2. Study on Development of Information Mapping System for Regional Vulnerability to Fire Spreading.

Noboru Kimata*, Toru Futagami**, Harutoshi Oga***, Mai Sasaki****

[Abstract] As decentralization of power, local governments are pressed to draw up their own master plan. In this paper, we try to support their endeavor by presenting systems for fundamental data collection and for evaluation of alternatives on fire prevention planning. First, we develop an algorithm to convert "land cover classification map" to "attributed mesh map" and do 20 case simulation, applying fire spreading simulation system previously developed by authors to maps generated by the algorithm mentioned above. Secondly, we construct regression model based on these simulation results, in which the ratio of wooden building, wind velocity and number of regions blocked by firebreak are selected as independent variables, and we get a coefficient which determinant is 0.85. We define rank of regional vulnerability to fire spreading based on this regression estimate calculation. Finally, we show a mapping system of these regional data using chromatic difference of red-color and demonstrate to output such colored map applying the system to K-city. We also demonstrate to output reevaluation map of fire prevention alternative in this city.

[Keyword] vulnerability to fire spreading, decentralization of power, regional fire prevention plan, land cover classification map, fire spreading simulation, regression model, colored map

1. Introduction

As a positive reaction for decentralization, local governments are going ahead with preparation of master plans. The ministry of land, infrastructure and transport aims nationwide arrangements to establish data base under it's scheme " Investigation of utilization of environmental information", which will be utilized to prepare master plans by the local governments independently. Preparation of *land cover classification map* by using aerial photographs is considered as one of them[1) ~ 2)]. This mapping information system is strong enough to represent the current situation of whole area because aerial photographs contain very accurate and wide area information. We discuss here method of usage of this information system for regional fire prevention planning.

Present authors developed a mesh type fire spreading simulation system to monitor hazards in urban areas. And we have confirmed the simulation of Sakata and Fukumitsu conflagration and estimated the safety against fire in newly planned Fukumitsu area. Also, we have proposed support for arrangement of the green belts and plan of fire protection zone[3)~6)].

In this study, linking these two method we are going to develop a mapping system of vulnerability to fire spreading, which can be used to make master plan to design fire safety urban area. At first, we are going to show how to make *attributed mesh map* that is used for fire spreading simulation, based on *land cover classification map*. Secondly, we will propose a regression model based on the result of the fire spreading simulation. Finally, mapping algorithm is introduced in order to demonstrate the vulnerability index on fire spreading. As an example, improvement of fire prevention of K city and its' present

* Member of JSCE, Professor, Department of Engineering, Kanazawa University (2-40-20 Kodatsuno Kanazawa City) tel:076-234-4914
** Member of JSCE, Department of Engineering, Ehime University(3 Bunkyocho Matsuyama City) tel:089-927-9837
*** Aero Asahi Co. Geoinformatic Dept. (3-1-1 Minamidai Kawagoe City) tel:049-244-6061
**** Aero Asahi Co. Air-Borne Survey Dept. Remote Sensing Group(1-18-1 Shinsayama Sayama City) tel:042-955-0975

situation is reported.

2. Conversion of Land Cover Classification Map into Attributed Mesh Map

2.1 Outline of Fire Spreading Simulation System

As mentioned above, a mesh type simulation system of fire spreading in urban area has been developed by the authors[3]. Simulation region is described by *attributed mesh map* in this simulation system. The spreading form of fire from the origin to surround meshes is calculated and displayed on the simulation system based on restored data of each attribAuted meshes and assumed data of wind.

Classification of attributed meshes and their stored data are shown in the Table 1.

"p"," rc", and "g" of restored data represent the ratio of mesh area to wooden buildings, fire resistant buildings and green lands area respectively. "gh" is height of trees and "q" is the ratio of fire protected wooden buildings. Attribute A and B represent combustible meshes with mainly wooden buildings and noncombustible meshes with fire resistant buildings respectively, while G represents green lands. Depending on the scale of fire and the height of trees, the G mesh is treated as combustible or noncombustible in this simulation.

The following three spreading patterns are dealt with by this simulation.

① Fire spreads from burning mesh to all adjacent combustible meshes.

② Fire spreads to the combustible leeward mesh just sheltered by vacant lot.

③ Fire spreads to the green lands meshes on the leeward and sideward of the wind.

This simulation system was verified with reoccurrence simulation of Sakata and Fukumitsu conflagration. The result of simulation shows that this system has sufficient reappearance on the leeward of the wind, in spite of slight overestimation on the sideward of the wind.

Table 1 Classification of Attribution of Meshes

Attribution	Symbol	Restored data
Combustible mesh	A	p, q, rc
Noncombustible mesh	B	
Green land mesh	G	g, gh
Vacant lot mesh	" "	

2.2 Conversion System to Attributed Mesh Map

Table 2 shows the contents of the classification of land cover. These 14 classifications of land cover are used in *land cover classification maps*[1]. As shown in the Fig. 1, the data is created by two-dimensional interpretation of regional aerial photographs and converted into three-dimensional by adding the relative heights calculated from the DSM (Digital Surface Model) and 50m mesh digital maps.

