INFLUENCE OF PERCOLATION PATTERNS ON GROWTH AND YIELD OF RICE PLANTS AND UPTAKE OF CADMIUM FROM POLLUTED PADDY FIELDS USING SOIL DRESSING MODELS

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THE UNITED GRADUATE SCHOOL OF AGRICULTURAL SCIENCES
IWATE UNIVERSITY
SCIENCE OF BIOTIC ENVIRONMENT
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JAPAN

2011. 9

DEDICATED

TO

MY YOUNGER BROTHER AND PARENTS

Abstract

We investigated that influence of percolation patterns on growth and yield of rice plants and uptake of cadmium from polluted paddy fields using soil dressing models. The experiment was conducted in the green house with open and closed system percolation models (M-1, M-2, M-3, M-4, M-5, M-6, M-7, M-8, M-9 and M-10). Those models were consisted of stratified soil layers and two different percolation systems (open and closed system percolation) and operated by 12.5 cm (M-1 to M-6), 15 cm (M-7 to M-8) and 20 cm (M-9 to M-10) soil dressing with stratified polluted paddy fields. The stratified paddy field models were constructed in an iron box (30x50x70 cm) with three layers of soil; those were plow layer (layer I; 0-12.5 cm), plowsole (layer II; 12.5-22.5 cm), and subsoil (layer III; 22.5-65cm) and constructed with Andosol or alluvial (layer I), Cd-polluted soil or Cd –polluted soil with alluvial (layer II) and gravel or Cd- polluted soil with gravel (III layer). In open system percolation models was planned in plowsole and subsoil but in the closed system percolation models, soil layers were planed under saturated condition. The two percolation systems were applied to paddy field models by controlling the ground water level at 57.5 cm and 12.5 cm for the open system and closed system model, respectively, using a subsurface drainage pipe.

In open system percolation, the pressure head of the plowsole and subsoil were negative but in closed system showed positive pressure. In the open system percolation models, plowsole and subsoil temperature almost similar to the air temperature but in closed system percolation models were higher than the air temperature. The soil redox (Eh) value in plow layer of both percolations was about -190 mV. But in the plowsole and subsoil were in oxidative condition (650mV) in open system percolation models. On the other hand, in the plowsole and subsoil were in reduction state (-200mV) in closed system percolation models. The average SPAD values in closed system percolation models were lower than the open system percolation models. In the harvesting period, the14th leaf was dry about 78% in closed system percolation but 43% in open system percolation models; this result indicated that the difference of photosynthesis ability of rice plants in two systems during ripening time. Moreover, the plant length, number of stem, number and weight of panicles, number and weight of grains were lower in open system percolation models than the closed system percolation models. Accumulation of cadmium in roots of each soil layer, stem and leaves and rice grain were higher in open system percolation than the closed system percolation models. In soil oxidation state, the insoluble cadmium metal in soil leading to soluble form with presence of oxygen which can be easily uptake by rice plants. As above mentioned, it was recognized that percolation pattern influenced on the growth and yields of rice plants and uptake of cadmium.

Keywords: Percolation pattern, Soil dressing, Cadmium soil, Cadmium accumulation in rice plants, Growth and yield of rice plants

Acknowledgements

First of all the author expresses his deepest sense of gratitude to the God for leading him up to this level and enabling him to complete this research work.

The author's greatest pleasure is to express his heartiest regards, sincere gratitude, deepest sense of appreciation and indebtedness to his respected Major advisor, Professor Sasaki Choichi, Department of Agriculture Science and Environmental Engineering, Faculty of Agriculture and Life Sciences, Hirosaki University, Japan for his valuable advice, active encouragement, ardent interest, rational criticism, and above all, the constant guidance to carry out the research work as well as to prepare this dissertation.

The author sincerely wishes to express his heartfelt respect, gratitude and high appreciation to honourable members of his advisory committee, Dr. Annaka Takeyuki, professor, Faculty of Agriculture, Yamagata University, Japan and Dr. Matsuyama Nobuhiko, Associate professor, Faculty of Agriculture and Life Sciences, Hirosaki University, Japan for their constant supervision, inspiration and valuable suggestions during this research work.

The author is highly grateful to Hirosaki city scholarship, Hirosaki-shi, Aomori, Japan and the Kawashima UFJ Bank Foundation, Tokyo, Japan to provide him scholarship to complete this research work in a pursuit to attain his Ph.D. Degree.

The author would like to take this opportunity to express his sincere thanks and gratitude to all of his teachers, students and staff of The United graduate School of Agricultural sciences, Iwate University, Japan for their active and cordial cooperation.

He would like to extend thanks to his fellow well wishers especially Takeshi Yoshimura, Dr. Bijon Kumar Mitra, Mr. Bipul Kumar Paul, Dr. Kaori Noda, Daisuke Iizima, Mrs.Chandana Pk, Mr. Gauri Maharjan, Mr.Kinta Hoshi, Mr.Minetaka Hama, and Mr. Kiichi Sasaki for their continuous inspiration and cooperation throughout this research work.

Finally, the author owes everything to his parents who are always anxious to send their son abroad to pursue higher education, and forever grateful to his brothers and other relatives for their inspiration and moral support throughout his life.

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Chapter 1: General Introduction

1.1 Background of the paddy field model

Percolation pattern related to hydraulic conductivities of soil. Also, the ground water level is important for percolation pattern which influence the soil profile. By this influence, we divided the paddy field into two types based on groundwater level. One is ill-drained paddy field (closed system percolation) in which the range of groundwater level is 0-0.7m during the cultivation. Other type is well- drained paddy field (open system percolation) in which the groundwater level is kept over about 1.0 m from the soil surface (Soil dictionary, 1993). Tokunaga and Sasaki (1990) could confirm the open system percolation under a fields condition (Fig. 1).

When the soil exposed, the soil air pressure is same to the atmospheric pressure. From this point of view, Japanese scientists had classified the paddy fields and Sasaki (1992) made two types of the stratified paddy fields model with different percolation system, i.e. closed system percolation and open system percolation. The closed system percolation was characterized by high ground water level and the water flow occurred under closed system (JSIDRE, 2003).

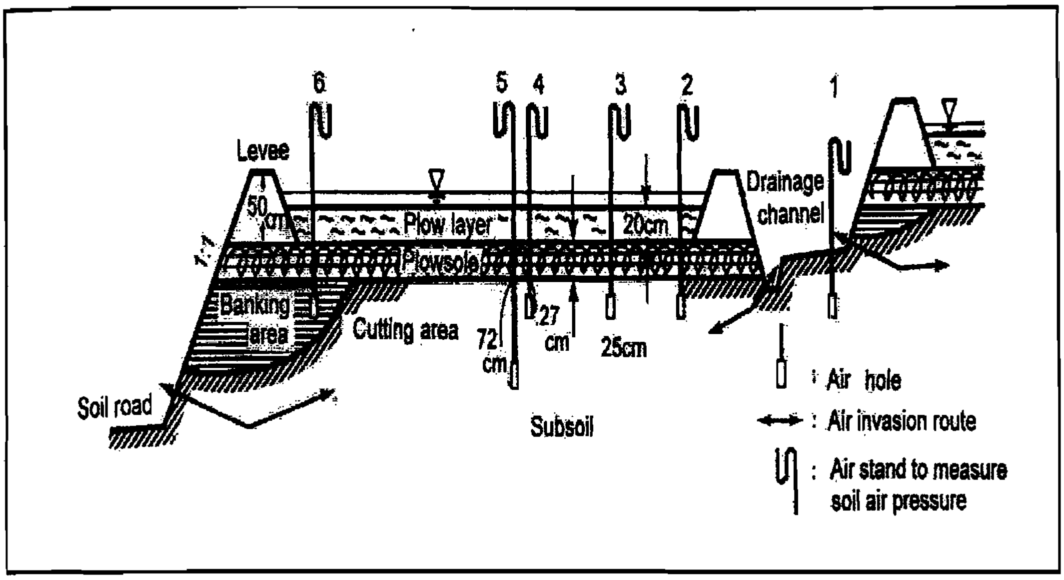


Fig. 1: A schematic diagram of the paddy field used to confirm the occurrence of the open system percolation (Tokunaga and Sasaki, 1990).

Due to saturated condition, several layers of soil were became reduced. On the other hand, open system percolation was characterized by low ground water level and the water flow occurred in under open system and subsoil was unsaturated condition (JSIDRE, 2003). There are two types of a percolation patterns happen in the soil layers of open and closed system percolation. In open system percolation, the soil air connected to the atmosphere when the water pressure head of soil layer is lower than the air entry pressure (Yamazaki, 1958) and in the closed system percolation were designed inundation condition.

Soil air pressure is very important for rice plants growth and producing soluble metals in the soil. In a stratified soil column experiment, Sasaki (1995) investigated the pressure head profile in percolation pattern of soil column. As illustrated Fig. 2, Sasaki (1995) showed the concepts of the difference in water flow. When the water pressure head of soil layer is higher than the air entry pressure, its water movement as saturated flow is known as positive pressure percolation. However, water pressure head of soil layer is lower than the air entry pressure, it become negative pressure percolation under unsaturated flow.

Percolation patterns are related to the hydraulic conductivities of the soil layers and hydraulic conditions such as groundwater level (Adachi *et al.*, 1992), which may acts as a controller of soil redox potential and consequently the uptake of Cd in rice plants. For this reason the percolation pattern become an important factor for land improvement and to solve environmental problems.

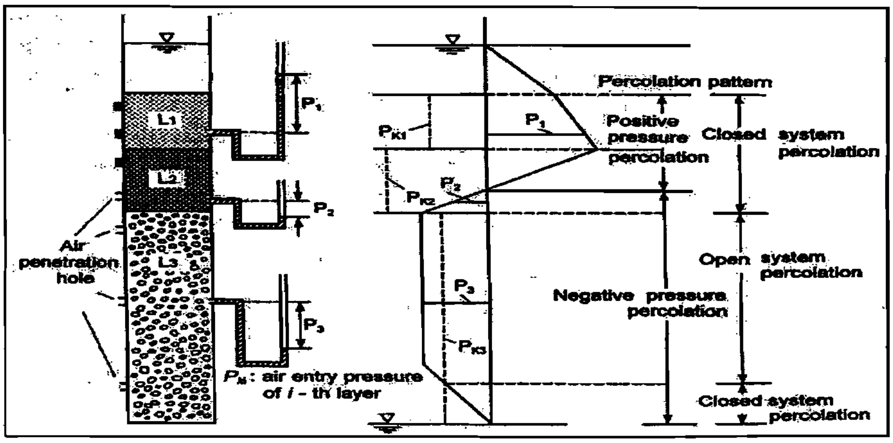


Fig. 2: Pressure head profile and percolation pattern in a stratified soil column (Sasaki, 1995).

Many scientists have conducted their research in a pot device (stratified soil column) but that pot experiments have only plow layer. Rice plant roots grow up to subsoil. Therefore influence of plowsole and subsoil on the rice growth, yields and metal uptake by rice plants could not be clear.

1.2 Cadmium study in rice cultivation

All forms of pollution have an adverse effect on the environment. Therefore, suitable environmental conditions must be maintained for life to flourish. Heavy metal pollution in soil is one form of pollution that has an adverse effect on plant growth and production. The daily expansion of industries and human habitats continues to contribute to increasing levels of pollution. In addition, the increase in contaminants in agricultural farmland has led to social issues in regard to food production safety. International organizations, such as the Food and Agriculture Organization (FAO) and the World Health Organization (WHO), have recently come to an agreement with respect to the authorization criteria of pollutants in agricultural products.

In Japan, many agriculture lands were contaminated by industrial effluents and it does create serious problem for public health. The cadmium content of soils also differs very much from place to place and this may be responsible for the difference in the amount of cadmium in plants foods produced from contaminated soil (Kawada and Suzuki, 1998). Many reports showed that rice cultivars varied significantly with regard to Cd uptake and accumulation. Morishita *et al.*, (1987) reported a comparative study on cadmium uptake by several rice cultivars in Andosol with a low total cadmium concentration in soil (0.102 mg kg^{-1}). It was observed that japonica brown rice varieties have the lowest average uptake rate compared to the other subspecies namely, javanica and indica .

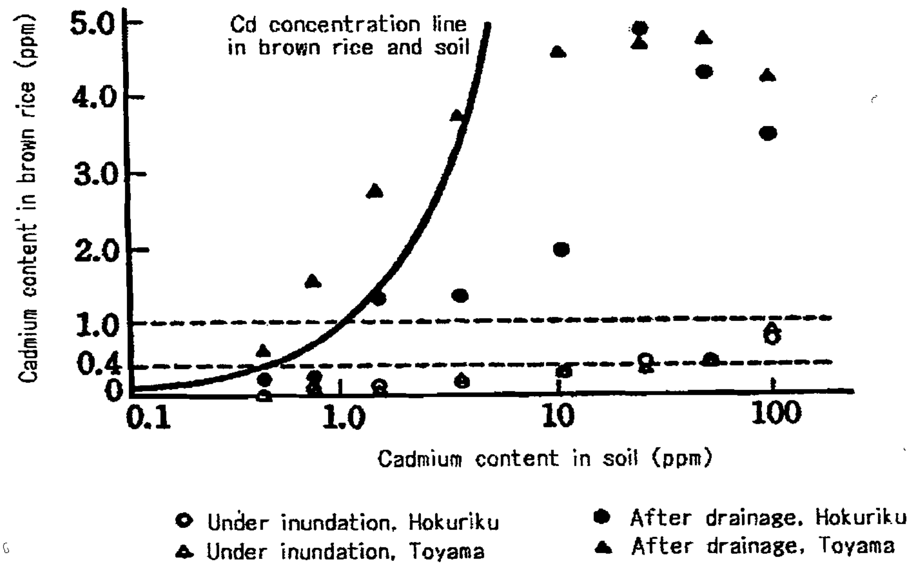


Fig. 3: Correlation between cadmium concentration in soil and brown rice in different water management (Iimura and Ito, 1975).

Cadmium leakage might occur in the soil solution in particular climatic condition due to high biological activity in soil (Morel and Gunckert, 1983). Furthermore, Haghiri (1973) was observed that between soil temperature and Cd –uptake by plants had a positive relationship. Numerous studies reported that the Cd concentration in rice was correlated with the amount of cadmium content in soil. According to Iimura and Ito (1975) studied that high Cd contained soil caused the high amount of Cd content in rice grain as shown in the Fig. 3.

The chemical specification of heavy metals in solution affects their availability and toxicity to plants (Parker *et al.*, 1995). For example, Cu^{2+} (Graham, 1981) and Cd^{2+} (Cabrera *et al.*, 1988) have shown high level of correlation with the activity of free metals ions in soil solution when plants uptake these metals. Soluble heavy metal concentrations in soils are likely to be influenced to some extent by the total concentrations of heavy metals present in soils. Thus, in uncontaminated soils, heavy metal bioavailability is likely to be related to the nature of the soil parent material and the degree of soil weathering (McLaren, 2003). In case of contaminated soils, solutions of heavy metal concentrations are likely to increase with total loading contaminant.

Colloids in soil that are able to absorb heavy metals will therefore have a major influence in controlling heavy metal availability to plants. Soil organic matter has a large capacity to absorb or complex heavy metals. Heavy metals may also be absorbed by clay minerals and oxides of Fe, Al, and Mn, but these may play a relatively minor role in maintaining solution of heavy metal concentrations compared to the overriding dominance of soil organic matter. The lack of significant correlations between heavy metal sorption and soil clay contents could be due to the low amounts of these constituents.

1.3 Cadmium pollution effect on plant growth

Rice plant grows on environmental and biological factors. The chemically form of Cd in soil solution is greatly dependent on soil oxidation-reduction state. According to Alloway (1990), the amount of Cd uptake by plants depends on the combination of soil and plant factors. Soil factors affecting the uptake of Cd by plants includes pH, soil type, temperature, Cd level, sorption capacity and redox potential and microorganism activity. "Cadmium uptake by rice plants is promoted under oxidative conditions because cadmium sulfide is oxidized and cadmium ions are dissolved into the soil solution" (Iimura 1981). Consequently:

$$Cd^{2+} + SO_4^{2-} \underset{\text{Reduction}}{\overset{\text{Oxidation}}{\leftrightarrows}} CdS$$

The toxic effects of Cd on biological systems have been reported by various authors (Mukherjee *et al.*, 1984 and Sharma *et al.*, 1985). Cd which is a non-essential metal and a powerful enzyme inhibitor (Lockwood, 1976), is considered to be an extremely significant pollutant because of its high toxicity and great solubility in water. Cadmium pollution in soil which is hindrance the uptake of micro and macro nutrient by plants, thus effect on the plants growth and production. According to Root *et al.* (1975), Cd induced choloris in corn leaves could be due to changes in Zn: Fe ratio. In addition, Cd toxicity appeared to induce phosphorus deficiency or reduce manganese transport problem (Godbold and Huttermann, 1985). In general, Cd has been shown to interfere with the uptake, transport and use of several elements (Ca, Mg, P and K) and water by plants. Soil temperature related to the Soil pH. When temperature increase then the pH of soil increase. Increasing pH usually increase the mortality in a wide range of species. According to Hinesly *et al.*, (1984) decreased uptake of heavy metals by plants with increase of soil pH. In addition, in the high level of soil pH, the microorganism's activity is comparatively increase as results the soil oxygen level will increase which is helps to produce soluble cadmium sulfide. Rosas *et al.*, (1984) reported that in plants exposed to Cd for 24 hours the Cd penetrated into the inducing cell physiological and genetically damages. The value of Soil oxidation-reduction potential value is an important factor for uptake of Cd or other heavy metals by rice plants. In soil oxidation condition promotes to produce Soluble Cd^{2+}which is easily uptake by rice plants.

1.4 Cadmium concentration in soil

As of 2005, In Japan about 8,000 ha land was polluted by Cd and it is taken 40,000 $/ha for soil dressing. In general the Cd concentration in the paddy field of surface layer (0~15 cm) is 0.265 ppm and subsoil layer (30~60 cm) is 0.140 ppm. However, the concentration of Cd in subsoil is less than the soil surface (MAFF, 2001). The concentration of Cd in the paddy fields is higher than the upland field and forest in Japan as shown in Table 1.

Table 1: Concentration of Cadmium in some fields of Japan (MAFF, 2001)

Soil type and depth	Paddy field	Upland field	Forest	Average
Surface layer(0~ 15cm)	0.265	0.177	0.118	0.176
Subsoil layer (Ground level: 30~60 cm)	0.140	0.092	0.077	0.100

(All unit: ppm)

1.5 Countermeasures against cadmium contamination of agricultural crops

In case of Japan, the minimum soil dressing is 12.5 cm for polluted agriculture land for minimize the heavy metal pollution. Some scientist conducted their research with 5 - 40 cm soil dressing. On the other hand, Yamada (2007) developed the soil dressing system. However, if the soil dressing is not sufficiently thick, the roots of rice will reach the contaminated soil, decreasing the effect of the countermeasure. So appropriate soil dressing and soil air entry value is most important for minimize the pollution.

Moreover, there are many methods to prevent Cd uptake by rice plants from contaminated paddy fields. One of the most popular methods is under flooding of paddy fields. The Ministry of Agriculture, Forestry and Fisheries and National Institute for Agro-Environmental Sciences, Japan (2002) recommended flooding paddies before and after heading time, soil improvement using fertilizers for minimizing Cd uptake in rice plants. Soil dressing is simple and widely used technique for heavily contaminated sites (Sakurai *et al.*, 1996, Vangronsveld *et al.*, 1998) and developed In-situ soil dressing system in applying removal of polluted soil replacing of unpolluted soil (Yamada *et al.*, 2007) and has been practiced phytoremediation in different contaminated area (Elliot *et al.*, 1999 and Suthersan, 2002). In addition that in agriculture sector for reduction of Cd by rice plants such as Cd sorption by ferric oxide (Kuo *et al.*, 1984) and lime is a greatly effect in reducing Cd and Cu uptake in the Cd and Cu contaminated soil (Xian *et al.*, 1989) and Cd complex decrease with carbonate and to remove hazardous metals from soil into aqueous solution with using extracting reagents (Elliot *et al.*, 1999). In paddy fields, water is needed for saturating the soil, surface flooded, percolation seepage (bund percolation) and evapo-transpiration (Adachi *et al.*, 1992).

Rice plants roots can grow up to subsoil. So if the plowsole and subsoil are oxidized condition, it is not safety for paddy cultivation due to insoluble Cd convert to soluble Cd forms in soil oxidation condition. We try to understand and establish this method by the open and closed system percolation with different soil dressing system.

