Université de Montréal

Application de la logique floue dans l'interpolation spatio-temporelle à l'aide d'un système d'information géographique

Par

Suzana Dragićević

Département de géographie

Faculté des arts et des sciences

Thèse présentée à la Faculté des études supérieures
en vue de l'obtention du grade de
Philosophiæ Doctor (Ph.D.)
en géographie

décembre 1998

Grade octroyé
à compter du
MAI 6 1999

Université de Montréal

Cette thèse intitulée :

Application de la logique floue dans l'interpolation spatio-temporelle à l'aide d'un système d'information géographique

présentée par :

Suzana Dragićević

A été évaluée par le jury composé des personnes suivantes :

Claude Manzagol :	président du jury (Université de Montréal)
Danielle Marceau :	directrice de recherche (Université de Montréal)
Claude Marois :	membre du jury (Université de Montréal)
Marius Thériault :	évaluateur externe (Université Laval)

Thèse acceptée le : février 1999

Sommaire

L'analyse de phénomènes géographiques dynamiques est un processus complexe dû à la nécessité de considérer les composantes spatiales et temporelles des données. Les systèmes d'information géographique (SIG) actuels sont limités par des modèles non flexibles de représentation du temps. L'élargissement des performances des SIGs et le développement de nouvelles approches pour traiter le problème de la composante temporelle des données géographiques représente un sujet de recherche très important. Les modèles de représentation du temps utilisés dans les SIG matriciels reposent sur le concept de séries de couches de données ou « snapshots », qui sont associées à des instants particuliers du temps. Un des problèmes majeurs rencontrés est la disponibilité de données à des instants dans le temps entre des couches consécutives, ce qui limite considérablement l'analyse des changements. En utilisant des sources de données conventionnelles, comme des cartes, des photographies aériennes ou des images de satellite, il est parfois impossible d'obtenir ou de vérifier sur le terrain l'information intermédiaire. Si les intervalles entre les couches de données sont trop longs, les informations sur les changements apparus dans le passé demeurent non détectés.

Les objectifs de cette étude sont: 1) développer une méthode d'interpolation spatio-temporelle basée sur la logique floue pour créer des couches de données intermédiaires dans une base de données matricielles d'un SIG et 2) appliquer cette méthode pour modéliser les changements survenus dans la région d'étude à une résolution temporelle fine.

Les données utilisées dans cette étude concernent la zone périurbaine de la rive Nord de Montréal et s'étalent sur la période de 1956 à 1986. La zone d'étude couvre un territoire de 1320 km^2 qui a connu des transformations radicales au cours de la période d'observation. Une forte dynamique de changement a été causée par la croissance de population et une transformation des terres agricoles ou des forêts au profit du développement urbain. Les principales variables considérées sont les zones urbaines, forestières et agricoles ainsi que le réseau routier. Des fonctions d'appartenance flous ont été développées pour chaque ensemble de variables basées sur l'estimation réaliste de la vitesse des changements. Différents scénarios d'évolution ont été conçus afin de pouvoir modéliser les changements d'utilisation du sol. La validation des résultats obtenus a été effectuée en comparant des couches de données obtenues par interpolation spatio-temporelle avec des données indépendantes provenant de photographies aériennes recueillies pour les années en question.

Les résultats sont présentés sous forme de quatre articles scientifiques. Les premiers deux articles sont de nature méthodologique où l'application de la logique floue dans la modélisation temporelle et le concept de l'interpolation spatio-temporelle dans un SIG sont présentés. Le troisième article porte sur une description détaillée du module Fuzzy_Temp, développé pour tester la méthodologie proposée, créé en langage C et intégré dans l'environnement GRASS. Enfin, le quatrième article porte sur la discussion générale de l'ensemble des résultats obtenus lors de la procédure de validation, démontre le potentiel de l'approche pour la modélisation de la dynamique urbaine et son utilité pour la visualisation.

L'intérêt de cette recherche est de remédier aux lacunes des modèles conventionnels de représentation du temps dans une base de données gérées à l'aide d'un SIG matriciel. Les résultats obtenus permettent d'accomplir l'interpolation spatiale et temporelle simultanément, de générer les informations intermédiaires dans la base de données avec une résolution temporelle d'un an et finalement de produire différents scénarios d'évolution basés sur le choix de fonctions d'appartenance. Les résultats de validation indiquent que l'approche proposée peut générer des scénarios réalistes de la dynamique des changements périurbains. Cette méthodologie peut être utilisée pour faciliter des tâches de planification urbaine lors de manipulation des bases de données historiques et est applicable aux autres études de phénomènes dynamiques.

Mots clés : SIG, logique floue, interpolation spatio-temporelle, modélisation temporelle, base de données historiques, périurbain, dynamique des changements.

Table des matières

Liste des tableaux viii

Liste des figures ix

Liste des symboles xiv

Remerciements xv

Avant propos xvi

Chapitre 1 : Introduction 1

1.1 Contexte 2

1.2 Problématique 3

1.3 Objectifs 5

1.4. Contributions 8

Chapitre 2 : A Fuzzy Set Approach for Modeling Time in GIS 10

2.1 Abstract 11

2.2 Introduction 11

2.3 Fuzzy Set Theory 13

2.4. Methodology 20

2.3.1 Generation of intermediate fuzzy layers 22

2.3.2 Time for cartographic updates 23

2.3.3 Choice of different scenarios 24

2.3.4 Cartographic temporal errors 27

2.3.5 Updating a database for a known change 28

2.4 Results 29

2.5 Conclusion 37

Paragraphe de liaison 39

Chapitre 3 : Spatio-Temporal Interpolation and Fuzzy Logic Reasoning for GIS Simulation of Rural-Urban Transition 40

3.1 Abstract 41

3.2 Introduction 41
3.3 The fuzzy logic theory and its applications to the spatio-temporal interpolation 45
3.4 Methodology 51
3.4.1. Generation of intermediate fuzzy layers 56
3.4.2. Choice of three possible scenarios for temporal simulation of rural-urban transition 57
3.5. Results 60
3.6. Conclusion 72
Paragraphe de liaison 74

Chapitre 4 : An Application of Fuzzy Logic Reasoning for GIS Temporal Modeling of Dynamic Processes 75
4.1. Abstract 76
4.2. Introduction 76
4.3. Methodology 78
4.3.1. Study area and data set 78
4.3.2. Linking fuzzy logic and spatio-temporal interpolation in a raster GIS database 80
4.3.3. Generation of possible scenarios 85
4.3.4. Description of new GRASS4.1 fuzzy logic application module 86
4.3.5. Validation procedure 87
4.4. Results 88
4.5. Conclusion 92
4.6. Apendix : The example of a FUZZY_TEMP session 94
Paragraphe de liaison 96

Chapitre 5 : Space, Time and Dynamics Modeling: A Fuzzy Logic Approach 97
5.1. Abstract 98

5.2. Context and Objectives 98

5.3. Methodology 102

  5.3.1. Study Area 102

  5.3.2. Fuzzy Logic in dynamics modeling 102

  5.3.3. Validation procedure 105

  5.3.4. Measures of dynamics of urban change 106

5.4. Results 107

5.5. Discussion 123

Chapitre 6 : Conclusion 127

6.1. Discussion générale de l'ensemble des résultats 128

6.2. Conclusion générale 130

Bibliographie 132

Liste des tableaux

Table 2.1 Resulting category contents for particular classes generated in fuzzy layers for both possible scenarios in the sub-site 1 32

Table 2.2 Resulting category contents for particular class generated in fuzzy layers for the case of the addition of an object in the database in the sub-site 2 36

Table 3.1 Category contents for fuzzy layers generated for every intermediate year between two snapshots in 1956 and 1966 and according to all three possible scenarios 66

Table 4.1 The comparison of surfaces covered by rural, urban and classes in transition generated with the spatio-temporal interpolation method (using three scenarios of change and three different dates) and surfaces of urban land-use calculated from digital aerial photographs 91

Table 5.1 Comparison of percentages of surfaces covered by rural, urban and classes in transition and percentages of surfaces of urban land-use calculated from digital aerial photographs 114

Table 5.2 Overview of the dynamics of change for all three study areas in three observation periods 119

Liste des figures

Figure 2.1 Possible cases for comparison of the same cell in two different snapshot layers 15

Figure 2.2 Fuzzy membership functions for classes A and B 17

Figure 2.3 The Montreal metropolitan area: The North Shore with two chosen sub-sites 21

Figure 2.4 Fuzzy membership functions for Scenario I (the earliest possible change) and for Scenario II (the latest possible change) 25

Figure 2.5 Example of membership function with only one scenario 27

Figure 2.6 Resulting maps of the sub-site 1 :
(a) snapshot layer in 1976 30
(b) snapshot layer in 1986 30
(c) generated fuzzy layer in the year 1977 31

Figure 2.7 Examples of fuzzy membership functions for the sub-site 2 33

Figure 2.8 Resulting maps for the case of database updating in the sub-site 2:
(a) snapshot layer in 1966 34
(b) generated fuzzy layer in 1969 35
(c) generated fuzzy layer with Mirabel's airport in 1975 35
(d) snapshot layer in 1976 36

Figure 3.1 Possible cases of spatial and temporal evolution of one geographic entity in two different snapshot layers 42

Figure 3.2 Example of fuzzy membership functions generating the change occurring during the transition from rural to urban land-use with an annual temporal resolution and three stages of spatial evolution 49

Figure 3.3 The North Shore of Montreal Metropolitan area with two chosen sub-areas 51

Figure 3.4 Schema illustrating the generation of a generic layer 53

Figure 3.5 Fuzzy membership functions for three possible scenarios 59

Figure 3.6 Resulting maps of sub-area 1:
(a) snapshot layer in 1956 61
(b) snapshot layer in 1966 61
(c) generic layer with surface interpolation distribution of rural-urban transformation 61

Figure 3.7 Generated fuzzy layers of sub-area 1 in 1958 :
(a) according to Scenario I 62
(b) according to Scenario II 62
(c) according to Scenario III 62

Figure 3.8 Generated fuzzy layers of sub-area 1 in 1963 :
(a) according to Scenario I 63
(b) according to Scenario II 63
(c) according to Scenario III 63

Figure 3.9 Histogram of percentage of surface under urban, rural and transition classes 65

Figure 3.10 Resulting maps of sub-area 2 :
(a) snapshot layer in 1976 68
(b) snapshot layer in 1986 68

Figure 3.11 Generated layers of sub-area 2 :
(a) generic layer with road influence distribution of rural to urban transformation 69
(b) fuzzy layer in 1982 and according to the Scenario III 69

Figure 3.12 Histogram of obtained percentage of surfaces by validation and simulation 71

Figure 4.1 The Montreal Metropolitan area with all municipality limits, The North Shore and the chosen sub-area of Repentigny in FUZZY_TEMP graphical context 79

Figure 4.2 Generic layer with surface interpolation determination of rural-urban boundaries from 1966 to 1976 transition represented in FUZZY_TEMP graphical context 82

Figure 4.3 Example of fuzzy membership functions and the generic layer for gradual simulation of change of a geographic entity with an annual temporal resolution and three stages of spatial evolution 83

Figure 4.4 Snapshot layer of study area in 1976 in a FUZZY_TEMP graphical context and the command line window for generation of an intermediate layer in 1975 89

Figure 4.5 Generated intermediate layer of study area in 1975 according to the first scenario shown in graphical context of FUZZY_TEMP along with its category contents 90

Figure 4.6 Organizational chart of FUZZY_TEMP graphical user interface for GRASS4.1 95

Figure 5.1 The Montreal Metropolitan area in Quebec, Canada 103

Figure 5.2 The North shore of Montreal metropolitan area with three study areas 108

Figure 5.3 Database initial snapshot layers of Study area 2 – city of Terrebonne :
(a) snapshot layer in 1956 109
(b) snapshot layer in 1966 109

Figure 5.4 Generic layers of Study area 2 for the transition period 1956-1966 :
(a) diffusive technique 110
(b) road influenced technique 110

Figure 5.5 Generated intermediate maps of Study area 2 in 1958 for the first scenario :
(a) diffusive technique 112
(b) road influenced technique 112

Figure 5.6 Generated intermediate maps of Study area 2 in 1958 with road influenced technique :
(a) second scenario 113
(b) third scenario 113

Figure 5.7 Histogram of census data from 1951 to 1986 :
(a) Population growth in absolute values 121
(b) Population density in absolute values 121

Figure 5.8 Visualization of one possible succession of urban boundaries for the town of Terrebonne from 1956 to 1986 generated with the best combination of spatio-temporal interpolation techniques and scenarios 125

Liste des symboles

t_i	temps au moment *i*
T	ensemble flou
$A, B, R, U, C,$	sous-ensembles flous de T par ordre d'apparition
$\mu_A(t_i)$	degré d'appartenance au sous-ensemble flou A pour le temps t_i
d_i	distance de pixel *i* à partir du pixel de valeur à estimer
$w(d_i)$	la fonction de pondération
z_i	la valeur du pixel *i*
$f(x,y)$	fonction d'interpolation de surface
p	exposant de la distance

Remerciements

Avant de commencer mes études doctorales, quelqu'un m'a dit que c'était une aventure. On s'embarque dans un canot et on essaie de trouver un îlot perdu dans l'océan. Parfois les marées, les courants et les orages peuvent bien jouer avec nous, on peut embarquer sur un faux îlot, mais à la fin, après avoir ramé sans relâche et à l'aide des Guides et du Dieu des mers, Poséidon, certains réussissent à atteindre le but. Honnêtement, au départ, je ne croyais pas que cela serait une si grande aventure, mais après un certain temps ...

Tout d'abord je voudrais remercier Danielle Marceau, directrice de ma recherche, pour m'avoir guidée avec autant d'enthousiasme, de patience et de motivation, pour m'avoir soutenue professionnellement et financièrement. Sans doute, elle était mon Poséidon tout au long de ce petit voyage sur l'Océan de la Connaissance.

Je veux également exprimer ma gratitude au CRSNG et au FCAR qui ont contribué à ma recherche et ont permis la réalisation de ce projet. Et plus, je veux remercier la FES et le Comité permanent sur le statut de la femme de l'Université de Montréal pour la bourse de maternité qui m'a été offerte au moment le plus joyeux de ma vie. Elle m'a redonné le goût de continuer d'explorer l'Océan avec un nouveau passager dans le canot.

Également, j'ai bénéficié au long de mon Voyage de l'aide qui semble être invisible, mais pourtant demeure importante, de la part des professeurs, du personnel du Département de géographie et des collègues du Laboratoire de géomatique et d'analyse spatiale. Professeurs Claude Marois, Pierre André, Marie-Josée Fortin et François Cavayas ainsi que Janet Zaki-Almeida, Cécile Fugulin, Rolland Renaud, Denis Harpin, Alain Lavoie et Jean Daoust méritent mes sincères remerciements.

Je veux remercier abondamment ma famille, mon mari Djordje et nos parents, pour m'avoir constamment encouragée et appuyée pour traverser toutes les vagues émouvantes et les courants difficiles sur ce chemin inoubliable de la recherche d'îlot. À Kim, un grand merci pour m'avoir mis en contact avec des Guides.

Finalement, pensez-vous, après autant d'aventures, que je serai capable de jeter l'ancre sur l'îlot finalement retrouvé ? À la fin, je m'aperçois que j'ai plutôt reçu des voiles pour me lancer plus loin sur l'Océan de la Connaissance.

Avant propos

Ô Maître, parle nous du *Temps* !
Et il répondit :

Vous voudriez mesurer le temps qui n'a pas de mesure et qu'on ne saurait mesurer.

Vous voudriez régler votre conduite et, aussi bien, orienter le cours de votre âme selon les heures et les saisons.

Du temps, vous aimerez faire un ruisseau et vous asseoir sur sa rive pour en regarder l'écoulement.

Mais l'intemporel en vous est conscient de l'intemporalité de la vie,

Et il sait qu'hier n'est que le souvenir d'aujourd'hui, et que demain n'ait d'aujourd'hui que le songe.

Et que chante en vous et qui médite n'a pas fini d'habiter les limites de cet instant initial qui dissémina les astres dans l'espace.

Qui ne ressent, parmi vous, que sa capacité d'amour est sans limite ?

Et pourtant qui, parmi vous, sent que cet amour, pour illimité qu'il soit, est étroit au cœur de son être, et qu'il ne migre pas d'une pensée d'amour à une autre pensée d'amour ni d'un acte d'amour à d'autres actes d'amour ?

Or le temps n'est il pas comme l'amour, non divisible et non mesurable ?

Mais si vous devez, en pensée, mesurer le temps par les saisons, faites en sorte que chaque saison contienne toutes les autres,

Et que le présent embrasse le passé par la vertu du souvenir et le futur par l'ardeur du désir.

