of reed vegetation (shoot lengths and shoot numbers) was completed twice a month. A rain gauge was installed at the outflow drain of the VSSF, and the rate of outflow was measured continuously. The ET was estimated based on the water budget method, and the PET was estimated using the Hamon equation. The experimental period of Run A and Run C was from April 2017 to Mach 2018 and that of Run B was from April 2018 to March 2019. Hereafter, these are referred to as 2017 and 2018.
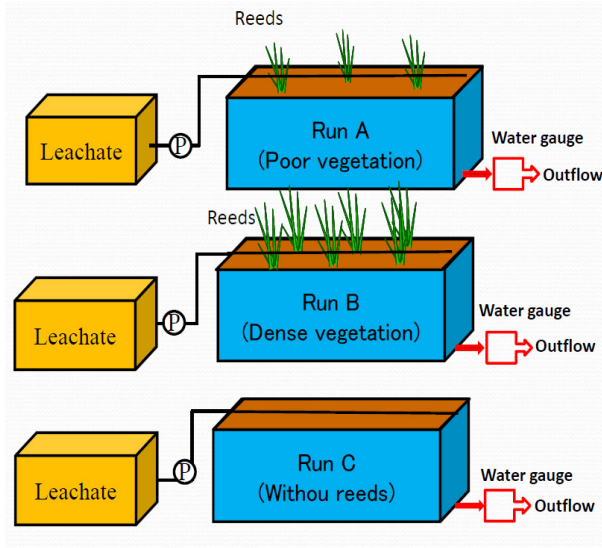
Figure 1. Schematic diagram of VSSFs

3. Results and Discussions

3.1. Salinity of CWs

Table1 shows the average salinity of inflow and outflow of Run A and Run B during the experimental period.

The average salinities of Run A and Run B inflow were 15.8 ± 1.9 and $15.5 \pm 2.8g \cdot Cl/L$, and those of Run A and Run B outflow were 12.0 ± 2.4 and $14.8\pm2.4gCl/L$, respectively. The salinity of the landfill leachate was very high, and was slightly lower than that of seawater. The salinity of the survival limit of a reed is reported within the range of $12-15g \cdot Cl^{-}/L$[26,27]. Therefore, it seemed that it was very difficult for the reed to grow

Table 1. Average salinity of Run A and Run B

|	unit	Run A	Run B
Inflow	$g \cdot Cl/L$	15.8 ± 1.9	15.5 ± 2.8
Outflow	$g \cdot Cl/L$	12.0 ± 2.4	14.8 ± 2.4

3.2. Reed Vegetation

Figures 2a and 2b show the growth change of the shoot length and the number of shoots for Runs A and B during the vegetation period of Run A and Run B. The shoot length was the average reed height from the top of 30 shoots. As shown in Figures 2a and 2b, the extension of the reeds of Run A and Run B was increasing until the end of July. The maximum length of Run A reached up to a height of 53.7 ± 8.1cm and that of Run B reached up to 86.7 ± 13.4 cm.

On the other hand, the number of the shoots per square meter of Run A gradually increased until the middle of August, reaching up to 71 shoots /m², and that of Run B

increased until the middle of August, reaching up to 798 shoots /m². In the reeds of Run A, the growth of shoot length and the increase of the number of shoots were remarkably suppressed and managed to survive under the high salinity condition. On the other hand, in the reeds of Run B, the growth of shoot length was suppressed, but the number of shoots continued to increase over the past 7 years to 789 shoots/m² under the high salinity condition.