In other word, four characteristics are used in *attributed mesh maps* for the hazard simulation as shown in Table 1 and there are five necessary data for these classification, namely P(I,J)~GH(I,J) shown as variables in the Table 3. The correspondence between these five values and 14 classifications can be determined as shown in the Table 3.

The fundamental size of attributed mesh in fire spreading simulation map is 20m. The length of 1 pixel in *land cover classification map* is 2m. Therefore, it is possible to determine the above parameters by summing upon image of 10 pixels × 10 pixels.

Table 2 Classification of Land Cover

No	Land cover classification (2-dimensino)	Land cover classification (3-dimensino)	Relative height	Color (3D)
1	buildings	high rise	30m~	red
2		tall buildings	16m~ 30m	purplish red
3		ordinary buildings	8m~ 16m	purple
4		flat house	~8m	light purple
5	trees	tall trees	8m~	green
6		short trees	~8m	yellow green
7	grassy land	grassy land		light green
8	rice field	rice field		yellow
9	field	field		yellow brown
10	exposure ground	exposure ground		brown
11	sea	sea		dark blue
12	river	river		blue
13	lake	lake		light blue
14	road	road		white

Table 3. Interpretation Table between Attribute Mesh Map and Land Cover Classification Map

Attributed Mesh Map	Contents	Land Cover Classification Map
P[I,J]	wooden building area	flat house(4)
RC[I,J]	fire resistant building area	high rise, tall and ordinary building (1~3)
G[I,J]	tree area	tall and short tree (5~6)
RR[I,J]	road and water area	sea, river, lake and road (11~14)
GH[I,J]	height of tree	height of tree (high and low tree)

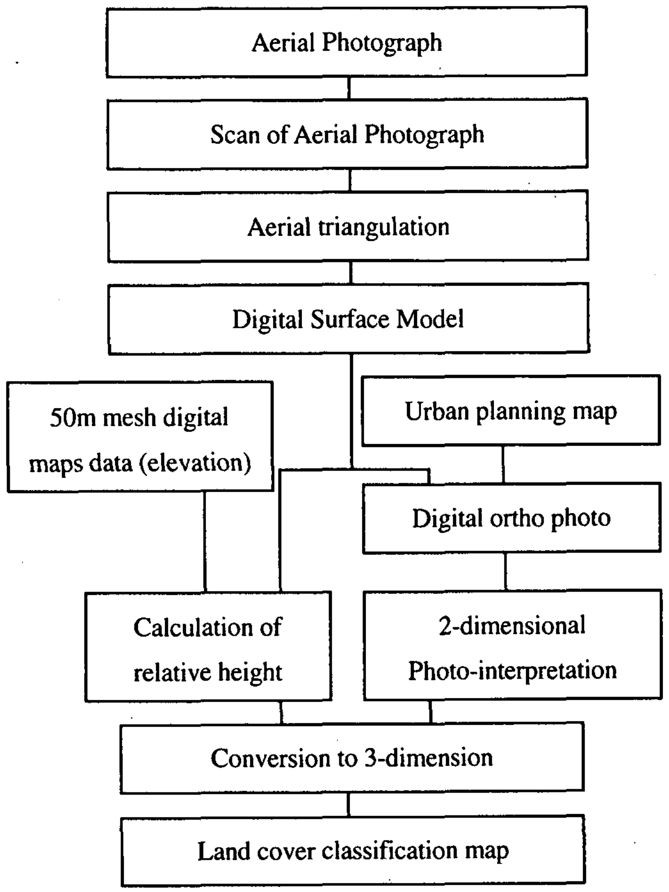


Fig. 1 Creation method of land cover classification map

That is, X[I,J], area of each P[I,J], RC[I,J], G[I,J] and RR[I,J] at Table 3, is fallowing:

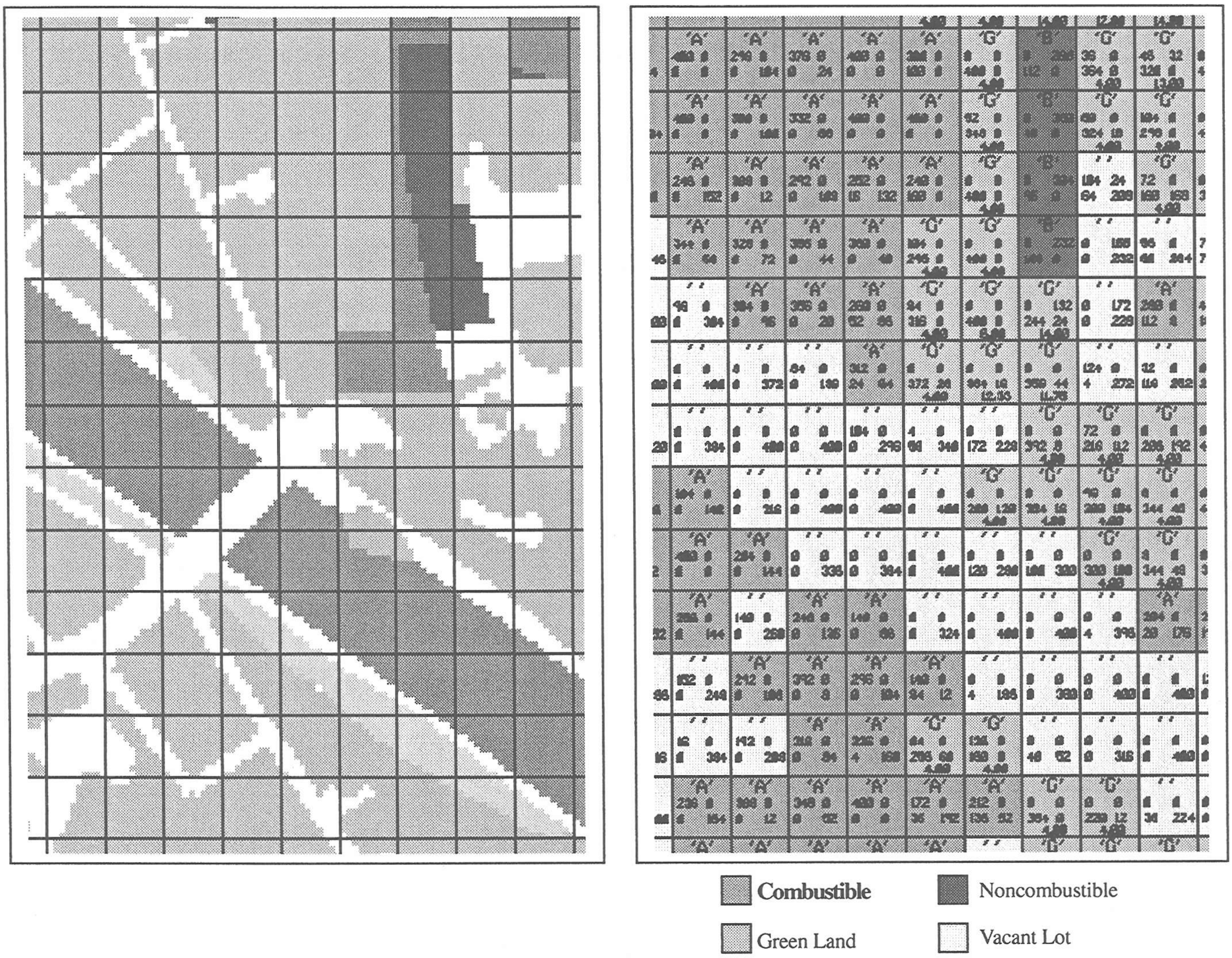
$$X[I,J] = (\text{number of discerned pixels}) \times (\text{area of pixel}) \quad \cdots(1)$$

The height of trees is estimated by following formula;

$$GH[I,J] = \{(\text{number of high tree pixel}) \times 14 + (\text{number of low tree pixel}) \times 4\} / \{(\text{number of high tree pixel}) + (\text{number of low tree pixel})\} \cdots(2)$$

In this formula, it is assumed that the height of tall tree is 14m on the average and short tree is 4m respectively.

Until now, input of *attributed mesh map* data was carried out by the dot counter method. By the current linking system with *land cover classification map*, it becomes possible to increase the accuracy of *attributed mesh map* in a wide range.



①Land Cover Classification Map (20m mesh) ②Attribute Mesh Map

Fig. 2 The Example of map output

Fig-2 shows an example of *land cover classification map* and correspondence *attributed mesh map*. The red color indicates the dangerous area where the density of wooden houses is very high. Deep gray, green and light blue indicate fire resistant buildings, green lands and vacant area respectively.

3. Construction of Regression Model for Vulnerability to Fire Spreading

3.1. Creation of Fundamental Data by Fire Spreading Simulation

Safety of district for fire is classified by evaluating three types of dangerousness and risks, namely, a) risk of outbreak of fire, b) risk of fire spreading and c) availability of fire extinguish. Here the risk of type b) is dealt with. The extent of fire spreading area, the base for this estimation, is calculated by the procedure starting from aerial photographs of the area and following the systematic methods shown in Fig. 3.

Firstly, based on aerial photographs, 15 *land cover classification maps* are prepared. Each map size is 1km square. Then 15 *attribute mesh maps* are created as described in the section 2-2. Secondly, regarding the condition of wind velocity and direction for simulation, investigation was carried out for weather conditions of

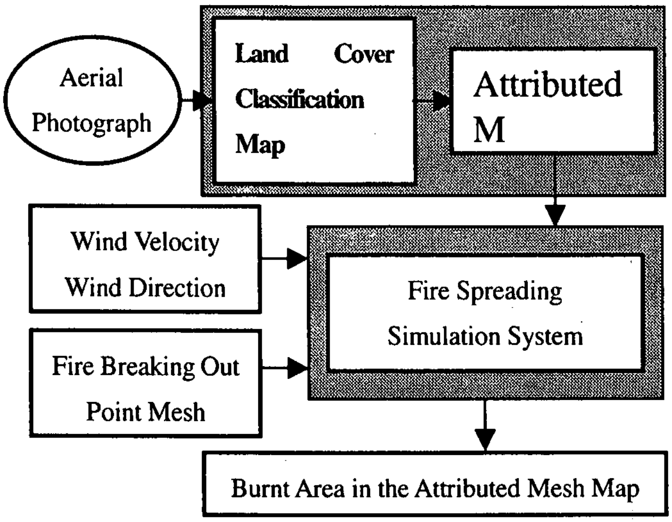


Fig. 3 Fundamental Data Creation by Fire Spreading Simulation

winter and summer and it was found that there were four areas with different velocities in the two seasons. Therefore, two cases for each of four areas are considered depending on the season. According to these data, 19 case simulations for 15 areas were designed. In addition to them, a special case was considered by assuming that whole area is covered with combustible meshes and has the wind velocity of 10m/s. Including the last case, the total cases of simulation is 20 which are shown in the Table-4.