Le Prophète, Khalil Gibran, 1923

Introduction

1.1. CONTEXTE

Pour étudier et analyser les phénomènes géographiques dynamiques, il est nécessaire de considérer ses deux composantes : l'espace et le temps. L'espace et le temps peuvent être définis d'un point de vue absolu ou relatif. Le point de vue absolu décrit l'espace comme un cube dans lequel tous les objets sont localisés et où la structure est définie par les trois dimensions euclidiennes. Les objets dans l'espace absolu peuvent être directeme mesurables et physiquement perceptibles dans toutes les directions. Le point de vue relatif décrit l'espace comme la mesure entre les relations parmi des objets ce qui demande des interprétations des formes et des processus dans un contexte spécifique (Peuquet, 1994). Pour sa part, le temps peut être décrit comme une ligne absolue et unidirectionnelle sur laquelle les événements ont un début et une fin, une durée, une succession, et où les intervalles entre plusieurs événements sont mesurables. Pourtant, l'espace et le temps relatifs sont inséparables et dans le monde physique rien n'est purement spatial ou purement temporel; tout est processus (Blaut, 1961). La liaison entre l'espace et le temps continus se réalise à travers le processus qui détermine leurs concepts spécifiques de représentation (Hazelton *et al.*, 1992; Chrisman 1998; Frank 1998).

La géographie et la cartographie sont des disciplines scientifiques qui étudient l'espace et le temps et leurs relations avec différents phénomènes qui se produisent à larges échelles et en interaction avec des humains. La notion du temps et de ses effets conduit les géographes à comprendre les changements qui surviennent dans l'espace et les cartographes, à les représenter sur des cartes (Vasiliev, 1998). L'analyse systématique du concept et de la représentation du temps est un phénomène relativement neuf qui a commencé il y a environ 30 ans. Le temps a été utilisé comme la mesure de l'activité humaine dans la nouvelle discipline de la géographie du temps (Hagerstrand, 1970) et il a été introduit comme variable nécessaire aux autres disciplines telles que la géographie historique, culturelle ou quantitative (Vasiliev, 1998). En même temps, grâce à l'augmentation des capacités des ordinateurs modernes, les systèmes d'information géographique (SIG) ont connu un développement remarquable. Ils sont en voie de devenir un outil puissant capable d'intégrer des composantes temporelles et spatiales pour l'analyse des phénomènes géographiques dynamiques.

1.2. PROBLÉMATIQUE

L'introduction de la composante temporelle dans les SIGs actuels n'est pas une tâche simple car le paradigme de représentation du temps dans les bases de données demeurent non résolu (Peuquet, 1994). Plusieurs efforts ont été faits pour l'incorporation de la composante temporelle dans les SIG (Price, 1989; Al-Taha *et al.*, 1990; Newell *et al.*, 1992; Langran 1992; Edwards *et al.*, 1993; Peuquet 1994; Warshowicz et Healey, 1994; Claramunt *et al.*, 1995) mais tous demeurent au niveau conceptuel. On peut différencier trois facteurs majeurs qui ont influencé la façon d'incorporer la composante du temps dans les SIGs actuels.

Le premier facteur est relié à l'influence cartographique sur la représentation du temps dans les SIGs. La cartographie représente un changement continuel en produisant des cartes statiques. Cette lacune a été transférée dans les bases de données numériques et les SIG sont limités par leur représentation statique des phénomènes géographiques dynamiques (Langran et Chrisman, 1988) où la composante du temps dans une base de données ne représente qu'un attribut de l'espace (Langran, 1993).

Le deuxième facteur résulte de la nature des données historiques. Les données disponibles ne sont souvent pas des informations idéales (Openshaw, 1994). Elles peuvent parvenir de différentes sources et de différentes échelles spatiales et temporelles, leur volume peut être large et elles ont pu être enregistrées dans des circonstances inconnues par l'utilisateur (Vrana, 1989; Hunter et Williamson, 1990; Raafat *et al.*, 1994). Souvent le changement n'est pas enregistré au moment où il est apparu mais lorsque la carte a été publiée (Langran, 1993) ou quand le satellite a fait son passage régulier. Si les données sont collectées à partir d'une série d'images ou de cartes acquises dans le passé, il n'y a aucune possibilité de vérifier ces données sur le terrain ou de compléter les informations manquantes sur les changements (Marceau et Dragicevic, 1998).

Le troisième facteur parvient des modèles de base de données utilisés dans les SIGs actuels et qui sont de nature atemporelle. Il n'est pas possible d'enregistrer des données géographiques de manière continue dans une base de données. Des phénomènes dynamiques doivent être enregistrés de façon discrète en données numériques et en série de couches qui correspondent à des instants particuliers du temps (Langran, 1989; Kemp et Kowalczyk, 1994). L'information sur le temps est associée, comme un attribut, à chaque couche de données en particulier et l'information sur le changement doit être extraite en calculant des différences entre des couches. L'analyse de changements ne met pas l'emphase sur l'étude de la dynamique des processus qui ont produit les changements (Chrisman, 1998; Stead, 1998), mais plutôt sur le taux de changement (Schlagel et Newton, 1996). Si l'intervalle entre les couches de données est trop long, tout le cycle d'événements peut ne pas être détecté (Dragicevic and Marceau, 1999a) et les informations obtenues peuvent donner une image déformée de la réalité qui demeure enregistrée dans la base de données (Chrisman, 1998).

Pour étudier et analyser des phénomènes géographiques dynamiques à l'aide des SIGs actuels, d'une part, on doit tenter de gérer les limitations présentées. D'autre part, il faut utiliser leur potentiel pour l'implantation de méthodes numériques de la modélisation des processus dynamiques (Deursen, 1995; Mitas *et al*, 1997; Kelmelis, 1998). Cette étude cherche à solutionner le problème d'une base de données historiques d'un SIG matriciel où les données géographiques sont enregistrées dans plusieurs couches de données consécutives, où l'information intermédiaire n'est pas disponible et est enregistrée dans des intervalles temporels inadéquats. L'hypothèse formulée dans ce travail est qu'un SIG matriciel peut permettre une modélisation spatio-temporelle des changements d'utilisation du sol dans une zone périurbaine ayant connu des transformations dynamiques dans le temps.

1.3. OBJECTIFS ET APPROCHE

En regard des limitations des SIGs actuels pour gérer l'information temporelle, les objectifs de cette recherche sont :

(1) de développer une méthode d'interpolation spatio-temporelle basée sur la logique floue pour créer des couches intermédiaires dans une base de données matricielle d'un SIG;

(2) d'appliquer cette méthode pour modéliser les changements d'utilisation du sol survenus dans la région d'étude à une résolution temporelle appropriée.

La théorie de la logique floue a été proposée par Zadeh (1965, 1972 et 1978). Jusqu'à présent elle a trouvé des applications diverses dans différentes disciplines scientifiques telles que la robotique, la linguistique, la météorologie, la mécanique quantique, l'intelligence artificielle et les systèmes de prise de décision (Dubois et Prade, 1980; Zimmermann, 1985; Terano, 1992). En géographie, des applications de la logique floue ont été réalisées dans le domaine de la télédétection et des SIGs. La plupart des approches en télédétection sont concentrées dans le domaine du traitement d'images lors de procédures de classification et de reconnaissance de formes (Bezdek 1981; Jeansoulin *et al.*, 1981, Cannon et al., 1986, Kent et Mardia, 1988; Wang *et al.*, 1990; Wang 1990b; Foody 1996).

La majorité des applications de la logique floue dans les SIGs s'est concentrée sur le problème de définition des limites entre des classes d'utilisation du sol. La logique booléenne, couramment utilisée dans les modules de classification des SIG, est basée sur des définitions strictes pour déterminer des frontières entre des classes. Elle ne correspond pas à la nature floue des frontières géographiques (Mark et Csillag, 1989; Heuvelink et Burrough, 1993; Burrough et Frank, 1995; Wang et Hall, 1996). La logique floue a été utilisée afin de représenter d'une manière graduelle la frontière des classes d'utilisation du sol (Burrough, 1989; Kollias et Voliotis, 1991; Burrough *et al.*, 1992; Sui, 1992; Hall *et al.*, 1992; Davidson *et a*l., 1994; Hootsmans, 1996).

Toutes ses applications particulières concernent la composante spatiale des données géographiques dans un SIG. Dans cette étude, le raisonnement de la logique floue et des ensembles flous est appliqué pour représenter simultanément la composante temporelle et spatiale des données géographiques. Une approche d'interpolation spatio-temporelle basée sur la logique floue est développée dans le but de générer les informations manquantes entre les couches consécutives d'une base de données d'un SIG matriciel. Selon une résolution temporelle choisie, la création des couches intermédiaires est basée sur la série des fonctions d'appartenance qui sont utilisées comme des règles pour la simulation des changements.

Pour répondre au deuxième objectif, le concept de temps dendritique a été utilisé. Ce modèle de temps comporte plusieurs branches où chacune représente un scénario possible des événements qui peuvent se réaliser dans le futur (Snodgrass, 1992; Frank, 1998). Ce modèle de temps dendritique permet également la simulation de différents scénarios des changements possibles apparus entre les états connus des couches consécutives enregistrées dans la base de données d'un SIG. L'approche d'interpolation spatio-temporelle a été appliquée pour la modélisation des changements d'utilisation du sol et donc, différents scénarios ont été conçus afin de pouvoir simuler plusieurs alternatives d'évolution. De plus, deux techniques de propagation sont utilisées pour simuler la dynamique des changements dans l'espace en utilisant l'interpolation de surface et des opérations de zones tampons.

La méthodologie proposée a été testée sur les données provenant de la région d'étude de la Rive Nord de Montréal. Cette région a été choisie à cause d'une forte dynamique de changement d'occupation du sol lors des dernières cinquante années. Les transformations radicales ont été causées par la croissance de la population, l'étalement urbain important sur les terres agricoles fertiles et forestières (Marois *et al.*, 1991; Marceau *et al*, 1995; Guindon, 1997). La région d'étude couvre un territoire de 1320 km^2. Des données sont disponibles de 1956 à 1986 à un intervalle de dix ans. Les principales classes d'occupation du sol considérées sont les zones urbaines, forestières, agricoles et le réseau routier.

L'ensemble de cette thèse se présente comme suit. De nature méthodologique, le chapitre 2 explique l'application de la théorie de la logique floue pour la gestion de l'information temporelle dans une base de données matricielle. Des fonctions d'appartenance sont conçues afin de modéliser toutes les transitions possibles entre les classes enregistrées dans quatre couches consécutives avec une résolution temporelle de dix ans. Deux scénarios spécifiques ont été développés afin de pouvoir modéliser les différents débuts de changements possibles. Le temps pour la mise-à-jour cartographique des sources des données a été considéré dans ce modèle ainsi que la possibilité d'intégrer la date exacte de l'apparition d'un objet lorsqu'elle est connue. Une revue des erreurs possibles incorporées dans ce modèle est aussi présentée. Les résultats sont produits grâce au module Fuzzy_Temp qui a été développé et incorporé dans le SIG GRASS4.1. Il permet l'implantation de fonctions d'appartenance de la logique floue pour la modélisation temporelle des changement d'utilisation du sol de la région d'étude.

Le chapitre 3 vise à répondre au deux premiers objectifs de la recherche. Il est de nature méthodologique et l'interpolation spatio-temporelle y est élaborée en détail. Le changement est modélisé simultanément en considérant les deux composantes : le temps et l'espace. Temporellement, les changements sont modélisés grâce à des fonctions d'appartenance floues et en utilisant trois scénarios. Ces scénarios sont conçus pour simuler les différentes durées possibles des changements. Spatialement, les changements sont modélisés en utilisant deux modules standard du SIG: l'interpolation de surface et l'opération de zones tampons autour des routes principales de la région. Les changements sont simulés à travers des étapes successives, dans lesquelles un changement débute et se termine au complet. Pour des raisons de simplicité, les résultats sont produits uniquement pour les transitions possibles entre deux classes: rural et urbain. Des fonctions spéciales sont ajoutées dans le module Fuzzy_Temp afin de pouvoir supporter cette méthodologie.

Le module Fuzzy_Temp est décrit plus en détail dans le chapitre 4. Afin de pouvoir tester l'approche d'interpolation spatio-temporelle basée sur la logique floue, ce module a été créé en langage C et incorporé dans GRASS4.1 et l'environnement UNIX. Une interface graphique a été créée pour faciliter l'utilisation du logiciel et un exemple d'une session du travail avec ce module est présenté. Les résultats obtenus dans cette recherche sont présentés dans ce chapitre en décrivant les fonctions principales des menus de ce module.

Le chapitre 5 est consacré à la présentation des résultats obtenus lors de la validation de la méthodologie proposée. Les limites urbaines obtenues par les procédures de simulation des changements dans trois zones urbaines de la région d'étude sont comparées avec les limites des même zones urbaines obtenues à partir des photographies aériennes à des dates particulières. Deux variables : la vitesse et le mechanisme de changement sont utilisées afin d'indiquer la dynamique possible de l'étalement urbain dans la région étudiée. Également, la possibilité d'utiliser l'approche d'interpolation spatio-temporelle basée sur la logique floue comme une technique de visualisation des changements gérés par un SIG est présentée.

La discussion sur l'ensemble des résultats obtenus et la conclusion générale sont présentés dans le dernier chapitre.

1.4. CONTRIBUTIONS

Les principales contributions originales de cette recherche sont les suivantes :

- L'utilisation de la théorie de la logique floue dans le domaine de la gestion de l'information temporelle représente l'ouverture d'un nouveau champ d'application.

- La méthode développée d'interpolation spatio-temporelle basée sur la logique floue représente une solution innovatrice pour gérer l'information manquante d'une base de données d'un SIG. Cela représente une contribution dans l'avancement des capacités de gestion de la composante temporelle de systèmes d'information géographique.

- La méthodologie développée représente une approche originale utilisée pour la modélisation des changements d'utilisation du sol et de l'étalement urbain. Elle peut être généralisée et appliquée pour la modélisation d'autres phénomènes géographiques dynamiques.

- Dans le but de tester les concepts proposés, le module Fuzzy_Temp a été développé et complètement vérifié. Il représente un outil flexible et original pour le développement de différents scénarios de transformations possibles d'utilisation du sol. Il renforce les capacités actuelles des SIG pour la modélisation en dépassant les limites imposées par l'approche des couches instantanées.

A Fuzzy Set Approach for Modeling Time in GIS

2.1. ABSTRACT

This paper describes an application of fuzzy set theory to perform temporal interpolation in a raster GIS database. Specific fuzzy membership functions have been derived to simulate spatial changes between consecutive snapshots registered in the database. The proposed approach is tested on a very dynamic rural-urban environment of Montreal Metropolitan area in Quebec, Canada, covering the period from 1956 to 1986 with a temporal resolution of ten years. A user friendly software package named FUZZY_TEMP was developed and integrated in the GRASS4.1 environment in order to perform the implementation of the developed concepts.

2.2. INTRODUCTION

In order to accurately analyze dynamic geographic phenomena, it is necessary to take into account their two basic components: spatial and temporal. Space and time are a continuo and do not exist without each other. They possess some correlated properties but also exhibit important differences. Both are considered unbounded and can be measured using well defined units (Snodgrass 1992). However, while space is three-dimensional and physically perceptible, time is characterized by its unidirectional continuous flow, infinitely stretching into the past and the future, which can only be observed through apparent changes of objects and its attributes occurring in space.

Current GISs have a strong potential for the analysis of dynamic geographic phenomena. However, because they are inspired by the conventional cartographic models, time is still often simply represented as an attribute of space (Langran and Chrisman, 1988). In data models currently used, temporal information is stored through a series of snapshots associated to particular instants in time. Therefore, information about change that occurred in the interval between two consecutive snapshots is not directly available. If the interval between the snapshots is too long, the exact beginning and duration of change that happened during this time interval is not known. Furthermore, collection of geographic data is often not exerted at the time when the geographic change had occurred (Langran, 1993). As described by Snodgrass (1992), in the context of a GIS database, there are several definitions of time: (1) the *real world time* when change really occurs, (2) the *updating time* when geographic data are recorded, (3) the *cartographic time* when data source is released and (4) the *database (transaction) time* when data are registered into the database. When the difference between the real world time and the updated, cartographic or database time is significant, essential information about the phenomenon under investigation may be omitted or misrepresented.