1.6 Effect of Cadmium (Cd) pollution on human health

Such pollutant levels in food have varied from country to country; for example, WHO (1992a) set the cadmium (Cd) level in rice grains to 0.1 ppm but the Japan government set it to 0.4 ppm. In Japan, Cd pollution in soil, attributed to mining, growing industries and sewage sludge, is a major problem in agriculture because an intake of high-Cd rice may cause Itai-Itai (Soft bone) disease, which was documented in Toyama prefecture of Japan (Kobayashi, 1978). According to Kawada *et al.*, 1998, the intake of Cd from rice grains in Japanese citizen is about 34-50%. There are many researches about on effect of Cd pollution on human health. It is known that serious systematic problems can develop as a result of increased accumulation of dietary heavy metals such as Cd and Pb in the human body (Oliver *et al.*, 1997). In addition that excessive accumulation of Lead (Pb) and Cadmium (Cd) in human bodies creates the problems like cardiovascular, kidney, nervous and bone disease (Jarup *et al.*, 2003, WHO 1992b and Steeland *et al.*, 2000).

1.7 Rationale of the study

The study was conducted to clarify the effect of a percolation pattern on growth and yields of rice plants and accumulation of Cd in various parts of rice plants. Cd-contaminated soil, Alluvial, Andosol and Gravel were used in the stratified paddy field model. Many scientists have conducted their research in the pot device to evaluate the Cd effect on rice plants. The pot device system did not represent the condition of an actual paddy field. Therefore stratified paddy field models were maintained the actual soil profile of paddy field. As a result rice plant roots can grow up to the subsoil. So this study was conducted in the stratified paddy fields. Therefore, the objectives of the study were as follows:

1. To investigate the influence of percolation pattern on growth and yields of rice plants.
2. To investigate the influence of percolation pattern on accumulation of cadmium in various part of rice plants.
3. To investigate the effect of percolation pattern on the soil physical and water quality
4. To evaluate the open and closed system percolation with 12.5, 15 and 20 cm soil dressing models.

For the circumstances, study were as follow in the chapter 1 general introduction, chapter 2 Material and methods, chapter 3, 4 and 5 Results and discussion, chapter 6 Summary of the study, chapter 7 Conclusion Chapter 8 Future plan and References.

Chapter 2: Materials and Methods

2.1 Introduction

The experiment was conducted in the green house at Hirosaki University, Hirosaki-shi, Aomori, Japan in 2009 and 2010. The study was performed to investigate the influence of percolation pattern on the oxidation-reduction potential of soil layer and also to observe the effect of percolation pattern on growth and yields of rice plants. Moreover, the study was also described the influence of percolation pattern to accumulation of cadmium by rice plants with stratified polluted paddy field models. The stratified paddy field models were operated with open and closed system percolation. Closed system percolation was an ill -drained paddy field models and open system percolation was a well -drained paddy field models. The stratified polluted paddy fields were constructed with 12.5, 15 and 20 cm soil dressing. According to Sasaki (1998), the closed system percolation paddy field was similar to actual paddy field. So this study was conducted and compare with the open and closed system percolation which was similar to the actual paddy field.

2.2 Experimental Design and Materials

The stratified paddy field models were subjected to two kinds of percolation patterns as an open system percolation and a closed system percolation as shown in Table 2 and 3.

In 2009 experiment, the stratified paddy field models M-1, M-2 and M-3 were open system percolation and M-4, M-5 and M-6 were closed system percolation models with constructed 12.5 cm soil dressing layer as a used of Andosol. There were two types of stratified paddy field and three models were applied to each paddy field. The stratified paddy field model was constructed in an iron box (30x50x70 cm) with three layers of soil; plow layer (layer I; 0-12.5 cm), plowsole (layer II; 12.5-22.5 cm), and subsoil (layer III; 22.5-42.5cm) that were constructed with Andosol (layer I), Cd-polluted soil (layer II) and gravel (layer III) as shown in Table 2.

In 2010 experiment, the stratified paddy field was constructed by 15 and 20 cm soil dressing layer as a used of alluvial soil. Every soil dressing system has two models with open and closed system percolation model as shown in Table 3. The stratified paddy field model of M-7, M-8, M-9 and M-10 were constructed in an iron box (30x50x70 cm) with three layers of soil; plow layer (layer I; 0-12.5 cm), plowsole (layer II; 12.5-22.5 cm), and subsoil (layer III; 22.5-42.5cm) that were constructed with alluvial (layer I), alluvial soil and Cd-polluted soil and (layer II) and Cd-polluted soil and gravel (III layer) as shown in Table 3. In the open percolation system, the plowsole and upper subsoil were open and plow layer and lower subsoil were closed percolation system. As a results, the plowsole and upper subsoil were became oxidized due to atmosphere entered easily into those layer by experimental iron box`s hole. As a consequences, open percolation system as a well-drained paddy field model due to low groundwater level (57.5 cm) was fixed in subsoil. On the other hand, plow layer and lower subsoil layer were referring to reduction layer due to saturated condition of those layers. In the closed system percolation models, maintained of all soil layers were in closed atmosphere condition and high groundwater (12.5 cm) table also regulated. As a result, soil became reduction condition conventional paddy field. This model is known as to the ill-drained paddy field model.

Table 2: Soil dressing models of 2009.

Soil layer	12.5 cm soil dressing model					
	Stratified paddy field model					
	Open system percolation			Closed system percolation		
	M-1	M-2	M-3	M-4	M-5	M-6
I Plow layer (12.5 cm)	● Andosol	● Andosol	Andosol	● Andosol	● Andosol	● Andosol
II Plowsole (10 cm)	Impermeable layer ○ Polluted soil	Impermeable layer ○ Polluted soil	Impermeable layer ○ Polluted soil	Impermeable layer ● Polluted soil	Impermeable layer ● Polluted soil	Impermeable layer ● Polluted soil
III Subsoil (42.5 cm)	○ Gravel ●	○ Gravel ●	○ Gravel ●	● Gravel ●	● Gravel ●	● Gravel ●

Table 3: Soil dressing models of 2010.

Soil layer	15 cm soil dressing model		20 cm soil dressing model	
	Startified paddy field Model			
	Closed system percolation	Open system percolation	Closed system percolation	Open system percolation
	M-7	M-8	M-9	M-10
I Plow layer (12.5 cm)	● Alluvial soil	● Alluvial soil	● Alluvial soil	● Alluvial soil
II o Plowsole (2.5 cm)	Impermeable layer	Impermeable layer	Impermeable layer	Impermeable layer
IIu Plowsole (7.5 cm)	● Polluted soil ●	○ Polluted soil ○	● Alluvial soil ●	○ Alluvial soil ○
III Subsoil (42.5 cm)	● ● Gravel ●	○ ○ Gravel ●	● Polluted soil ● Gravel ●	○ Polluted soil ○ Gravel ●

○: Open system percolation, ●: Closed system percolation

Andosol: Chitose farm, Hirosaki University, Japan, Polluted soil: Cd-accumulated (Polluted) soil was taken from a Cd-contaminated area in A-prefecture, Japan, Alluvial soil: Kanagi farm of Hirosaki University, Japan, Gravel: Gravel was obtained from the Iwaki Mountains

The cadmium contaminated soil was collected from high Cd-accumulated area in A-prefecture, Japan. The alluvial and Andosol were collected from Hirosaki University Farm. The physical and chemical properties of Andosol, alluvial soil, Cd-accumulated soil and gravel were analyze using air dry soil and procedures follow by the Japanese standard method (MAFF, 1979a) as shown in Table 4. Finally Cd concentration in soil was measured by the atomic absorption method (Model Z2000, Hitachi High Technologies Co., Ltd.).

Table 4: Physical and chemical properties of soil

Sample	Density (g/cm^3)	Soil texture	MgO	Na_2O	CaO	K_2O	Total iron *	Cd *	T-N (%)	T-P (%)	OM (%)
Andosol	2.592	SCL	918	84	1,530	159	5,683	0.19	0.44	0.60	6.0
Polluted soil	2.453	L	496	114	2,909	311	2,820	3.39	0.40	0.15	4.8
Alluvial soil	2.595	Lic	997	97	1,530	95	34,700	0.27	0.24	0.13	2.9
Gravel	2.680	-	147	18	539	58	600	0.13	0.00	0.35	0.05

Soil texture is based on the International Soil Society classification; SCL and L stand for: L = Loamy; SCL = Silt Clay Loam *represents mg/kg dry soil. Gravel diameter size: 2.00-4.75mm.

2.3 Experimental equipment

2.3.1 Preparation of soil

All of plant roots and stones removed from Andosol, alluvial and polluted soil. The soil balls were made from roots and stones free soil with adequate water and the diameter was 10-12 cm as show in the Fig.4a. The prepared soil balls were kept on above of the polythene sheet for air drying as shown in Fig. 4b. The soil balls were easily broken by hand and those soil balls were appropriate for making soil coarse and used for construction of soil layer. Dry soil were broken by wooden hammer and the size of the coarse about 1 cm diameter then coarse soil kept in plastic bucket that show in the Fig. 5. The crash soil kept on the seep for separating of soil coarse with using by 2 mm diameter sieved net as shown in Fig.6.

Fig. 4a: Preparation of soil ball

Fig. 4b: Drying of soil ball

Fig. 5: Crash of the soil ball

Fig. 6: Sieving of soil

2.3.2 Construction of soil layer

The each model has the dimension of 30x50x70 cm was practiced in Iron box and operated at 5 cm puddling depth. Both of the percolation pattern, the bulk density of I, II and III layer`s were 0.91, 0.66 and 1.40 g/cm^{3}and for the impermeable layer was 0.88 g/cm3as shown in Fig. 7. The construction procedure of both model were four steps. The first step was made of subsoil layer with gravel as a consequently of 5 cm thickness part of gravel was made of uniform density as shown in Fig. 8. The second steps was, set up of wood stick along the inner side of the iron box and fill up of granules polluted soil to make the plowsole as shown in Fig. 9 and 10. The iron plate with pore was setted on the plowsole as shown in Fig. 11. The third step was to make the impermeable layer which has the thickness 2.5 cm as shown in Fig.12. After construction of the compact layer then observed the water permeability per day as shown in Fig.13. The suitable value of percolation rate for rice plants is 20-30 mm/day but percolation rate in alluvial soil of paddy field become less than 10 mm/day (Tabuchi and Hasegawa, 1995). The average range of water permeability of compact layer was 2-4.75 mm/day. The fourth step was made of plow layer. The plow layer were made of Andosol or alluvial soil with puddling condition and mixed with fertilizer as a rate of Tsugaru roman cultivar. After construction of plow layer then rice plants were transplanted on the plow layer.

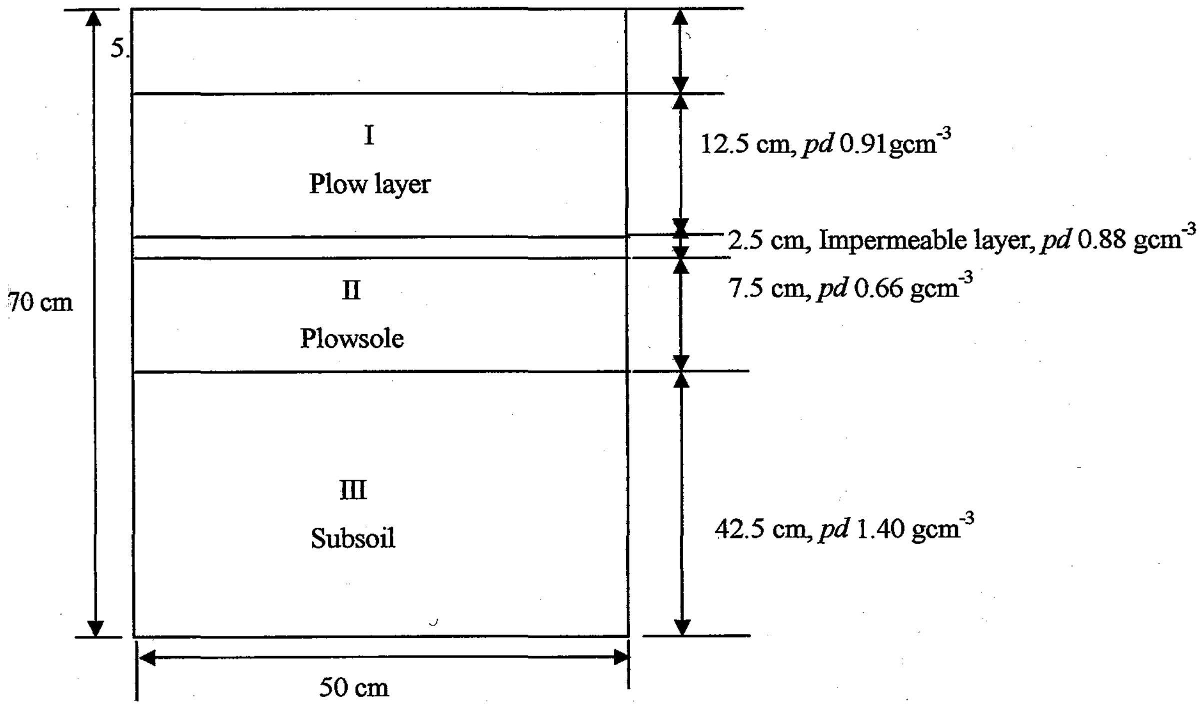


Fig.7: Soil layers of stratified paddy field model.

Fig.8: Fill up of gravel into the iron box

Fig.9: Set up of wood stick in inner side of iron box

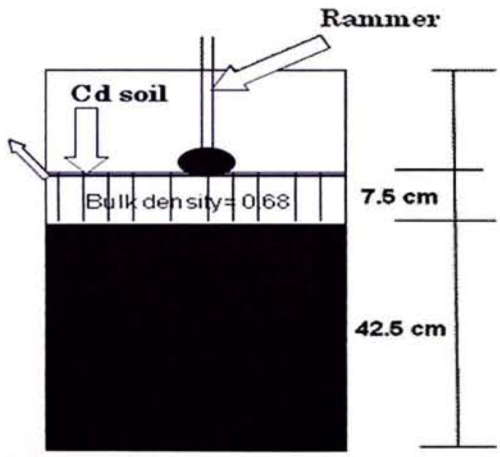


Fig.10 a): Filling of polluted soil

Fig.10 b) Schematic diagram of polluted soil into the iron box.

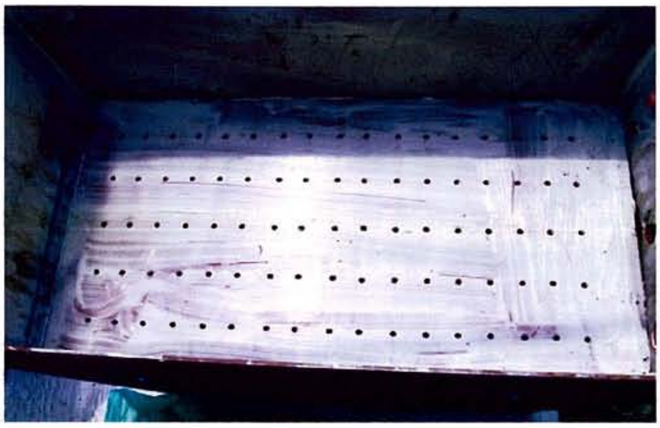


Fig.11: Setting of iron plate into the iron box.

Fig.12: a) Preparation of impermeable layer

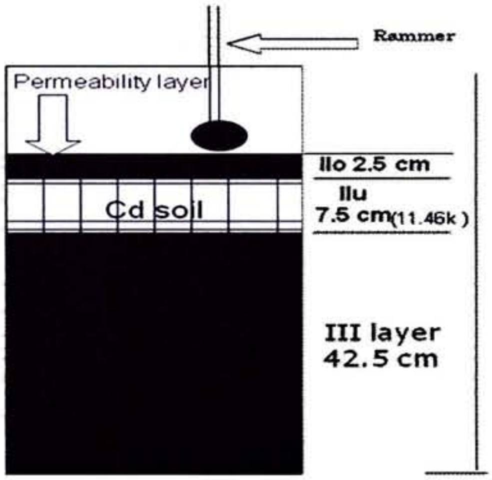


Fig.12: b) Schematic diagram of impermeable layer.

Fig.13: Check of water permeability

In open system percolation model, the groundwater table was kept at 57.5 cm depth from soil surface and closed system percolation model was kept at 12.5 cm depth from soil surface as shown in Fig. 14. The groundwater calculated by the equation as follows L= H-h, where H is total soil depth, L is groundwater level and h is water level from soil surface.

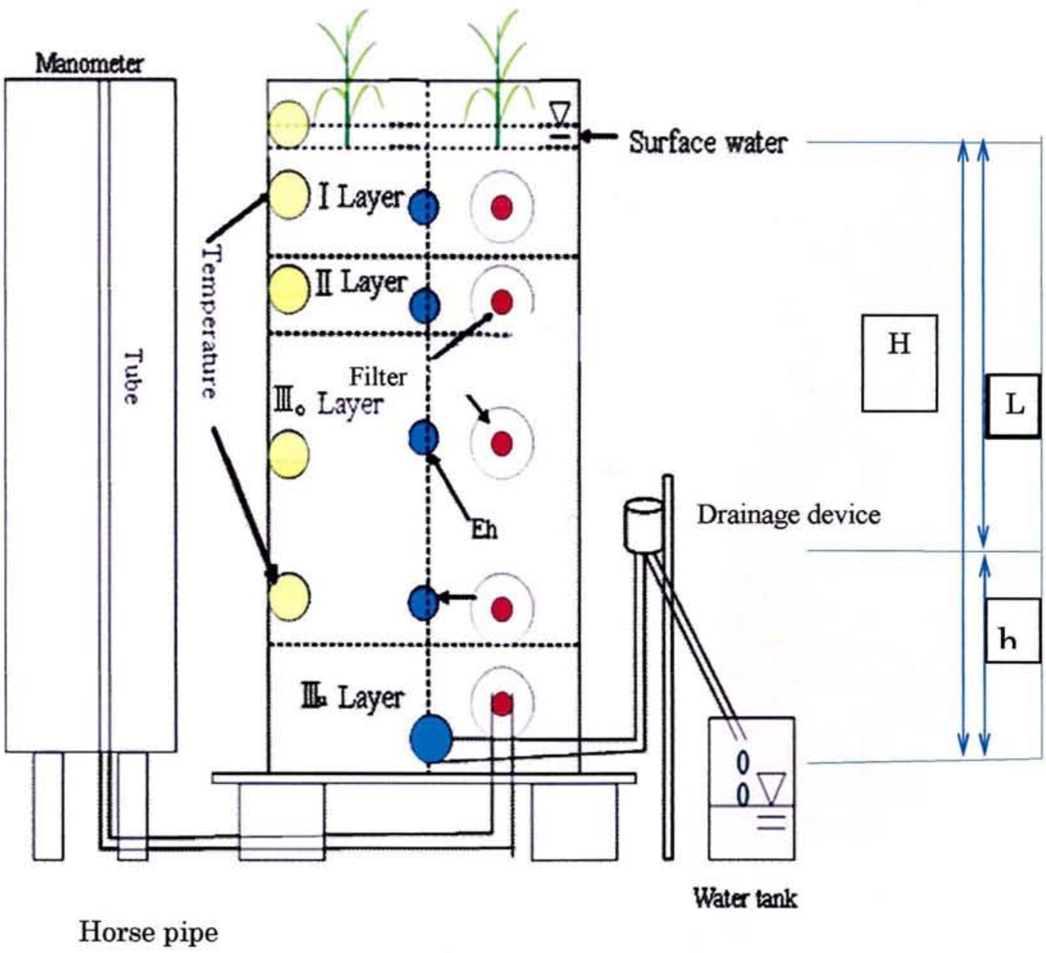
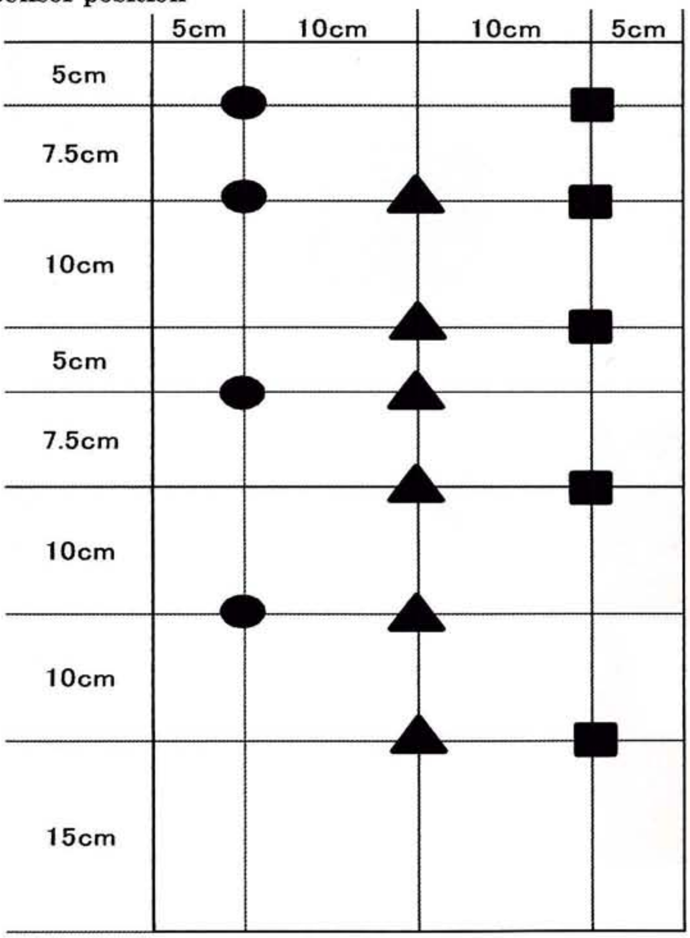


Fig.14: Layout of the experimental device

There were Eh, temperature and pressure sensor of each soil layer for measuring the soil physical and water condition in the model as shown in Fig. 15. The Sensor setted of each soil layer as in Surface water (one temperature and one pressure sensor), plow layer (one temperature, one Eh sensor and one pressure sensors), plowsole (one temperature sensor, two Eh sensors and one pressure sensor) and the subsoil (one temperature sensor, three Eh sensors and two pressure sensors).

