Use of GIS in Prediction of Soil Electrical Conductivity for Water Management against Soil Salinity

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Abstract: On Kawauchi Region on mouth of Yoshino River in Japan, which used to be a wetland, farm land has been developed by land reclamation. In this region, rice, lotus root and sweet potato are mainly cultivated.
However because of the high salt concentration in groundwater due to seawater intrusion, crops are subjected to damage by salt. Especially in the paddy fields and lotus fields, salinity damage could be serious because of the fine texture of the soil and flooding surplus water for salt removal is practiced. To establish the most efficient management of irrigation water, water demand including water for salt removal has to be known.
So in this study, we investigated the possibility of salinity damage in the fields by the measurement of electrical conductivity (EC) at a number of points that were considered to be critical for water quality management and the spatial distribution of EC was predicted with geostatistical analysis.
The EC value in the groundwater was high in the area near the riparian and, in such areas surplus water for the salt removal was considered necessary. On the other hand, there were areas in paddy fields and lotus fields where the EC in the surface water was high regardless of the distance from the river. In such areas, irrigation water might contain salt and management of irrigation water had to be improved.
By linking the prediction values of EC with the database of each plot, it is possible to propose methods for efficient water management and effective quality control of crops in a form that is easily understood by farmers.
Keywords: Salinity, Deterioration of agriculture fields, Irrigation water, Geostatistical analysis

1. Introduction

The best way of water management depends on the features and environment of each region. So it is important to investigate region features, such as land use and the other local features concerning special problems in each region. Recent advancement in GIS and RS technique makes it easy to grasp the features and problems of each region. So we tried to find more effective applications of GIS to water management, in the case study on Kawauchi region in Japan. The region has a problem of salinity damage on agriculture fields.
Kawauchi Region is located on the mouth of Yoshino River in Tokushima prefecture and farmland has been developed by land reclamation. In the agricultural area, rice, lotus root and sweet potato are cultivated flourishingly. But salinity damage has been caused often by seawater intrusion originally. In 1974, estuary weir was constructed to supply freshwater to the fields. But damage by salt could happen after the completion of the weir. There would be two reasons;
1) salt rises from the groundwater to plowed layer by capillary action of soil water. 2) drainwater from salinized fields contains salt, and it flows into irrigation canal. To avoid the damage of salt, surplus water would be needed for leaching salt.
Akae et al.(2000)[1] and (2005)[3] showed that degree of salt accumulation depended on soil texture and cultivation management. Upland fields, especially southeast part of the region, have been reclaimed sand dressing. Salt accumulation might not appear at the part of upland fields, because capillary water of the sandy soil that transports salt upward could go up by only 20cm above the groundwater table. On the other hand, in paddy fields and lotus fields, which consist of alluvial soil, salinity damage could happen easily, because capillary rise in these fields could get to 200cm above the groundwater table. And it was also shown that in these fields, salt accumulation could be prevented by flooding of freshwater during irrigation period. But during non-irrigation period, when soil was dry, salt

was accumulated by capillary action.

Degree of salt accumulation also depends on the location of fields such as distance from river in addition to these factors.

Here, to understand the actual state of soil salinity, we created prediction maps of spatial distribution of EC, using observed EC values and land use. We also analyzed the spatial distribution EC profile. And we tried to find an area where surplus water for salt removal is necessary.

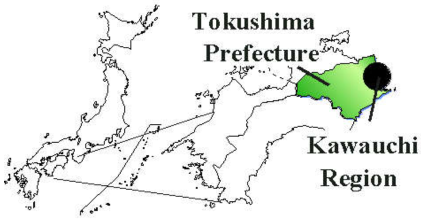

Fig. 1 Location of Kawauchi Region

2. Materials and Methods

2.1 Site Description

The study area is Kawauchi Region, which is located on the mouth of Yoshino River in Tokushima prefecture in Japan. Fig. 1 shows the location of the Kawauchi Rigion, and Fig. 2 shows the IKONOS image(observed on 2001/3/16) of this region. This region is one of great agriculture zones in this prefecture. It is located on the delta surrounded by the Yoshino River and Imakiri River. Because of the low altitude between 0 to 2 meters above sea level, groundwater is salinized. And due to recent urbanizing, irrigation water has been deteriorated by domestic wastewater that flows into the irrigation canal. So, water management in this region is reviewed, to improve the quality of irrigation water. The water requirements have to include additional water for salt removal in addition to conventional irrigation water.