Introducing the temporal dimension into a GIS framework has not yet been fully accomplished since the paradigm for temporal data representation still remains unresolved. However, many efforts have been done at the conceptual level to improve temporal dynamic representation into GISs (Al-Taha *et al.,* 1990; Hazelton *et al.,* 1992; Langran, 1992; Edwards *et al.,* 1993; Peuquet, 1994; Claramunt *et al.,* 1995). In the raster model considered in this paper, one of the approaches intended to enhance the temporal representation in GIS databases is the event-based approach presented in Peuquet *et al.* (1995). An event is associated with each change and the corresponding time is then stored in increasing order from the state at the initial time to the latest recorded change. This approach enables the basic retrieval tasks related to location in order to facilitate database queries. It can be effectively used when a continuous monitoring and recording of events is available. However, this approach cannot be successfully implemented to study changes which occurred at specific time instances that did not correspond to times at data collection using the conventional sources (topographic and thematic maps, satellite and airborne data, census data).

When studying a dynamic phenomenon that happened in the past, one possible solution to obtain information associated with change is to apply temporal interpolation between consecutive snapshots, using an appropriate temporal resolution, to simulate the change that occurred in the interval. In this paper, an approach based on the fuzzy set theory is proposed to generate new data layers at time intermediate to already existing data layers.

Fuzzy membership functions are developed to build different possible scenarios when some event/change had appeared between two snapshots registered in the database. It is also possible to introduce information related to the exact timing of change of a particular object in the database when it is available from other sources. The proposed approach, tested on the rural-urban fringe of the Montreal Metropolitan area, brings the following benefits:

(1) Estimates the information in intermediate time periods at a chosen temporal resolution;
(2) Allows the user to create different scenarios based on a choice of membership functions;
(3) Considers the time for cartographic updates;
(4) Considers the cartographic errors between two snapshots in a database;
(5) Adds an object appearing at a particular moment in time to the intermediate fuzzy layer.

2.3. THE FUZZY SET THEORY

According to crisp set theory, when trying to manage the land-use classification problems, an abrupt boundary exists between geographic classes. A geographic entity fully belongs to one class, and is totally out of another class. The inclusion or exclusion of an entity within the class is usually decided based on some chosen criterion. However, an appropriate criterion is not always easy to define and often the theory of probability may be employed (Burrough and Frank, 1995). There is no overlap between class memberships and often the results of such strict Boolean logic impose unrealistic preciseness in classification and change analysis (Hall *et al.*, 1992; Heuvelink and Burrough, 1993).

The fuzzy set theory as described in Zadeh (1965; 1978) was proposed to extend crisp set theory in order to deal with continuous classifications. This approach has been mainly applied in geography on problems related to soil classification and definition of boundaries between soil classes (Burrough, 1989; Kollias *et al.*, 1991; Banai, 1993; Davidson *et al.*, 1994). The fuzzy aspect of boundaries in geographic space (Mark and Csillag, 1989; Wang and Hall, 1996) and its relation to change in time is now fully recognized and fuzzy logic has been recommended as a means of tackling this problem in current GISs (NCGIA 1994). In this paper, a new approach to manage time based on a fuzzy logic methodology is outlined. The following section describes the basic concepts and definitions related to fuzzy logic and its linkage with GIS database.

The raster GIS data model is based on the notion of a *cell,* a smallest space entity, to associate the geographic information with spatial coordinates. A cell can be mathematically described as an element of a large matrix, usually called layer, used to model a complex geographic region. Therefore, a cell is characterized in a georeferenced GIS by four attributes, namely, a row and column coordinates, a thematic value and the description of its category content. The thematic value identifies the geographic entity that is modeled e.g. forest, agricultural or urban area. A time component is brought in the spatial raster database through defining a set of layers for the same geographic region but for different time periods. Therefore, a particular cell belonging to one layer which characterizes a specific time period may contain a different value in a layer describing another time period (Figure 2.1). This implies that the geographic item had changed with time (e.g. in 1965 it was forest and in 1977 the urban area is found at the same location).

Thus, given two layers captured at two time instants t_1 and t_2, the completion of temporal information would consist of creating a set of new layers in order to describe the change of considered geographic entity at time periods between t_1 and t_2. The simplest way of doing this is through direct comparison of values contained in the corresponding cells at given periods to check if the change occurred. The following outcomes are possible:

(I) If the value in the cell examined is the same for both layers (t_1 and t_2), the conclusion is that for any time period t_i between t_1 and t_2 the value in that cell

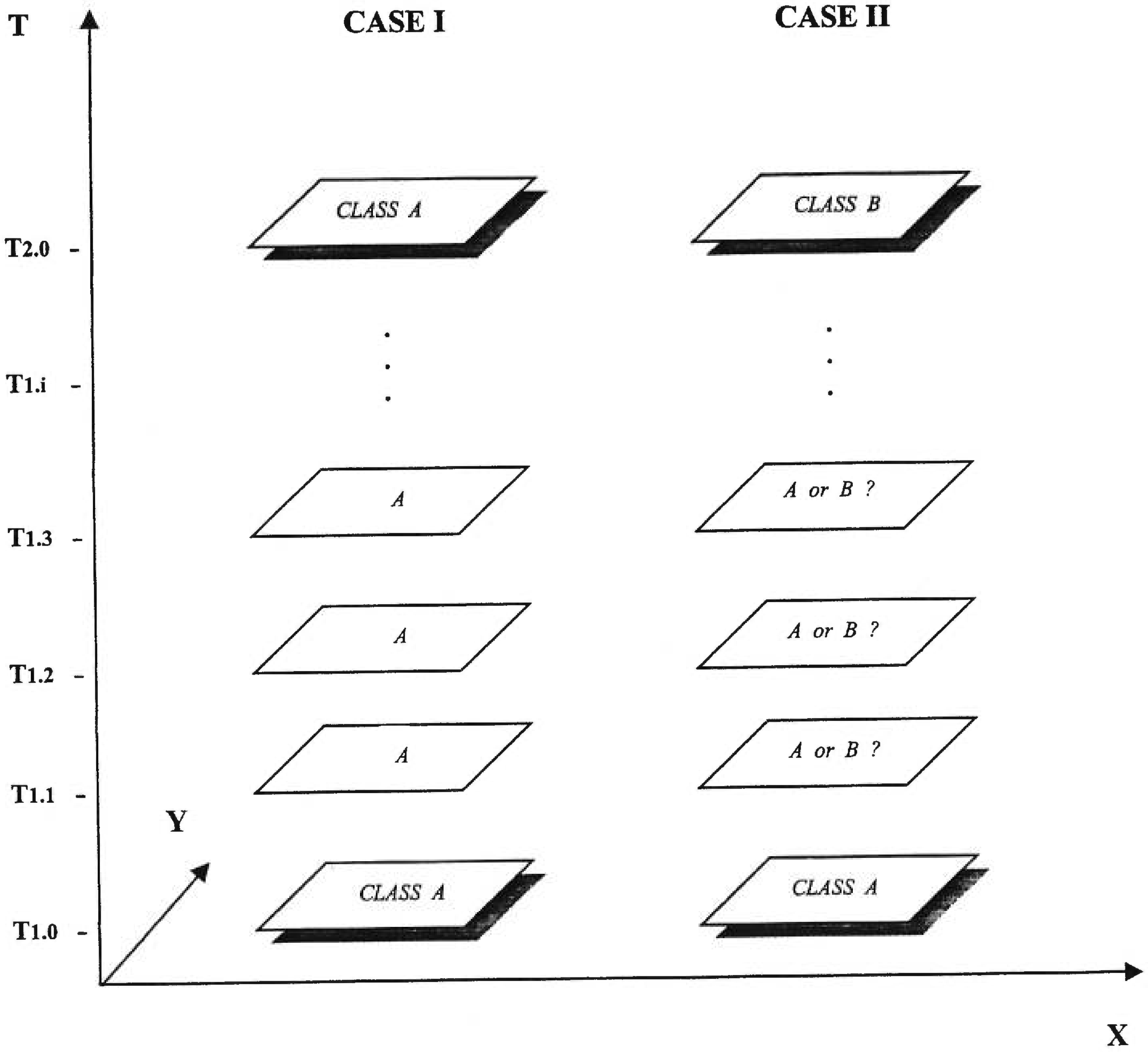


Figure 2.1 Possible cases for comparison of the same cell in two different snapshot layers

would stay unchanged with the highest possibility of 100% or 1.0 degree of belonging (Figure 2.1 - Case I).

(II) If the value in the cell examined is different at t_1 and t_2, it could be concluded that the geographic entity had changed between these two snapshots. The main problem here consists of determining the possible time when the change really occurred thereby permitting the creation of new fuzzy layers (Figure 2.1 - Case II).

The fuzzy logic approach was developed to tackle the problem described in II. The values in a given cell at given time periods t_1 and t_2 indicate 100% or 1.0 full membership to a specific geographic class. A class represents a particular geographic entity such as forest, urban or agricultural land. Therefore, if it were possible to construct a function that can be used to perform the calculation of the degree of belonging for a given element, the problem of classifying elements into the appropriate sets would be significantly simplified. Fuzzy logic theory suggests such an approach where the so-called fuzzy functions could be used to evaluate the membership grade.

A membership function is developed to estimate the possible change of a geographic entity between two time snapshots for any pair of classes (Figure 2.2). Membership functions are conceived based on the realistic speed and timing of a particular change appearing from class A to class B. This model thereby allows the estimation of a possible type and possible moment in time when the geographic change between two well established states had occurred.

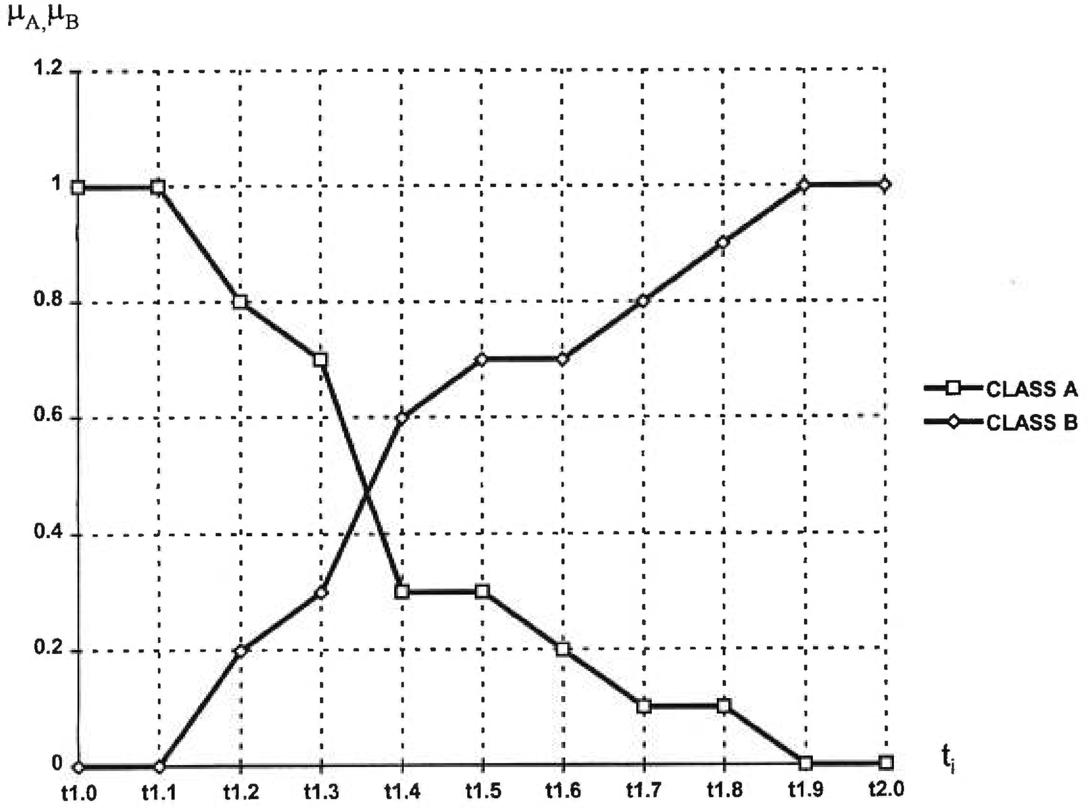


Figure 2.2 Fuzzy membership functions for classes A and B

Consider a set T that contains set of n elements t_i which represents different moments in time. In order to determine a level of membership of an element of T in a specific subset A of T representing a geographic class, the following relations are used:

$$\mu_A(t_i) = \begin{cases} 1 & \text{if } t_i \in A \\ 0 & \text{if } t_i \notin A \end{cases} \qquad \text{(Equation 2.1)}$$

where $\mu_A(t_i)$ is the characteristic function used to calculate the degree of membership between two extremes states (0 and 1) (Dubois *et al.*, 1980).

In the case where the set {0,1} is possible to define as the real interval [0,1], the subset A of T represents the fuzzy set and the function establishes $\mu_A(t_i)$ the grade of membership of an element in a geographic class A for the moment t_i. The closer the value of $\mu_A(t_i)$ is to 1, the higher degree of membership of the element is assigned to the subset A. Therefore, A is a subset of T that has no sharp boundary. For example if T denotes a finite set $\{t_1, \ldots, t_n\}$, a fuzzy set could be expressed with the usual notation (Zadeh, 1972) and is as follows:

$$A = \mu_A(t_1)/t_1 + \ldots . + \mu_A(t_n)/t_n = \sum_{i=1}^{n} \mu_A(t_i)/t_i \qquad \text{(Equation 2.2)}$$

However, if T is not finite it is possible to write:

$$A = \int_A \mu_A(t)/t \qquad \text{(Equation 2.3)}$$

A fuzzy subset of a geographic class A describes vagueness in the subset's boundary region that is not reflected by the crisp subset. This is accomplished by transferring the original values to some real value on a continuous scale from 0 to 1 which indicates the relative membership grade of the set in question.

Instead of having only two extreme truth values: *absolutely true* = 1 and *absolutely false* = 0, all other values between 0 an 1 are also considered and used to model a relative membership grade (Hootsmans, 1996). For example, the value of 0.3 would mean that the considered element would have 30 % of possibility or 0.3 degree of belonging to the set. Such a representation allows expressing the gradual transition between two extremes like truth and falsehood used in a Boolean logic approach.

One example of a generic fuzzy membership function is presented in Figure 2.2. Thus, at the time t_1 the value in the cell considered indicates the 100% or 1.0 membership to the geographic class A while the value in the same cell at the time t_2 indicates the 100% or 1.0 degree of belonging to the class B. As shown in Figure 2.2, the function is piece-wise linear i.e. the points corresponding to temporal interpolation intervals $[0,10]$ are connected by linear segments with annual temporal resolution. The new intermediate layer is created at time t_{1i} on the basis of membership grade according to fuzzy functions A and B which are not necessary complementary:

$$A = \sum_{i=1}^{n} \mu_A(t_i) / t_i \quad \text{and} \quad B = \sum_{i=1}^{n} \mu_B(t_i) / t_i \qquad \text{(Equation 2.4)}$$

One example of how these functions can be used to estimate the change of a geographic entity is as follows:

$$A = \{ 1.0/t_{1.0}, 1.0/t_{1.1}, 0.8/t_{1.2}, 0.7/t_{1.3}, 0.3/t_{1.4}, 0.3/t_{1.5}, 0.2/t_{1.6}, 0.1/t_{1.7}, 0.1/t_{1.8}, 0.0/t_{1.9}, 0.0/t_{2.0} \}$$

$$B = \{ 0.0/t_{1.0}, 0.0/t_{1.1}, 0.2/t_{1.2}, 0.3/t_{1.3}, 0.6/t_{1.4}, 0.7/t_{1.5}, 0.7/t_{1.6}, 0.8/t_{1.7}, 0.9/t_{1.8}, 1.0/t_{1.9}, 1.0/t_{2.0} \}$$

(Equation 2.5)

Let the objective be to determine the cell value at the moment $t_{1.7}$ corresponding to the seventh year after time $t_{1.0}$. Using the function illustrated in Figure 2.2, the degrees of possibility of belonging to geographic classes A and B are *0.1* and *0.8*, respectively. This information is then used to derive the thematic value that is then put in the considered cell for the instant $t_{1.7}$. Each defined thematic value matches one particular category content that carries the values assigned to two degrees of membership. The thematic value obtained must be different for each possible combination of degrees of belonging for any pair of classes considered. For example, the thematic value calculated for *(0.1, 0.8)* degrees related to classes A and B must be different from the thematic value obtained for *(0.2, 0.6)* degrees of membership to some other classes C and D or A and D. There are basically two approaches to meet this condition. The first method consists of developing a mathematical formula to calculate the thematic value in such a way to ensure the uniqueness of the calculated result for each pair of classes and each combination of membership grades. The other approach is to let the user adopting a new thematic value for any new membership combination. The latter approach has been adopted in this study. The most important task is to fill the database, layer by layer, with the fuzzy category contents associated with each cell value in question. Thus, for the time $t_{1.7}$, according to membership functions used in the example shown in Figure 2.2, the cell is in transition from class *A* to class *B* with possible degrees of belonging of *0.1* to class *A* and *0.8* to class *B*. The category contents associated to a particular cell in the intermediate layer is therefore *« A* $\rightarrow$ *B, possibly 0.1/A + 0.8/B»*.