The shoot length of the Run B reed was 1.5 times that of the Run A reed, and the number of shoots in Run B was more than 10 times that of Run A. In this way, the degree of vegetation greatly differs between the Run A reed and the Run B reed. That is, Run A contained poor vegetation and Run B contained dense vegetation.
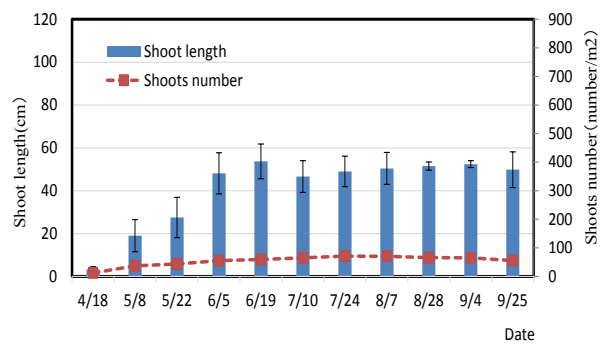
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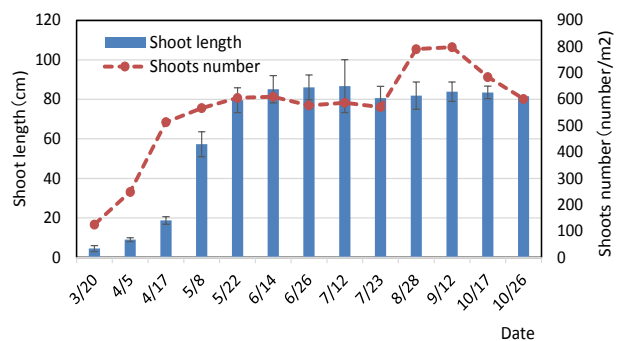
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Figure 2. Seasonal growth change of reeds (a: Run A, b: Run B)

3.3. Water Budget of CWs

The evapotranspiration of plants has a close relation to the water budget in the CWs and influenced the purification process [28].

Unlike natural systems, water behavior in CW is partly controlled by human interests. In the present experiment, the input streams from the system do not exit, since all treatment beds were sealed. Therefore, the parameters of the water budget are inflow, precipitation, evaporation, transpiration and outflow. The water budget of the CW is expressed as follows [29, 30].

$$ET = Q_{in} + P - Q_{out} \qquad (1)$$

ET: Evapotranspiraion (mm/d)
P: Daily Precipitation (mm/d)
Q_{in}: Inflow (mm/d)
Q_{out}: Outflow (mm/d)

ET=Evaporation + Transpiration

Total inflow= Inflow + Precipitation

Figure 3 shows the variation in the daily water balance (total inflow, outflow and ET) of each run during the period of April 2017 to Mach 2018 and that of April 2018 to March 2019. Figure 3-a, 3-b and 3-c are Run A, Run B, and Run C, respectively. In Figure 3-a, ET gradually increased in April, remained around 5-7mm/d from June to December, and then decreased to 2mm/d. ET in Run A was slightly affected by air temperature. The increase of ET might be due to the growth of reeds. The average of ET in Run A was 4.2 ± 2.7mm/d. The maximum rate of ET was 11.3mm/d and the minimum rate was -7.3mm/d. In figure 3-b, ET in Run B remained in the range of