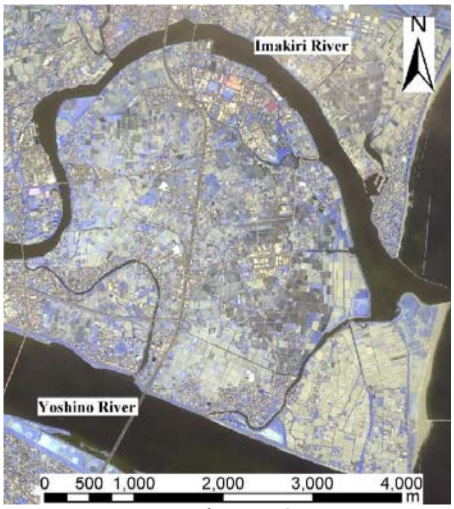

Fig.2 Image of Kawauchi Region
(IKONOS, 2001/3/16)

2.2 Measurement Data

Dataset for the analysis was soil EC profiles measured by Akae et al.(2003)[2] Measurements were conducted on Dec.25 and 26 in 2003 on non-irrigation period, and on Sep.17 and 18 in 2004 soon after rice harvesting at 31 lotus fields, 32 paddy fields and 27 upland fields. Because situations of paddy fields in September 2004 were still strongly affected by irrigation, we considered this season as irrigation period in the following discussion. The measurement locations with the map of land use are shown in Fig.3. At lotus fields, apparent EC was measured by four-electrodes methods (ECa), and measurement depths of EC were 10, 20, 30, 40, 50, 60, 70 and 80cm. At paddy fields and upland fields, $EC_{1:5}$ (EC of solution extracted from a 1:5 soil–water mixture) was measured, and sampling depths were 5, 15, 25, 35, 50 and 70cm. In some fields, measurements were impossible in some depths due to cracks of the ground.

By the way, it is often said that $EC_{1:5}$ would underestimate the concentration of salinity, in the case of low soil water content. So, we converted $EC_{1:5}$ to ECe(EC of saturation paste extracted method) with Eq.(1), which removed the influence of water content,

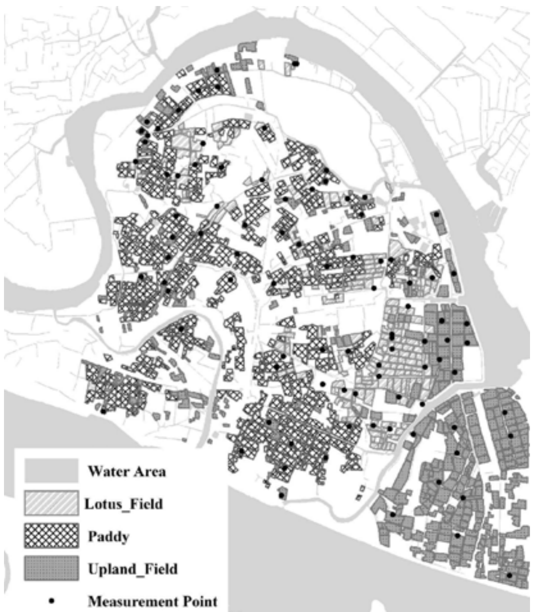

Fig. 3 Land Use of Kawauchi Region
and Measurement Points of EC

$$ECe = EC_{1:5} \times 500/Ws \quad (1)$$

where Ws is the percentage of saturated soil water content by weight.

ECe could be a parameter of growth inhibition activity of salt to crops. The limit ECe value with which most crops cannot grow without damages is 4mS/cm.

While, ECa was considered to be close to ECe value in the case soil was saturated with water. In lotus fields, in which soil moisture was approximate saturation, ECa could be considered equal to ECe.

Now we used ECe values in analysis, which converted from $EC_{1:5}$ and ECa, as a parameter of degree of salt accumulation.

2.3 Prediction Method

The method to predict spatial distribution of ECe is Kriging. Kriging is one of the method of interpolation, which based on analysis of spatial dependence of distribution of features using semivariogram. The outline of this method is as followings:

Semivariogram shows the relation of lag(h) and semivariance $\gamma(h)$ and semivariance is calculated using Eq.(2)

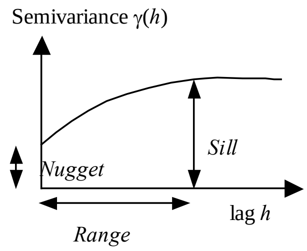

Fig. 4 Conceptual Figure of Semivariogram

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_{i+h})]^2 \qquad (2)$$

where $N(h)$ is the number of all pairs when lag is h and $Z(x_i)$ is sampling data at point x_i. Fig. 4 shows the conceptual figure of semivariogram. Semivariogram often has a limit value, and this is called *Sill*. It is equal to the variance of random variable. The value of h when $\gamma(h)$ first gets to *Sill* is called *Range*. It is an important parameter and represents the limit distance of spatial dependence of feature. So distances between measurement points have to be shorter than *Range*. There is one more important parameter. It is called Q, and is calculated by Eq.(3)

$$Q = (Sill - Nugget) / Sill \qquad (3)$$

Nugget represents independent error, measurement error and microscale variation at spatial scales that are too fine to detect. When Q is close to1, the spatial structure of features is developed and when Q is close to 0, the spatial structure of features is not developed and Range has no mean. To calculate these parameters, semivariogram is approximated by models, such as spherical model, circular model and so on. As an example, spherical model is shown in Eq.(4)

$$\gamma(h) = Nugget + (Sill - Nugget) \times \left[\frac{3h}{Range} - \frac{1}{2}\left(\frac{h}{Range}\right)^3 \right] (0 < h \le Range) \qquad (4)$$
$$= Sill(h \ge Range)$$

Kriging is the method to predict the value of feature at unknown point using these parameter. Expectance at given point x_0, $z'(x_0)$ is calculated by Eq.(5), using measurement data $z(x_i)$ in the *Range*

$$z'(x_0) = \sum_{i=1}^{n} \lambda_i z(x_i) \qquad (5)$$

$$\sum_{i=1}^{n} \lambda_i = 1 \qquad (6)$$

where λ_i is statistical weight and its value is selected in such a way that the prediction error would be the minimum.