2.4. METHODOLOGY

The fuzzy logic approach proposed in this paper was applied to study the evolution of the North Shore of the Montreal Metropolitan area in Quebec, Canada, covering a surface of 1320 km^2 (Figure 2.3). This area was radically transformed during the last forty years due to considerable and fast expansion of urban population. One consequence is the loss of natural vegetation and agricultural lands to the benefit of residential and commercial developments. The related issues of concentration of human population and constant urban expansion are beginning to be fully recognized as a significant global problem (Acevedo *et al*, 1996) and tools like GIS can play an important role in order to better understand these dynamic geographical phenomena (Marceau *et al.*, 1995).

The main source of data used to create a raster database is topographic maps produced by the Survey and Mapping Branch of the Department of Energy, Mines and Resources, Canada at the scale 1:50 000, UTM projection zone 18 and NAD27. Thirty-two maps corresponding to the years 1956, 1966, 1976 and 1986 were digitized using the MapInfo3.0 desktop mapping software. These digitized data were incorporated in the GRASS4.1 geo-referenced raster database with a final spatial resolution of 10 m. Major

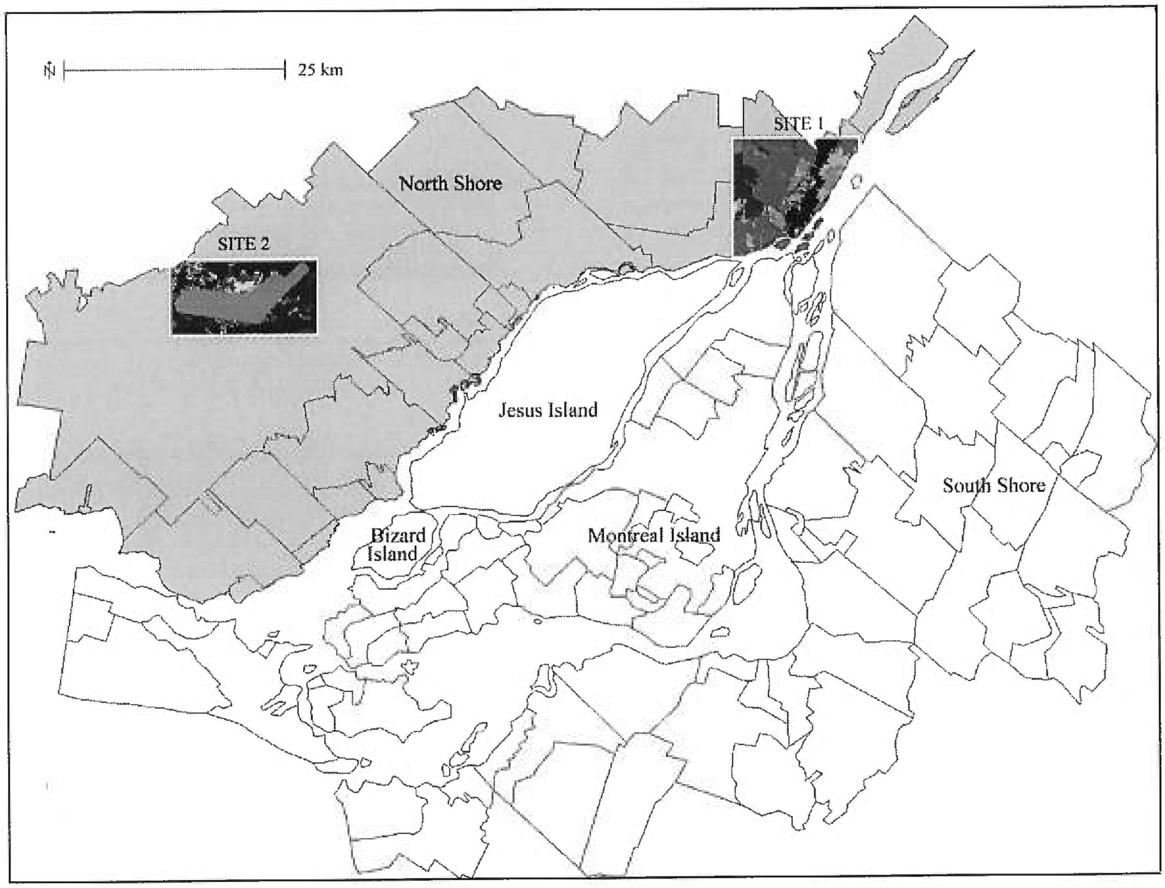


Figure 2.3 The Montreal metropolitan area: The North Shore with two chosen sub-sites

land-use classes were defined on each snapshot layer as follows: urban area, forested area, agricultural land, principal road network, hydrography, airport, national park and indian reserve.

A set of new routines has been developed using C programming language in order to implement the fuzzy logic approach to model temporal information in GIS. These C functions perform the following tasks:

(I) *Calculation of degrees of membership.* These routines contain encoded definitions of the fuzzy membership functions derived. All principal land-use classes are considered for the development of these functions.

(II) *Calculation of the category content.* These functions encompass a set of rules that are processed when assigning the corresponding category content. Given the thematic value as an input, the appropriate rule is used to yield the resulting category content that includes fuzzy membership degrees and the corresponding transition.

The above mentioned new routines are grouped into a module named FUZZY_TEMP and integrated into the GRASS4.1 environment which is user friendly and possesses various powerful facilities for manipulating and analyzing geographic information. The basic functions and the advantages of this module are now discussed in more detail.

2.4.1. Generation of intermediate fuzzy layers

The definition of membership functions is a very important issue while working with fuzzy sets (Zadeh, 1965). They should fit the problem at hand and be easy to calculate (Dombi, 1990). They can also be the result of a subjective process, but should not be arbitrary (Burrough, 1989). By changing the function parameters, the obtained results could lead to different outcomes (Hootsmans, 1996). There is two basic methods for building membership functions: the similarity relation model and the semantic import model (Robinson, 1988). The first one is a data-driven approach when clustering of data determines the definition of subsets and membership functions. If an object belongs to a subset it cannot be a member of any other subset (McBratney and De Gruijter, 1992).

The second model is characterized by the fact that only expert knowledge can provide a reasonable assignment of membership grades which describe discriminating criteria according to the theoretical or empirical evidence (Hootsmans, 1996). In this study, fuzzy membership functions are conceived on the basis of this model and without direct reference to the data values. Only lower and upper boundary values for each class have to be defined. The functions are usually of asymmetrical ranges in order to describe the smooth temporal transition from one class to another. The values of membership grades are derived by the user as a result of consultation with experts, and the realistic estimates of time needed for various transitions to be accomplished were considered. These functions were developed for all possible combinations of transitions among variables. For example, the change from the forest to the urban area takes four years; the change from forest to road takes two years; while the transition from forest to agricultural land requires three years. Transitions which are not seem realistic to appear in reality, such as the transition from urban area to forest or agricultural land are not considered in this study.

For simplicity reasons, a temporal resolution equal to one year has been chosen as the most appropriate to enable the modeling all possible transitions of database classes. According to the evaluation of possible duration of transitions between the database cells, a minimum of two years was estimated for more rapid change and is considered for illustrating the fuzzy-temporal model of land use change. The temporal resolution of ten years between initial database snapshots layers are a limiting factor that did not permit to model cyclical and sequential changes.

Using an annual temporal resolution, FUZZY_TEMP generates intermediate layers through comparison of variables in each cell of two consecutive input snapshot layers. The comparison is accomplished using the developed fuzzy membership functions that in turn serve to determine the most accurate degrees of membership as related to the above two input states.

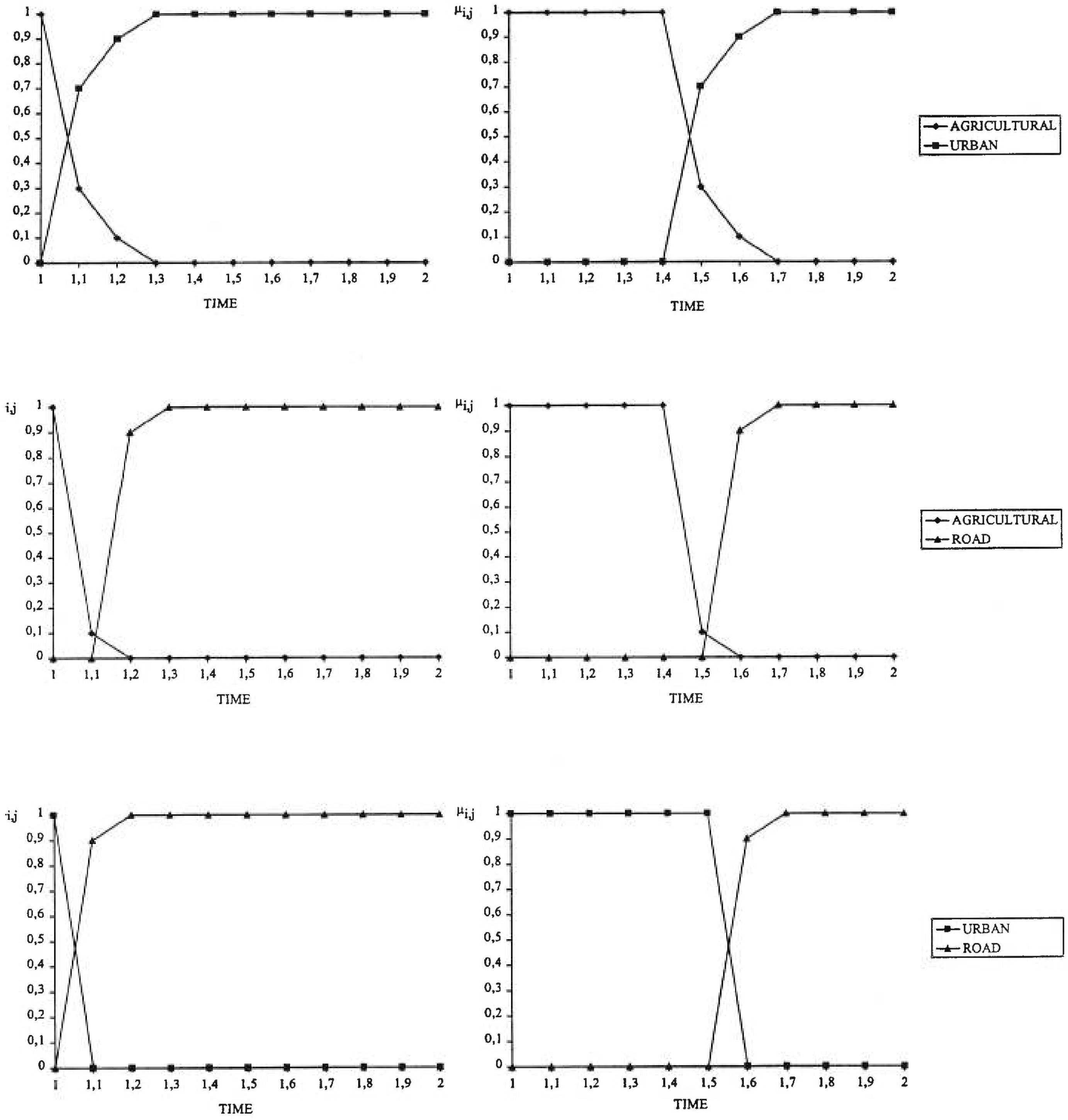
2.4.2. Time for cartographic updates

Through the observation of the topographic maps used in the study, it was found that there are always a few years of difference between the time when aerial photographs are taken and the time when the corresponding maps are printed. The analysis of the 32 maps used to generate the temporal database showed that the average time which elapses between the update time and cartographic time is four years. This reflect the usual cartographic problem of producing maps when the data collection is spread out in time and when change is still in progress when map is printed. In this study there is a tentative to handle this problem in a simplified manner. The difference between update and cartographic time is considered in the development of the fuzzy functions: there are only six years available for a change to be modeled. In this way an attempt is made to bring the model of temporal change as close as possible to the real world and to model a change in the period of time when it realistically occurred. The updating and cartographic times are thereby introduced in the temporal database.

2.4.3. Choice of different scenarios

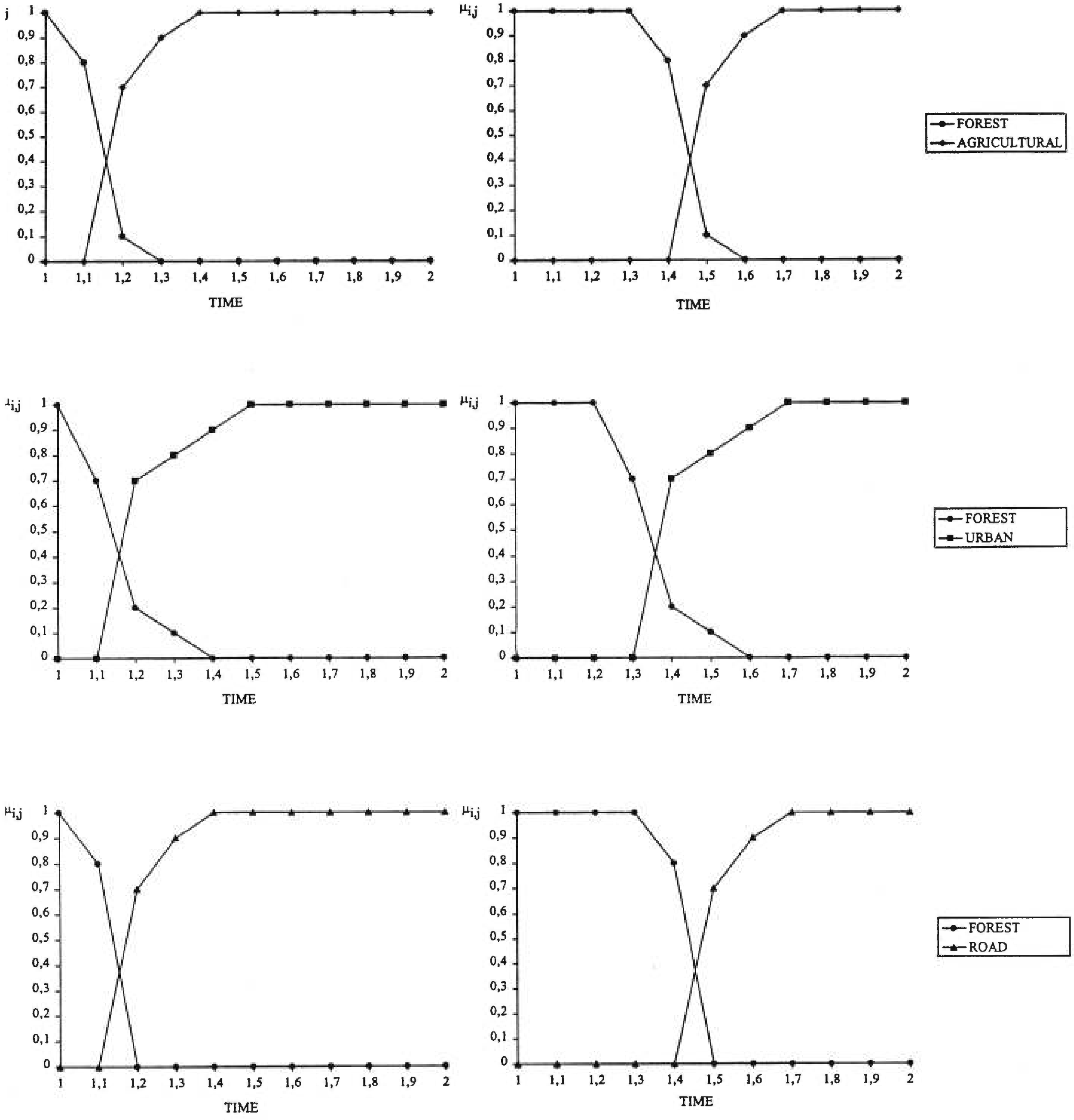
Since the most accurate information related to the exact time when change begins and how long it progresses are usually unknown, and since the changes of the same type do not occur at the same time throughout the study region, two extreme possible scenarios are proposed. They are conceived in order to model different change progressions and assume the earliest and the latest possible beginnings of the change. Figure 2.4 depicts the membership functions corresponding to these two scenarios. They have been developed for all pair of classes, except when the transition from the agricultural land to forest is considered (Figure 2.5). Only one scenario is possible here since this change requires a significantly long period of time. When developing the fuzzy membership functions, care is taken of the facts that the change starts at the time corresponding to the previous snapshot layer, and that the last change must be completed by the time corresponding to the cartographic update.