6-8.5mm/d throughout the experiment, and was almost constant. That is, the ET in Run B did not appear to be affected by air temperature at all. The average rate of ET in Run B was 7.4 ± 2.5mm/d. The maximum rate of ET was 20.8mm/d and the minimum was 0.5mm/d. In Figure 3-c, the ET rate in Run C remained in the range of 3-4.5mm/d from April to December, and then decreased to 1mm/d. ET in Run C was slightly affected by air temperature, as in Run A. The average rate of ET in Run C was 3.0 ± 2.4mm/d. The maximum rate of ET was 10.0mm/d and the minimum was -11.8mm/d. Therefore, the highest ET was in the dense vegetation Run B, followed by the poor vegetation Run A, and the lowest was Run C without reeds. In our study, the ETs in the poor vegetation bed and dense vegetation bed were higher than that in the willow bed in Poland which was demonstrated by Agopsowicz [31]. The difference may be due to climatic conditions such as temperature in the two countries.
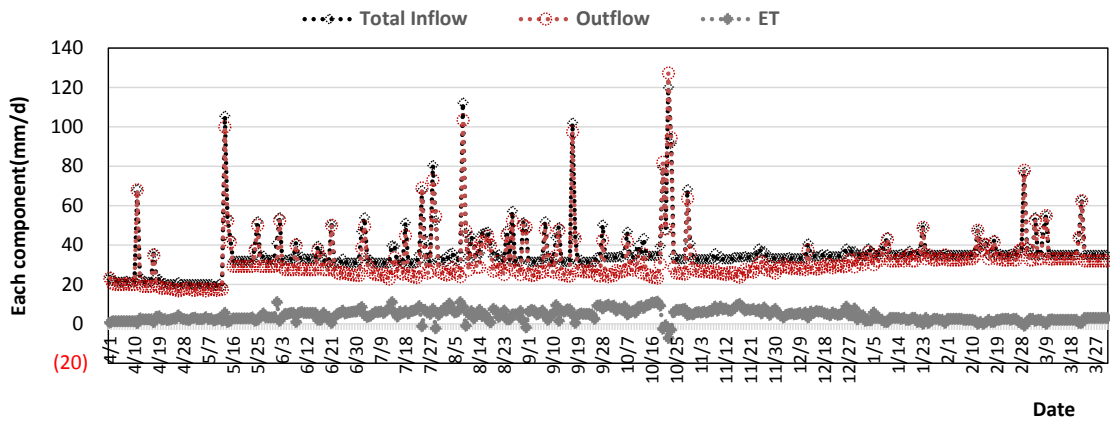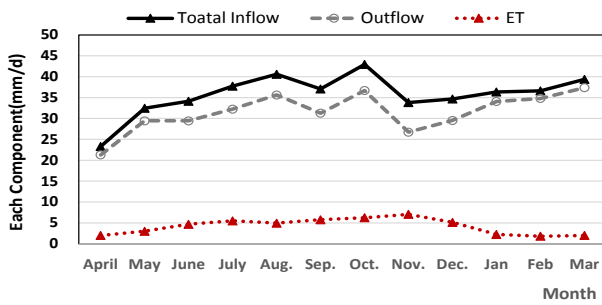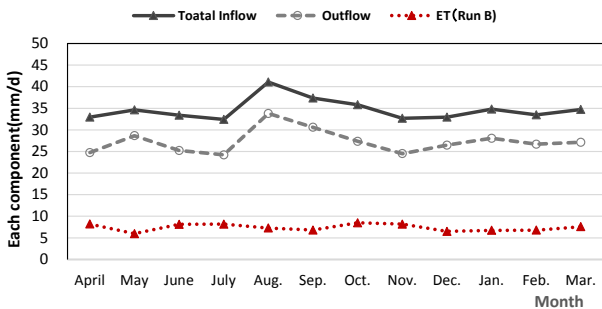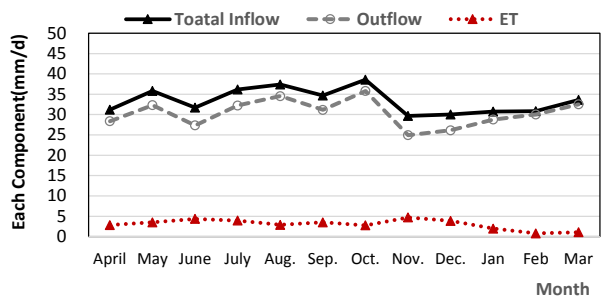