The detail of Kriging is described by Yanai et al.[4]

3 Results and Discussion

3.1 Salinization of Each Field

3.1.1 EC Value in Plowed layer

Fig. 5 shows ECe in plowed layer measured in Dec.- 2003 and Sept.- 2004. Here, ECe value in plowed layer was calculated as the average of EC values measured at the depth between 0 to 30cm in each field.

ECe in lotus fields were much lower than that in other fields, and the averages in Dec. -2003 and Sept. -2004 were both 0.3mS/cm. On the contrary, ECe in paddy fields and upland fields were higher, and averages in Dec. -2003 and Sept. -2004 were 2.9mS/cm and 1.4mS/cm

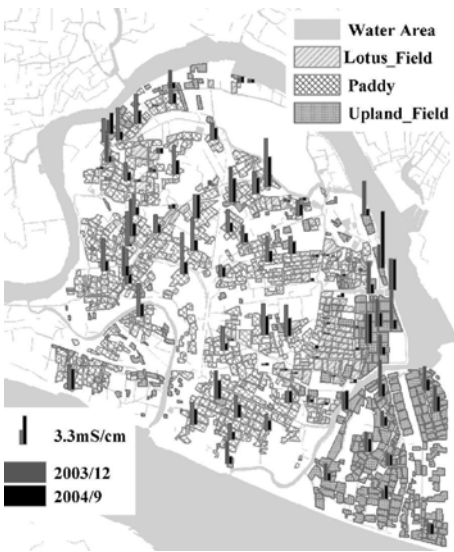

Fig. 5 Measurement Value of ECe in Plowed layer

in paddy fields, and 2.8mS/cm and 1.7mS/cm in upland fields. In upland fields located on the southeast part of the region, named block A (Fig. 6), ECe values were lower than those in the other region, and averages in Dec. -2003 and Sept. -2004 were 2.2mS/cm and 1.5mS/cm in block A, and 3.2mS/cm and 1.9mS/cm in upland fields in the region except block A. This was attributed to the dressed sand soil for reclamation of the fields, which prevented salt rising from groundwater. So it was obvious that degrees of salt accumulation depended on land use and soil texture.

Degrees of salt accumulation depended on not only cultivated crops but also the season. ECe values measured in paddy fields and upland fields in Dec. -2003 were much higher than that measured in Sept. -2004. In Dec. -2003, non-irrigation period, soil was dry and salt was transported upward from groundwater. On the other hand, in Sept. -2004, irrigation period, salt in plowed layer was removed by flooding water.

Fig. 6 Location of Block A

3.1.2 Prediction Map of EC Value in Plowed layer

To know the spatial change of ECe, distributions of ECe were predicted using the measured data. As stated above, ECe values depended on cultivated crops and observation dates, such as irrigation or non-irrigation period. So, the prediction maps of ECe in plowed layer were created on each observation day on each land use (lotus, paddy, upland), using the respective observation data. For creating maps, we adapted Kriging method.

These maps are shown in Fig. 7. The maximum values in the prediction maps are 5.0mS/cm for paddy and upland fields, and 0.5mS/cm for lotus fields. In addition, in making maps for upland fields, we estimated block A independently, because soils in block A were the dressed sand and were independent from the soils in other region in characteristics.