Sensor position



●: Temperature ▲: Eh sensor■: Filter sensor

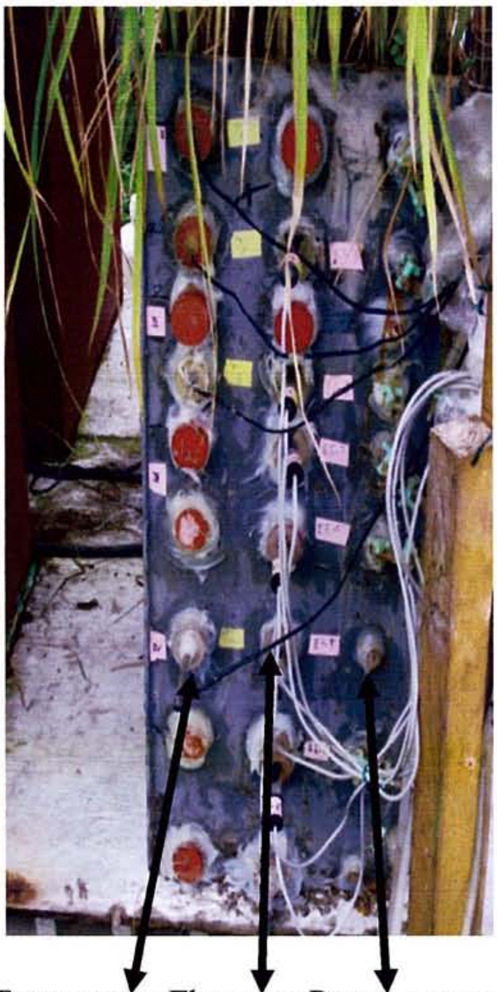
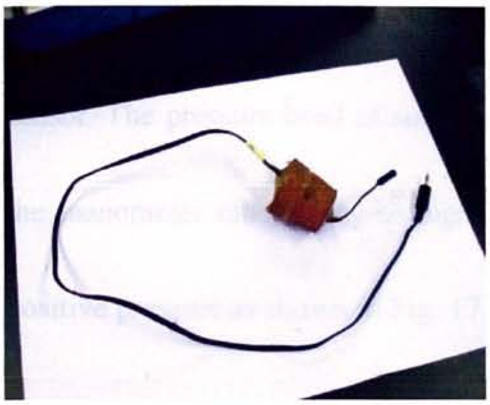
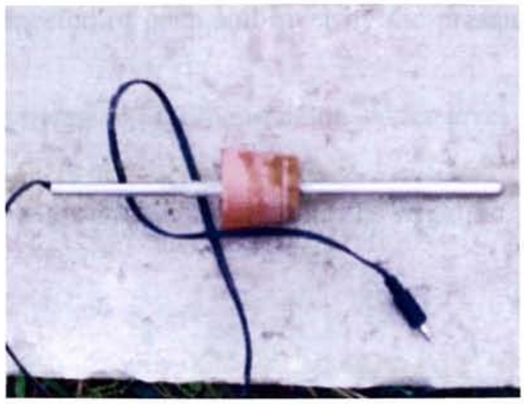


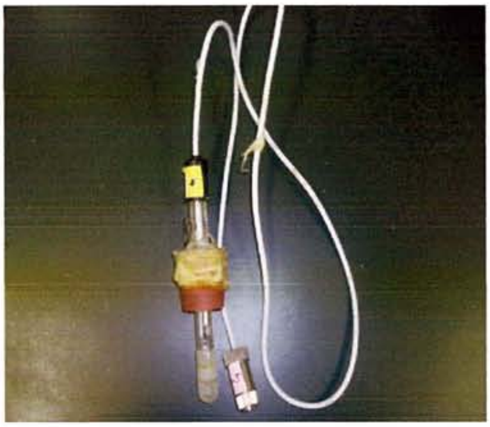
Fig. 15: Sensor position and setting



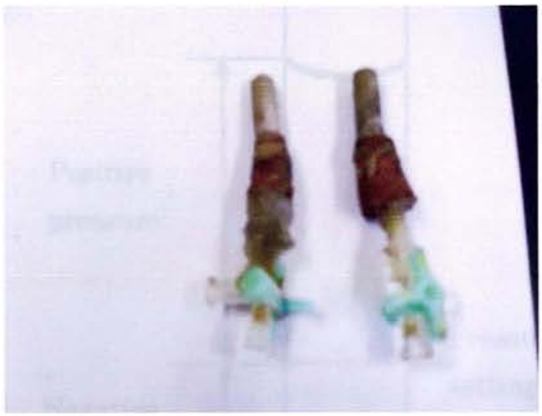
a) Temperature sensor (Type A)



b) Temperature sensor (Type B)



c) Eh sensor



d) Pressure sensor

e) Temperature recorder

f) ORP data logger

Fig.16: Sensors, temperature recorder and ORP data logger

The pressure head distribution tubes were connected of each soil layer by the pressure sensor. The pressure head of soil profile were measured by manometer. Water level in the manometer tube below or high to the pressure sensor level indicates negative or positive pressure as shown in Fig. 17.

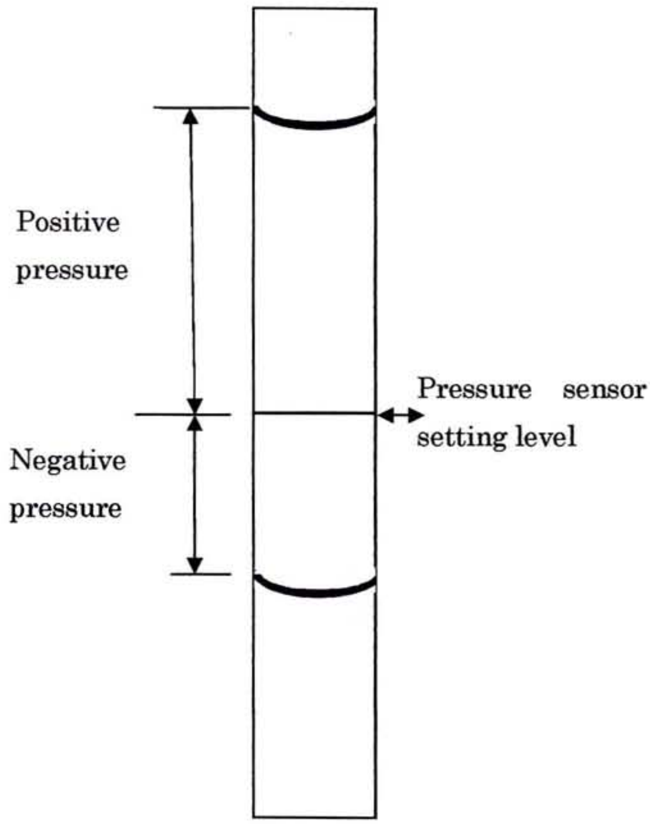


Fig.17: Manometer board

2.3.3 Design of transplanting

There were 15 of rice plants (Cultivar: Tsugaru-Roman) were transplanted in each paddy field model with 10 cm planting distance. The rice plant length range was 18.0~21.0 cm and Number of leaf 4.2~4.6 in 2009 and 2010. The design of transplanting in the model was shown in Fig.18.

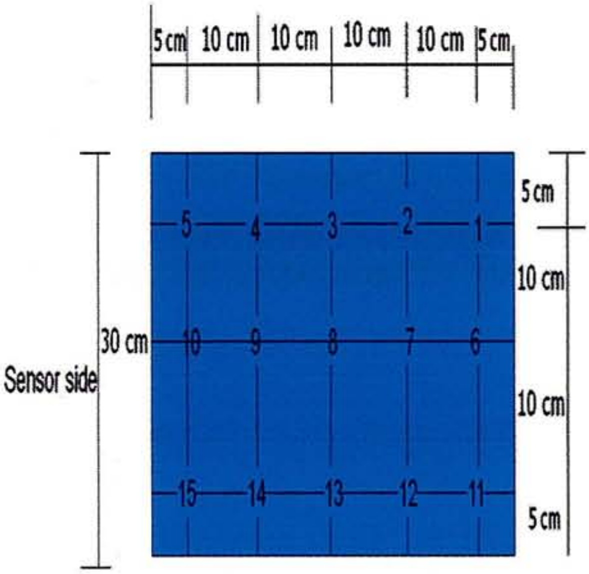


Fig.18: Design of transplanting into iron box and schematic diagram

2.3.4 Application of fertilizer

Four types of fertilizer elements were used for fertilization. The chemically form of those fertilizers were $Ca(H_2PO_4)_2+CaSO_4$ (20.5%), K_2SO_4 (50.5 %), Ca_2SiO_4 (30%) and $(NH_4)_2SO_4$ (21%) which were known as phosphorus, potassium, calcium and nitrogen. The dose of fertilizer of each iron box was 9.76 g (phosphorus), 3.96 g (potassium), 40.0 g (calcium) and 9.52 g (nitrogen). The application of fertilizer in one time was used during preparing of puddling layer.

2.3.5 Properties of supply water

Supply of Ground water for irrigation is an important for plant growth, human consumption and industrial usage. The concentration of Electrical conductivity was 10.43 mS/m which was good for irrigation. The Cd concentration in the irrigation water was near about 0 and other elements such as ferrous (Fe), Potassium (K), Sodium (Na), Calcium (Ca) and Magnesium (Mg) were within the normal range for irrigation as shown in Table 5.

Table 5: Properties of irrigation water

	pH	DO	EC	Fe	Cd	K	Na	Ca	Mg	T-N	T-P
		(mg/L)	(mS/m)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Average	6.5	7.8	10.4	1.2	0.00>	12.9	19.0	9.0	4.1	1.3	0.04
CV (%)	3.53	21.3	24.0	141.9	0	55.2	18.1	19.2	26.3	56.2	25.4

2.4 Measurement methods

Oxidation-reduction potential (ORP) of each soil layer were measured by electrometrically using ORP meter (Central Science Co., Ltd., model UC-203) from planting to harvesting period. Manometer board was settted to measure water pressure of soil profile by pressure sensor. Thermo recorder was used to record the greenhouse and soil temperature. Daily water requirement was measured by caliper as shown in Fig. 19. Water sample were collected from surface and outlet water for measurement of pH, EC, Na, K, Ca, Fe and Mg. The pH value of the sample water was measured by pH meter and electric conductivity (EC) was measured by EC meter (Horiba meter). On the other hand, Ca, Mg, Na, K and Fe were measured of those samples by atomic spectrometry analyzer. (Model Z2000, Hitachi High Technologies Co., Ltd.).

In the running time of experiment, irrigation water was supply of each stratified paddy twice time per day by irrigation machine as shown in Fig. 20. The plant height, number of leaf and number of stem of each rice plants were measured weekly between planting to harvest period as shown in Fig. 21. The color amount in rice blade was measured with using soil and plant analyzer development (Type of No. SPAD-502) as shown in Fig. 22. The dates of blooming start and end were investigated. The 14th leaf height and color were measured up to harvesting period.

The rice plants were harvested from the stratified model and every plant were tagged and hung on the rope for sun drying as shown in Fig. 23. Each of soil layer were separately and collected and kept in plastic bag and then plants roots were collected from each soil layer and then dry by oven at 70℃ for 7 days as shown in Fig. 24. The length and number of perfect and imperfect panicle, dry weight of straw, dry weight of roots of each soil layer, number and weight of rice grain, percentage of grain fill up, water content in rice grain and moreover weight of 1000 kernel were measured. Moreover, determine the Cadmium contains in rice grain, roots, stem and leaf which were extracted by nitric acid and sulfuric acid and then analyzed by AAS as described by MAFF (1979b).

Fig.19: Measurement of water velocity by caliper

Fig.20: Automatic water supply irrigation machine

Fig. 21: Measurement of Plant length

Fig.22: Measurement of SPAD value of rice plant

Fig. 23: Sun drying of rice plants.

a) Root separate from soil

b) Root separate from Gravel

c) Root dry at 70℃ for 7 days

Fig. 24: Plants roots were separated from soil and gravel

Chapter 3: Influence of percolation pattern on soil redox condition and water quality of stratified polluted paddy field

3.1 Introduction

The paddy fields were subjected two kinds those were closed and open system percolation. Open percolation pattern was characterized by low ground water table in which air can penetrate into soil layer horizontally and therefore plowsole and subsoil layer oxidized. In the closed system percolation, the soil layers were in saturated condition due to high ground water table was adjusted. The stratified paddy fields exemplified the actual paddy fields. In previous study, Sasaki (1993 and 1994) stated that removal of iron and manganese in soil layer were influenced by percolation pattern. Sasaki *et al.*, (2001) stated that concentration of nitrate, iron, and manganese ion and dissolved oxygen in water of the closed system percolation increased more than those in the open system percolation. The growth of rice plants roots showed vegetative growth under oxidative condition that was described by the Kawaguchi (1978).

In the open system percolation, plowsole and subsoil has negative pressure but positive pressure was showed in closed system percolation due to saturated condition of all soil layers by the water. This section will describe the influence of percolation pattern on physical properties of soil, supply water and drainage water of stratified paddy field models.

3.2 Pressure head distribution

In 2009 experiment, the open system percolation (M-1, M-2 and M-3) showed positive pressure in plow layer but plowsole and subsoil were negative pressure due to unsaturated condition of those soil layers and air enter into those soil layers and in additional water pressure of plowsole and subsoil layers were lower than the air entry pressure (-2.0 cm) in agreement with the previous study by Sasaki (1994). It indicated that those layers were open system percolation. On the other hand, closed system percolation (M-4, M-5 and M-6) showed positive pressure of plow layer, plowsole and subsoil at the soil depth of 7.5 cm, 17.5 cm, 30 cm, 50 cm and 62.5 cm respectively due to saturated condition of those soil layer by water that shown in Fig. 25 and 26.

In 2010 experiment, the Model of M-8 and M-10 which were oriented as open system percolation pattern and showed positive pressure in plow layer but negative pressure in plowsole and subsoil. On the other hand, closed system percolation (M-7 and M-9) showed positive pressure of plow layer, plowsole and subsoil due to saturated condition by water as shown in Fig. 27 and 28. Sasaki *et al.*, (2001) described that positive pressure of soil layer were performed in closed percolation pattern and negative pressure in an open system percolation which is supported this study. Positive pressure of soil layer performed by ill- drained paddy field and negative pressure by well-drained paddy field due to water movement from higher potential to the lower point as described Hillel *et al.*, (1998). The total potential of water pressure in the open system percolation was nearly equal to the pond level in plow layer. The high loss of water potential occurred in plowsole and subsoil had water loss in proportion with depth. The total potential of water pressure in plowsole and subsoil of open system percolation were less than the closed system percolation but total potential loss was less than that of the open system percolation due to the condition of plowsole.

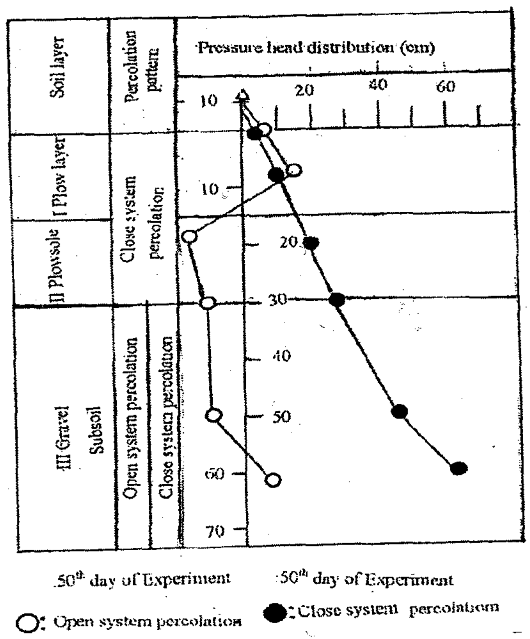


Fig.25: The pressure head profile in open (M-1) and closed (M-4) system percolation at 50^{th} day-2009.

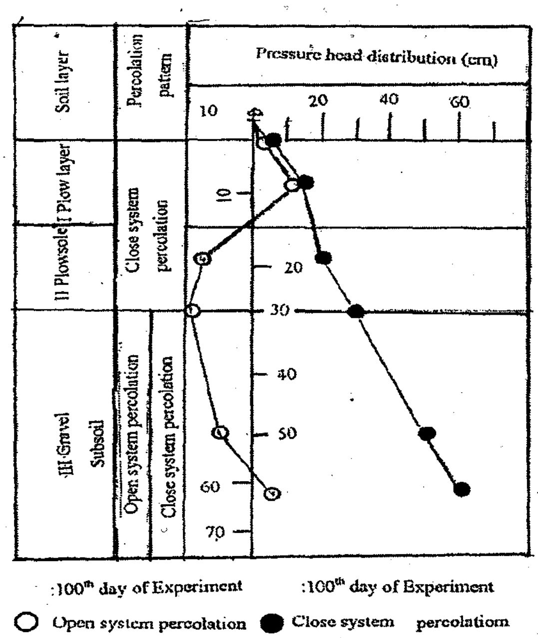


Fig.26: The pressure head profile in open (M-1) and closed (M-4) system percolation at 100^{th} day-2009.

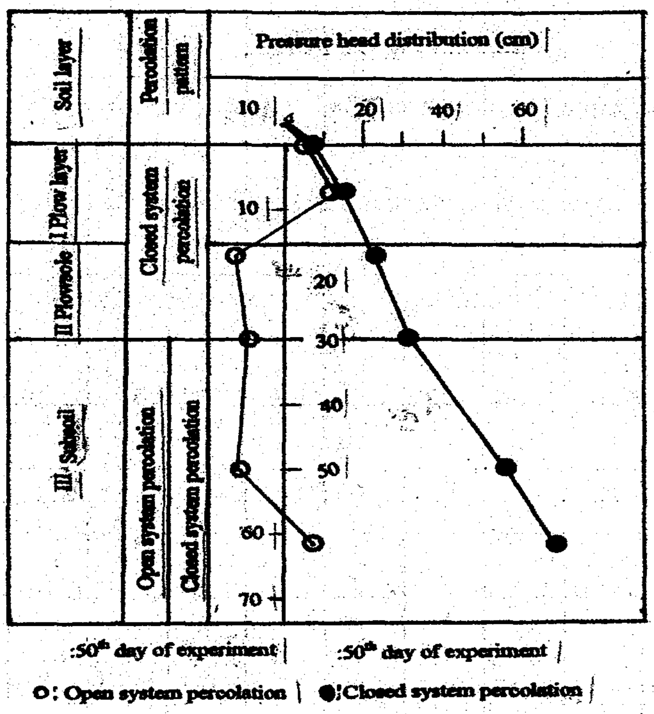


Fig.27: The pressure head profile in open (M-8) and closed (M-7) system percolation at 50^{th} day-2010.