Next, a randomly selected mesh in the group of combustible meshes closer to the center of each map is assumed to be the mesh of fire origin. By employing this method, extent of fire spreading within 150 minutes was simulated 5 times by randomly changing only the mesh of fire origin. And extent of fire spreading was estimated by the following formula.

$$Yi = EFi + \sqrt{VFi} \quad i = 1, \cdots 20 \quad \cdots (3)$$

Here, EFi is mean value of simulated 5 results of case i and VFi is variance. Simulation result of 20 cases is shown in Table-4.

Table 4. Simulation Case and its Result

Case	Map Area No	Wind velocity	EF	√VF	Y
1	1	7	163.2	51.5	214.7
2	2	7	138.1	61.7	199.8
3	3	7	131.9	72.3	204.2
4	4	7	265.3	92.2	357.5
5	5	8	124	74.6	198.6
6		7	101.8	60.2	162
7	6	8	95.6	24.0	119.6
8		7	67.6	21.2	88.8
9	7	8	234.6	56.0	290.6
10		7	237.6	50.1	287.7
11	8	8	139.4	67.2	206.6
12		7	142.8	21.9	164.7
13	9	6	48.6	22.1	70.7
14	10	6	148.6	58.6	207.2
15	11	6	231.0	88.8	319.8
16	12	6	195.8	59.3	255.1
17	13	7	66.3	24.8	91.1
18	14	7	138.8	46.6	185.4
19	15	7	148.4	76.7	225.1
20	Wooden buildingsonly	10	–	–	663

3.2. Multiple regression model of vulnerability to fire spreading

In this section, we are trying to propose an assessment system without the simulation procedure by constructing a meta-model to evaluate Yi.

Fire spreading in urban areas is determined by both factors of accelerative and resistive in the area. Density of wooden buildings and wind velocity is accelerative factors. As mentioned above, the availability of fire fighting is not taken into consideration when vulnerability to fire spreading is evaluated. So here resistive factors are fire resistant buildings, green belt, and vacant lots like roads and

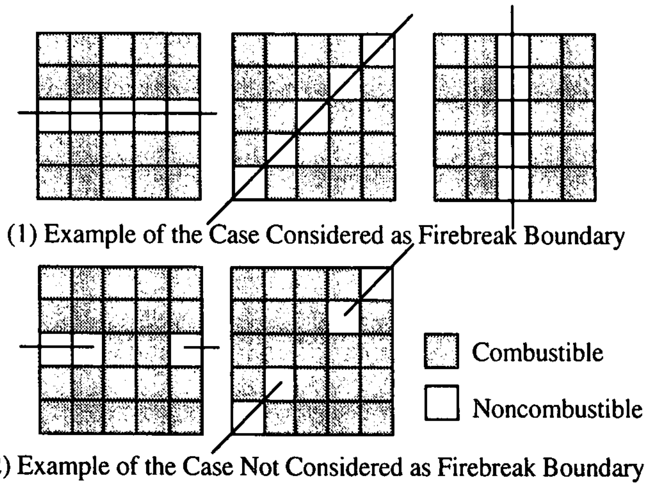


Fig. 4 Criteria for the Estimation of Blocked Zone

rivers etc. The authors have already confirmed the simulation results that the fire spreading is prevented by blocked belt consisting of those factors.

As a meta-model of the fire spreading simulation system, we are trying to establish a multiple regression model with respect to two accelerative factors mentioned above and one resistive factor, number of blocked zones, by using the 20 cases of simulation results in Table 4.

Yi, the variable in Table 4, can be written as following formula. Here X_{1i} is the ratio of wooden houses in the mesh map of case i, X_{2i} is the number of blocked zones in the mesh map of case i, and X_{3i} is the wind velocity of case i.

$$Yi=a_1X_{1i}+a_2X_{2i}+a_3X_{3i} \quad (i=1, 2, 3, \ldots 20) \quad \cdots(4)$$

All variables in the above formula except the number of blocked zones in mesh map are known and easily calculated. “Blocked” means here the state that a group of combustible meshes A’s are almost surrounded by noncombustible meshes like B, G and “ ” listed in Table 1.