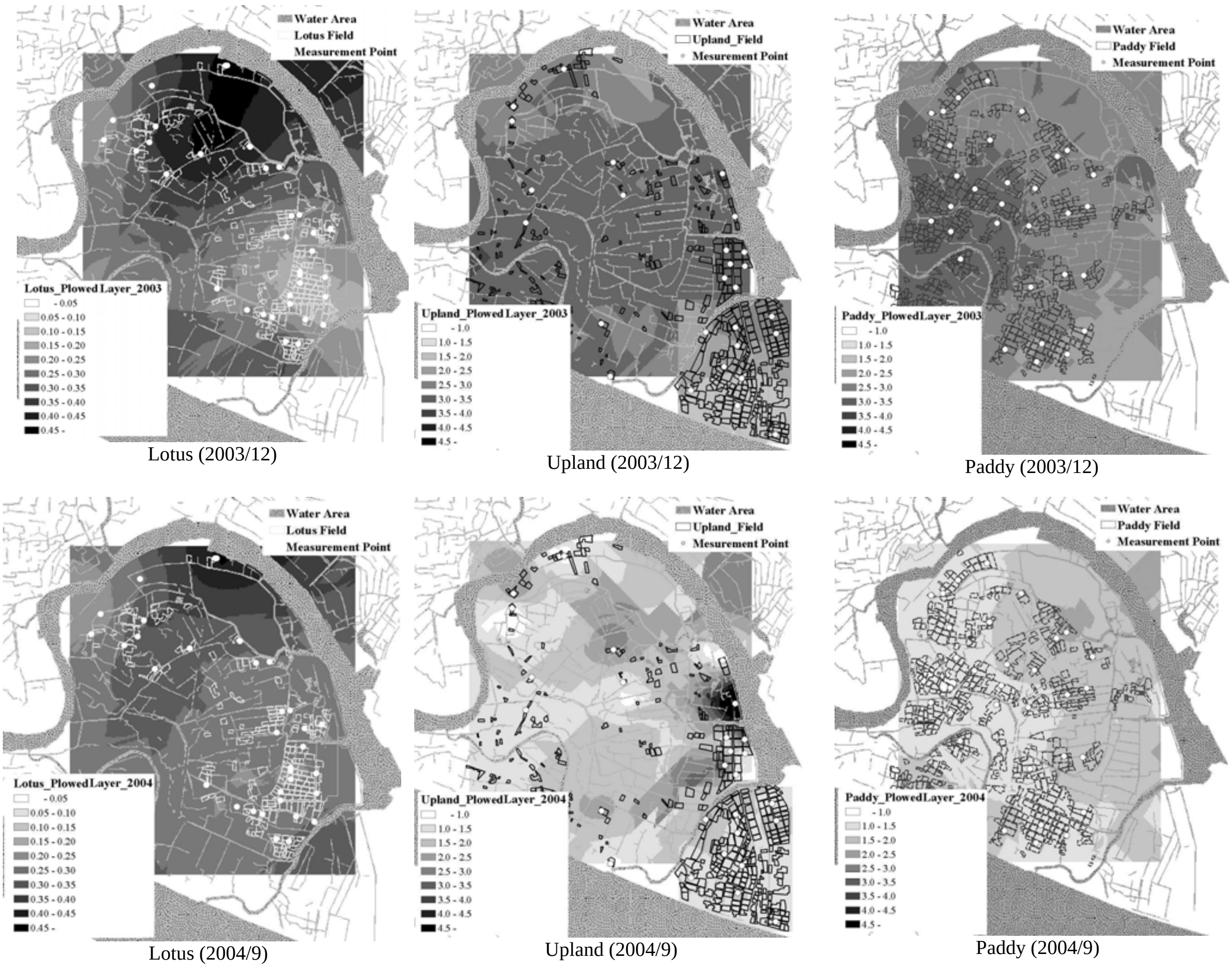

Fig. 7 Prediction Maps of EC Distribution in plowed layer (Depth:0~30cm) for Lotus, Upland and Paddy Field

Statistical values of datasets used in making the prediction maps, parameters of semivariogram model which represent the spatial dependence of features, and results of the cross validation of the prediction model are shown in Table 1 to evaluate precision of the prediction maps.

Table 1 Statistics Values of Samples of EC, Parameter of Semivariogram for Prediction Model
and Results of Cross Validation of Prediction Map at Plowed layer

Plowed Layer		Lotus		Upland_BlockA		Upland(Except BlockA)		Paddy	
		Dec-03	Sep-04	Dec-03	Sep-04	Dec-03	Sep-04	Dec-03	Sep-04
Statistical Value of Sample	count	34	34	10	10	17	17	32	32
	min	0.07	0.00	1.03	0.95	1.68	0.70	1.36	0.19
	max	0.79	0.71	4.28	2.19	4.61	6.60	5.63	3.50
	mean	0.28	0.29	2.20	1.45	3.21	1.91	2.92	1.45
	Standard Deviation	0.18	0.14	0.96	0.35	0.84	1.53	1.00	0.63
	Coefficient of Variation	0.63	0.48	0.44	0.24	0.26	0.80	0.34	0.43
Parameter of SemiVariogram	Sill(S)	0.040	0.025	1.011	0.123	0.686	6.114	1.057	0.415
	Nugget(N)	0.017	0.010	0.650	0.000	0.579	0.000	0.909	0.282
	Q((S-N)/S)	0.578	0.595	0.357	1.000	0.155	1.000	0.140	0.321
	Range	3245	3245	1408	448	1261	874	1867	1209
Result of CrossVaridation	Mean Error	0.002	0.001	0.000	-0.019	0.066	0.124	0.014	-0.010
	Root-Mean-Square Error	0.159	0.148	0.844	0.421	0.927	1.906	1.004	0.623
	Average Standard Error	0.153	0.118	0.985	0.369	0.870	2.166	1.031	0.634
	Mean Standardized Error	0.010	0.005	-0.008	-0.041	0.071	0.044	0.011	-0.009
	Root-Mean-Square Standardized Error	1.039	1.237	0.879	1.098	1.061	0.958	0.975	0.983

CV, one of the statistical values, is coefficient of variation, calculated as standard deviation divided by mean of samples. It is used to compare the variations of samples whose means are different. The parameters of semivariogram means are previously mentioned (2.3 Prediction Method).

Cross validation, which compare a measured value of x_i with its expectance calculated by the model defined by the measurement data except x_i-, is used to show how well the model predicts unknown values. With accurate models, mean prediction error would be close to 0, root-mean-square standardized prediction error would be close to 1 and root-mean-square prediction error should be as small as possible.