Figure 2.4 Fuzzy membership functions for Scenario I (the earliest possible change) and for Scenario II (the latest possible change)



Scenario I

Scenario II



Scenario I

Scenario II

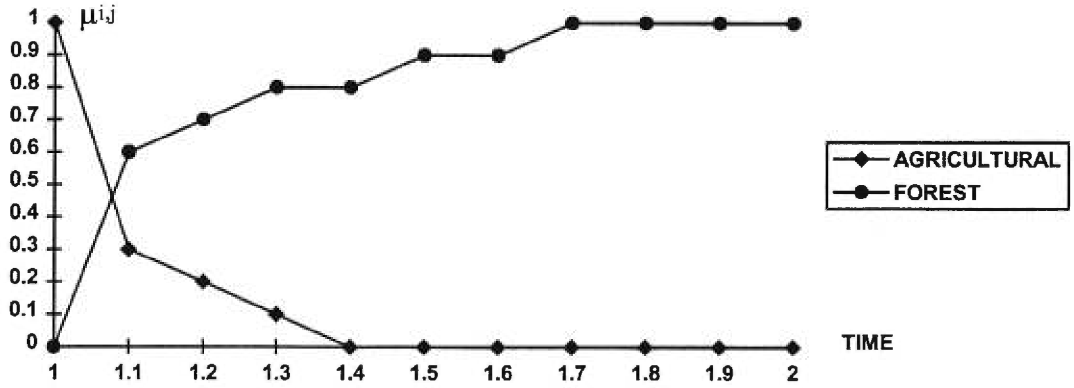


Figure 2.5 Example of membership function with only one scenario

2.4.4. Cartographic temporal errors

The usual quality problem of map accuracy could be characterized with errors in boundaries' locations, in map's geometry and in classification (Drummond, 1987; Kiiveri, 1997). This situation can be explained by the way how urban boundaries are defined during the map production. The functional definition refers to human activities such as residential, commercial, industrial or recreational, and also depends on the housing density. The physical definition states that urban boundaries depend on the population size and its density (Bell *et al.*, 1995). Depending on which definition is adopted, different classification of urban land-use can occur on different maps.

In addition, some other factors related to the raster data model are also involved. The first factor results from positional inconsistency in a series of adjacent maps or between maps corresponding to different time periods. The second factor is the influence of map digitizing errors (Youcai and Wenbao, 1997), the production of misclassification errors due to vector to raster conversion (Veregin, 1989; Van Der Knaap, 1992; Carver and Brunsdon, 1994), and errors arising from raster data manipulations (Newcomer and Szajgin, 1984; Arbia *et al.*, 1998). All these factors have an impact on the positional accuracy of generated raster database snapshot layers (Dunn *et al.*, 1990; Caspary and Scheuring, 1993), and usually they have a tendency to accumulate (Heuvelnik *et al.*, 1989; Hunter and Goodchild, 1993). This leads to misregistration between snapshots that could cause the appearance of vacillating change and finally to provoke errors in a fuzzy temporal modeling.

In the course of creation of the intermediate fuzzy layers, it was found that some cells corresponding to the urban land registered in an older snapshot layer did not appear in a more recent layer at the same location. This implies that the urban land was physically replaced by another land occupation, such as forest or agricultural land-use, which is not likely to happen in reality. This could be explaining also by the accumulation and propagation of different errors. In this study, when such situation as illogical transitions of cells is encountered while creating the new intermediate layers in the database, FUZZY_TEMP warns the user by displaying a category content named *« cartographic error »*.

2.4.5. Updating a database for a known change

In the real world, many entities, such as highways, airports or new residential areas, get created during the interval between two snapshots registered in the database. Sometimes, information related to the time when these entities appeared can be available. In that case, it becomes possible to perform an update of the database by inserting these spatial objects in the layer that corresponds to the year of object creation. This approach is an attempt to introduce the *real world time* in the temporal database. FUZZY_TEMP program possesses the capability to handle the insertion of such objects when creating the corresponding intermediate fuzzy layers. In that context, a special kind of membership functions have been developed for handling the following objects: Mirabel airport opened in 1975, the establishment of the provincial park Oka in 1962, the indian reserve in 1976, and the principal highways constructed during the last 30 years.

The incorporation of the above-mentioned objects into the corresponding fuzzy layer has an impact on the creation of membership functions. The effect is mostly seen as a reduction of the interval for the development of these functions. This is so since the placement of the particular object which appears at a given year in the corresponding layer sets the known constant cell thematic value and the category content for this object from that year to the end of the interval. This also implies that the membership function is developed only for one scenario. Consequently, FUZZY_TEMP includes a set of special membership functions developed for objects for which the year of their creation is known.

2.5. RESULTS

The following section discusses in more detail the results obtained through the implementation of FUZZY_TEMP in the analysis of urban spread in the North Shore region of Montreal. To illustrate the results, two sub-sites have been chosen (Figure 2.3) because they exhibit quantitatively significant changes during the period of observation.

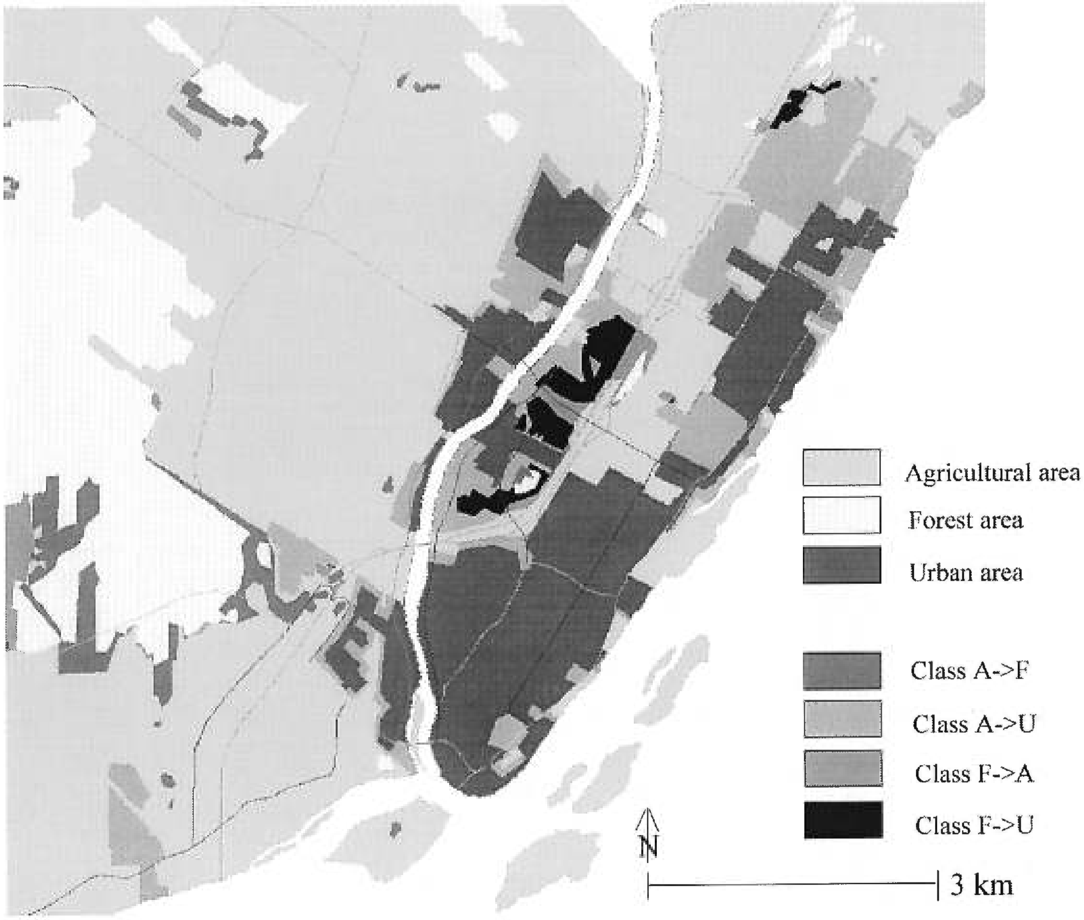
The sub-site 1 is centered at $73^0 29'$W and $45^0 44'$N and covers an area of 65.72 km^2. It encompasses the municipalities of Charlemagne, Lachinaie, Mascouche, Le Gardeur and Repentigny, and is used to show the change modeled in the period between 1976 and 1986 (Figure 2.6 (a) and (b)). The resulting map obtained from the generated intermediate fuzzy layer in year 1977 for the earliest possible scenario is presented on Figure 2.6 (c).

Table 2.1 contains the detailed description of the transition for each land-use class. It also provides the description of the category contents for each generated fuzzy layer for the years 1977, 1978, 1981, 1982, and 1985, considering both scenarios. For example, FUZZY_TEMP generates the possible change from agricultural to urban land-use in 1977 with the degrees of belonging of 0.3 to agricultural and 0.7 to urban. The category

Figure 2.6 Resulting maps of the sub-site 1 :

(a) snapshot layer in 1976

(b) snapshot layer in 1986



(c) generated fuzzy layer in the year 1977

content associated for particulars cell in this class A→U is therefore « *A→ U, possible 0.3/A+0.7/U* ». This answer is obtained for the scenario I of the earliest possible change. On the other hand, if scenario II of the latest possible change is considered, for the same year 1977, transition from agricultural to urban land-use does not appear yet. The degrees of belonging to agricultural and urban land-use are still 1.0 and 0.0, respectively. The category content associated for the same classes A→U is therefore « *A→ U, possible 1.0/A+0.0/ U* ». It can be seen that this change will take place later, in 1981, and the category content is then « A→ *U, possible 0.3/A+0.7/U* ».

Table 2.1 Resulting category contents for particular classes generated in fuzzy layers for both possible scenarios in the sub-site 1

SCENARIO I : The Earliest Possible

Class	**TRANSITION** from → to	**1977**	**1978**	**1981**	**1982**	**1985**
		possible	possible	possible	possible	possible
Class A→F	AGRICULTURAL→FOREST	0.3/A+0.6/F	0.2/A+0.7/F	0.0/A+0.9/F	0.0/A+0.9/F	0.0/A+1.0/F
Class A→U	AGRICULTURAL→URBAN	0.3/A+0.7/U	0.1/A+0.9/U	0.0/A+1.0/U	0.0/A+1.0/U	0.0/A+1.0/U
Class F→A	FOREST→AGRICULTURAL	0.8/F+0.0/A	0.1/F+0.7/A	0.0/F+1.0/A	0.0/F+1.0/A	0.0/F+1.0/A
Class F→U	FOREST→URBAN	0.7/F+0.0/U	0.2/F+0.7/U	0.0/F+1.0/U	0.0/F+1.0/U	0.0/F+1.0/U

SCENARIO II : The Latest Possible

		possible	possible	possible	possible	possible
Class A→F	AGRICULTURAL→FOREST	0.3/A+0.6/F	0.2/A+0.7/F	0.0/A+0.9/F	0.0/A+0.9/F	0.0/A+1.0/F
Class A→U	AGRICULTURAL→URBAN	1.0/A+0.0/U	1.0/A+0.0/U	0.3/A+0.7/U	0.1/A+0.9/U	0.0/A+1.0/U
Class F→A	FOREST→AGRICULTURAL	1.0/F+0.0/A	1.0/F+0.0/A	0.1/F+0.7/A	0.0/F+0.9/A	0.0/F+1.0/A
Class F→U	FOREST→URBAN	1.0/F+0.0/U	1.0/F+0.0/U	0.1/F+0.8/U	0.0/F+0.9/U	0.0/F+1.0/U

The second example provided on sub-site 2 (Figure 2.3) that illustrates the inclusion of Mirabel airport in the database. This sub-site covers an area of 70.41 km^2 and is centered at $74^0$03'W and $45^0$41'N in the municipality of Mirabel. Figure 2.7 shows the specific fuzzy functions that present a transition from forest and agricultural land to the airport land-use in the characteristic period between 1966 and 1976. Note that the transition period for the development of a fuzzy function is less than 10 years since the Mirabel airport appears in the layer corresponding to the year 1975 when it was officially opened.

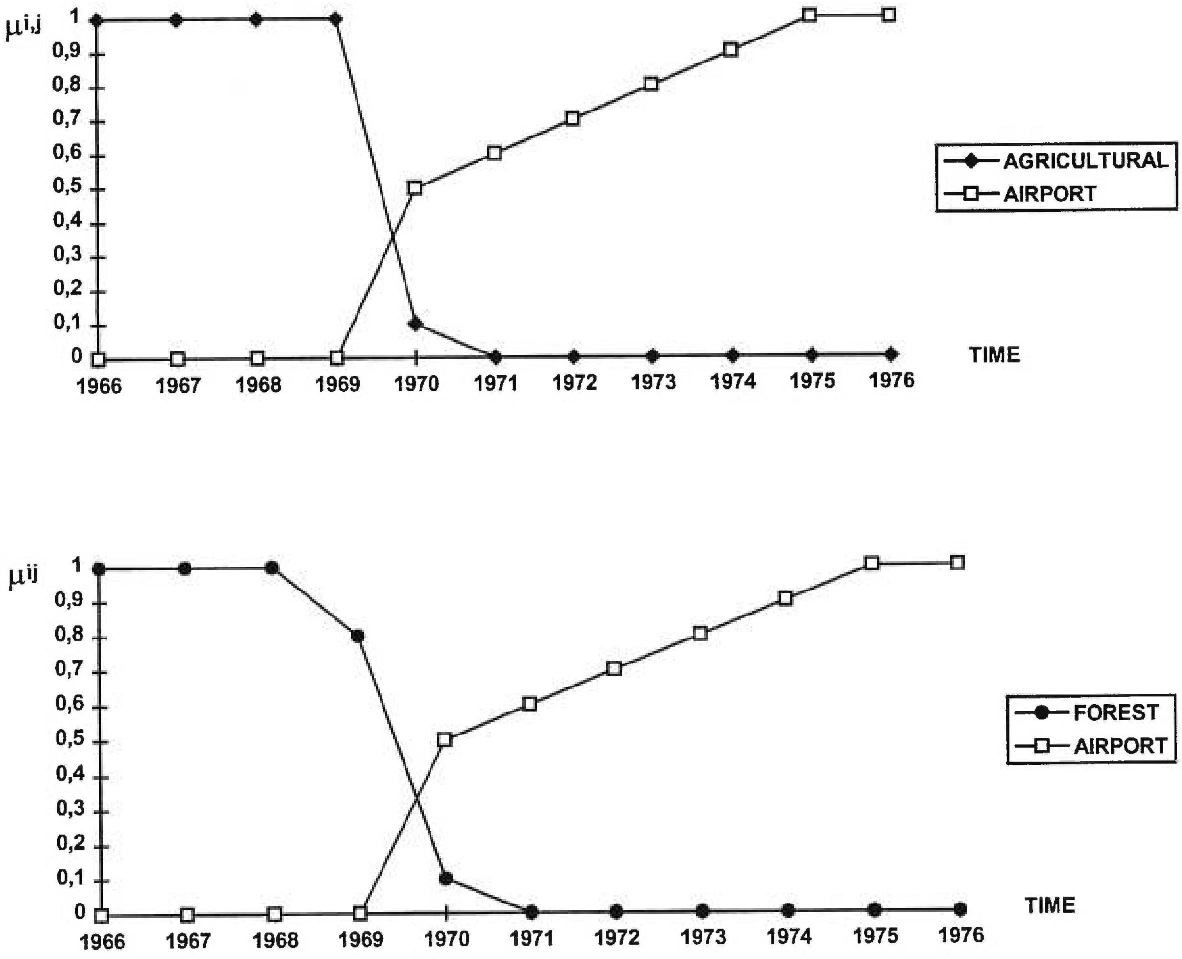
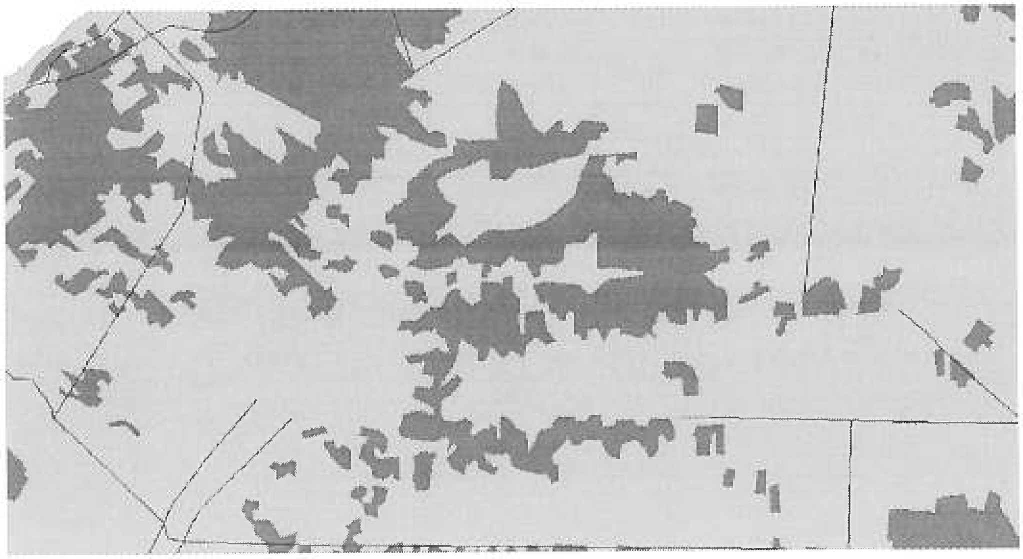