However, though there are approximate criteria as shown in the Fig. 4, judgments may depend on an operator. To prevent from these biasing, we are trying as can as

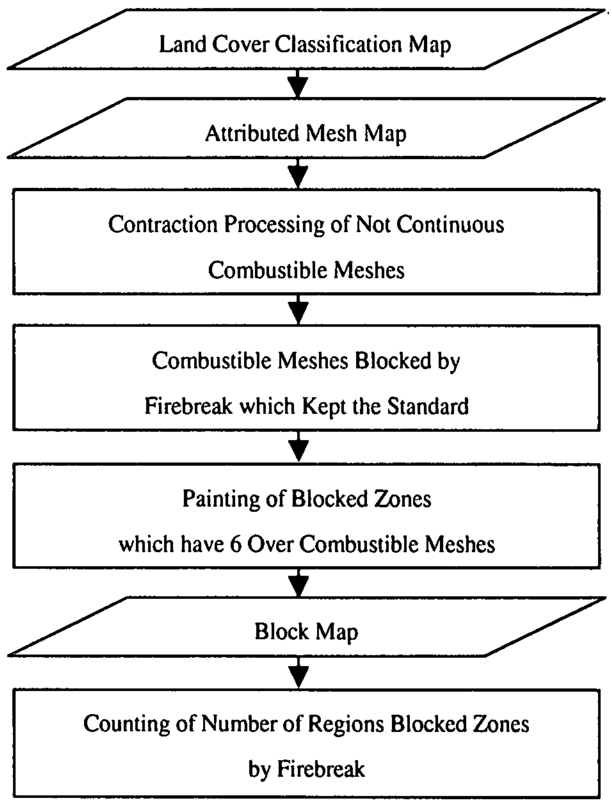


Fig. 5 Automatic Counting Flow of Number of Blocked Zones

possible to automate the method of counting number of blocked zones X_{2i} in *attributed mesh maps*. The flowchart of this automatic algorithm is shown in the Fig. 5.

In this counting system, at first, contraction processing from A to B is carried out. Those combustible meshes A’s have no continuity in the *mesh map*. Next, by referring to the criteria given in Fig.4, recognized blocked zones are painted by different colors to form a working block map. If the size of blocked zones is too much small, it may be difficult to acquire the reality of the ground features. Therefore, such zones that contain less than 6 combustible meshes are not considered as blocked one in this algorithm. In the present counting system, painting blocked zones are carried out manually but number of blocked zones is calculated automatically by counting the

Table 5 Fundamental Data and Results of Prediction and Error by Regression

Case	X_1	X_2	X_3	Y	Y of Prediction	Error (%)
1	43	18	7	214.7	236.5	10.2
2	34	14	7	199.8	194.5	-2.7
3	45	18	7	204.2	254.3	24.5
4	54	14	7	357.5	372.0	4.1
5	36	15	8	198.6	206.3	3.9
6	36	15	7	162	202.8	25.2
7	33	16	8	119.6	170.2	42.3
8	33	16	7	88.8	166.6	87.7
9	36	6	8	290.6	291.5	0.3
10	36	6	7	287.7	287.9	0.1
11	37	16	8	206.6	205.7	-0.4
12	37	16	7	164.7	202.2	22.7
13	30	23	6	70.7	70.2	-0.7
14	45	16	6	207.2	269.6	30.1
15	39	9	6	319.8	282.6	-11.6
16	37	23	6	255.1	132.4	-48.1
17	25	24	7	91.1	19.9	-78.1
18	33	16	7	185.4	166.6	-10.1
19	37	17	7	225.1	192.7	-14.4
20	64	1	10	663	594.6	-10.3

number of painted colors.

In this paper, elimination of human biasing is considered as an important task, and we try to establish a meta-model for estimation of Yi by applying this automatic oriented system.

First, number of blocked zones (X_{2i}) in each *attributed mesh maps* of 15 areas shown in Table 4 were calculated by using the counting system mentioned above. The result is shown in Table 5 along with X_{1i} and X_{3i}. Then, using this table, regression analysis was carried out and the result is shown in Table 6.

According to results, the regression formula becomes

$$Y = 8.88X_1 - 9.46X_2 + 3.57X_3 \dots (5)$$

Table 6. Result of Regression Calculation

Contents	X_1	X_2	X_3
Coefficient	8.88	-9.46	3.57
Standard error	1.56	1.72	9.61
T-test	5.70	-5.52	0.37
Coefficient of determination	0.85		
Multiple correlation coefficient	0.92		

Table 7 Classification of Error Types

Error type	Case	%	Existence situation of Blocked Zone
~5%	2, 4, 5, 9, 10,11, 13	35	It is possible to recognize suitably of blocked zones.
~15%	1, 15, 18, 19,20	25	There are a few large blocked zones that need to divide.
~30%	3, 6, 11, 14	20	Small blocked zones are dotted in the area. And there are a few large blocked zones.
Special (+)	7(42%), 8(87%)	10	There are green land or noncombustible land within a large blocked zone.
(−)	16(-48%) 17(-78%)	10	There area thin and long blocked zones and small blocked zones.

The coefficient of determination of this formula is 0.85 and multiple correlation coefficient is 0.92. These values mean good result. With regard to t-test values, coefficients of X_1 and X_2 are bigger than X_3 and have nearly equal value. This also implies that it is needed further research to develop automatic counting system for elimination of human biasing.

In Table 5, the difference between predicted extent of fire spreading area by eq. (5) and simulated value is also shown. If the error is positive, regression model is over estimated and if negative, regression model is under estimated. The error analysis is shown in the Table 7.