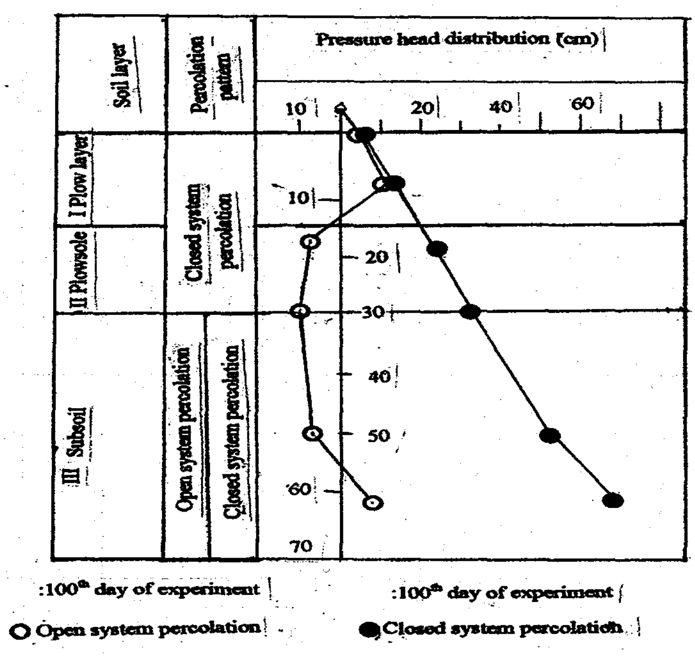


Fig.28: The pressure head profile in open (M-8) and closed (M-7) system percolation at 100^{th} day-2010.

3.3 Water requirement rate

Irrigation water is very important for rice plants growth and yields. In this study, the sufficient irrigation water was supplied continuously at the level of 4 to 5 cm. The water requirement rate was controlled by the impermeable layer of both percolation systems. The average water requirement rate of models M-1, M-2, M-3, M-4, M-5, M-6, M-7, M-8, M-9 and M-10 were 26.7, 37.7, 37.6, 21.7, 40.1, 56.3, 44, 51.7, 46.9 and 40.9 mm/day as shown in Fig. 29 and 30. The average of water requirement rate was low the beginning time and the late period of the experiment and became higher from 45^{th} to 90^{th} days of experiment. However the drained water from subsoil was gradually decreased of both percolations. The water requirement rate in the closed system percolation was controlled by subsurface drainage device as shown in Fig.14. Finally, percolation rate of the open system percolation (38.9 mm/day) was lower than the closed system percolation (41.9 mm/day). This difference of the percolation rate happened the decreased of permeability of plowsole. According to Hasegawa and Tabuchi (1995), the total irrigation water at paddy fields requires 15-25 mm/day with depth during a rice season. The percolation rate was decrease late of the experiment of both models which was similar to the study of Sasaki *et al.*, (1992).

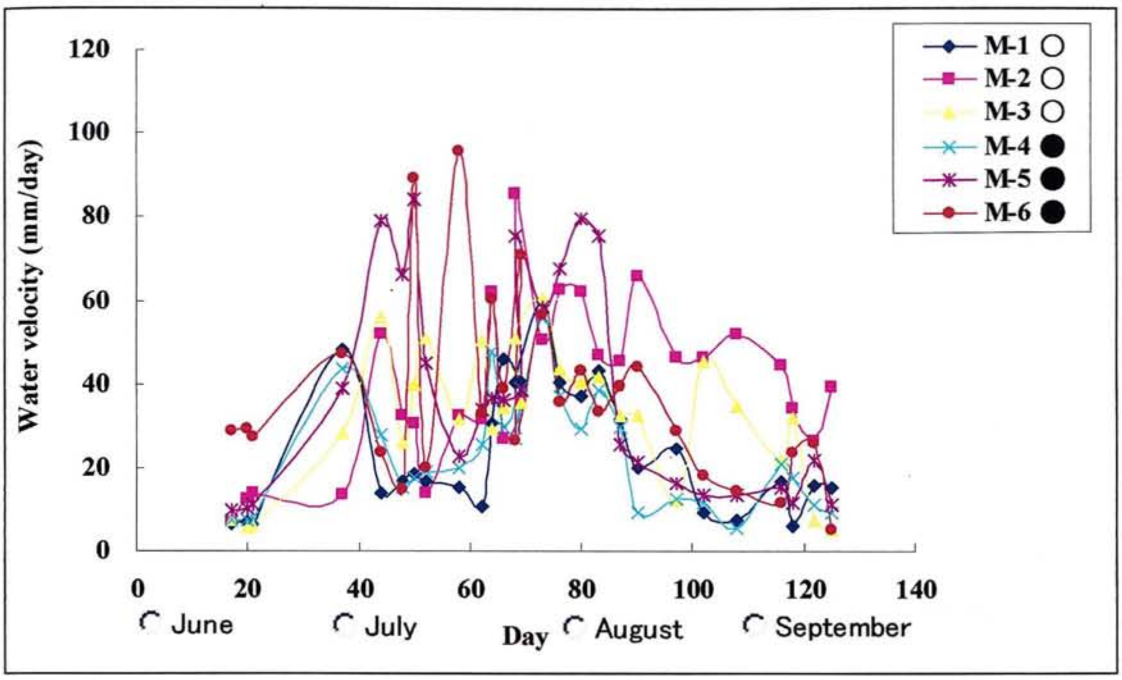


Fig.29: Water requirement rate in stratified paddy field model under open and closed system percolation in 2009 (M-1~M-6).

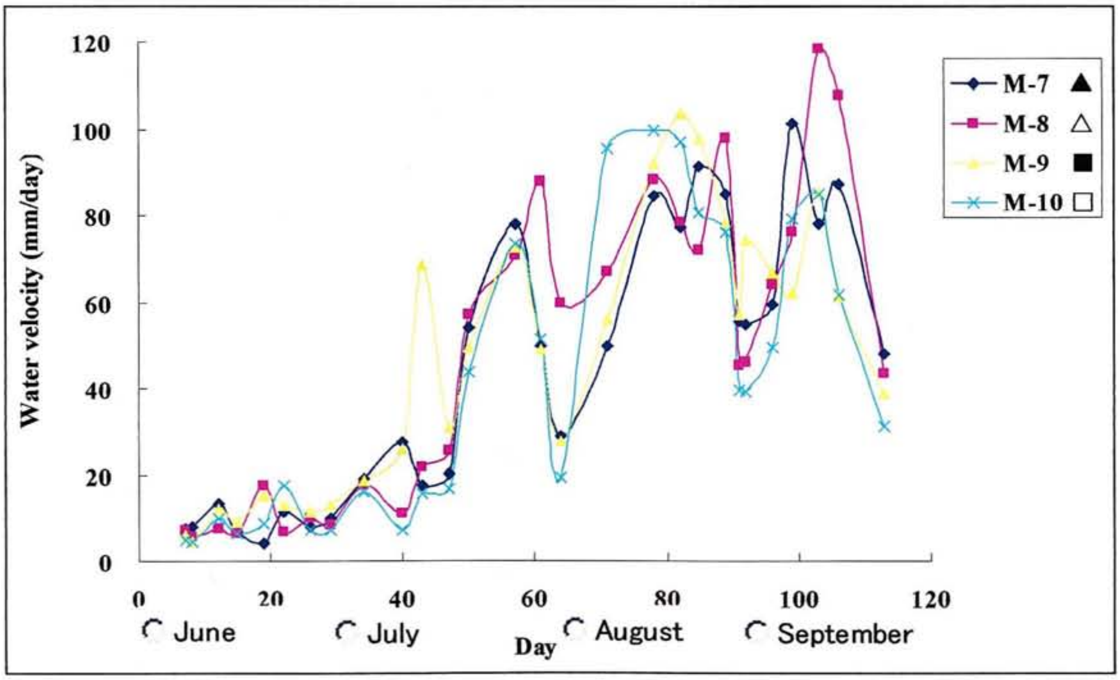


Fig.30: Water requirement rate in stratified paddy field model under open and closed system percolation in 2010 (M-7~M-10).

3.4 Soil temperature

The leaf, stems and roots growth of rice plants depend on many factors. Low soil temperature during the growing season may cause substantial reductions in the growth of plants in agronomic and native ecosystems.

In this study, soil temperatures were observed of each soil layer from the period of transplanting to harvest. Although the air temperature of green house was observed during from June to September. The average air temperature of green house in 2009 and 2010 were 23.5^{0}C and 26.0^{0}C, respectively as showed in Fig. 30. The highest air temperatures were observed in the green house in August that's 25^{0}C (2009) and 30^{0}C (2010) and lower in June that's were 21^{0}C (2009) and 23^{0}C (2010). For the suitable plant growth under the optimum temperature ranges 17^{0}C to 25^{0}C during ripening time (Aimi *et al.*, 1959). So in this study, the green house temperature was normal range for rice plant growth.

The average flood water temperature was about 23℃ in 2009 and 25 ℃ in 2010. These results showed that air temperature was higher than the flood water temperature. If the flood water temperature is higher than the air temperature, the plant growth might be disturbed by the cold damage (Tabuchi and Hasegawa, 1995). On the other hand, Takenaga (1995) stated that the paddy field is damage by the cool weather due to low temperature and lack of solar radiation. In this study, during the cultivation period did not occur by cool damaged.

Each of soil layer temperature in different percolation pattern was observed every day during the cultivation. In closed system percolation; the plow layer, plowsole and subsoil temperature were about similar temperature and higher to flood water temperature that occurred in the experiment of 2009 and 2010, respectively as shown in Fig. 32 and 33. But the open system percolation, plowsole and subsoil temperature almost similar to the air temperature due to soil were exposed. The temperature of plow layer was higher than the air and flood water temperature due to inundation condition of plow layer as shown in Fig. 31 and 33.

The flood water temperature in both percolation systems was lower that of all soil layers and air temperature altered supplied cool water in the experiment. The unsaturated soil under the open system percolation can be cool down firstly the saturated soil under the closed system percolation. It might be due to the specific heat of soil particles are approximately 0.20cal/g and the dry soil with 50% porosity has specific heat is 0.75 cal/g (kohnke, 1968). So the wet soil has higher heat capacity than the dry soil. From the results as shown Fig.32 33, 34 and 35, the optimum tendency of soil temperature in the open system percolation can be manipulated easier than that in the closed system percolation, this might be the ample diffusion of heat in the open system percolation due to higher temperature were increase the diffusion rate of soil aeration.

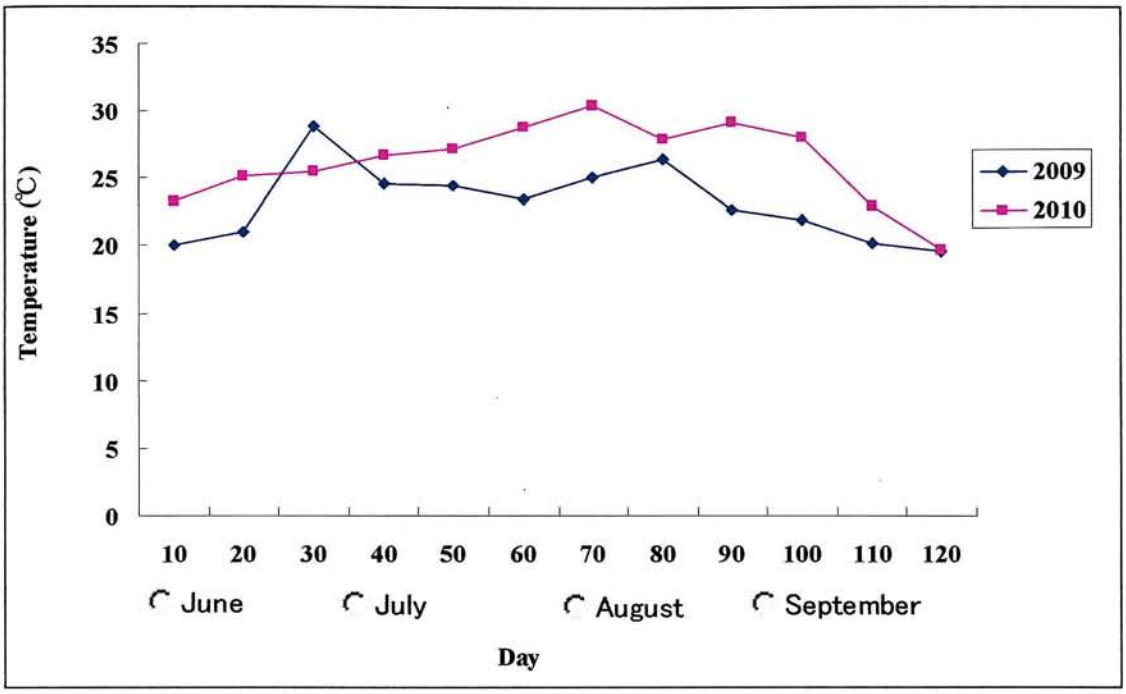


Fig. 31: Air temperatures of Green house in 2009 and 2010.

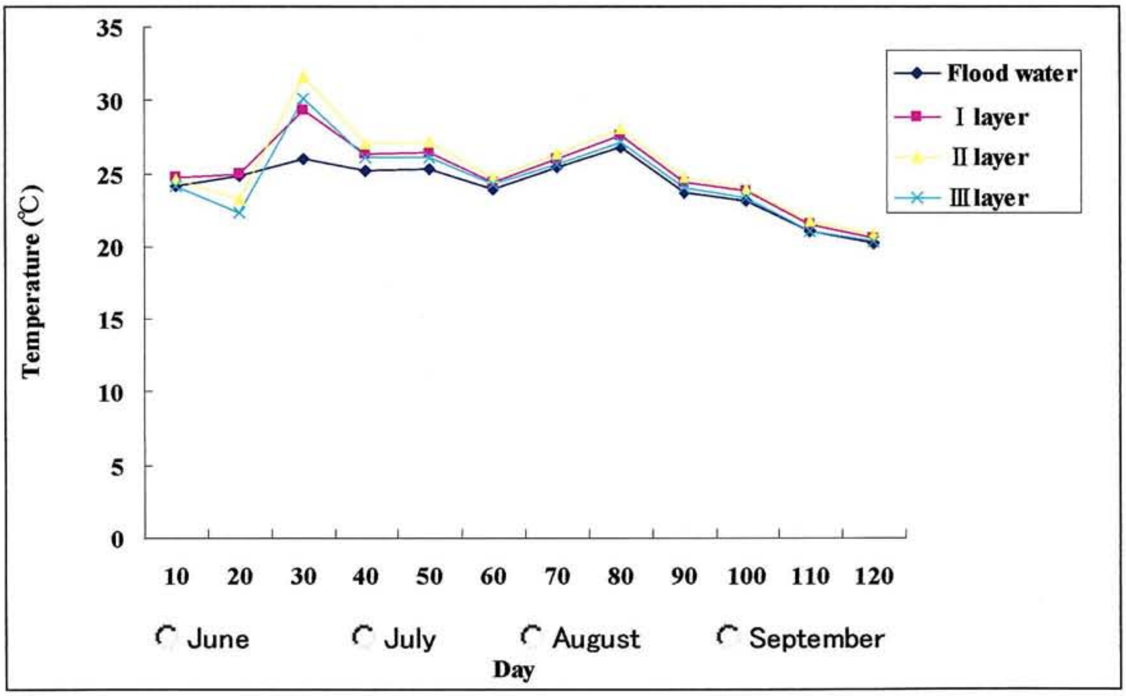


Fig. 32: Temperatures of flood water, plow layer, plowsole and subsoil in closed system percolation models: 2009 (M-4 model).

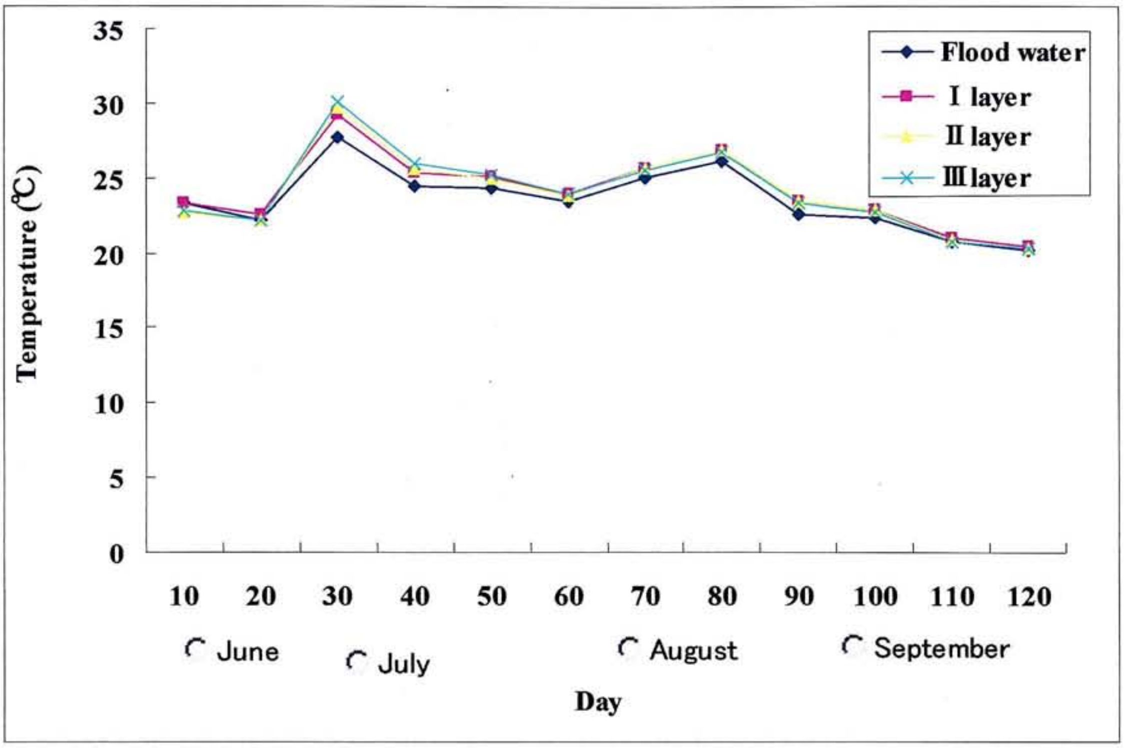


Fig. 33: Temperatures of flood water, plow layer, plowsole and subsoil in open system percolation model: 2009 (M-1 model).

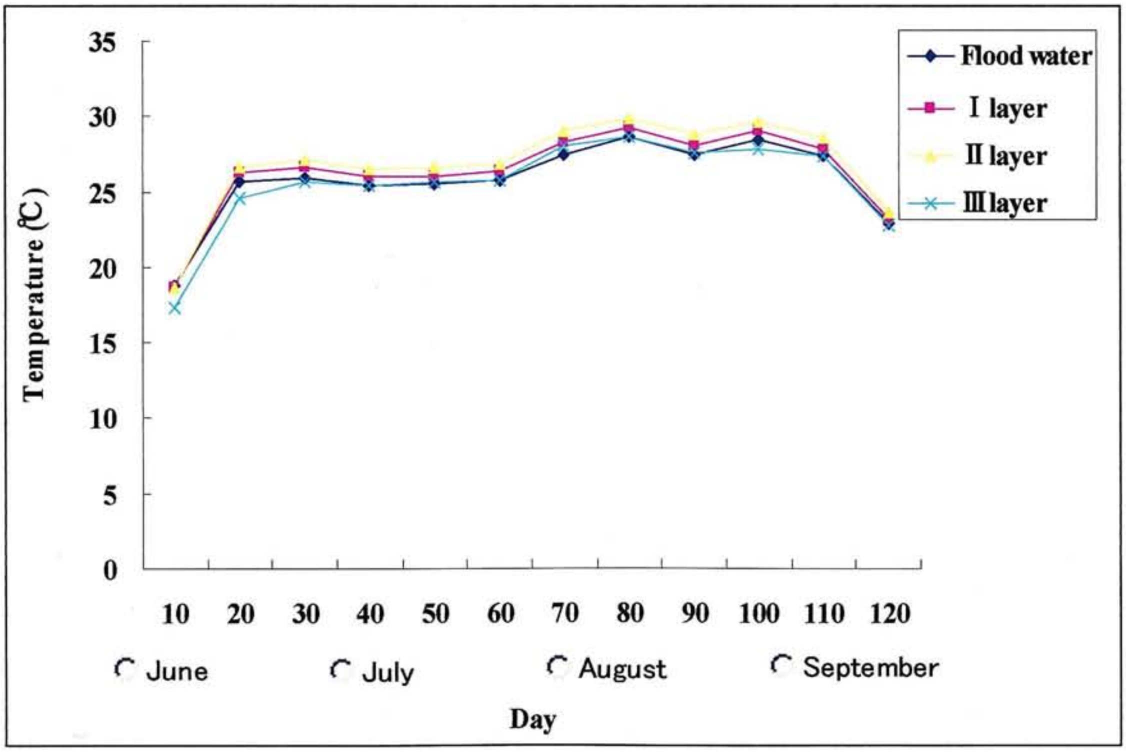


Fig. 34: Temperatures of flood water, plow layer, plowsole and subsoil in closed system percolation model: 2010 (M-4 model).