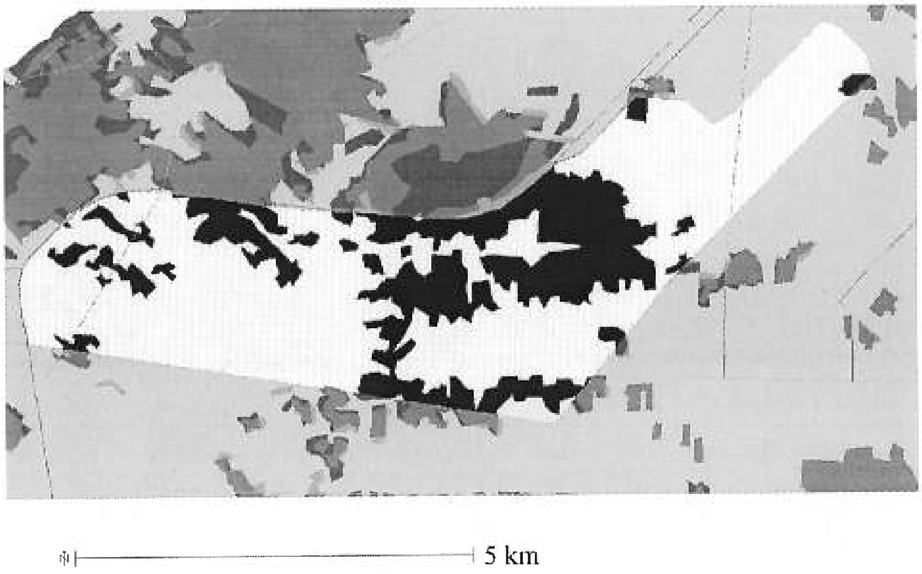
Figure 2.7 Examples of fuzzy membership functions for the sub-site 2

Figure 2.8 (a) and (d) represent the snapshot layers in 1966 and 1976. Resulting maps for the particular intermediate layers corresponding to years 1969 and 1975 are outlined on Figure 2.8 (b) and (c), respectively. Table II presents the category contents corresponding to the specific class transitions which appears in the intermediate fuzzy layers for the years 1969, 1972, 1973, and 1975. For example, for the transition from forest to airport land-use, FUZZY_TEMP generates category contents that show the gradual change appearing during the time needed for the construction of the airport. For the year 1969 when the construction began, it is *« F→AP, possible 0.8/F+0.0/AP »*. For the year 1973, when the construction is about to finish, the category content becomes *« F→AP, possible 0.0/F+0.8/AP »*. Finally, at the year 1975, when the airport is officially opened, the generated category content is *« Mirabel airport »*.

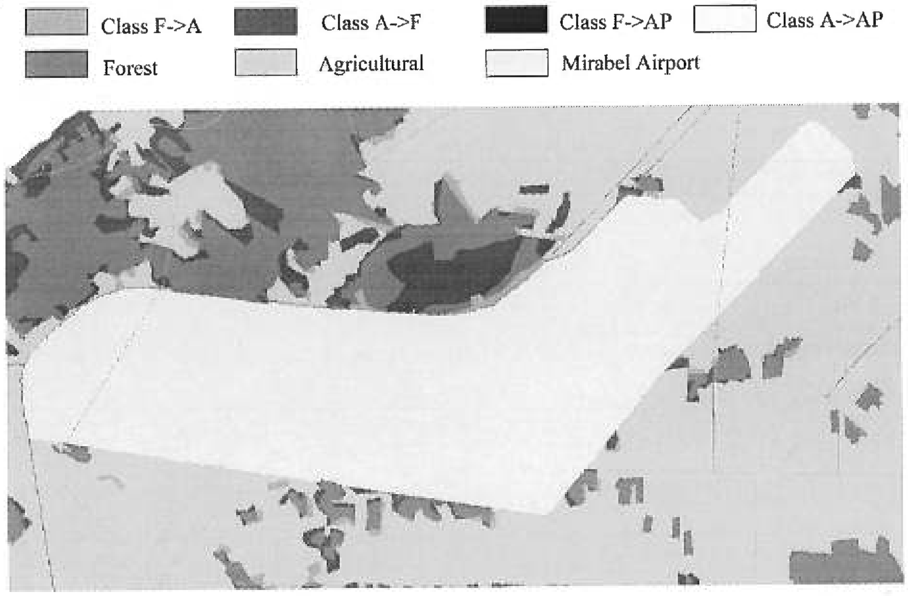
Figure 2.8 Resulting maps for the case of database updating in the sub-site 2:



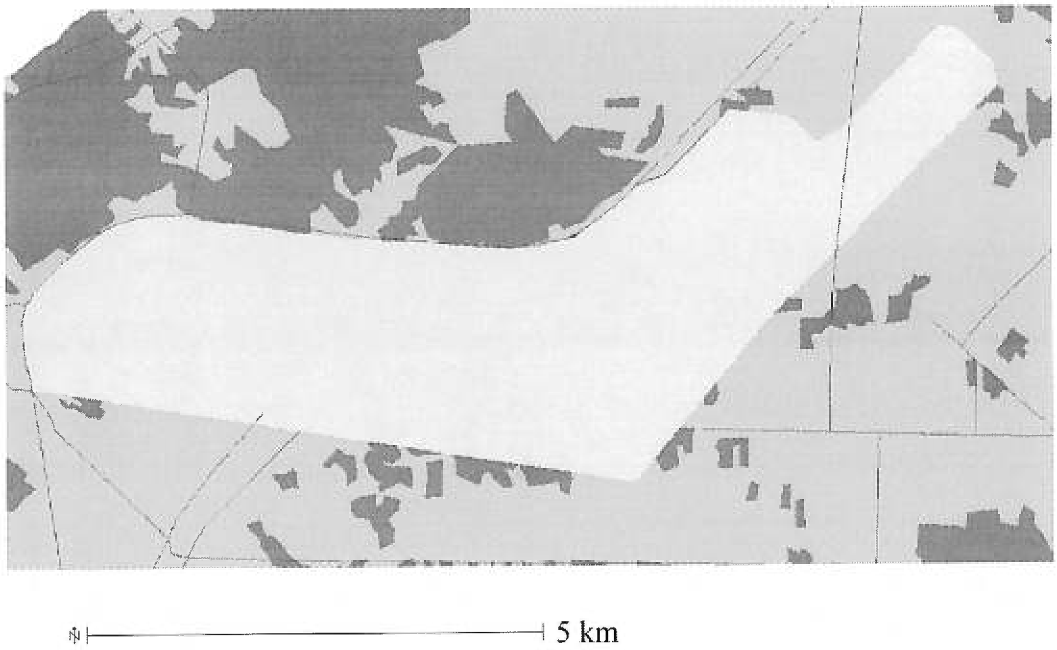
(a) snapshot layer in 1966



(b) generated fuzzy layer in 1969



(c) generated fuzzy layer with Mirabel's airport in 1975



(d) snapshot layer in 1975

Table 2.2 Resulting category contents for particular class generated in fuzzy layers for the case of the addition of an object in the database in the sub-site 2

Addition of an object in the database

Class	**TRANSITION** from → to	**1969**	**1972**	**1973**	**1975**
		possible	possible	possible	possible
Class F→ A	FOREST→AGRICULTURAL	1.0/F+0.0/A	0.0/F+0.9/A	0.0/F+1.0/A	0.0/F+1.0/A
Class A→F	AGRICULTURAL→FOREST	0.1/A+0.8/F	0.0/A+0.9/F	0.0/A+1.0/F	0.0/A+1.0/F
Class F→AP	FOREST→ AIRPORT	0.8/F+0.0/AP	0.0/F+0.7/AP	0.0/A+0.8/AP	MIRABEL AIRPORT
Class A→AP	AGRICULTURAL→AIRPORT	1.0/A+0.0/AP	0.0/A+0.7/AP	0.0/A+0.8/AP	

2.6. CONCLUSION

This paper addresses the problem of modeling time in current raster GISs. The proposed method based on the fuzzy logic theory enables the generation of intermediate layers in a snapshot database by choosing the most appropriate temporal resolution for the dynamic phenomenon under investigation. If a very small temporal resolution is adopted, this methodology could reconcile two different definitions of time, namely the real world time and its representation in a GIS database. This difference is reflected in the fact that the former is continuous while the later still remains discrete. Such a model could closely simulate the evolution occurring in the real world given that an optimal temporal resolution is chosen. Consequently, the database representation of time can approach the real world continuum.

The approach tested in this study offers a lot of flexibility in the development of fuzzy membership functions which could be conceived based on the user's experience as well as through consulting experts in the domain. This may represent a slight disadvantage due to the personal judgment that is involved. However, it allows freedom for developing various scenarios to model different evolution of geographic phenomena under study. This imply the construction of new fuzzy membership functions to deal with different temporal resolutions than those adopted in this study. In the case of larger temporal intervals the modeling of cyclical changes that have a period shorter than the elapsed time between snapshots may be considered. Sequential changes that could generate an intermediate class between two consecutive snapshot layers could also be modeled. This approach can be easily generalized and applied on more complex dynamic phenomena. An extension of this approach is a fuzzy spatio-temporal interpolation that takes into account different stages of evolution of the land-use transformation (Dragicevic and Marceau, 1999b and c).

The most significant land-use transformations that took place during the study period can be instantaneously calculated from intermediate layers without using the tedious procedures of change-detection analysis and cross tabulation. Another advantage of this type of temporal database is the great flexibility for the application of spatio-temporal queries which in turn facilitates the understanding of various causality relationships.

A user-friendly software package named FUZZY_TEMP was developed and integrated into the GRASS4.1 environment. This software can be successfully applied to various geographic phenomena and also be easily extended for temporal extrapolation that can significantly facilitate land-use planning tasks.

Le chapitre 2 est de nature méthodologique et explique l'introduction de la logique floue dans la dimension temporelle d'un SIG. Le développement de différentes fonctions d'appartenance a été présenté afin de pouvoir décrire la simulation de toutes les transitions possibles entre les classes enregistrées dans la base de données d'un SIG. Deux scénarios ont été utilisés pour illustrer la modélisation des transitions possibles entre les classes enregistrées dans quatre couches avec une résolution temporelle de dix ans et spatiale de dix mètres. Un scénario est basé sur le fait que le changement débute le plus tôt possible alors que dans le deuxième cas le changement survient le plus tard possible à l'intérieur de l'intervalle de dix ans. Cette interpolation temporelle implique que la dimension spatiale demeure statique.

Dans le chapitre 3, la modélisation du changement spatial est ajoutée en utilisant deux techniques de SIG. L'approche d'interpolation spatio-temporelle basée sur la logique floue est présentée afin de répondre au premier et au deuxième objectif de cette recherche. Temporellement, les changements sont modélisés grâce à des fonctions d'appartenance floues et en utilisant trois scénarios. Les scénarios sont développés pour simuler différentes durées de changements. Spatialement, les changements sont modélisés en utilisant l'interpolation de surface et l'opération des zones tampons autour du réseau routier dans la région d'étude. Le concept d'étapes d'évolution du changement est utilisé pour rapprocher davantage la modélisation des changements de la classe rurale vers la classe urbaine à la réalité. Ce chapitre est de nature méthodologique, mais présente aussi des résultats obtenus pour deux sites d'étude.

Spatio-Temporal Interpolation and Fuzzy Logic Reasoning for GIS Simulation of Rural-Urban Transition

3.1. ABSTRACT

When studying dynamic geographic phenomena, such as rural-urban transformation, in a raster GIS environment, information between two consecutive snapshot layers is not available. This paper describes an application of fuzzy logic to enable the completion of unknown information into generated intermediate layers using the annual temporal resolution and spatio-temporal interpolation. Change is modelled temporally by performing three possible scenarios with different duration of rural-urban transition, and spatially by applying two standard GIS methods. This methodology is tested with data from the Montreal Metropolitan area in Quebec, Canada, covering the period from 1956 to 1986 with a temporal resolution of ten years. User-friendly modules were developed and incorporated in GRASS4.1 environment in order to simulate the spatio-temporal changes which occur in the study area.

3.2. INTRODUCTION

In current GIS raster databases, data is stored through a series of snapshot layers associated to particular instants in time. Therefore, information about the change that occurred in the interval between two consecutive snapshots is not available. When studying dynamic geographic phenomena which happened in the past, it is often impossible to obtain the missing information from data sources such as maps or remote sensing images. One possible solution to that problem consists of performing a temporal interpolation between two consecutive snapshot layers registered in the raster GIS database. Such an approach has been developed where fuzzy logic reasoning was applied to generate intermediate layers in a raster database to study land-use transformations in a rural-urban environment over the last fifty years (Dragicevic and Marceau, 1997).

These basic concepts of fuzzy logic are illustrated in Figure 3.1 and are explained in the transition from rural to urban land-use. Given two snapshots layers captured at two time instants t_1 and t_2, two basic cases can occur during the transformation in the database.

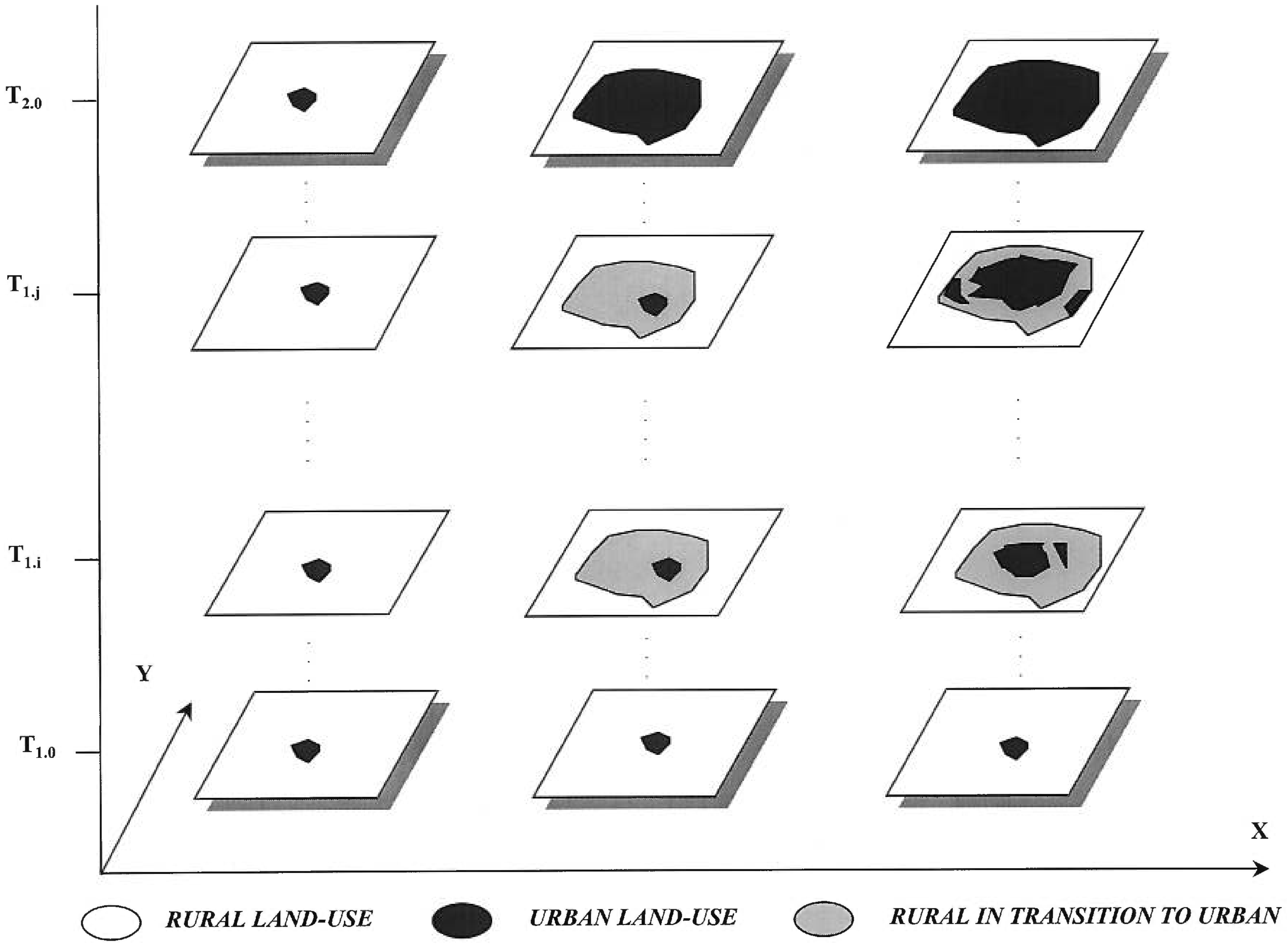


Figure 3.1 Possible cases of spatial and temporal evolution of one geographic entity in two different snapshot layers

Case I shows that a geographic entity may stay unchanged in both instants t_1 and t_2; thus the generated cells corresponding to the intermediate layers at instants t_{1i} and t_{1j} remain unchanged. In case II, the boundaries of the geographic entity have changed; therefore, some generated cells do not preserve their values since they are engaged in the transition. The cell which is in the transition receives values determined by a set of membership functions which describe the current change. Furthermore, all cells known to be in the transition in every intermediate layer will carry the information about the change. This information varies depending on the grades of membership specified in one set of membership functions. The transition modeling is based on the temporal proximity of the cell to the older or more recent snapshot layer. For example, as shown in Figure 3.1, for the intermediate layer at $t_{1.i}$ which is closer in time to the older snapshot at $t_{1.0}$, the lower value of membership grade to the urban land-use and the higher value of membership grade to the rural land-use is assigned to the cell. On the other hand, for the intermediate layer at $t_{1.j}$ which is temporally closer to the more recent snapshot at $t_{2.0}$, the higher value of membership grade to the urban land-use and the lower value of grade of membership to the rural land-use is assigned to the cell. Similarly, all other transitions could be considered such as forest to agricultural land-use, agricultural to road land-use or forest to urban land-use (Dragicevic and Marceau, 1997).