In the areas where there are no considerable errors, noncombustible, green, or vacant lot meshes are found with continuity and suitable recognition of blocked zones is possible by our proposed system.

In the areas with about 30% error, several zones were not recognized as blocked zones due to judging as discontinuity by the criteria shown in Fig.4, or small zones were recognized as blocked zones and were dotted in the area.

Special characteristics can be seen in the area 6 that combustible meshes zone is distributed unevenly due to the existence of a river in the middle of this area. In the case that there are green lands or noncombustible lands within the large blocked zone, they can be taken into consideration by our fire spreading simulation system. But it is difficult to be considered in the present meta-model.

In the other special cases of 12 and 13, it can be assumed that number of blocked zones is overestimated because a thin and long combustible meshes zones had been formed by the simple criteria that whether or not the zone contain more than six combustible meshes. From these reasons, it is needed further study to improve the algorithm to take account of configuration of blocked zones and to form more reliable meta-model.

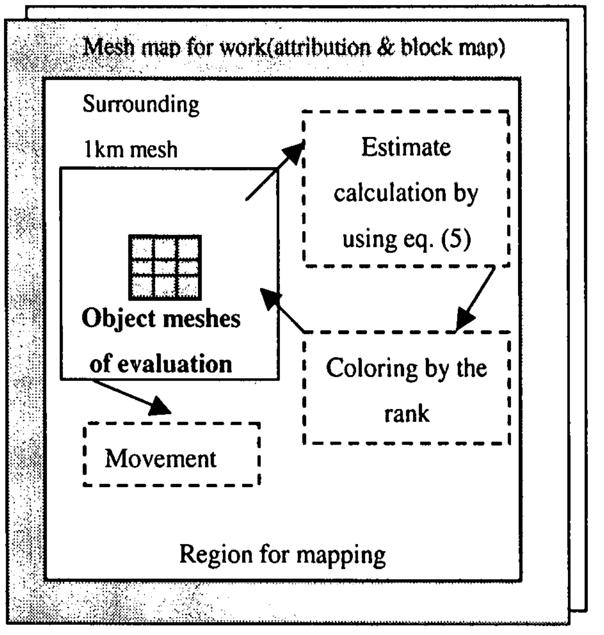


Fig. 6 Basic Concept of Mapping Algorithm of Vulnerability Index on Fire Spreading

Table 8 Rank of Estimate

Fiducially value	Rank of estimate
Y ≧ 1×SF	1
Y ≧ 0.8×SF	2
Y ≧ 0.6×SF	3
Y ≧ 0.4×SF	4
Y < 0.4×SF	5

4. Construction of Mapping System of Vulnerability Index for Fire Spreading

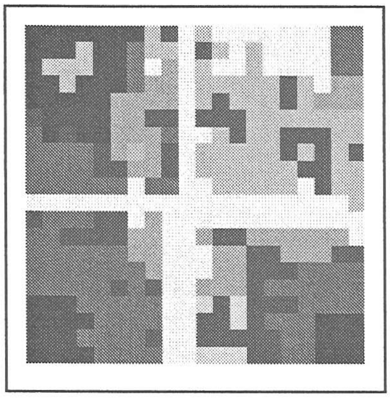
4.1 Basic Algorithm of Index Mapping

It is obvious that eq. (5) is the regression formula to evaluate fire spreading risk in a 1km square.

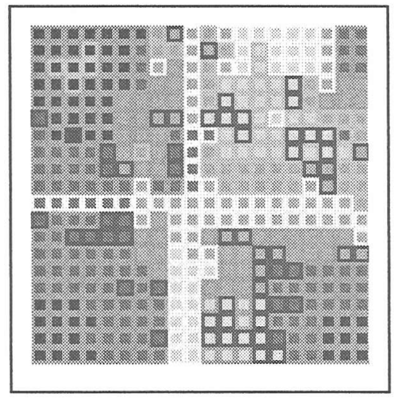
This is rather rough to deal with regional fire hazard. In the present study, we try to evaluate risk of each 60m square unit which consists of 3×3 meshes if mesh size is 20m. Vulnerability index is a measure of fire spreading risk. In the case of 60m square, estimation of risk should be a function of surrounding conditions.

So as shown in Fig. 6, the calculated value by applying eq. (5) to the mesh map of 1km square from the center of selected 3×3 meshes, is assigned to all 3×3 meshes using two type of working maps. By moving the center of selected 3×3 meshes throughout the whole area, this procedure is applied to each 60m mesh unit.

Concerning the evaluation of Yi and painting of index assigned to meshes, the following method is adopted. The verification of fire spreading simulation on



①Only combustible meshes are painted using estimated ranking color



②All meshes are painted using estimated ranking color and boundaries of mesh are drawn by the color itself

Fig. 7 The Example of Two Algorithms of Fire Spreading Information Map

which the regression formula of eq. (5) is based, was carried out using Sakata conflagration. Then ranking of Yi was carried out as shown in Table 8 by taking the 150 minuets after extent of Sakata conflagration (SF) as standard value. And for representation of the estimated index, *Red color system* was used and difference of rank is shown by difference of the brightness of red color.