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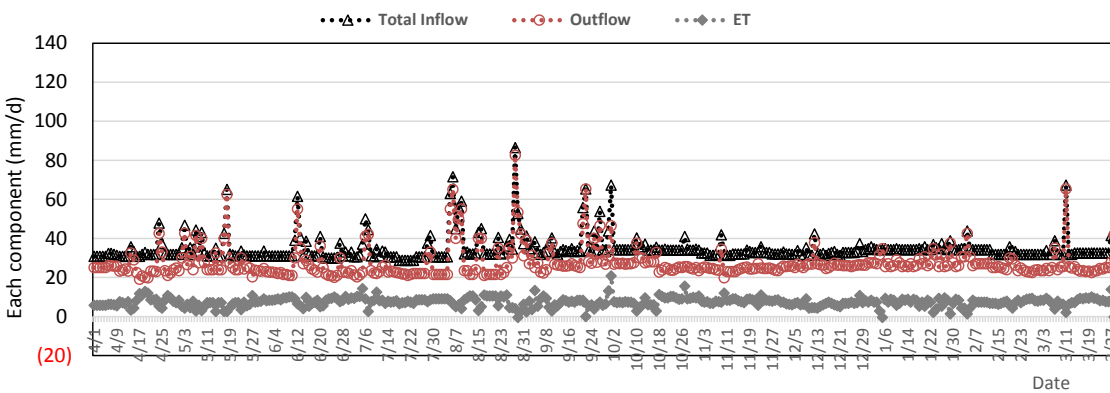
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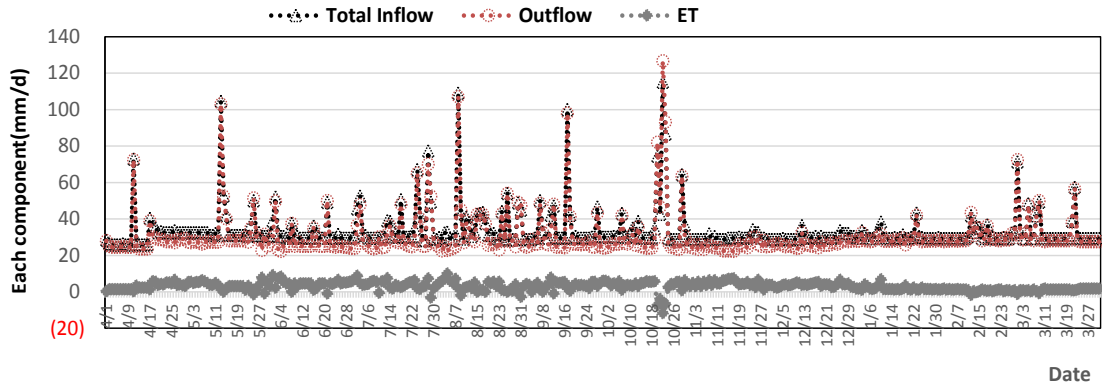
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Figure 3. Variation of water balance (a: Run A, b: Run B, c: Run C)

a

Figure 4 shows the monthly mean water balance of the three runs. The ET was estimated on the basis of the water budget method. Figure 4-a, 4-b, 4-c are the water balance of Run A, that of Run B, and that of Run C, respectively. In Figure 4-a, the ET rate of Run A gradually increased from April to November, and reached a peak with an ET rate of 7mm/d in November. In figure 4-b, that of Run B remained 6-8.5mm throughout the year. In Figure 4-c, the ET rate in Run C remained in the range of 3-4.5mm/d from April to December, and then decreased to 1mm/d.

3.4. Monthly Ratio of ET to Total Inflow

Figure 5 shows the ratio of ET to total inflow of the three runs.

b
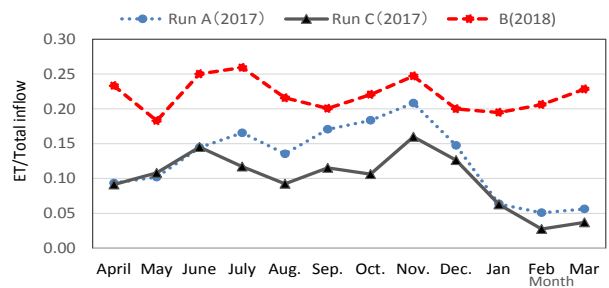
Figure 5. Monthly ratio of ET to total inflow of three runs

Run A was within the range of 0.05 to 0.21, and with an average of 0.13. Run C was within the range of 0.03 to 0.16, and with an average of 0.10. Although the ratio of Run A was higher than that of Run C from July to November, the trend of the monthly variation of Run A and Run C was very similar. That is, the monthly change of the evapotranspirated volumes in the poor vegetation bed was similar to that of the bed without reeds. On the other hand, Run B was within the range of 0.19 to 0.26, and with an average of 0.22, and fairly constant throughout the year with no seasonal variation. Thus, there was large difference in the ET variation between

c

Figure 4. Variation of monthly mean water balance (a: Run A, b: Run B, c: Run C)

dense vegetation and poor vegetation. Silva, et al. demonstrated that the ratio of evapotranspirated volumes were 0.38 in plant beds and 0.16 in beds without plants in sub-humid tropical climates in Brazil where temperatures remained at an average 16℃ to 30℃[32]. Sendai is in the temperate zone where temperatures remained at an average 1.5 ℃ to 24 ℃. Therefore, the ratio of evapotranspirated volumes varied greatly with climatic condition such as subtropical and temperate zones.