Table 2 Distances between
Each Measurement Point

		Upland		
	Lotus	BlockA	Except A	Paddy
Max(m)	478.4	589.4	784.1	1022.3
Min(m)	18.4	217.7	173.9	140.0
Average(m)	194.7	323.2	365.5	319.8

Distances between each measurement point of each type of field are shown in Table 2. The Ranges of most maps (Table 1) are longer than the distance between each measurement point. But, values of Q of many models are small, and dependence of spatial distribution has not been well developed. So values of Range were not well significant. Results of cross validation showed that precision of map was not very good. However they were still good enough as we figure out the outline of distribution of salt accumulation. So, we used these maps for following consideration.

3.1.3 Seasonal Change of Distribution of ECe

As shown in Fig. 7, ECe values in non-irrigation period (Dec. -2003) were greater than those in irrigation period. Comparing distribution patterns, the maps for upland and lotus fields show similar patterns in these periods. On the other hand, maps for paddy have not similar distribution profiles in each period. In non-irrigation period, the west area of region was marked with higher value, and in irrigation period, the east area of region marked higher value. Fig. 8 shows a map of different ECe values for paddy fields, calculated by ECe values of map in Dec. -2003 minus that in Sept. -2004. In the west part of the

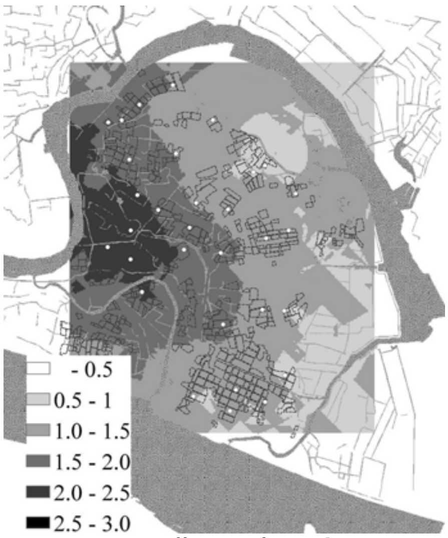

Fig. 8 Difference of EC Value
in Paddy Field (2003/12-2004/9)

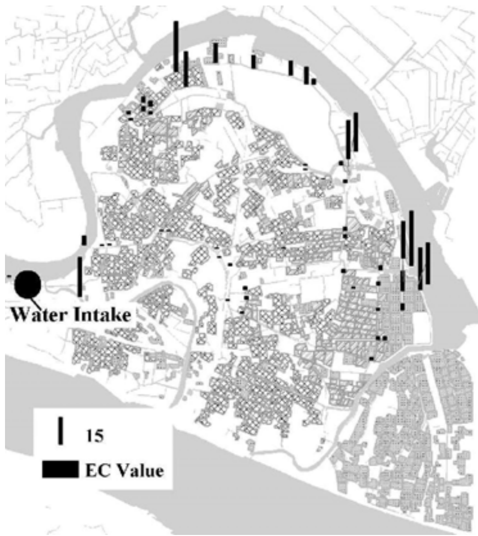

Fig. 9 EC Value
in Irrigation Canal

region, the ECe value decreased remarkably because salt in plowed layer was leached by fresh irrigation water. EC value in irrigation canals in Sept. -2003 is shown in Fig. 9. Irrigation water was taken from the water intake located on the river in the west (Fig. 9). EC values were lower in the upstream region and higher downstream. Drained water from the upstream fields, which contains salt leached from salinized soil, may flow into irrigation canal. In addition, seawater may intrude into canal at the perimeter of the region. So it was considered that more fresh water was applied to the fields located on west part of the region and the soil in the west part of the region was highly permeable to be leached well.
It was found that irrigation water played an important role to remove salt in plowed layer.

3.2 Probability of Salinizaton

3.2.1 Distribution of ECe in Subsoil

In section 3.1, we focused on salt accumulation only in the plowed layer, which affected growth of crops directly. But salt accumulation in soil could happen by transport of salt from lower layer. Now we focused on the ECe in subsoil and examined the potential of salinization. Here we defined ECe in subsoil as the average of ECe measured the depths between 30cm to 60cm. Fig. 10 shows the prediction maps of ECe distribution in subsoil on each observation day in regards to each cultivated crop. The maximum values of ECe was 5.0mS/cm in the prediction maps for paddy and upland fields, and 1.0mS/cm for lotus fields. We also prepared maps separately for block A(shown in Fig. 6).
Table 3 shows statistical values of datasets used in making the prediction map, parameters of semivariogram model which represents the spatial dependence of features, and the results of the cross validation of the prediction model. Statistical values of dataset showed that variation of measurement data is bigger than that of the plowed layer. Precisions of maps were not good, but it could be used for finding the trend of distribution of ECe.
Fig.10 shows that ECe value in subsoil in non-irrigation period is higher than that in irrigation period as was shown in plowed layer. In upland fields in block A, the seasonal changes of these maps were different from the other. This might be attributable to rising of groundwater that contained high concentration of salt with seawater intrusion.
Salt in subsoil had a potential to cause salt accumulation in plowed layer by rising up to plowed layer. So, we compared the maps in plowed layer and subsoil to consider the possibility of salt accumulation.