In general, 3×3 meshes contain not only combustible meshes but also some other type meshes. Combustible meshes should be colored according to estimated ranking. Concerning the color of other attributed mesh, another proposal may be possible from readability of as fire spreading information maps.

Present study carried out two algorithms as described below and demonstrated in Fig. 7:

①Only combustible meshes are painted using estimated ranking color.

②All meshes of 3×3 mesh are painted in accordance to the ranking color, and the boundaries of mesh are drawn with by the mesh attribute color itself.

4.2. Example and Consideration of Algorithm for Mapping

These systems were applied for an area of 10 square km, bounded by 2.5km along east-west direction and 4km along north-south direction using *land cover classification map* of 3.5km east-west and 5km north-south as basic working map.

Concerning the wind velocity, average of maximum wind velocity of each month, 14.2 m/s, was adopted. On the base of working area map and this wind velocity, colored index map were output by two method described in 4.1. Fig.8 is output by type of ②mentioned above. As shown in Fig.8, almost all area become high bright red except the part of near the center.

In our system, the index rank of an area becomes higher when the wind velocity becomes higher. Also when the density of wooden buildings becomes higher and number of blocked zones becomes smaller.

Among those factors, accuracy of estimated density of wooden buildings is high. On the other hand, wind velocity is a set up value and here high one had been assumed. This is one of the reason why the map showed a highly risk color. Further, due to automatic algorithm during the development, estimated number of blocked