3.5. Comparison of ET and PET

The PET was estimated on the basis of Hamon equation. Hamon equation was expressed as follow [33]:

$$PET=0.14D_0{}^2P_i \qquad (2)$$

PET: Potential evapotranspiration (mm/d),
D_0: Day time length (x/12hrs),
P_i: Saturated absolute humidity (mg/m^3)

Figure 6 shows the variation of the monthly average air temperature and the monthly average of PET. Figure 6-a is the change in 2017 and Figure 6-b is that in 2018. In both figures, the PET began higher with rising air temperatures from spring to summer, reaching a peak in July and began lower with descent of the air temperature from autumn to winter. The PET was influenced strongly by air temperature. The variations of PET in 2017 and 2018 showed the same shape.

Figure 7 shows the comparison of the monthly average of PET and the monthly average of ET of three runs. Figure 7-a shows the variation of the ET of Run A and Run B in 2017, and Figure 7-b is that of Run B in 2018. In figure 7-a, the changes in the PET and the ET of Run A and Run C were similar from April to July, but after August, they behaved differently. In figure 7-b, the changes in the PET and the ET of Run B were quite different. Thus, the changes in the ET in VSSFs differed according to the vegetation difference of reeds, and also in PET.
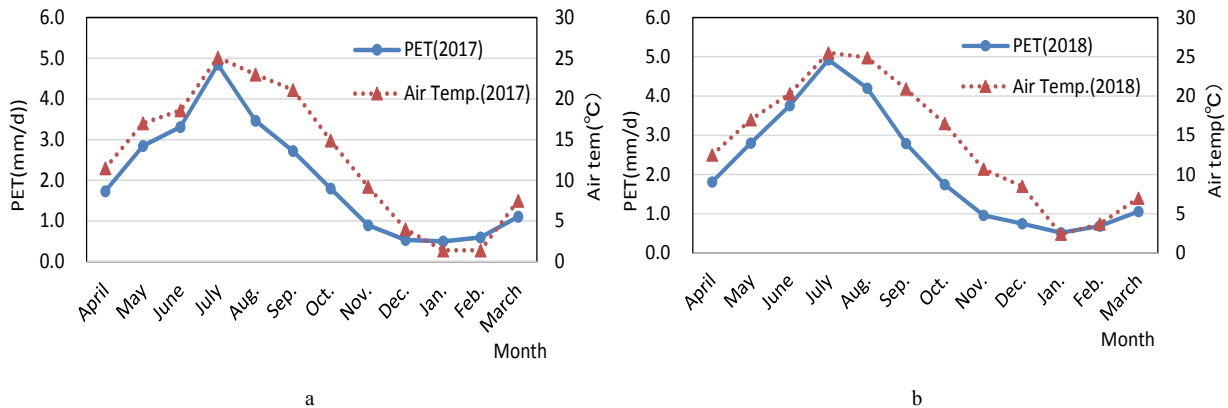

Figure 6. Average of monthly variations of PET and air temperature (a: 2017, b: 2018)
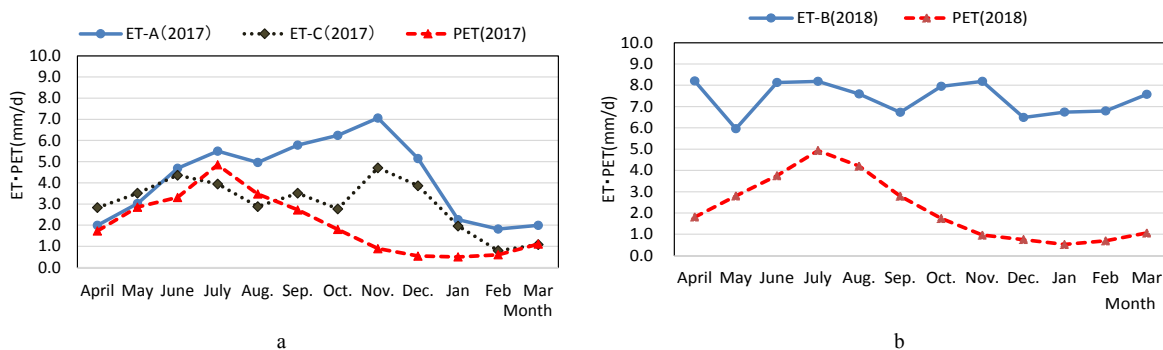