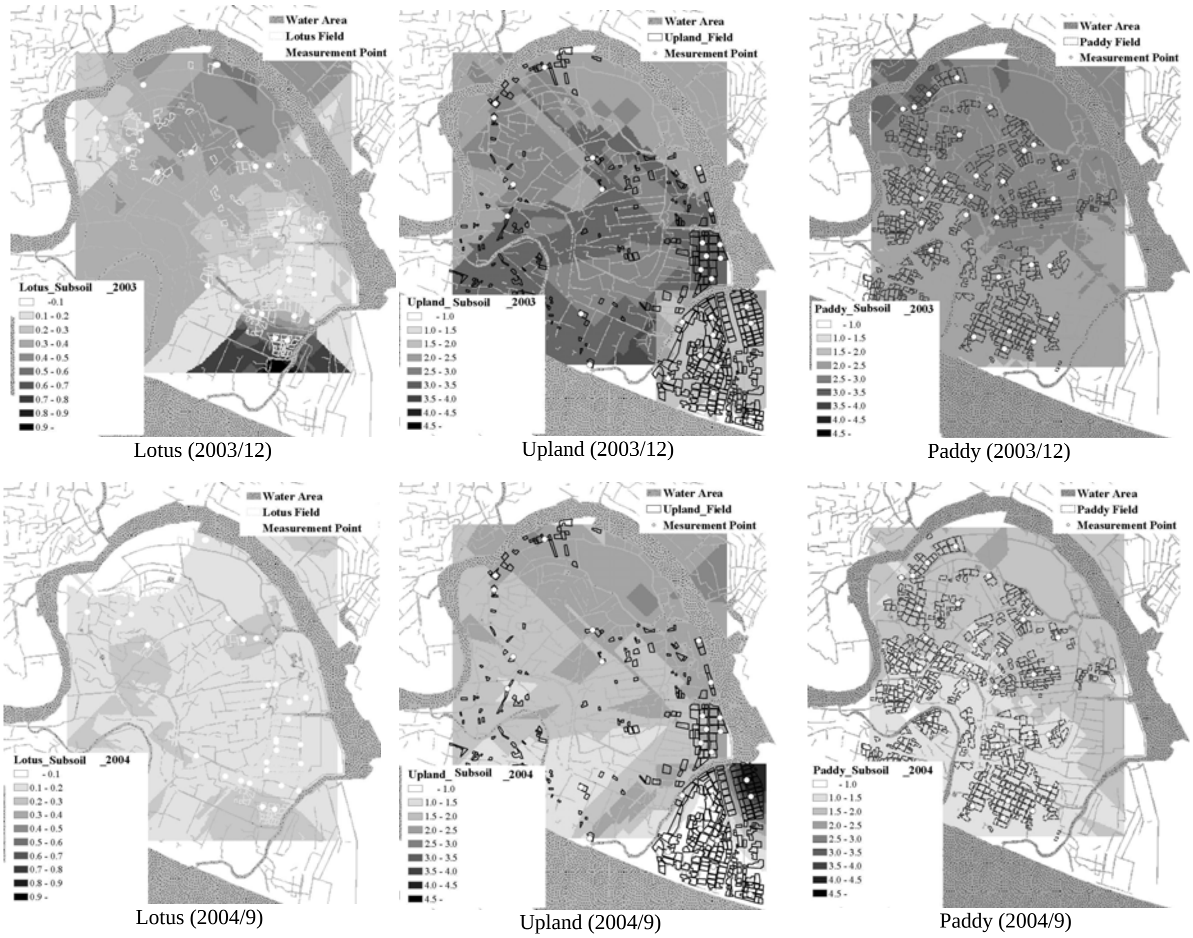

Fig. 10 Prediction Maps of ECe Distribution in Subsoil (Depth:30~60cm)
for Lotus, Upland and Paddy Field

Table 3 Statistical Values of Samples of ECe, Parameter of Semivariogram for Prediction Model and Results of Cross Validation of Prediction Map at Subsoil

Subsoil		Lotus		Upland_BlockA		Upland(Except BlockA)		Paddy	
		Dec-03	Sep-04	Dec-03	Sep-04	Dec-03	Sep-04	Dec-03	Sep-04
Statistical Value of Dataset	count	34	34	10	10	17	17	32	32
	min	0.00	0.00	0.46	0.39	0.75	0.48	0.67	0.20
	max	2.19	0.59	0.74	4.52	11.19	6.56	5.31	3.42
	mean	0.30	0.15	1.77	1.46	2.92	2.00	2.55	1.57
	Standard Deviation	0.38	0.15	2.03	1.49	2.48	1.78	1.17	0.85
	Coefficient of Variation	1.25	0.94	1.15	1.02	0.85	0.89	0.46	0.54
Parameter of SemiVariogram	Sill(S)	0.139	0.023	4.031	3.108	6.166	3.184	1.579	0.720
	Nugget(N)	0.117	0.013	4.031	0.000	6.166	3.184	1.053	0.720
	Q((S-N)/S)	0.157	0.465	0.000	1.000	0.000	0.000	0.333	0.000
	Range(m)	499	1653	1353	1408	3594	3594	3386	3242
Result of CrossVaridation	Mean Error	-0.013	0.002	-0.030	-0.031	0.030	-0.033	0.015	-0.046
	Root-Mean-Square Error	0.388	0.165	2.124	0.846	2.534	1.835	1.259	0.884
	Average Standard Error	0.393	0.134	2.133	1.226	2.593	1.864	1.135	0.880
	Mean Standardized Error	-0.034	0.010	-0.014	-0.030	0.010	-0.018	0.008	-0.052
	Root-Mean-Square Standardized Error	0.992	1.216	0.997	0.737	0.979	0.984	1.106	1.004

3.2.2 Difference between ECe in Plowed layer and Subsoil

Fig.11 shows the maps of difference in ECe value between subsoil and plowed layer. Areas where values of ECe in subsoil are lower than that in plowed layer were colored with white, and the areas where values of ECe in subsoil are higher than that in plowed layer were colored with dark color. The maximum values are 1.0mS/cm in the maps for paddy and lotus fields, and 2.0mS/cm for upland fields.