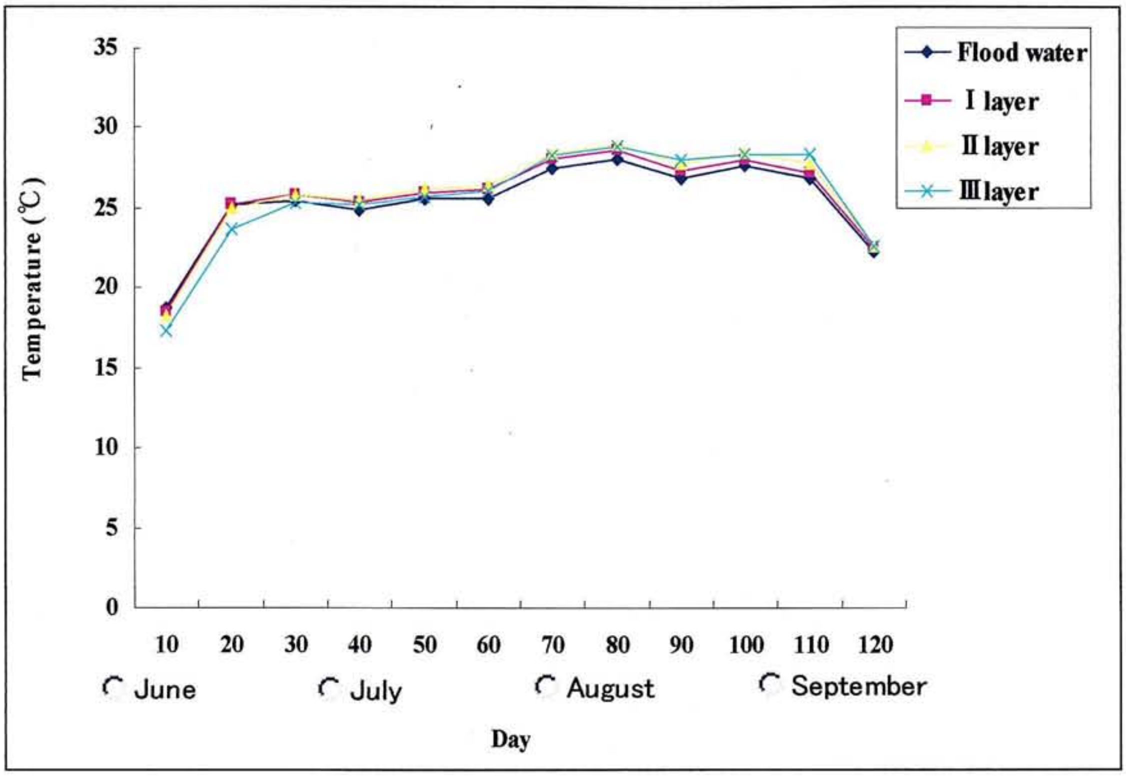


Fig. 35: Temperatures of flood water, plow layer, plowsole and subsoil in open system percolation model: 2010 (M-8 and M-10 model).

3.5 Water quality parameters

In the experiment, the water quality such as pH, EC, Na, Fe, K, Mg and Ca measured from flood water and outlet water in closed and open system percolation models.

3.5.1 pH value of flood and outlet water

pH value in irrigation water and soil is very important for rice cultivation. The average pH value of irrigation water was 6.3. In 2009 and 2010; the average flood water pH value in closed system percolation was 6.3 but in open system percolation was 6.4 as shown in Fig.36 and Fig.37. Actually both of the models, the flood water were almost similar. In fact, the pH value in flood water was slightly difference within the closed and open percolation pattern. In the flooding water become higher both of the percolation comparatively to supply water due to floating weed supplied oxygen which make high pH condition.

In 2009, the average pH value of downward water in closed and open system percolation were about 6.6 and 6.8 respectively, as shown in Fig.38. On the other hand, the average pH value of downward water in open and closed system percolation were 6.9 and 6.5 in 2010 as shown in Fig. 39. Actually in open system percolation , the lower plowsole and subsoil became oxidized as a results pH was higher in those soil water but in closed system percolation , the all of soil layer were became in reduction condition and soil water pH became reduce. Sasaki *et al.*, (2001) reported that, the pH value is lower in reduction condition of soil layer comparatively to unsaturated condition of soil layer that is supported to the present study.

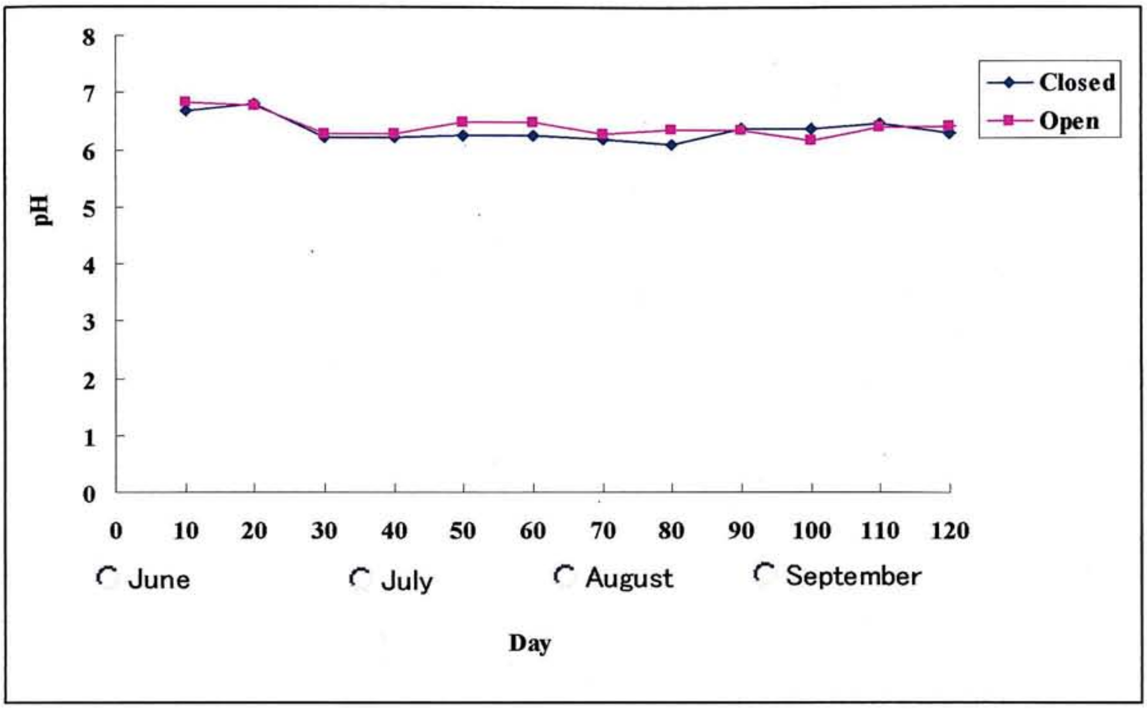


Fig. 36: The pH value of the flood water in open and closed system percolation: 2009.

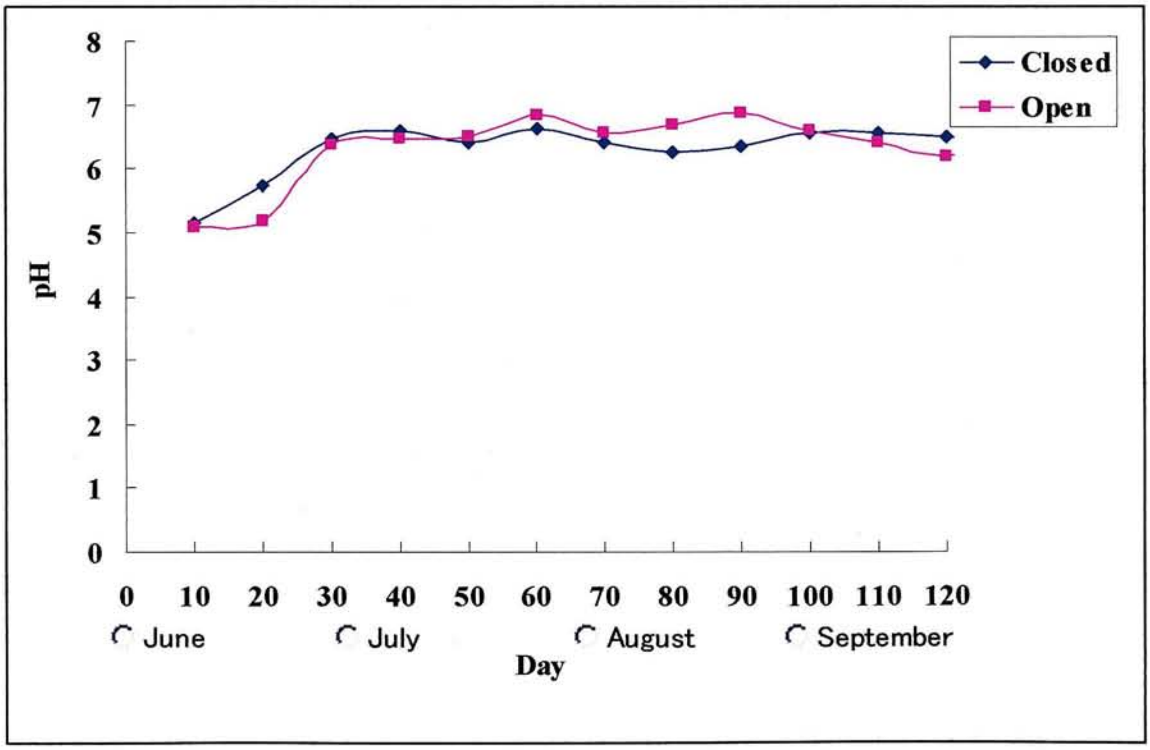


Fig. 37: The pH value of the flood water in open and closed system percolation: 2010.

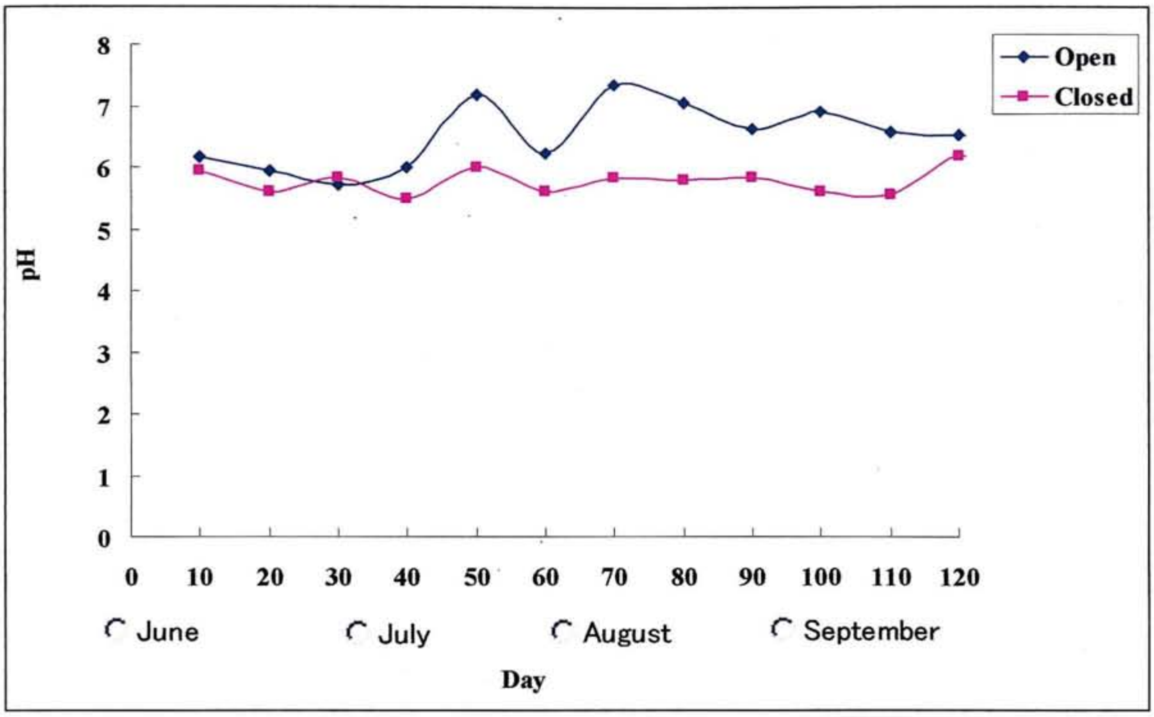


Fig. 38: pH value in outlet water in 2009.

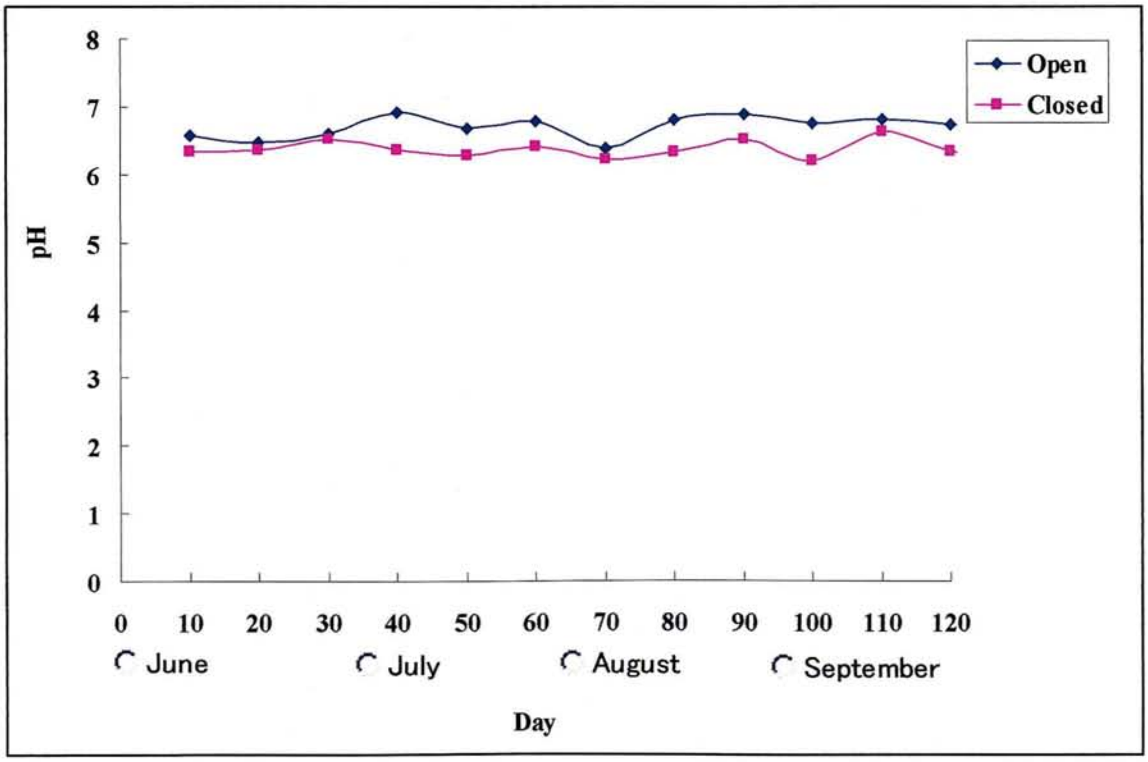


Fig. 39: pH value in outlet water in 2010.

3.5.2 Electric conductivity (EC)

Electric conductivity (EC) was one kind of parameters to measure the water quality. In this study, the water quality of EC was measured in flood water and outlet water. In 2009, the average EC value of flood water in open system percolation was 17.5 mS/m but in closed system percolation was 16.6 mS/m, respectively. In 2010, in closed system percolation; the average value of EC was 15.2 mS/m and 14.9 mS/m in open system percolation, respectively. From the beginning of the experiment, the EC values were higher in both percolation and gradually decrease with increasing the cultivation period due to the effect of fertilization as shown in Fig.40 and 41. According to Sukutai *et al.*, (2005) has stated that the EC value in flood water was 20 mS/m which was similar to the present study.

On the other hand, the average EC value in outlet of closed system percolation was 53.8 mS/m and 46.2 mS/m in open system percolation, respectively; as shown in Fig. 42. The average EC value of outlet was 57.9 in closed system and 45.8 mS/m in open system percolation as shown in Fig.43.

The EC values of both percolation patterns were decreased start from late June to July and remain about constant value from August to September of 2009 and 2010 soil column models. The EC value of outlet water was higher in closed system percolation than the open system percolation; this might be soil reduction condition in closed system percolation. According to Sukuthai *et al.*, (2005), the EC value of outlet water in closed system is higher than the open system percolation due to some dissolve elements precipitation passed by oxidized layer which was similar to the present study.