A geographic entity is, however, subject to continuous spatial changes in time. Case III (Figure 3.1) illustrates a progressive spatial change of a geographic entity from layer to layer, until it reaches its ultimate boundaries at the snapshot layer t_2. Therefore, the information about change varies from one intermediate layer to another and does not depend only on one set of fuzzy membership functions, but also depends on the model of spatial propagation of an entity during this period of time.

In this paper, an extension to the approach developed by Dragicevic and Marceau (1997) is proposed in order to solve the problem of missing information about a continuous change occurs in time. For simplicity reasons, the rural-to-urban transition is used to illustrate the proposed approach.

There exist various approaches for urban expansion simulation (Méaille and Wald, 1990; Landis, 1994; Batty and Xie, 1994; Clarke *et al.*, 1997; Allen, 1997) but they are often implemented in temporal extrapolation i.e. in prediction processes. These approaches are also based on a large volume of data when the urban growth is observed over a long period of time (more then 100 years) and with a large number of snapshots (Acevedo *et al.*, 1996; Crawford-Tilley *et al.*, 1996; Bell *et al.*, 1995). Consequently, it is possible to employ the probability theory in order to estimate the trend of urban growth patterns. These models integrate a large number of parameters which may influence the urban expansion such as socio-economic factors, road and hydrographic network, slope, demography or urban morphology. When studying the urban expansion that occurred in the past, the most accurate and sufficient information related to the exact way on how the spatial expansion process is progressing may not be accessible. Therefore, when simulating these processes only the information stored in the database snapshots may be available.

The objective of this study is to simulate the progressive change of rural-urban transition by means of spatio-temporal interpolation in the condition of lacking the essential information about the urban growth. This approach is based on fuzzy logic reasoning with its multiple series of fuzzy membership functions which were developed for each intermediate layer separately. The rural-urban transition is modeled temporally by performing three possible scenarios of different duration, and spatially by performing two standard GIS methods (surface interpolation and buffer operation) for simulating the spatial evolution of a transition. The methodology is tested on North Shore of Montreal Metropolitan area in Quebec, Canada.

3.3. THE FUZZY LOGIC THEORY AND ITS APPLICATION TO THE SPATIO-TEMPORAL INTERPOLATION

This section describes basic concepts related to fuzzy logic, as developed by Zadeh (1965; 1978), and its applications to spatio-temporal interpolation in a raster GIS database.

Any classical set is characterized by an abrupt boundary which could be drawn between two classes of elements: those which fully belong to the set and those out of the set which belong to the set's complement. As opposed to the classical set, a fuzzy set consists of its elements and their respective degrees of membership in the set. For example, if T is considered to be a set of n elements t_i, their respective degrees of membership are $\mu(t_i)$. A fuzzy subset A of T is characterized by a membership function $\mu_A:T\rightarrow[0,1]$, which is used to calculate a degree of membership $\mu_A(t)$ between two extreme states: 0 and 1. The value of 0 indicates that the considered element does not belong to the fuzzy subset A; the value of 1 denotes a full membership to the fuzzy set. The closer the value is to 1, the higher is the element's degree of belonging to the set.

Recently, fuzzy reasoning has found its use in the areas of remote sensing and GIS. Some scientists pointed out that the classical Boolean approach to the representation of geographic phenomena used in current geographic information systems (GIS) is not always appropriate because of inherent fuzziness in the nature of geographic data (Peuquet, 1984; Robinson, 1988) and geographic boundaries (Mark and Csillag, 1989). This causes the inadequacy of GIS representation of geographic phenomena (Wang *et al.*, 1990; Banai, 1993) leading to imprecision in spatial analytical processes (Altman, 1994; Hootsmans, 1996).

Diverse approaches based on the fuzzy logic have been developed for land-cover classification of remotely sensed data (Bezdek, 1981; Jeansoulin *et al.*, 1981; Cannon *et al.*,1986; Kent and Mardia, 1988; Wang, 1990a; Foody, 1996). Furthermore, Wang

(1990b) proposed an approach to improve remote sensing image analysis through fuzzy information representation while Zhu (1997) employed fuzzy logic theory in analysing the uncertainty in the classification process of geographic entities.

Fuzzy method for determining land suitability and evaluation have also been explored (Burrough, 1989; Burrough *et al.*, 1992; Sui, 1992; Hall *et al.*, 1992; Davidson *et al.*, 1994). Other applications of fuzzy logic are in forestry (Mendoza and Sprouse, 1989; Lowell, 1994), in climatic classification (McBratney and Moore, 1985), in viewshed operations (Fisher, 1994), in evaluation of transportation options (Smith, 1992), in slope stability prediction (Davis and Keller, 1997) and in decision making models (Xiang *et al.*, 1992). Fuzzy reasoning is also employed in the construction of natural expressions of spatial query languages (Wang, 1994; Dawson and Jones, 1995) as well as in fuzzy retrieval capabilities in GIS database (Kollias and Voliotis, 1991). Fuzzy logic has been successfully applied to handle problems related to the fuzzy nature of geographic boundaries (Wang and Hall, 1996) in GIS context.

These particular applications of fuzzy logic in GIS and remote sensing are used to only handle the spatial context of geographic data. In this paper, fuzzy logic reasoning is applied to simultaneously manage both, spatial and temporal context of geographical data in order to simulate dynamic geographic phenomena such as the rural-to-urban transition in a classical raster snapshot database. The simulation of a gradual change which can occur between two consecutive snapshots layers is accomplished using a spatio-temporal interpolation based on fuzzy membership functions. This is developed in three steps.

The first step is to determine a number of intermediate layers between two consecutive snapshot layers captured at time instances t_1 and t_2. These layers correspond to the shortest possible transition time for a cell to change from one geographic class to another. In the database the classes are represented with different cell values. The second step is to determine the generic layers to contain the information about the change of spatial boundaries for the given number of temporal intervals. Generic layers are defined using standard GIS methods such as spatial interpolation or buffer operations applied on rural-urban boundaries from two known snapshots states. The third step consists of implementing fuzzy logic in order to generate the lacking information about the change of geographic entities in the intermediate layers through the analysis of the generic and two basic snapshots layers. In that respect, fuzzy membership functions are used. The selection of suitable membership functions is dependent on the subject under investigation. As discussed in Robinson (1988) and Burrough, (1989), it is possible in some cases to determine the value of a membership function when depending on the used classifier, and this approach is known as a method of fuzzy k-means. In this study, the *a priori* approach is used, when membership functions are conceived by the user. The fuzzy membership grades are determined throughout the consultations with experts, and based on the realistic estimation of time needed for a possible duration of change for each stage of the urbanization process. The selection of different membership functions provides the different accuracy of the obtained results (Kollias and Voilotis, 1991). Therefore, three possible scenarios containing three different sets of fuzzy membership functions are conceived in order to simulate the different possible outcomes of rural-to-urban transition.

The value in the same cell in two consecutive time intervals serves as a criterion to determine whether the change of a geographic entity has occurred. Thus, the following outcomes are possible:

1. If the value in the cell examined is the same for both snapshot layers (t_1 and t_2), the value in the corresponding cell in any intermediate layer at time t_i would stay unchanged with the highest degree of belonging (1.0).

2. If the value in the cell examined is different at t_1 and t_2, it is concluded that the geographic entity had changed between these two snapshot layers.

The spatio-temporal interpolation based on fuzzy-logic reasoning is used to address the second outcome, and is presented in Figure 3.2. A generic layer contains ten urban boundaries corresponding to each year of newly created intermediate layer. The process of rural-to-urban transition is subdivided into several stages where each stage can contain one or more boundaries determined from the generic layer. The stages are used to represent different dynamics of change that could appear during different periods of time between two snapshots. Therefore different sets of membership functions are developed to estimate the possible change for each stage of transition and can be referred to by few intermediate layers.

As shown at Figure 3.2, if the value in the cell at the time t_1 indicates that it is rural land-use, then its degree of membership is 1.0 to the class R (rural land-use). Respectively, if the value in the same cell at the time t_2 indicates that it is urban land-use the degree of belonging to the class U (urban land-use) is then 1.0. A new intermediate layer is created at time t_{1i} based on the membership degree ($\mu_R(t_i)$ or $\mu_U(t_i)$) calculated according to fuzzy functions for belonging to the class R or to the class U and to the particular stage of evolution. The temporal resolution of one year is chosen. The usual fuzzy set notation (Zadeh, 1972) is adopted in this example and is as follows:

$$R = \sum_{i=1}^{n} \mu_R(t_i) / t_i \quad \text{and} \quad U = \sum_{i=1}^{n} \mu_U(t_i) / t_i \qquad \text{(Equation 3.1)}$$

In each moment $t_{1.i}$, the *i*-th intermediate database layer is created whereby the exact number of layers corresponds to one particular stage in the rural-urban transition. For example the particular cell in Figure 3.2 which is in the transition from class R to class U is assigned different degrees of belonging for different time instants. At the initial time $t_{1.0}$, the cell is belonging to the rural land-use, i.e. class R and at the ending time $t_{2.0}$ to the urban land-use, i.e. class U. The category contents of this particular cell will vary from

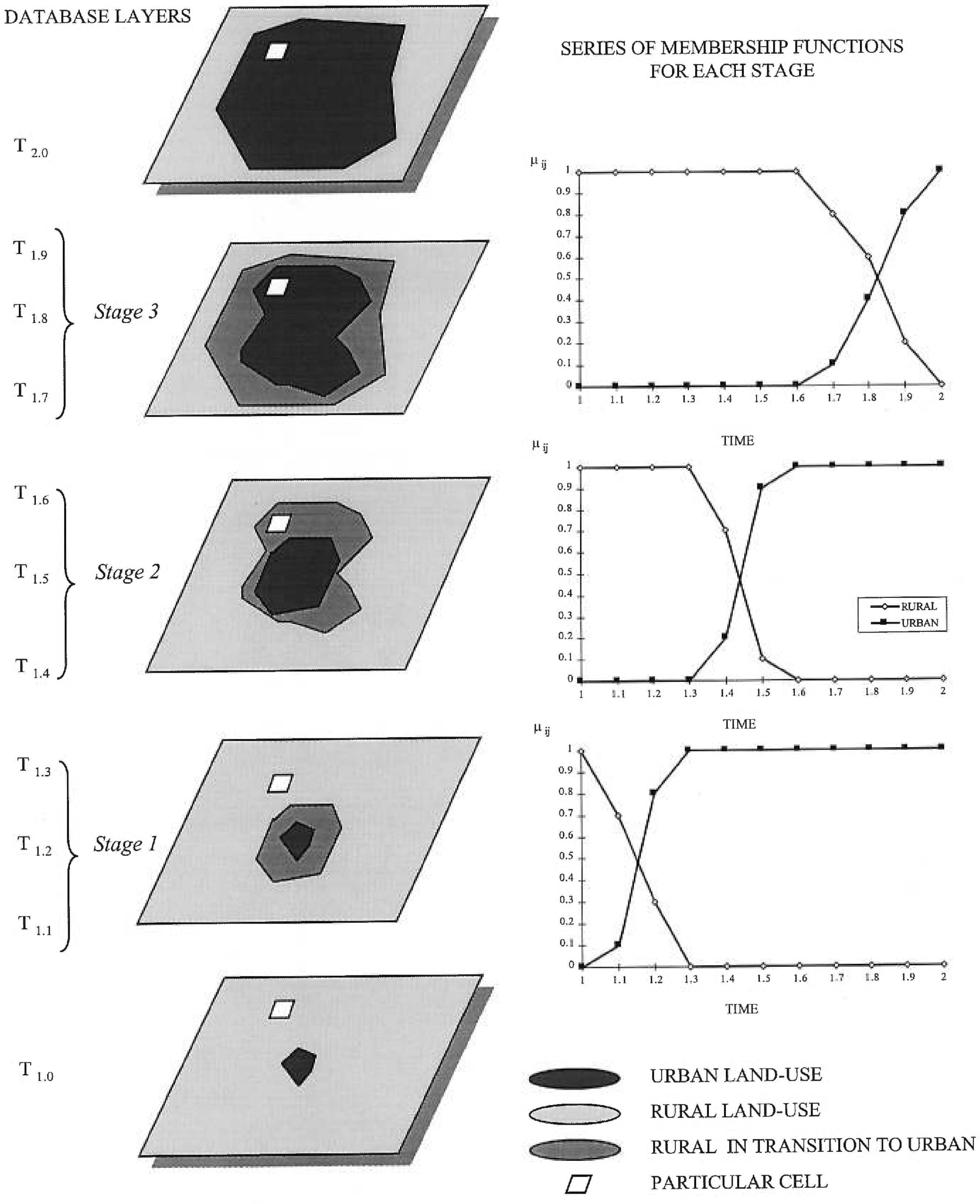


Figure 3.2 Example of fuzzy membership functions generating the change occurring during the transition from rural to urban land-use with an annual temporal resolution and three stages of spatial evolution

intermediate time instants $t_{1.i}$ that is from stage to stage. For example, in stage 1 for the time instants $t_{1.1}$, $t_{1.2}$ and $t_{1.3}$, the category contents of the cell is: *« R→ U, possibly 1.0/R + 0.0/U »,* because the urban boundaries do not yet include the cell in question and it still remains in rural area. In stage 2 the cell is in the belt showing the transition from rural to urban land-use. Therefore, the category contents for the same cell vary and are at the time instant $t_{1.4}$: *« R→ U, possibly 0.7/R + 0.2/U»,* at the time instant $t_{1.5}$: *« R→ U, possibly 0.1/R + 0.9/U »* and finally at the time instant $t_{1.6}$: *« R→ U, possibly 0.0/R + 1.0/U ».* In stage 3 at the time instants $t_{1.7}$, $t_{1.8}$ and $t_{1.9}$ the category contents of the same particular cell are: *« R→ U, possibly 0.0/R + 1.0/U »* because the cell already achieves the transition in urban land-use in stage 2 and its category contents still remains the same. It is important to notice that each defined cell value matches one particular category content and must be different for each possible combination of degrees. For example, the cell value calculated for (0.7, 0.2) degrees related to classes R and U must be different from the cell value obtained for (0.7, 0.2) degrees of membership to some other possible transitions like rural to road. In the case of the addition of other possible transitions, the user should adopt a different cell value for any new membership combination thereby ensuring that the above condition is met. The most important task is to fill the database, cell by cell, and layer by layer, with the fuzzy category contents associated with each cell in transition.