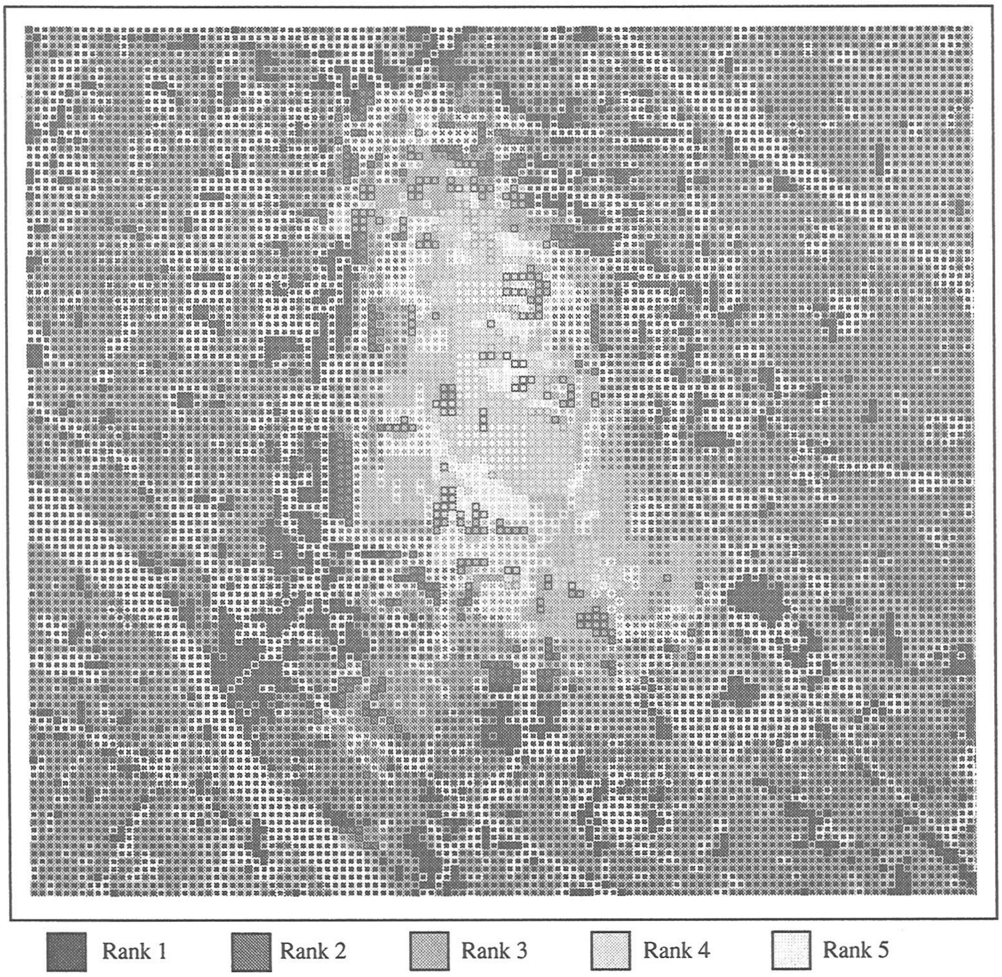


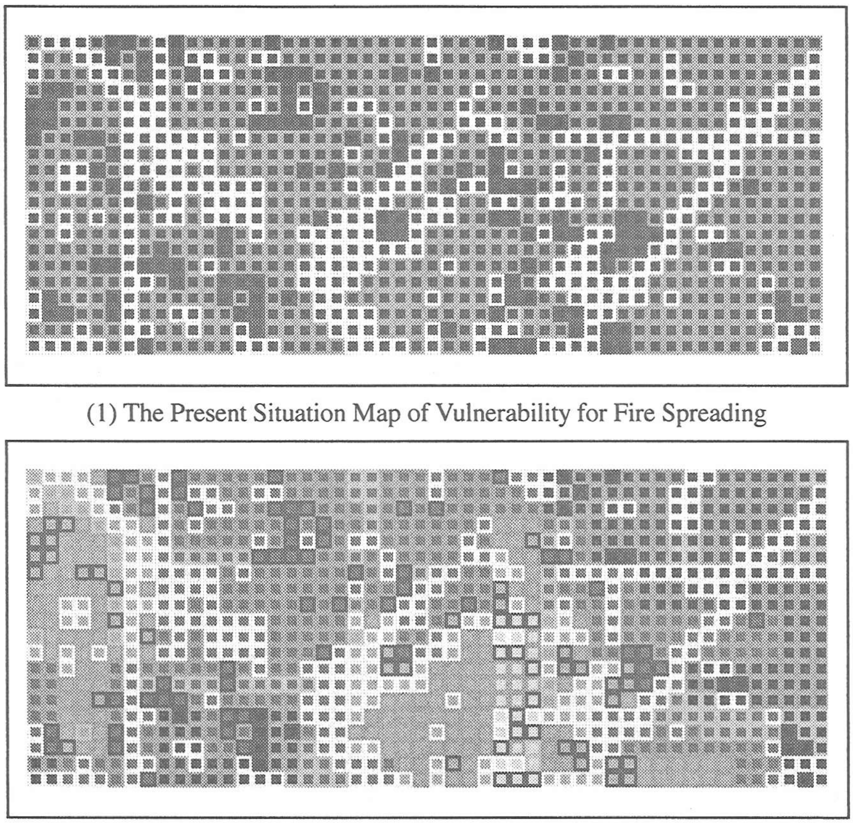
Fig. 8 Output Map of Vulnerability to Fire Spreading

Table 9 Comparison on Number of Blocked Zones

	Automatic	Experiential
Mean value	14.20	18.14
Standard deviation	4.41	3.19
Minimum value	3	9
Max value	28	27
The whole number of blocked zones	200	239

zones may be inaccurate and become smaller. Among those factors, accuracy of estimated density of wooden buildings is high. On the other hand, wind velocity is a set up value and here high one had been assumed. This is one of the reason why the map showed a highly risk color. Further, due to automatic algorithm during the development, estimated number of blocked zones may be inaccurate and become smaller.

Table 9 is a statistical comparison between automatically and experiential calculated number of blocked zones for this application map. According to the Table 9, the total number of blocked zones in automatic system is 16% less than that of experiential system. Similarly, the average is 21% less than experiential system. The maximum number of blocked zones is nearly equal in both systems while the minimum number is less in automatic system. From these consideration, it can be assumed that the high vulnerability of K-city was overestimated due to under estimation of numbers of blocked zones by automatic counting system.



(1) The Present Situation Map of Vulnerability for Fire Spreading

(2) The Modified Situation Map of Vulnerability for Fire Spreading

Fig. 9 Comparison on Evaluation of Disaster Prevention Alternatives

In the present study, automatic algorithm was carried out on the base of simple criteria as shown in Fig. 4. This methodology is worth while for elimination of human biasing. However, there is a little contradiction with human recognition for blocked zones. Hence, it is required further research to take into account of sophisticated judgement in experiential counting system.

Finally, investigation was carried out to use this mapping system as a supporting system for disaster prevention planning. Planning for disaster prevention means here how to increase resistive factors for fire expansion in order to improve vulnerability index to a target rank by using vulnerability index mapping system. In detail, for the areas where risk of fire spreading is high and covered densely by meshes painted as red, it means how to construct a plan of fire prevention belt by starting from present resistive meshes and changing some combustible meshes into vacant lot, green, or noncombustible meshes.

As shown in Fig. 9, it can be seen that risk of fire spreading has become low not only in the relevant area but also in adjacent areas as a result of this planning. Since *land cover classification maps* with 2m resolution have been used, it becomes possible to create fire prevention mesh map of low combustibility in much detail and with much reliability. And even if the local bodies carry out a part of the plan, risk in adjacent area is expected to become low. So, this methodology is suited for the local bodies to carry out fire prevention plan with low cost and within limited budget.

5. Conclusion

In the present study, first of all *attributed mesh map* used fire spreading simulation system was produced by conversion system and interpretation of *land cover classification map* with 2m resolution. Secondly, a regression model for assessment of regional vulnerability to fire spreading was constructed by using the result of fire spreading simulation and automatic counting system of number of blocked zone. And ranking criteria of vulnerability index and their coloring system was proposed based on the regression model. Finally, mapping system of vulnerability index was developed and applied to discuss K-city disaster prevent planning.

Further research is needed to overcome following problems.

① Taking account of configuration c blocked zone into the automati algorithm for counting of the number c blocked zones and improvement c coefficient of determination of th regression model.

② Consideration of painting form of valunability index mapping system from readability as risk map.

③Formation of fire prevention belt in a more systematic way by using *land cover classification map* with 2m resolutions, and adding of information of extinguish facilities such as fire fighting center, water for fire fighting etc.

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