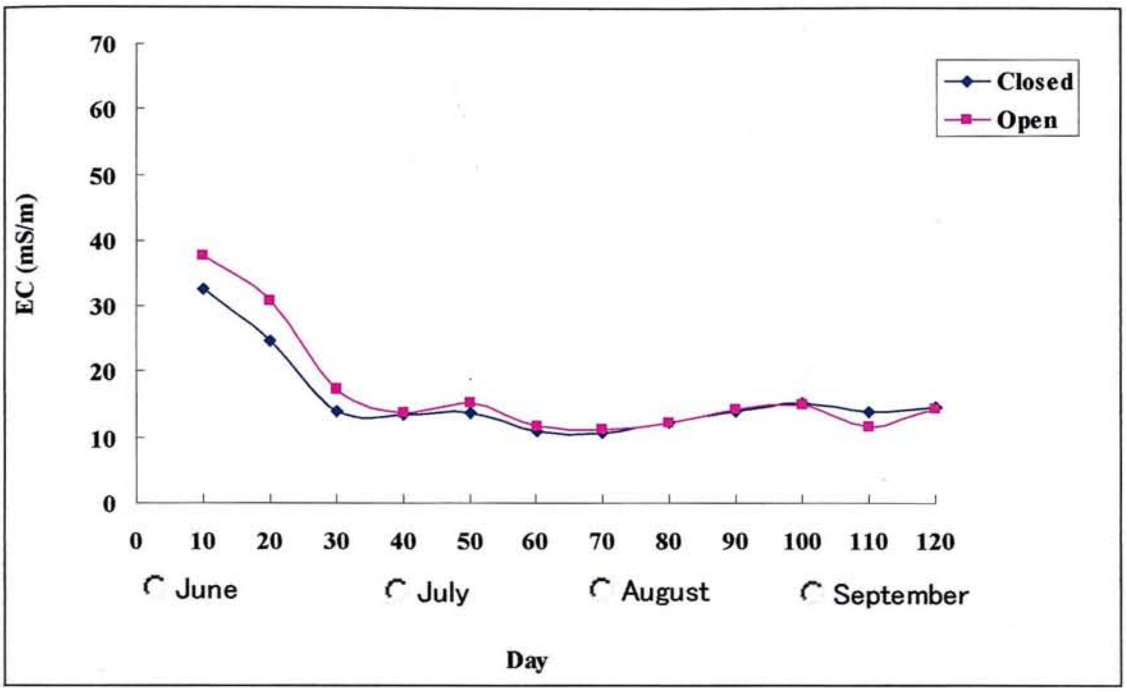


Fig.40: Electric conductivity value in flood water: 2009

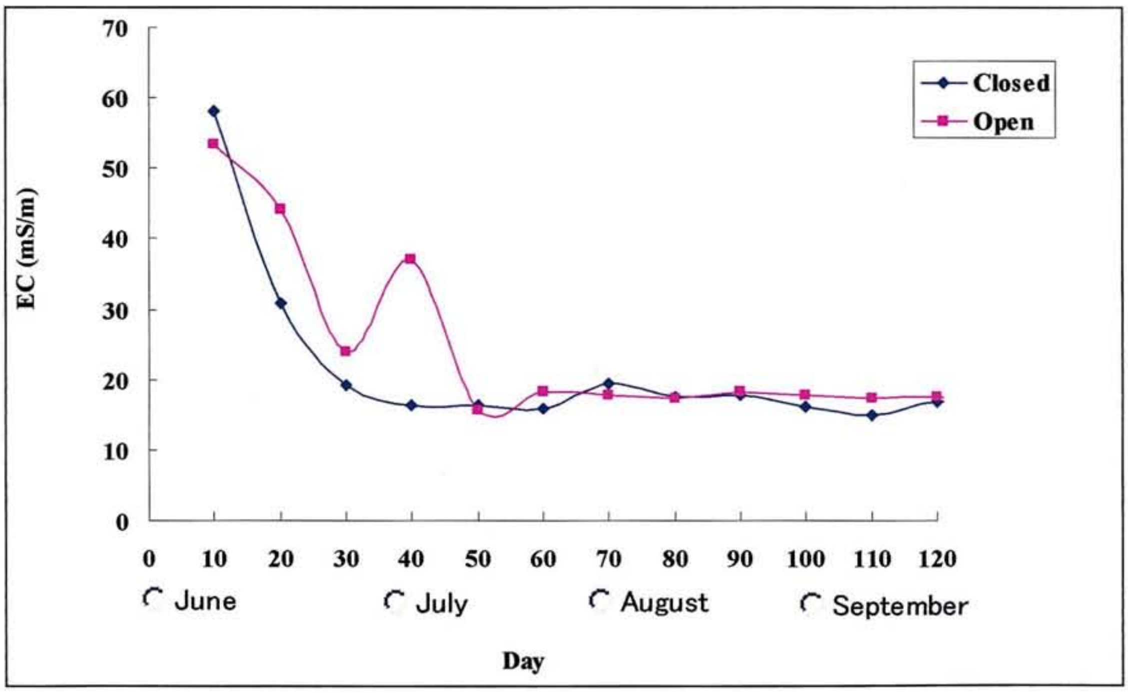


Fig.41: Electric conductivity value in flood water: 2010

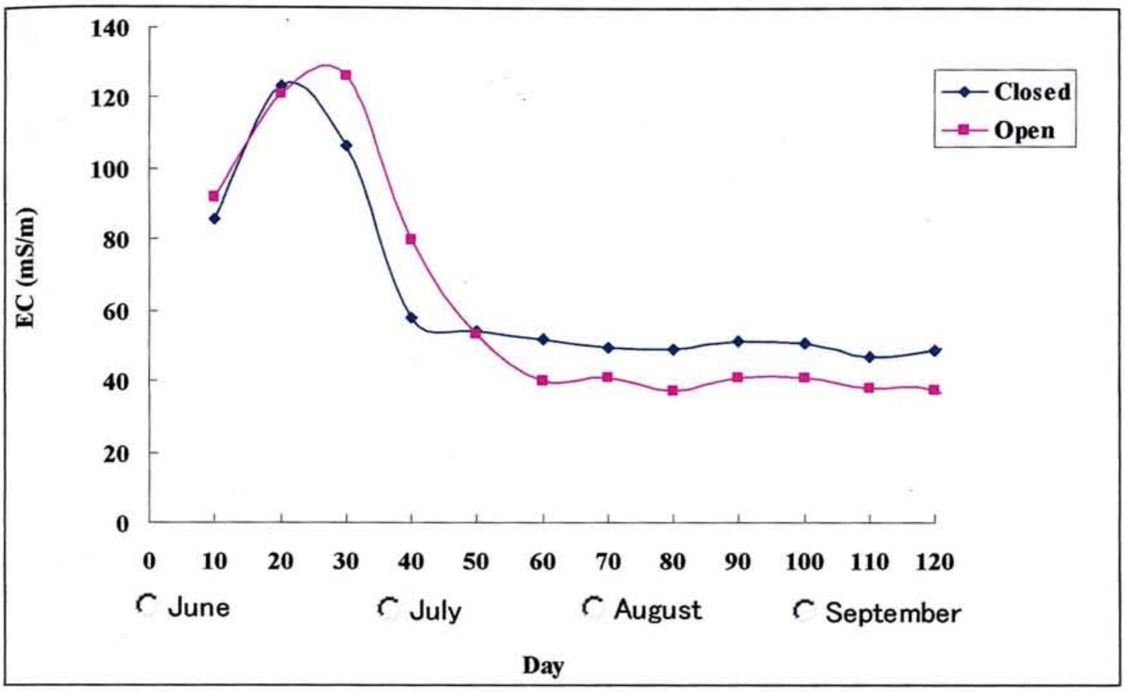


Fig. 42: Electric conductivity value in outlet water: 2009

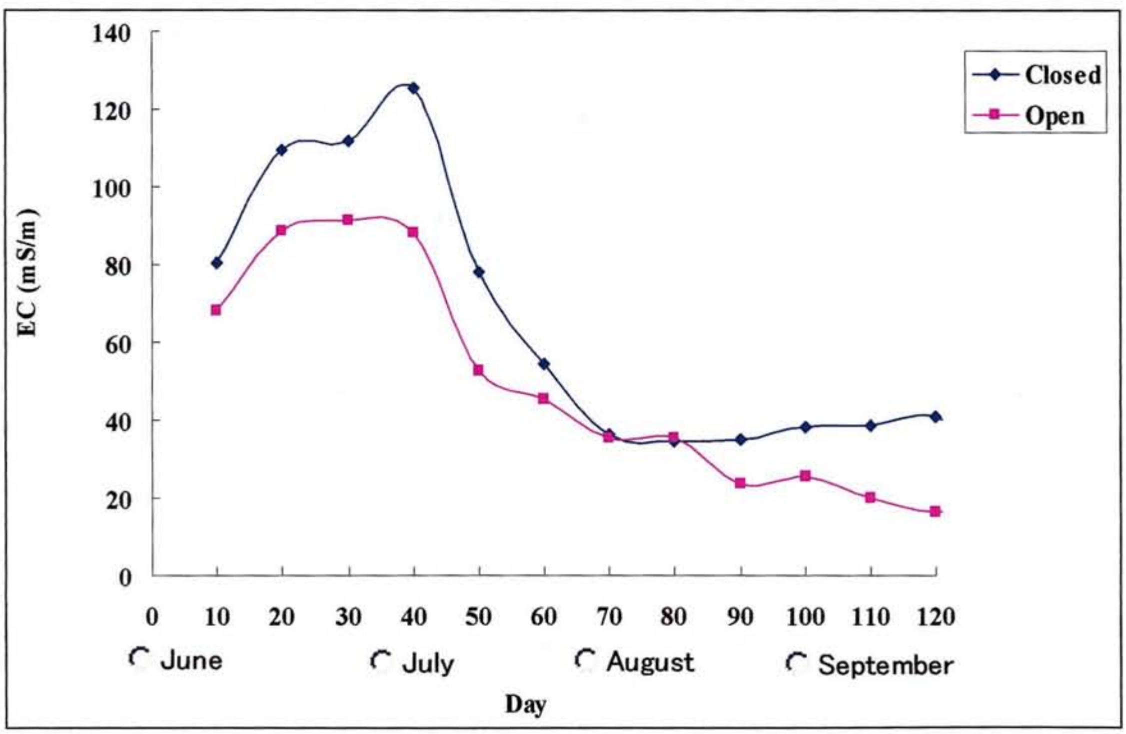


Fig.43: Electric conductivity value in outlet water: 2010

3.5.3 Concentration of ions in flood water

In the percolation models of 2009 and 2010, the ions of flood water in open system percolation were measured and the range of Na, K, Fe, Ca and Mg were 18~41 mg/l, 9~25 mg/l, 2~3 mg/l, 6~10 mg/l and 1.5~ 4 mg/l, respectively as shown in Fig. 45 and 47. The ions in flood water of closed system percolation were measured in 2009 and 2010, and the range of Na, K, Fe, Ca and Mg value of flood water were 18~38 mg/l, 5~29 mg/l, 2~3 mg/l, 6~12 mg/l and 1.5~ 9 mg/l, respectively as shown in Fig. 44 and 46. The average ions concentration of flood water in both percolation pattern models has no significance difference. In both percolation patterns, the flood water Na concentration was higher than the other K, Fe, Ca and Mg in 2009 and 2010. In the beginning of the study, the ions concentrations were higher and gradually decrease due to the effect of fertilizer.

3.3.4 Concentration of ions in outlet water

In open system percolation model of 2009 and 2010, the concentration of ions (Na, K, Fe, Ca and Mg) range in outlet water were 21~76 mg/l, 14~29 mg/l, 0.1~0.6 mg/l, 40~120 mg/l and 4~18 mg/l, respectively as shown in Fig. 49 and 51. On the other hand, the concentration of Na, K, Fe, Ca and Mg ions in outlet water of closed system percolation were the average range of 19~58 mg/l, 6~20 mg/l, 2~3 mg/l, 35~80 mg/l and 3~15 mg/l, respectively in 2009 and 2010 as shown in Fig. 48 and 50. The average ions concentration in outlet water were Na (31 mg/l), Fe (2.8 mg/l), K (15mg/l), Ca (59 mg/l) and Mg (10.7 mg/l) in closed system percolation but in the open system percolation were Na (31 mg/l), K (20 mg/l) , Fe (0.5 mg/l), Ca (66 mg/l) and Mg (12 mg/l) in 2010 and 2009. The concentrations of ions in outlet water were higher than the flood water due to the mixed of fertilizer of the percolated water. Moreover, the average concentration of irons in outlet water was low in open system percolation than the closed system percolation due to plowsole and subsoil became oxidized and precipitated on the soil. According to Sasaki et al (2001) stated that Na , K and Mn concentration in outlet water were higher in closed system percolation than the open system percolation but the Fe concentration were low in open system percolation that statement was supported to the present study.

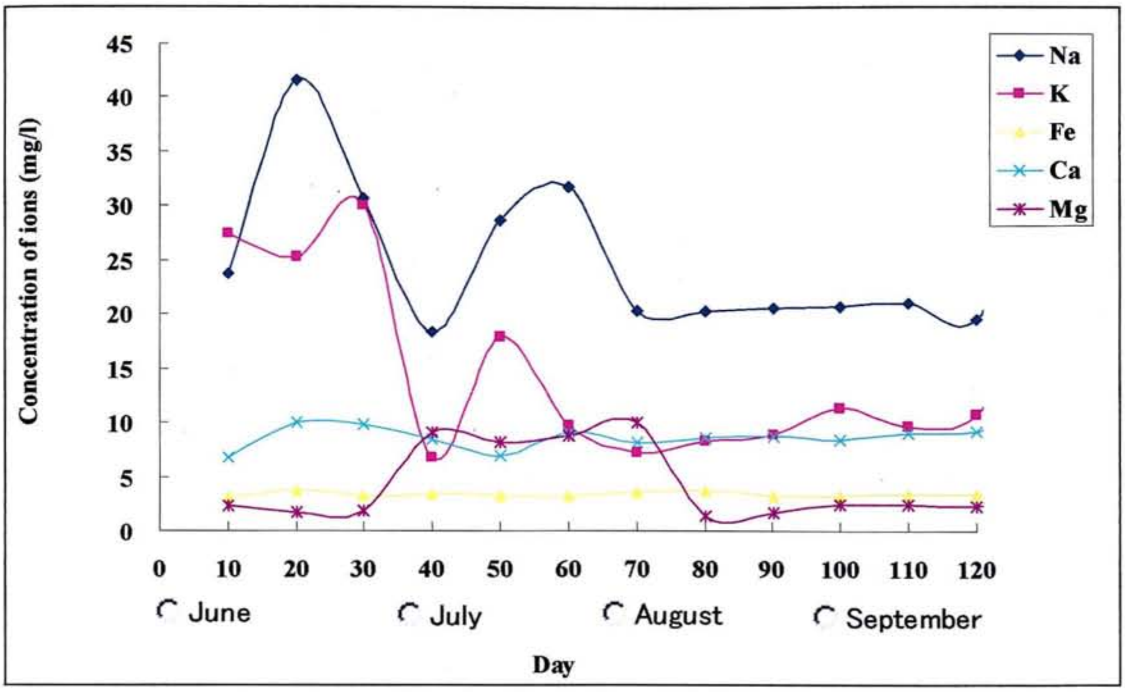


Fig.44: Concentration of Na, K, Fe, Ca and mg in flood water of closed system percolation: 2009.

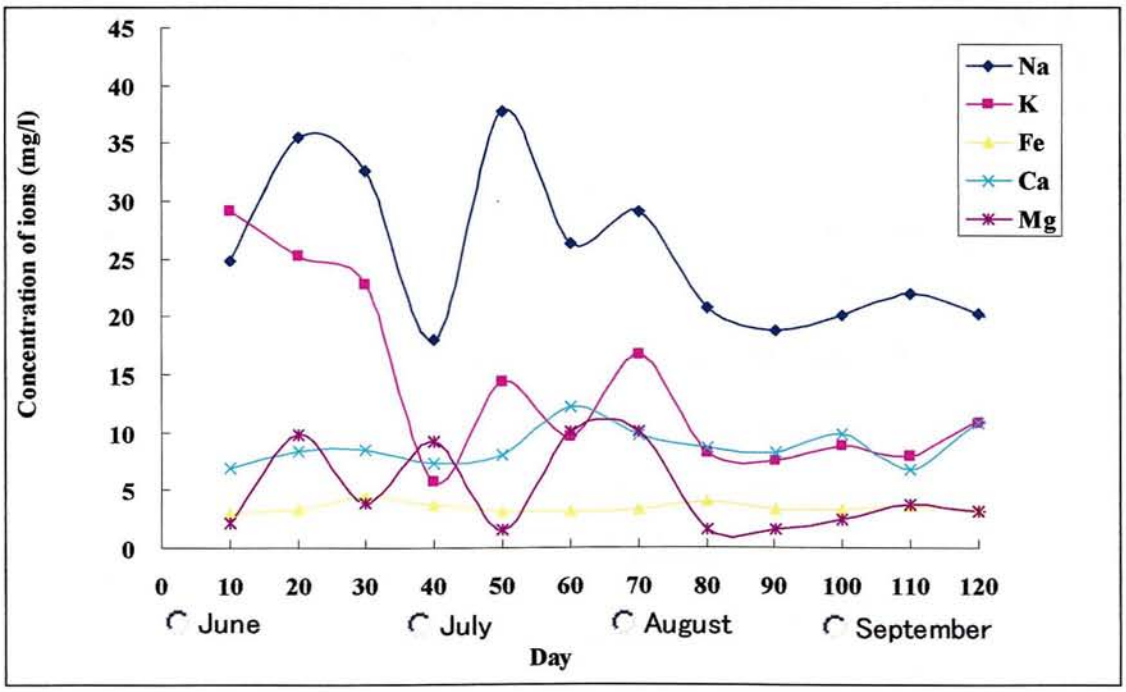


Fig.45: Concentration of Na, K, Fe, Ca and Mg in flood water of open system percolation: 2009.

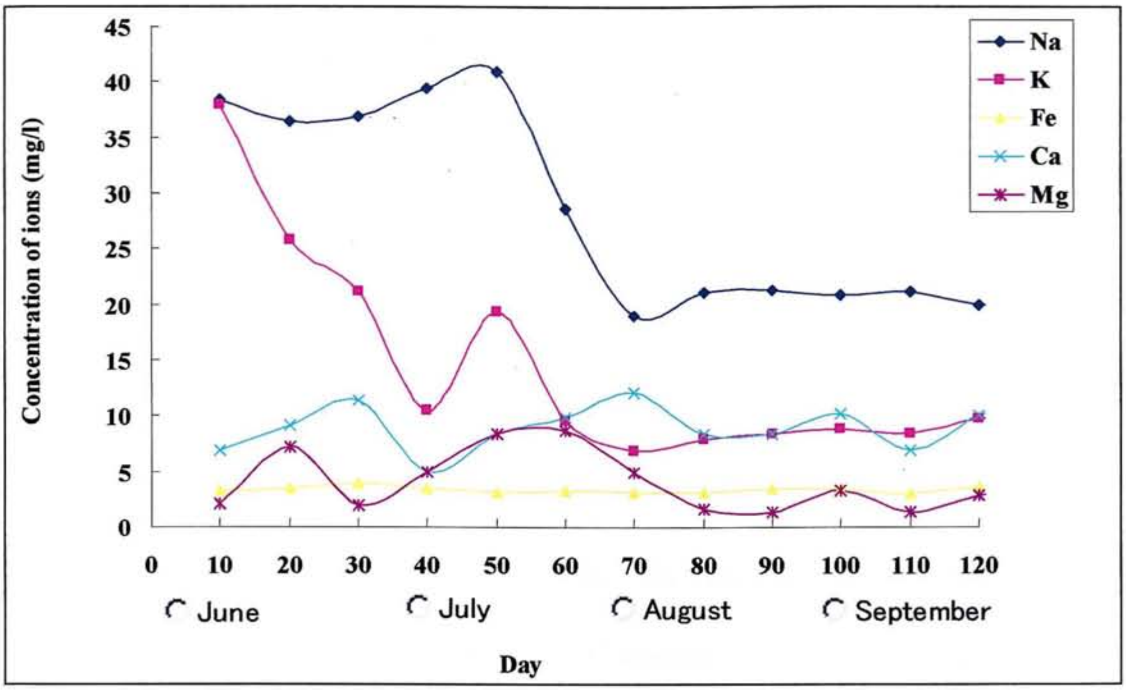


Fig.46: Concentration of Na, K, Fe, Ca and mg in flood water of closed system percolation: 2010.