Figure 7. Comparison of average of monthly variations of ET and PET (a: 2017, b: 2018)

Figure 8 shows the annual ET rate and the annual PET rate in 2017 and 2018. The ET rates of Run A, Run B and Run C were 1535mm, 2702mm and 1101mm, respectively. On the other hand, the annual PET rates in 2017and 2018 were 741mm and 791mm, respectively. The ET rate of the dense reed vegetation was higher than that of a poor reed vegetation and a lack of reeds. There was a difference in the ET rate due to the difference in reed vegetation in VSSF. Furthermore, the ET rate is much different from the PET rate. When assessing ET of CWs, it is necessary to consider the vegetation.
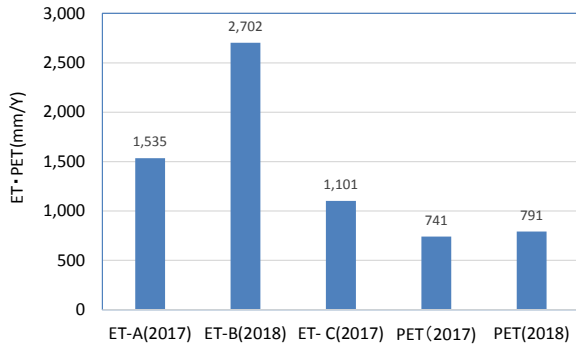

Figure 8.   Annual ET rate and PET rate of 2017and 2018

The annual precipitation rates in 2017 and in 2018 were 1420mm and 1077mm. The annual ET rate in Run A was 1.08 times higher than the precipitation rate in 2017. That in Run B was 2.51 times higher than the precipitation rate in 2018. That in Run C was 0.78 times lower than the precipitation rate in 2017. Agopsowicz demonstrated that ET of three-month-old willow sprouts was 1.6-1.8 times higher than the average precipitation rate in Poland [31]

3.6. Treatment Performance

In the VSSF of Run B, where water loss was typically high, the calculation of pollutant removal efficiency using results of concentration might lead to significant errors. Therefore, it was necessary to evaluate the load reduction rate obtained from the water budget.

Removal efficiencies of pollutants in VSSF were calculated, based on concentrations (eq.(3)) and load reduction rates were calculated based on loads (eq.(4)).

$$\text{Removal efficiency (RE) } = \frac{C_{in} - C_{out}}{C_{in}} \times 100 \text{ \%} \quad (3)$$

Where C_{in} and C_{out} are the mean concentrations (mg/L) of a pollutant in the inflow and the outflow, respectively.

$$\text{Load reduction rate (LRR) } =$$

$$= \frac{(C_{in} \times Q_{in}) - (C_{out} \times Q_{out})}{C_{in} \times Q_{in}} \times 100 \text{ \%} \quad (4)$$

Where Q_{in} and Q_{out} are the amount of inflow and outflow, and $C_{in} \times Q_{in} = M_{in}$ (mg) and $C_{out} \times Q_{out} = M_{out}$ are inflow and outflow mass load, respectively.

Table 2, 3 and 4 show the removal efficiencies and the load reduction rates of COD, NH$_4$-N and TN of three runs. In Table 2, the REs of COD of Run A, Run B and Run C were 43.7 ± 18.7, 46.6 ± 12.6, 37.4 ± 18.8%, respectively. The highest RE was Run B, followed by Run A, and the lowest RE was Run C. However, the difference in RE between Run A and Run B was very small. The LRRs of the COD of Run A, Run B and Run C were 44.9 ± 15.6, 54.9 ± 10.5, 36.0 ± 17.4%, respectively. The order of the LRR was the same as that of the RE. However, the difference in LRR among the three runs was larger than that in RE. Compared to the RE and LRR of COD, both were almost the same in Run A and Run C. On the other hand, LRR was 8.8% higher than RE. Thus, large water loss due to dense vegetation ET provided a great influence on the treatment performance.