In non-irrigation period, ECe in plowed layer was higher than that in subsoil for paddy and upland fields. In

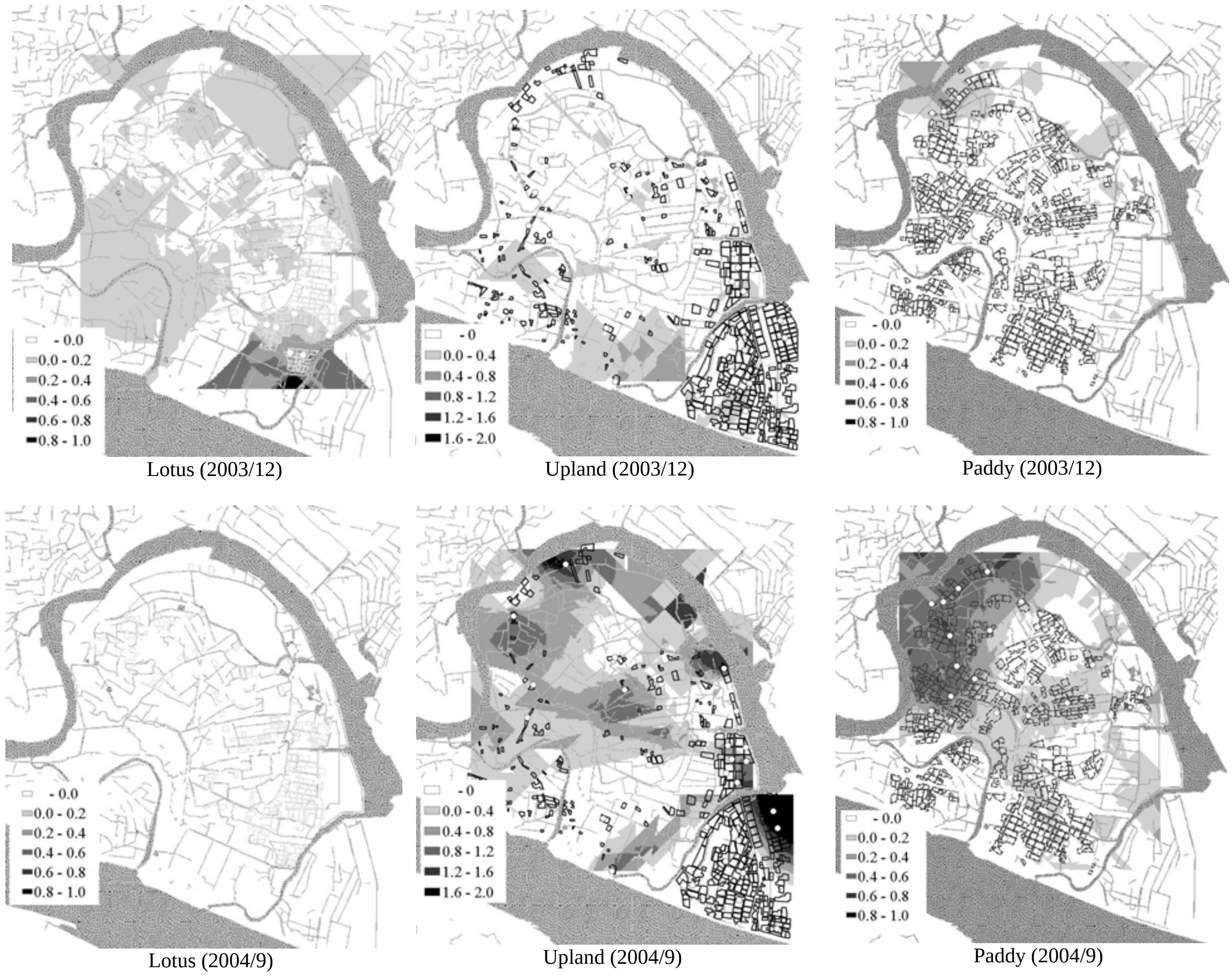

Fig. 11 Difference Maps of ECe Value between Subsoil and Plowed layer

irrigation period, ECe in subsoil was higher than that in plowed layer for paddy and upland fields, especially in the west part of the region. This showed that salt leached from plowed layer by irrigation water accumulated in the subsoil. In lotus fields, the seasonal changes shown in these maps were different from the others, but the values were far lower.
We could find the possibility of salt transport from the lower layer in these maps. But to estimate the risk of salinity damage, we must consider both degree of salt accumulation in plowed layer and possibility of salt rising from subsoil.