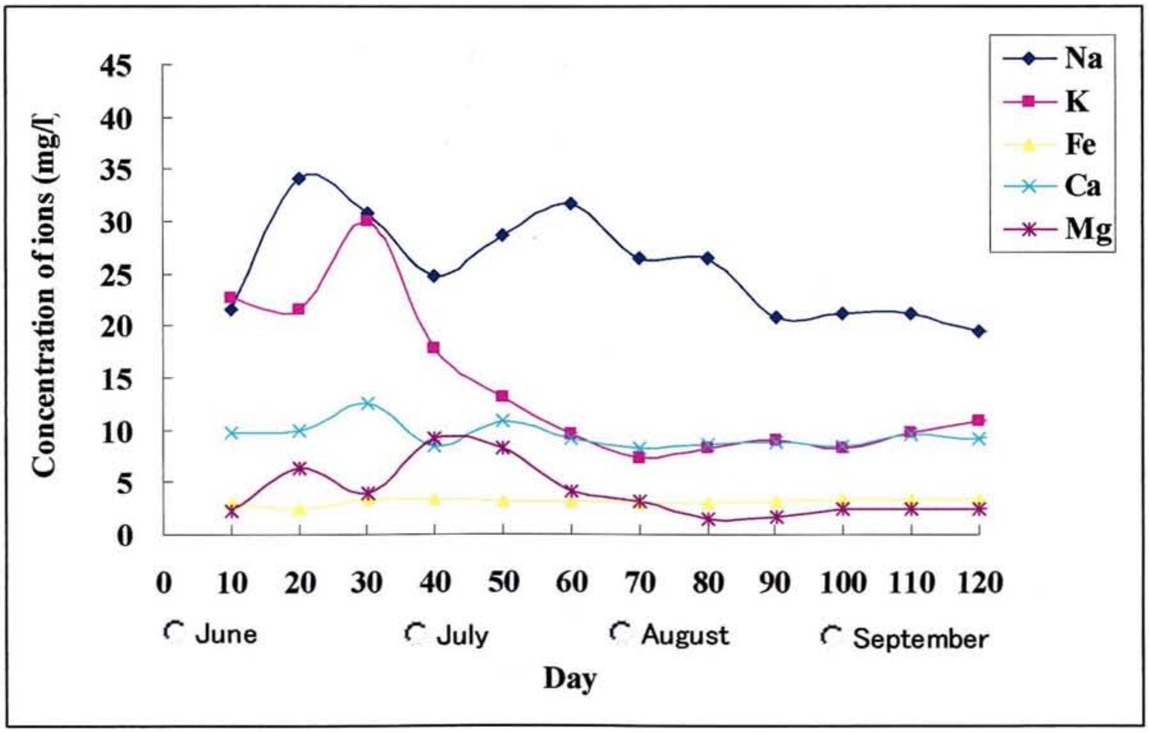


Fig.47: Concentration of Na, K, Fe, Ca and mg in flood water of open system percolation: 2010

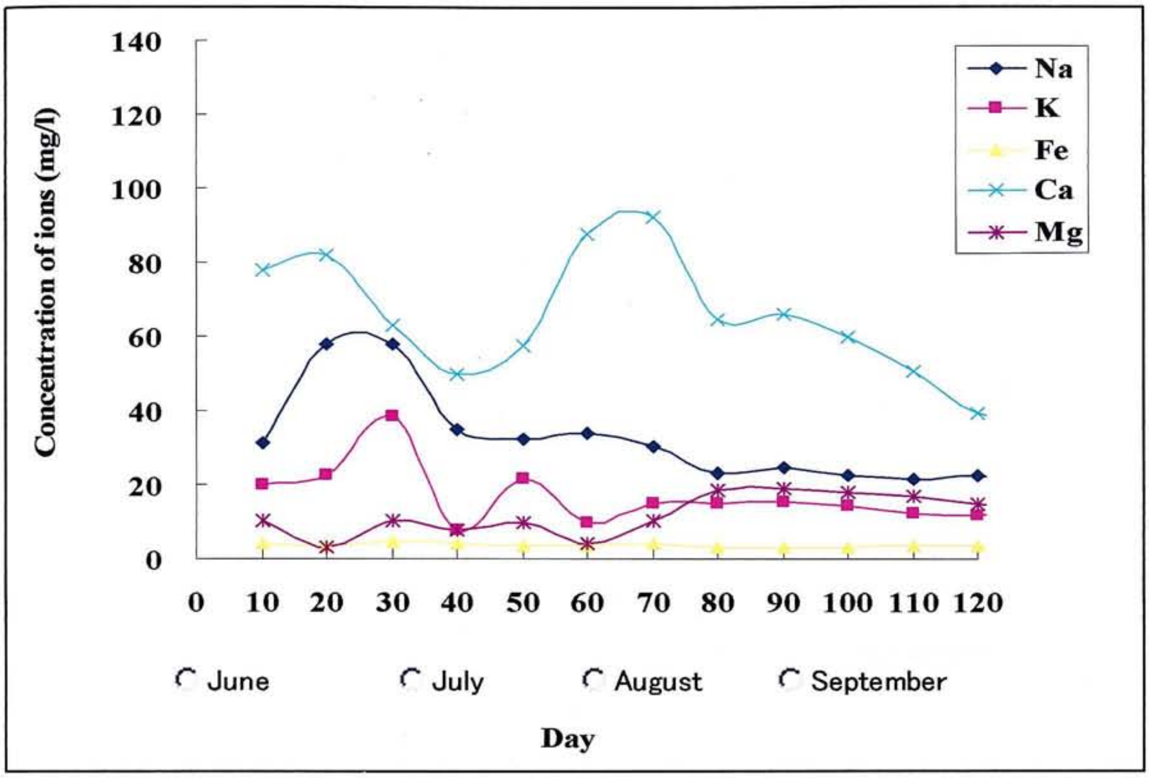


Fig. 48: Concentration of Na, K, Fe, Ca and mg in outlet water of closed system percolation: 2009.

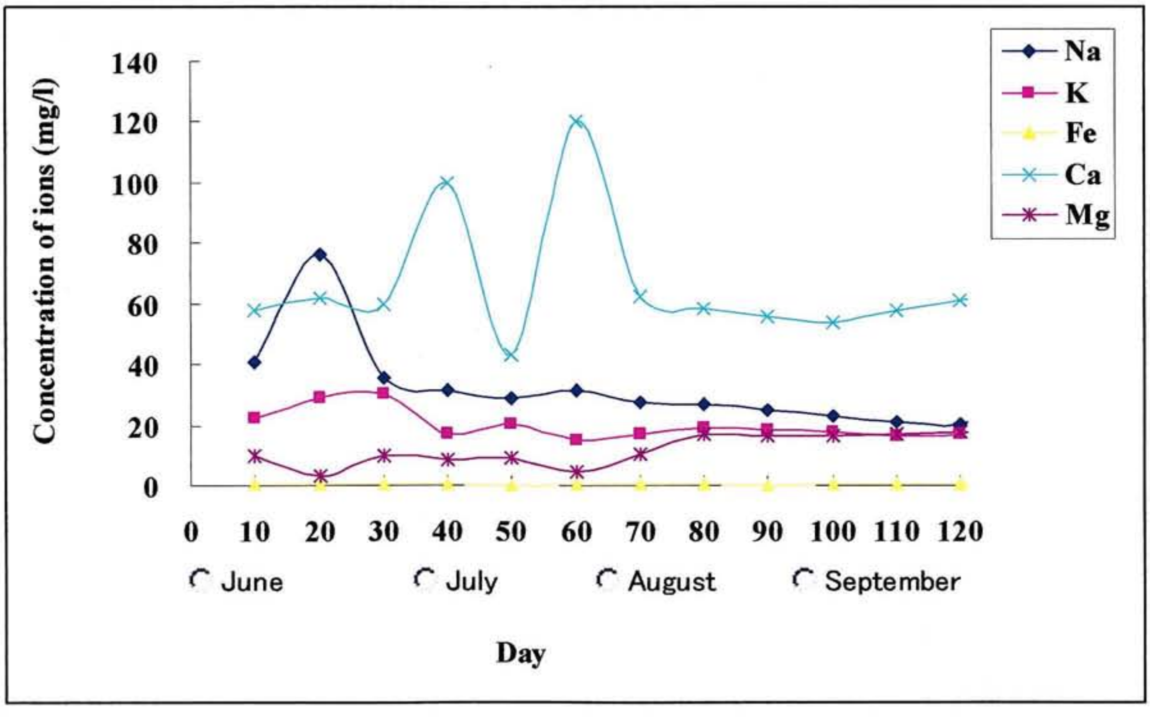


Fig.49: Concentration of Na, K, Fe, Ca and mg in outlet water of open system percolation: 2009.

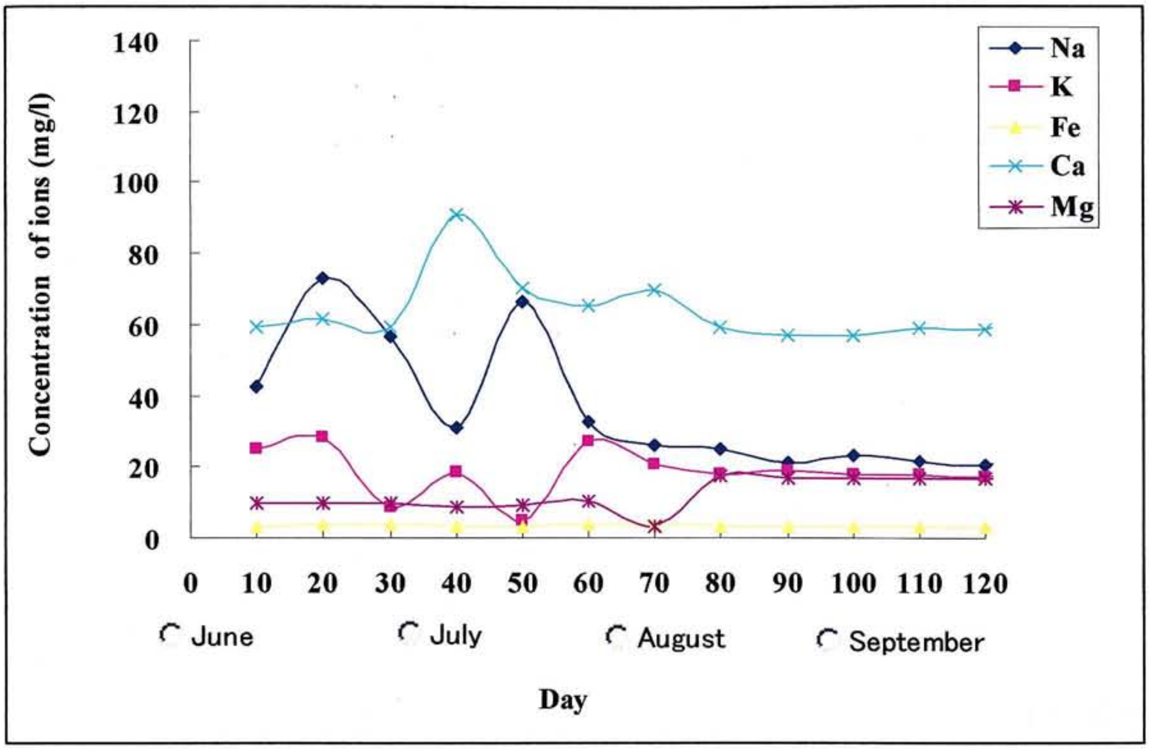


Fig.50: Concentration of Na, K, Fe, Ca and mg in outlet water of closed system percolation: 2010

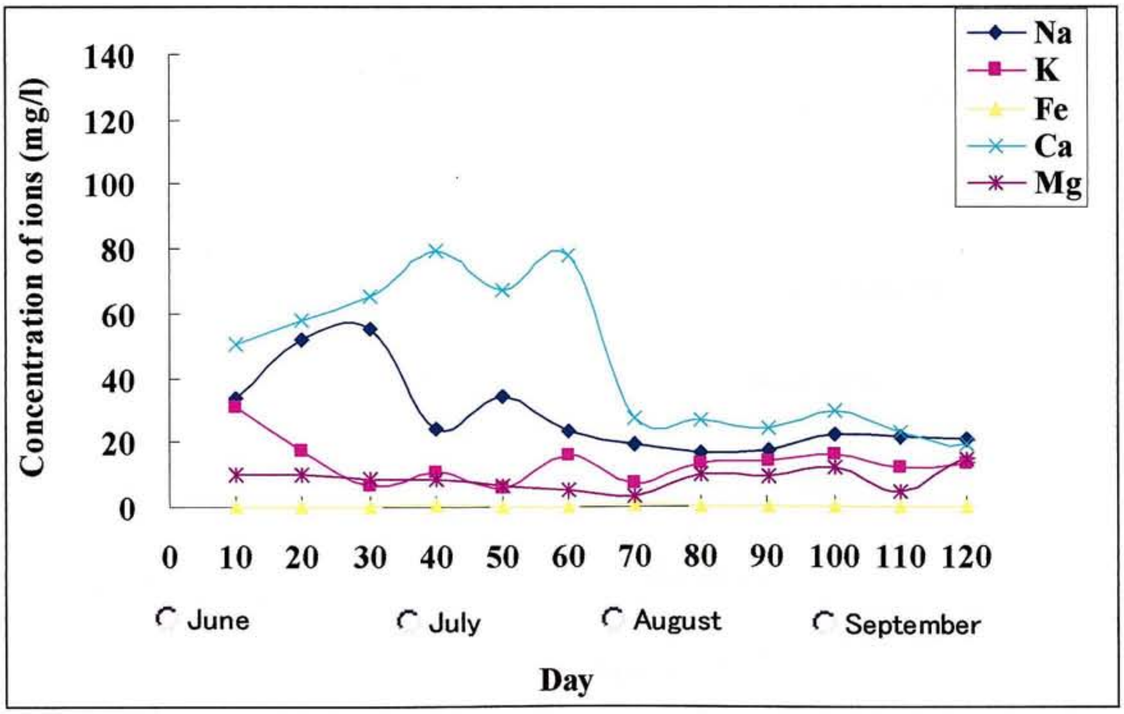


Fig. 51: Concentration of Na, K, Fe, Ca and mg in outlet water of open system percolation: 2010

3.6 Oxidation- reduction potential (Eh)

Oxidation reduction potential is known as redox potential (Eh). In this study the redox potential value were measure of plow layer, plowsole and subsoil of each model in 2009 and 2010. Many scientists have been reported; most of the metals are uptake by rice plants, especially cadmium during the cultivation periods and depends on to the soil oxidation-reduction state.

3.6.1 Reduction potential in closed system percolation

The percolation models of M-4, M-5, M-6, M-7 and M-9 were closed system percolation in the study. The Eh values of soil were measured at the depth of 7.5 cm, 17.5 cm, 22.5 cm, 30 cm, 40 cm and 50 cm in each model. In closed system percolation models, the Eh value were gradually decreased due to became saturated condition of soil. The Eh value in plow layer of all models was about -190 mV after flooding condition and that tendency is like as actual paddy fields. From the start of the experiment, the Eh value in plow layer, plowsole and subsoil were less than 300 mV and gradually decrease and up to -200 mV were observed in late June to October. This similar result was reported by Sasaki *et al.*, (1998). In the closed system percolation models, the plow layer and plowsole became higher reductive condition comparatively to subsoil due to presence of low organic matter and bacterial activity and soil microorganism consume oxygen from the percolated water. On the other hand, subsoil was lower change from oxidative to reductive state due to lack of microorganism in that layer. So finally, the soil layer of all closed system percolation models were in reduction condition as shown in Fig. 55, 56, 57, 58 and 60.

3.6.2 Oxidation potential in open system percolation

The ORP value more than 300 mV is an indicator of oxidation condition and lower than 300 mV indicates reduction condition. The models of M-1, M-2, M-3, M-8 and M-10 were open system percolation and the Eh value of plowsole and subsoil layer was gradually increased up to about 300~650 mV (Fig. 52, 53, 54, 59 and 61) due to those layer were in unsaturated condition. The Eh value in plowsole and subsoil greater than 300 mV, this means that those layer were became oxidized. On the other hand, the lower subsoil was become in reduction condition. This cause was guessed by Sasaki (2001) as follow; the gravel layer contained low amount of organic matter resulting in less growth of microorganisms. Thus the Eh value of gravel layer was decreased slowly. As state above, the Eh value of all soil layers were controls by the ground water level with percolated water velocity. In open system percolation, the plowsole and subsoil layer were in oxidation condition but plow layer was in reduction state. The reduction condition of soil is a principal to reduce uptake of Cd by rice plants. According to Iimura (1981), when the redox potential (Eh) of soils decrease about -130 mV, the proportion of soluble cadmium decrease abruptly.

Finally, most of the metals are uptake during the blooming period. So the soil oxidation-reduction state indicated in the Fig. 51 to Fig. 60. The soil oxidation-reduction state depends on percolate water which was controlled by impermeable layer. In oxidation state of soil, soluble Cd ions formation with the presence of atmospheric oxygen. On the other hand in reduction state of soil, formation of low amount of soluble Cd ions due presence of lack of oxygen which was consumed by soil microorganisms. So percolation pattern can controlled soil oxidation-reduction and formation of soluble and insoluble Cd ions.

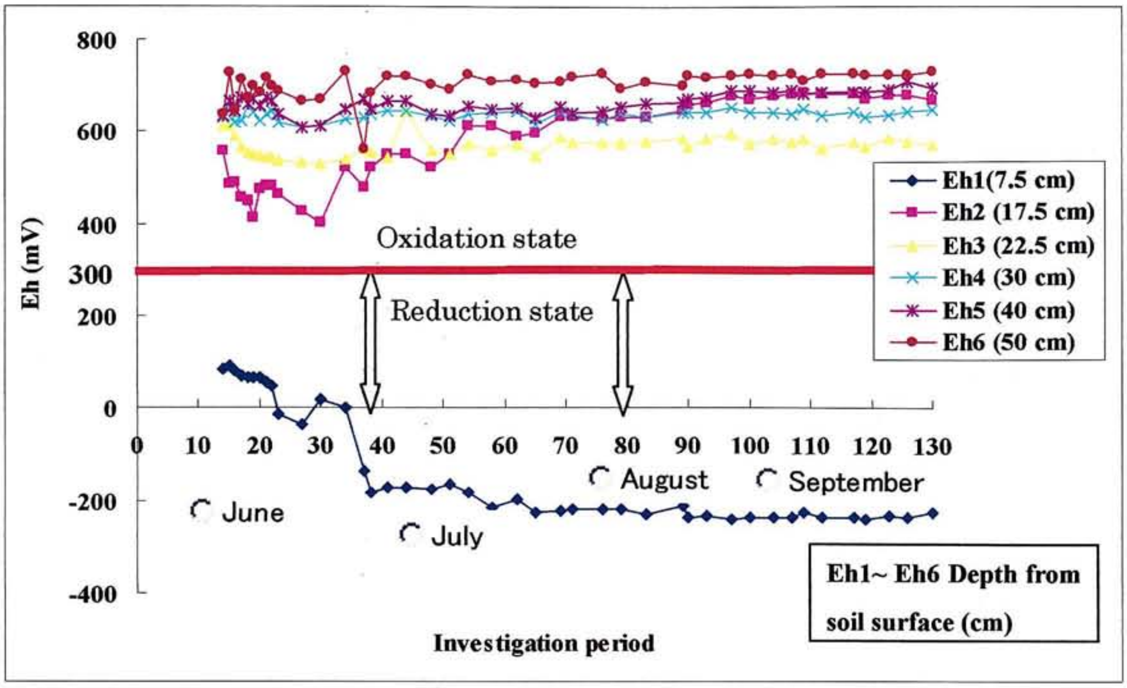


Fig. 52: Oxidation- reduction potential in soil layers of the open system percolation model: M-1.

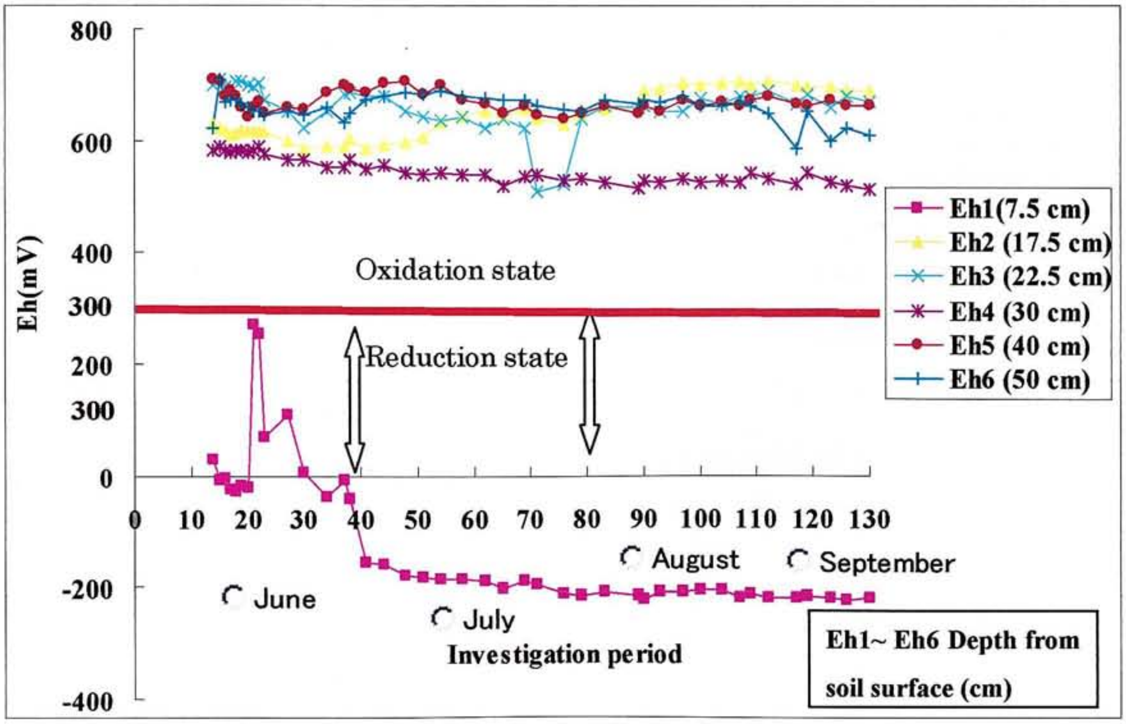


Fig. 53: Oxidation- reduction potential in soil layers of the open system percolation model: M-2.