In Table 3, the REs of the NH$_4$-N of Run A, Run B and Run C were 40.3 ± 22.8, 40.2 ± 15.5, 33.8 ± 9.48%, respectively. There were no differences in the removal efficiency between Run A and Run B. The LRRs of the NH$_4$-N of the three runs were 41.5 ± 10.8, 49.1 ± 12.4, 31.6 ± 9.4%, respectively. The highest LRR was Run B, followed by Run A, and the lowest LRR was Run C. Although there were no differences between the RE and LRR in Run A and Run C, there was large difference between the RE and LRR in Run B. Compared to the RE and LRR of NH$_4$-N, both are almost the same in Run A and Run C. On the other hand, LRR was 8.9% higher than RE.

In Table 4, the REs of the TN of Run A, Run B and Run C were 30.0 ± 22.8, 27.5 ± 28.5, 29.5 ± 21.78%, respectively. There were no differences in the removal efficiency among the three runs.

The LRRs of TN of the three runs were 31.4 ± 20.7, 38.3 ± 19.5, 26.2 ± 21.6%, respectively. The highest LRR was Run B, followed by Run A, and the lowest LRR was Run C. However, there were no differences between the RE and LRR in Run A and Run C. On the other hand, Run B had a large difference between the RE and LRR.

Similar to COD and NH$_4$-N, the LRR in TN was higher than the RE.

The reed vegetation did not affect the RE estimated from the pollutants concentration in the VSSFs, but provided a large impact on the LRR estimated from the water budget.

Table 2.   Treatment performance of COD

	unit	Run A	Run B	Run C
Inflow	mg/L	242.3 ± 34.5	255.1 ± 25.4	237.6 ± 36.2
Outflow	mg/L	133.9 ± 43.1	136.2 ± 24.4	146.2 ± 43.3
Removal efficiency	%	43.7± 18.7	46.6 ±12.6	37.4 ±18.8
Inflow load	g/d	15.3 ± 2.4	16.4 ± 2.0	13.9 ± 2.2
Outflow load	g/d	8.4 ± 3.0	7.4 ± 2.4	8.7 ± 2.2
Load reduction rate	%	44.9 ± 15.6	54.9 ± 10.5	36.0 ± 17.4

Table 3.   Treatment performance of NH₄-N

	unit	Run A	Run B	Run C
Inflow	mg/L	318.9 ± 48.8	327.8 ± 30.7	299.6 ± 42.8
Outflow	mg/L	186.9 ± 75.1	196.2 ± 41.7	196.0 ± 30.5
Removal efficiency	%	40.3 ± 22.8	40.2 ± 15.5	33.8 ± 12.3
Inflow load	g/d	20.2 ± 4.0	21.0 ± 1.8	17.5 ± 2.5
Outflow load	g/d	11.7 ± 5.3	10.7 ± 2.3	11.8 ± 1.3
Load reduction rate	%	41.5 ± 10.8	49.1 ± 1 2.4	31.6 ± 9.4

Table 4.   Treatment performance of TN

	unit	Run A	Run B	Run C
Inflow	mg/L	333.1 ± 47.5	345.5 ± 29.9	330.1 ± 48.8
Outflow	mg/L	229.5 ± 77.9	250.5 ± 33.5	232.8 ± 70.0
Removal efficiency	%	30.0 ± 22.8	27.5 ± 28.5	29.5 ± 21.5
Inflow load	g/d	21.1 ± 4.1	22.2 ± 3.1	19.3 ± 2.9
Outflow load	g/d	14.4 ± 5.5	13.7 ± 3.5	13.9 ± 3.9
Load reduction rate	%	31.4 ± 2 0.7	38.3 ± 19.5	26.2 ± 21.6

4. Conclusions

We examined the effect of the reed vegetation on the ET and treatment performance using VSSFs, and obtained the following conclusions. The difference in the reed vegetation provided a large difference in the ET rate in VSSFs. That is, the ET in the dense vegetation bed was higher than that of the poor vegetation bed. The high ET in the VSSFs reduced the outflow load and affected the removal efficiency. The annual variation of ET and PET was very different, and the seasonal variation was small.

Even in the water balance of VSSFs, it was necessary to estimate the ET in consideration with the reed vegetation.

Although the removal rates calculated from the concentration between inflow and outflow did not differ between the dense vegetation bed and the poor vegetation bed, the load reduction rates calculated from the water budget differed between the dense vegetation and the poor vegetation.

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