3.3 Risk of Salinization in Each Field

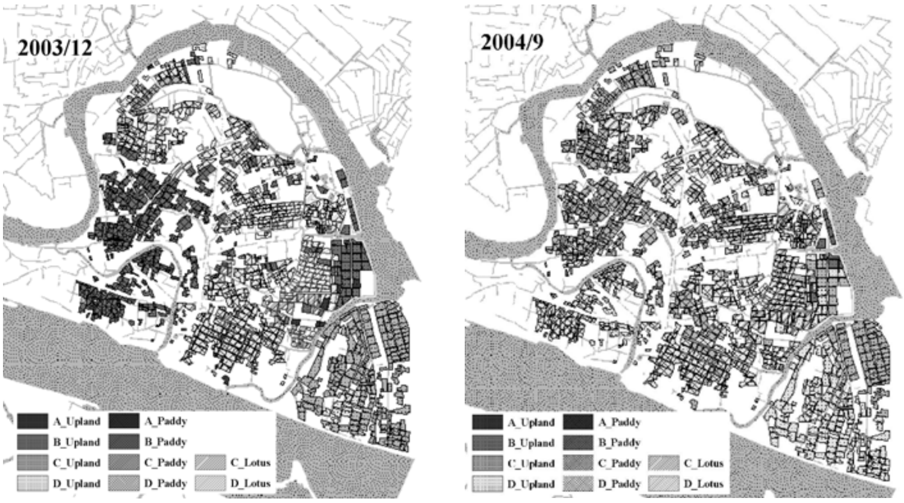

Fig. 12 Risk Map of Salinization in each Fields

To consider the salinity risk in each field, expectancies of ECe of each field (value at the center point of the field as representative value) were extracted from each prediction map based on the field types (lotus, upland, paddy). And we classified the risk of each field to four levels by two conditions, or degrees and probability of salt accumulation, as shown in Table 4. Here, EC_P is the expectancy of ECe in plowed layer, and EC_L is that in subsoil. Each level of risk was defined as follows. Level A, in the case that EC_P was higher than 3 mS/cm and EC_L was higher than EC_P, salt had accumulated already and salt accumulation was ongoing by rising up of salt from subsoil. Level B, in the case that EC_P was higher than 3 mS/cm and EC_L was smaller than EC_P, salt had accumulated at that time but risk of salt rise from subsoil would be smaller than Level A. Level C, in the case that EC_P was lower than 3 mS/cm and EC_L was higher than EC_P, salt had not accumulated at that time, but rising of salt could cause salt accumulation. Level D, in the case that EC_P was smaller than 3 mS/cm and EC_L was lower than EC_P, salt had not accumulated at that time, and rising of salt from subsoil would not occur.
Fig.12 shows the risk maps of fields marked with classification by the above conditions. The risk levels of paddy fields were higher than other fields. In non-irrigation periods, many fields were marked with level B, because of the transport of salt from lower layer. On the other hand, in irrigation periods, many fields marked with level C. It shows that salt leached by irrigation water were accumulated in the subsoil, and had potential to return to plowed layer. Upland fields except in block A showed the same tendency as paddy fields. Upland fields in block A, which were mostly marked with C in both periods, had potentials to be damaged if groundwater table would rise by the excessive irrigation water. All of lotus fields marked with level C or D, and it was shown that lotus fields had low risk to be damaged by salinity.
To focus on spatial distribution, fields in the west part of the region, that was near the water intake of irrigation water (shown in Fig. 9), were marked with a high risk. This might be attributed to salt accumulated before 1974 when the estuary weir was constructed. Fields on the east part of region, which faced on the sea, were marked with higher levels. As a result, fields that need surplus water for salt removal were paddy fields located in the west part. Use of water before planting crops was found to be effective. Upland fields located in the east part of region also needed surplus water. –although we have to be careful to irrigate moderate amount of water. Too much irrigation water would cause rising of salted groundwater.
Using these maps, we could know easily how to distribute irrigation water for effective water management.

Table 4 Classification of Salinity Risk

Risk Level		Conditions	
		Degree	Probability
A	Salt has accumulated, and accumulation are ongoing	$EC_p>3$	$EC_P<EC_L$
B	Salt has accumulated, but it could be removed easily.	$EC_p>3$	$EC_P>EC_L$
C	No problem at present, but there is fear of accumulation of salt	$EC_p<3$	$EC_P<EC_L$
D	No problem	$EC_p<3$	$EC_P>EC_L$

EC_p: Prediction value of ECe in plowed layer , EC_L: Prediction value of ECe in Subsoil

4. Conclusion

In this paper, we examined how to use GIS to find out better irrigation management in the case study of Kawauchi region. Using risk, resulting from the analysis of the spatial distribution and profile of ECe, we could extract the area where surplus water would be needed. Seasonal changes should also be taken into consideration.
This method that combines the expectance of feature considering seasonal changes and GIS database, could be used effectively to approach the regional problems.
But we must remember that the prediction method in this paper did not consider the influence of irrigation network and cultivation method by each farmer. To suggest the most effective water management, more precise method would be needed that could consider many factors concerning the problems.

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