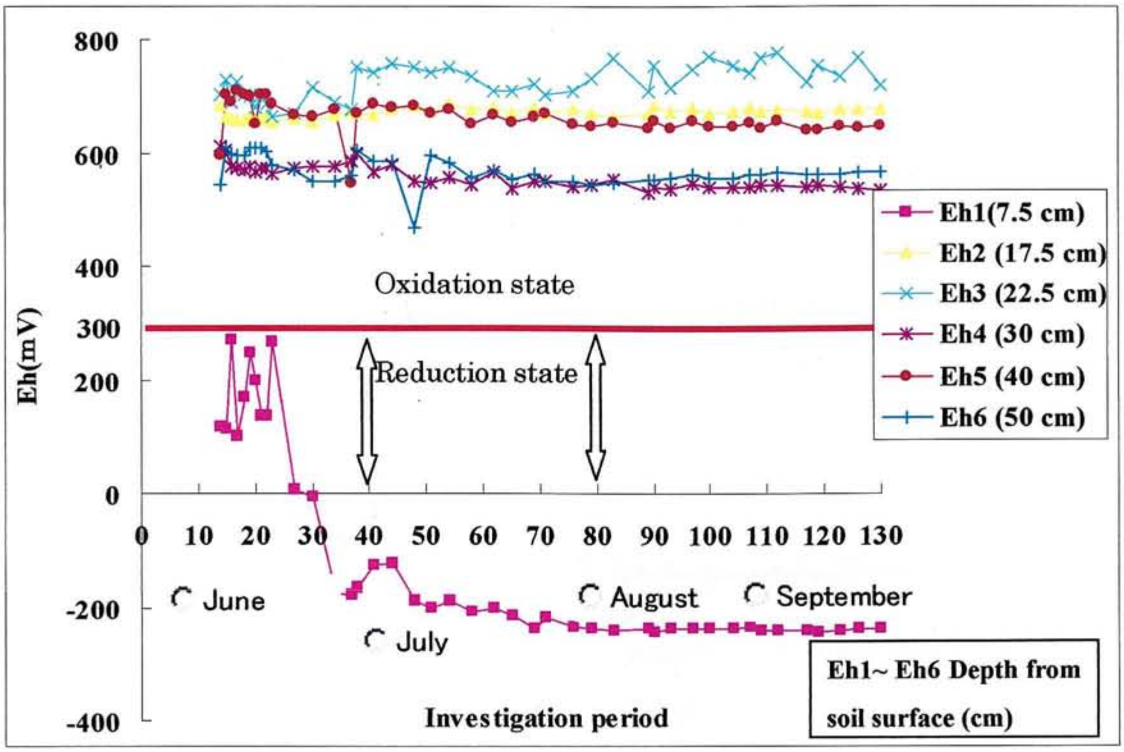


Fig. 54: Oxidation- reduction potential in soil layers of the open system percolation model: M-3.

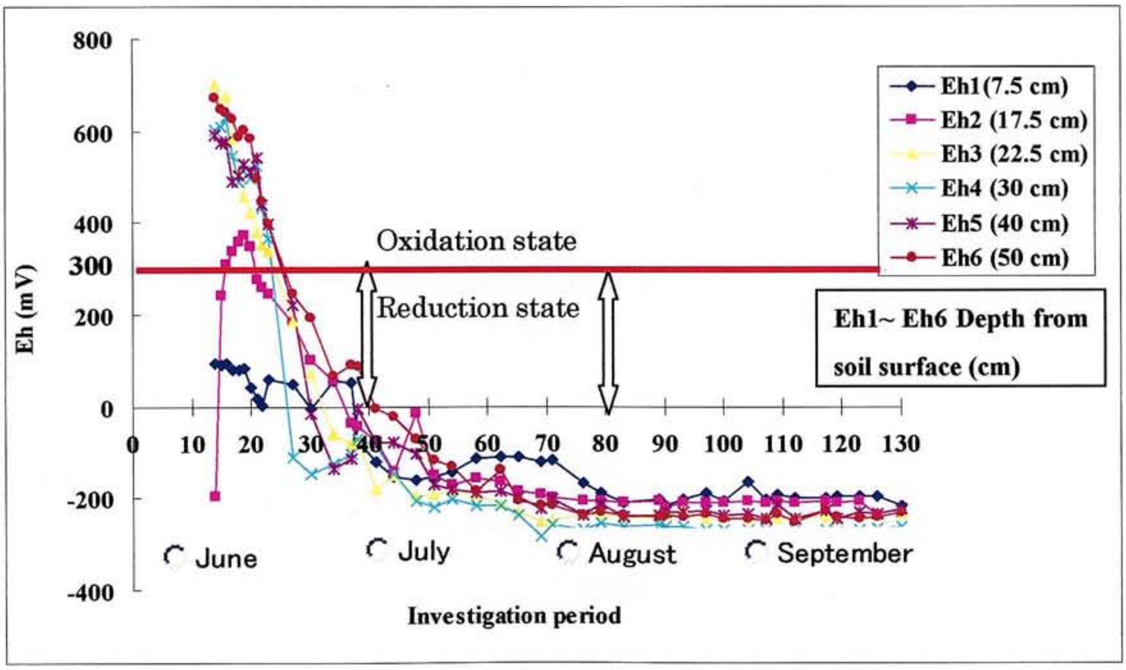


Fig.55: Oxidation -reduction potential in soil layers of the closed system percolation model: M-4.

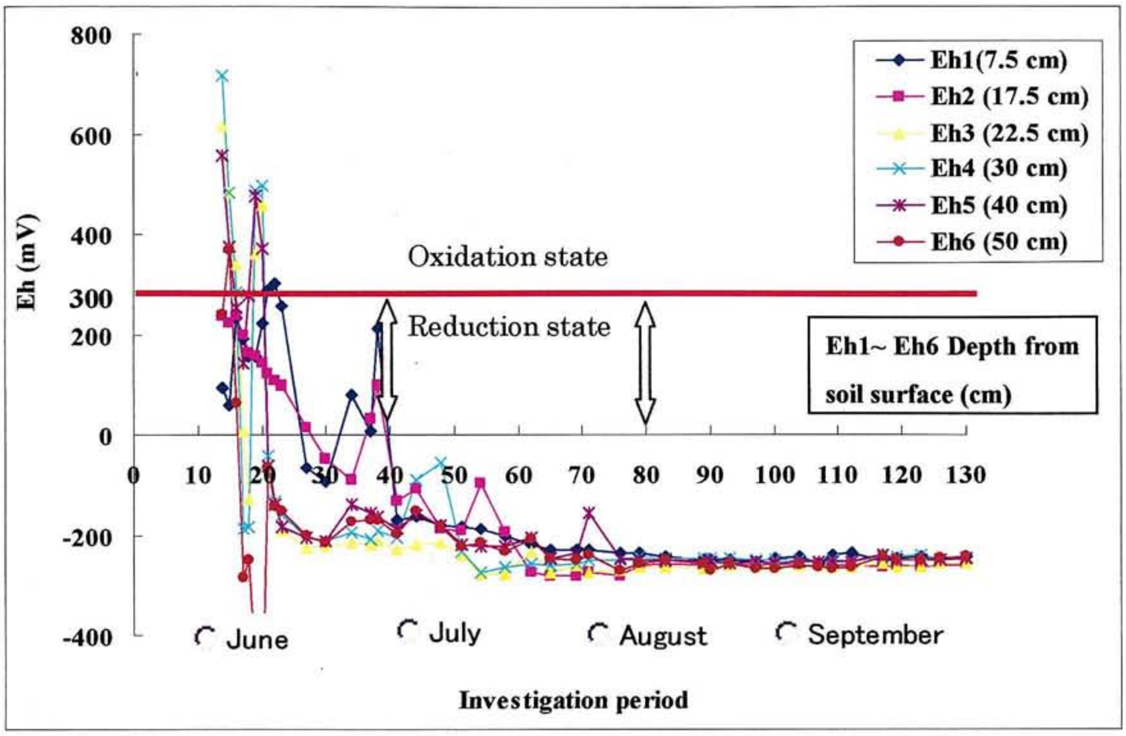


Fig.55: Oxidation- reduction potential in soil layers of the closed system percolation model: M-5.

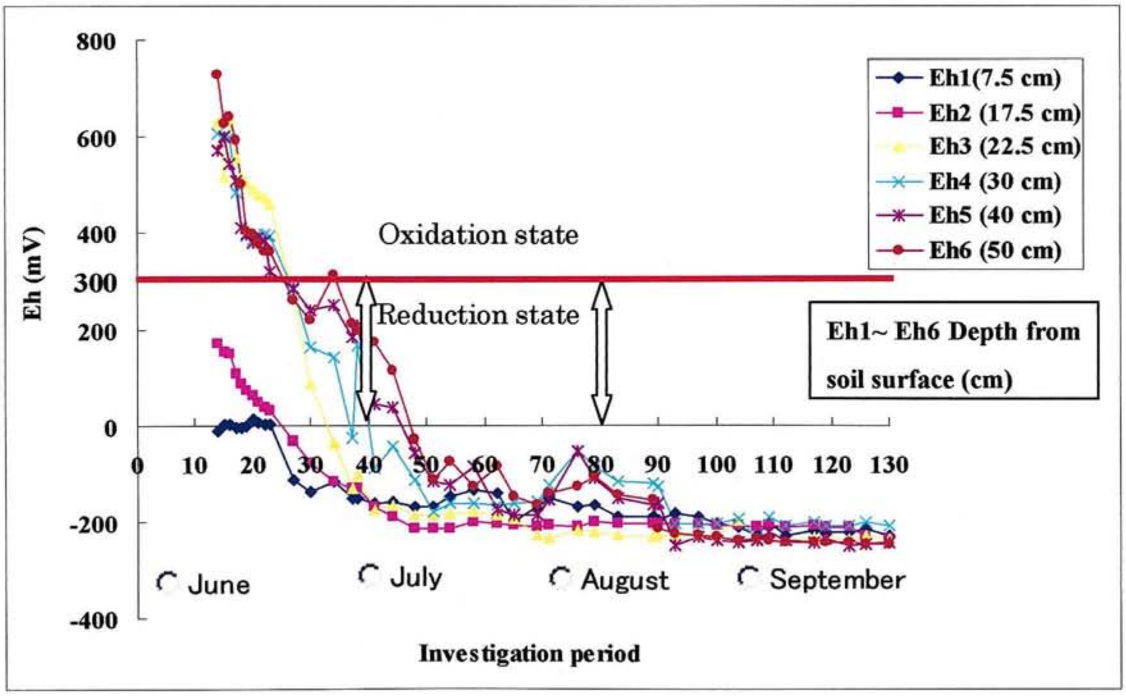


Fig.57: Oxidation- reduction potential in soil layers of the closed system percolation model: M-6.

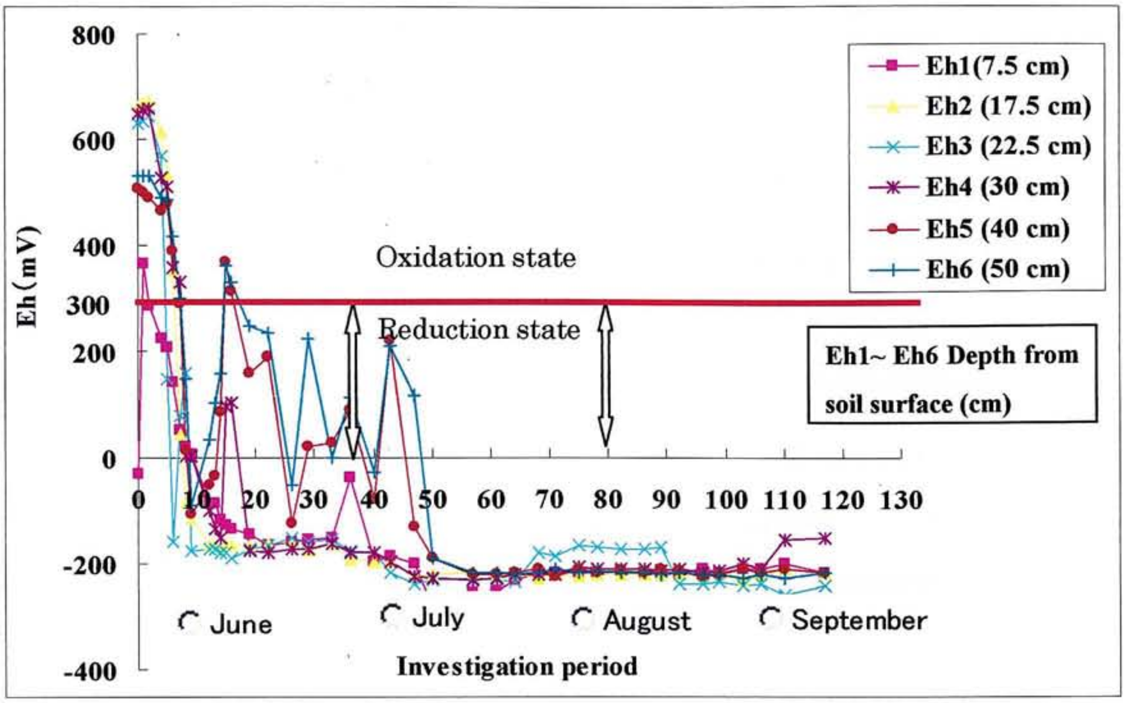


Fig.58: Oxidation- reduction potential in soil layers of the closed system percolation model: M-7.

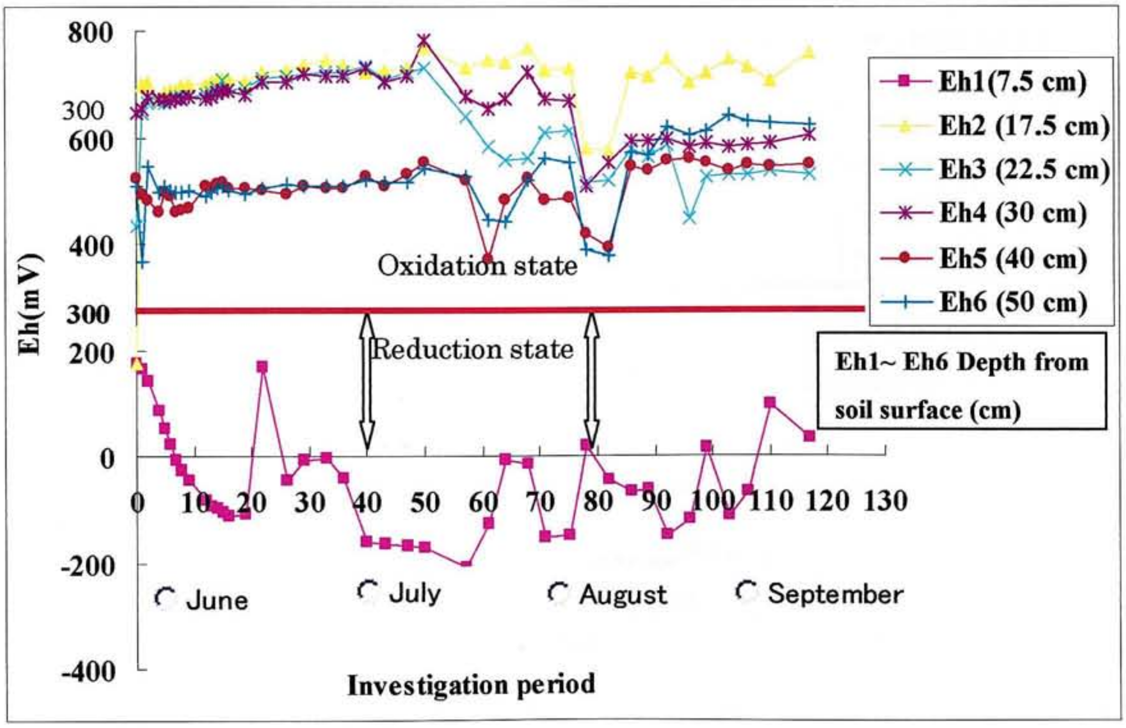


Fig. 59: Oxidation- reduction potential in soil layers of the open system percolation model: M-8.

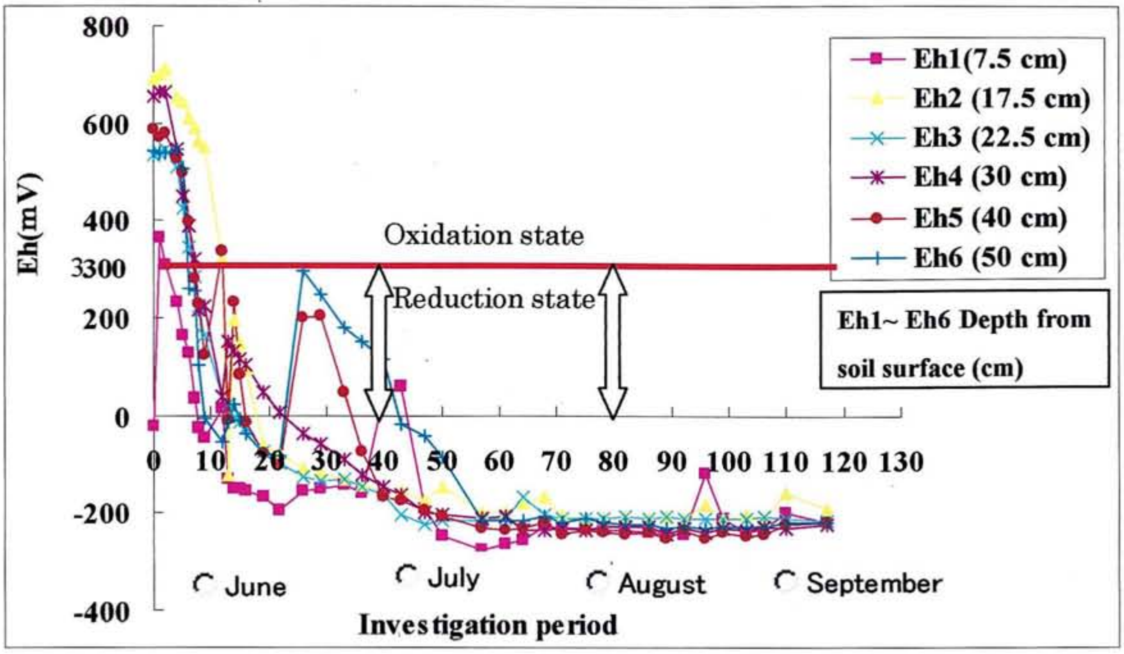


Fig.60: Oxidation- reduction potential in soil layers of the closed system percolation model: M-9.

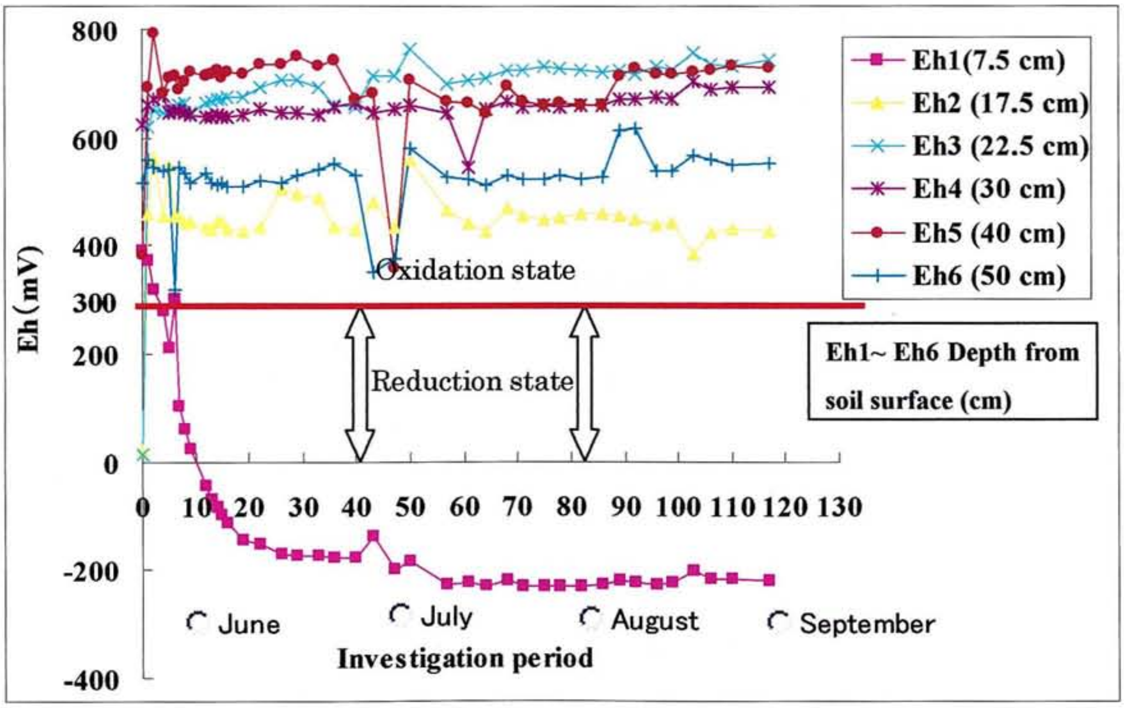


Fig.61: Oxidation- reduction potential in soil layers of the open system percolation model: M-10.