The cell category content within one stage, as shown in Figure 3.2, varies according to membership functions. This variation is reflected by a value of the membership degree such that the bigger value indicates the higher degree of belonging while the smaller value denotes the lower degree of belonging to one of the classes (R or U). In this way, it is possible to simulate the rural-to-urban transition within one stage and from stage to stage. The end of the stage is considered when all cells belong to the urban land-use and when, the new stage of urban evolution can begin. The boundaries of the urban land-use are defined in the generic layer for each year $t_{1.i}$ and for each stage. More detail related to the creation of the generic layer is provided in the subsequent sections.

3.4. METHODOLOGY

The fuzzy logic approach proposed in this paper is tested on a very dynamic rural-urban fringe of Montreal Metropolitan area in Quebec, Canada: the North Shore of Montreal (Figure 3.3). This region was radically transformed due to the urbanisation process, population growth and the extension of the regional road network during the last 40 years.

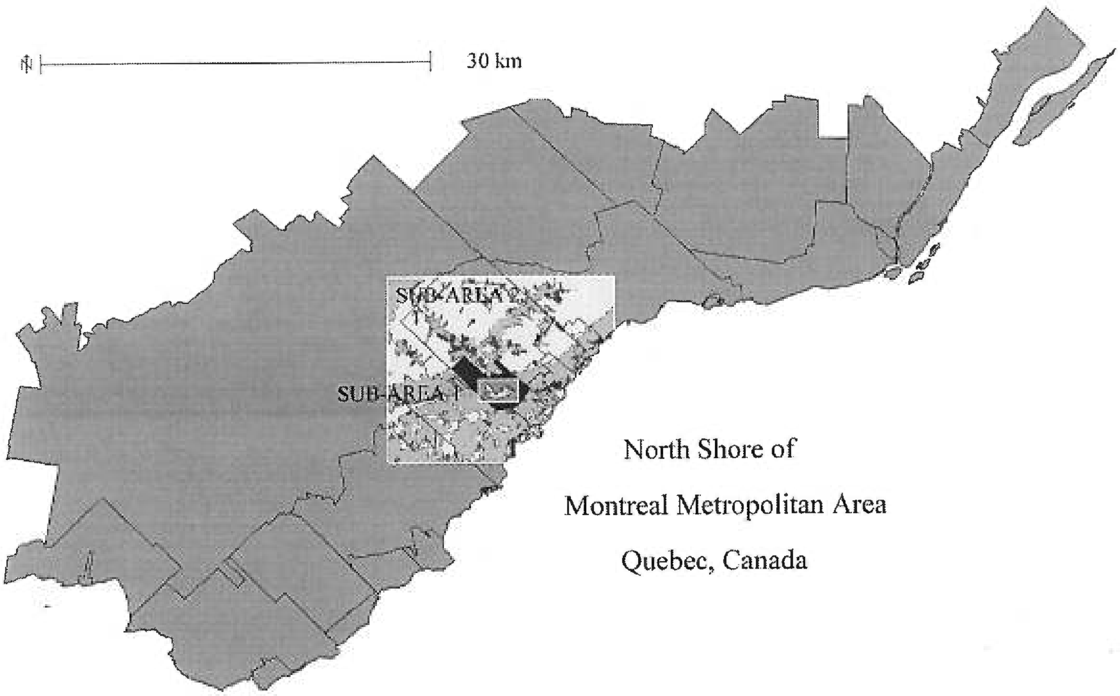


Figure 3.3 The North Shore of Montreal Metropolitan area with two chosen sub-areas

The main source of data integrated in a raster GIS database consists of topographic maps produced in 1956, 1966, 1976, and 1986. The 32 map sheets used are issued by the Survey and Mapping Branch of the Department of Energy, Mines and Resources, Canada at the scale 1: 50000, UTM projection zone 18 and NAD27. Data were digitized using MapInfo3.0 software and incorporated in GRASS4.1 raster database in four snapshot layers with a temporal resolution of 10 years. Final spatial resolution is 10 m. Major land-use classes which were defined for each snapshot layer are rural and urban areas as well as principal road and hydro-graphic networks. In this paper, the proposed methodology is tested solely on the rural-urban transition.

A set of C language routines called FUZZY_TEMP have been developed and incorporated in GRASS4.1 environment in order to implement the fuzzy logic approach to model changes (Dragicevic and Marceau, 1997). These routines are used to calculate the estimated degree of membership using the fuzzy functions derived for classes which model all possible transitions which may occur in the database. The special function *Fuzzy_Fun* is designated to manage all kinds of membership functions to model cell transitions which could appear in the region. The function *Fuzzy_Cat* encompasses a set of rules which are processed when assigning the corresponding category contents to the new classes created in the process of generation of intermediate layers. A user-friendly interface was developed to support the manipulation and analysis of layers in the database. Changes occurring over time can be easily sequentially displayed on the computer screen. For this study, another function named *Fuzzy_Interpol* was developed to address the specific problem related to simultaneous spatio-temporal interpolation. This function relies on existing routines from FUZZY_TEMP and is used exclusively in the case of rural-urban transition. Moreover, this function utilizes its specific fuzzy membership functions as well as the information from the generic layer. This layer is necessary since it determines the boundaries of the urban land-use for each intermediate instance in time. The simulation of the urbanization process is accomplished by two basic GIS methods used to create the generic layer, namely, *surface interpolation* and *buffer operations*. These methods are chosen as the most appropriate tools for the representation of intermediate spatial changes.

Figure 3.4 illustrates the process of creation of the generic layer. First, process starts with overlaying urban-land boundaries from two consecutive snapshot layers. An operation of reclassification is then performed so that the surface surrounded by older boundaries

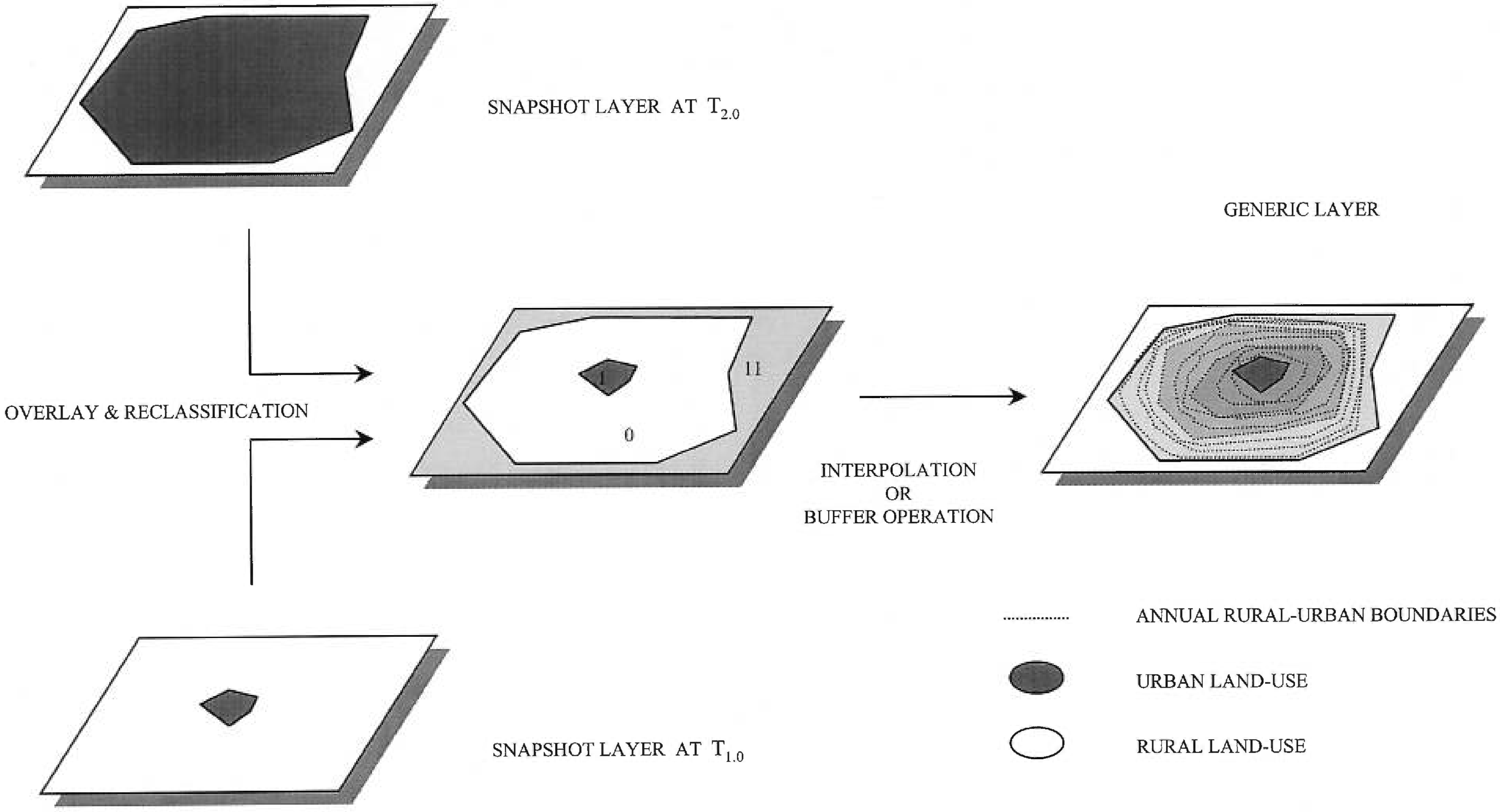


Figure 3.4 Schema illustrating the generation of a generic layer

takes the value of 1 while the surface located outside more recent boundaries takes the value of 11. The difference between these surfaces takes the value of 0 and it represents the surface which is treated by one of the GIS methods for spatial interpolation for generation of the intermediate spatial boundaries. Thus, since the difference between two ultimate boundaries corresponds to the interval of ten years and since an annual temporal resolution is chosen, nine intermediate belts are generated. Therefore, by using the method of spatial interpolation, each of the nine generated belts will correspond to the annual spatial change of rural-urban boundaries. Several annual rural-urban boundaries constitute one stage in the urban evolution. Moreover, the generic layer which uses the method of buffer operations is constructed in the same way in order to generate nine buffers corresponding to the annual spatial change of rural-urban boundaries.

The particularities of these two specific GIS methods used for simulation of spatial urban expansion are now described.

A - Surface Interpolation

The generic spatial evolution layer is generated by a common GRASS4.1 command which performs surface interpolation between two ultimate boundaries of urban land-use in two known consecutive snapshot layers. This command uses a numerical approximation technique based on the distance weighting method applied to the cell (thematic) value of the nearest neighbouring cells (U.S.Army CERL, 1993). The weighting function is the inverse square of the distance from known cells which belong to the boundaries of the urban land-use in two known consecutive snapshot layers. In the process of estimating the unknown cell values, this method assigns more weight to the nearby cells than to the more distant cells (Lam 1983). The estimated value $f(x,y)$ of the unknown cell is actually a number which represents the estimated time t in which the spatial changes of urban boundaries will develop. Thus, in the case of annual temporal resolution and the ten years temporal resolution of the initial database, the value $f(x,y)=t$ is ranging between 2 and 11 (Figure 3.4). This value represents the estimation of a year in which the new boundary of rural-urban land-use was created. This value is then calculated based on the following expression:

$$f(x,y) = t = \frac{\sum_{i=1}^{n} w(d_i) z_i}{\sum_{i=1}^{n} w(d_i)} \quad , \quad w(d_i) = \frac{1}{d_i^{\,p}} \qquad \text{(Equation 3.2)}$$

where $w(d_1)$ $w(d_2)$,..., $w(d_n)$, are the weighting functions, d_1, d_2, ... ,d_n are the distances from each of the n cells locations to the cell being estimated, z_1, z_2, ... ,z_n are the known cell thematic values and p is the exponent applied to distance. The weight for each cell is inversely proportional to the power of the distance measured from the cell being estimated. The choice of p is rather arbitrary but the most common choice is two since this entails fewer calculations and is therefore making the estimation process computationally efficient (Isaaks and Srivastava, 1989; Robeson, 1997). The number of nearest data points used to determine the interpolation value of a cell is chosen by the user. The search neighbourhood is usually an ellipse centred at the cell being estimated. In this study, several attempts have been made to chose the optimal number of cells and the best results are obtained by choosing the nearest n=3500 cells (out of 22 100 cells) as well as by using p=2.

The generic layer, newly created by using surface interpolation, comprises new boundaries which represent a limit to possible urban expansion for each year for which the new layers will be generated by *Fuzzy_Interpol.*

B - Buffer Operations

The other way of creating the generic layer assumes that the urban expansion was driven by development of the regional road network. Thus, the generic layer of spatial evolution can be made by using the common GRASS4.1 command which performs buffer operations around the road network in the oldest known snapshot layer (U.S. Army

CERL, 1993). The width of the buffer zone could be defined either by the user or by taking into account the ultimate urban boundaries in both known snapshot layers. Cell values in generic layer also varies from 2 to 11 which conforms to the annual temporal resolution of intermediate layers and the ten year temporal resolution of the initial database (Figure 3.4). The newly created generic layer contains new boundaries of possible urban expansion under the road network influence for each year for which the intermediate layer will be generated by *Fuzzy_Interpol*.

Once the generic layer with buffer zones has been created in the database, the *Fuzzy_Interpol* function can be used since it takes into account only cells which conform to the appropriate number of buffer corresponding to the year of urban expansion. The unknown cell in the generated intermediate layer is then created according to the specific transition of a cell value, by the application of the specific fuzzy membership function and by using the buffer number which is found in the generic layer. The basic features of *Fuzzy_Interpol* are now discussed in more detail.

3.4.1. Generation of intermediate fuzzy layers

The realistic estimates of the time needed to complete a transition from rural to urban classes were made through the consultations with experts. *Fuzzy_Interpol* generates intermediate fuzzy layers by comparing thematic values in each cell of two input snapshot layers and of one generic layer which conforms to the spatial simulation of the urbanization process. This urbanization process is represented to flow in several stages. The information about stage is obtained from the generic layer. Once all three values defining the cell states are known, it is possible, based on those values, to choose the appropriate fuzzy membership functions.

Transition from urban to rural is considered to be unfeasible and is therefore characterized as a cartographic classification error. This situation can be explained by the fact that urban boundaries on two consecutive topographic maps are defined differently.

The miss-classification of urban land-use occurring on different maps can then be incorporated in a snapshot layer of the database in the course of digitalization of the topographic map. If such a situation is encountered during the creation of the new intermediate layers in the database, *Fuzzy_Interpol* issues a warning to the user by displaying a special category content named *« cartographic error »*.

3.4.2. Choice of three possible scenarios for temporal simulation of rural-urban transition

In the raster snapshot GIS database, the most accurate information related to the duration of change, the exact moment of its beginning and its end are usually not available. In addition, the surface under change in the intermediate periods and the relative speed of a change cannot also be evaluated although these data which are of significant importance for the analysis of dynamic phenomenon. The rural-urban transition evolves from the boundaries of the urban land-use in the older snapshot layer towards the boundaries of the more recent snapshot layer. Thus, the generation of scenarios depends on the number of years for which the creation of possible changes is determined. Three possible scenarios conceived in order to model various duration of rural-urban transformation are considered in this paper:

Scenario I - The shortest possible duration of transition;
Scenario II - The longest possible duration of transition;
Scenario III - The various (mixed) possible duration of transition.

Two extreme situations are considered in order to model temporal change namely, the shortest and the longest possible duration of urbanisation process for the completion transition. The rural-urban transition must terminate in the period of ten years, which corresponds to the initial temporal resolution of the database. Since the annual temporal resolution of generated snapshot layers is adopted, there are limitations in the creation of possible scenarios. This implies that the urban process is progressing in several stages which represent a number of years needed for the completion of the rural-urban land-use transformation. Thus, according to scenario I (Figure 3.5), the transition lasts only two years which means that there are five stages for the total period of ten years. In scenario II, the transition lasts five years hence two stages are needed for the completion of transitions. Scenario III assumes that each stage in the urban expansion is progressing with different time duration. It is chosen that the urbanisation proceeds in three stages which are scheduled to last three, five and two years. Thus, a series of membership functions has been developed based on the adopted speed of rural-urban transition.

Figure 3.5 depicts a set of membership functions developed for each of the three possible scenarios. It can be observed that the first scenario contains a series of five sets of membership functions, the second scenario contains two while the third scenario has three sets of functions which is in accordance with the number of stages for which the rural-urban transition will be carried out.

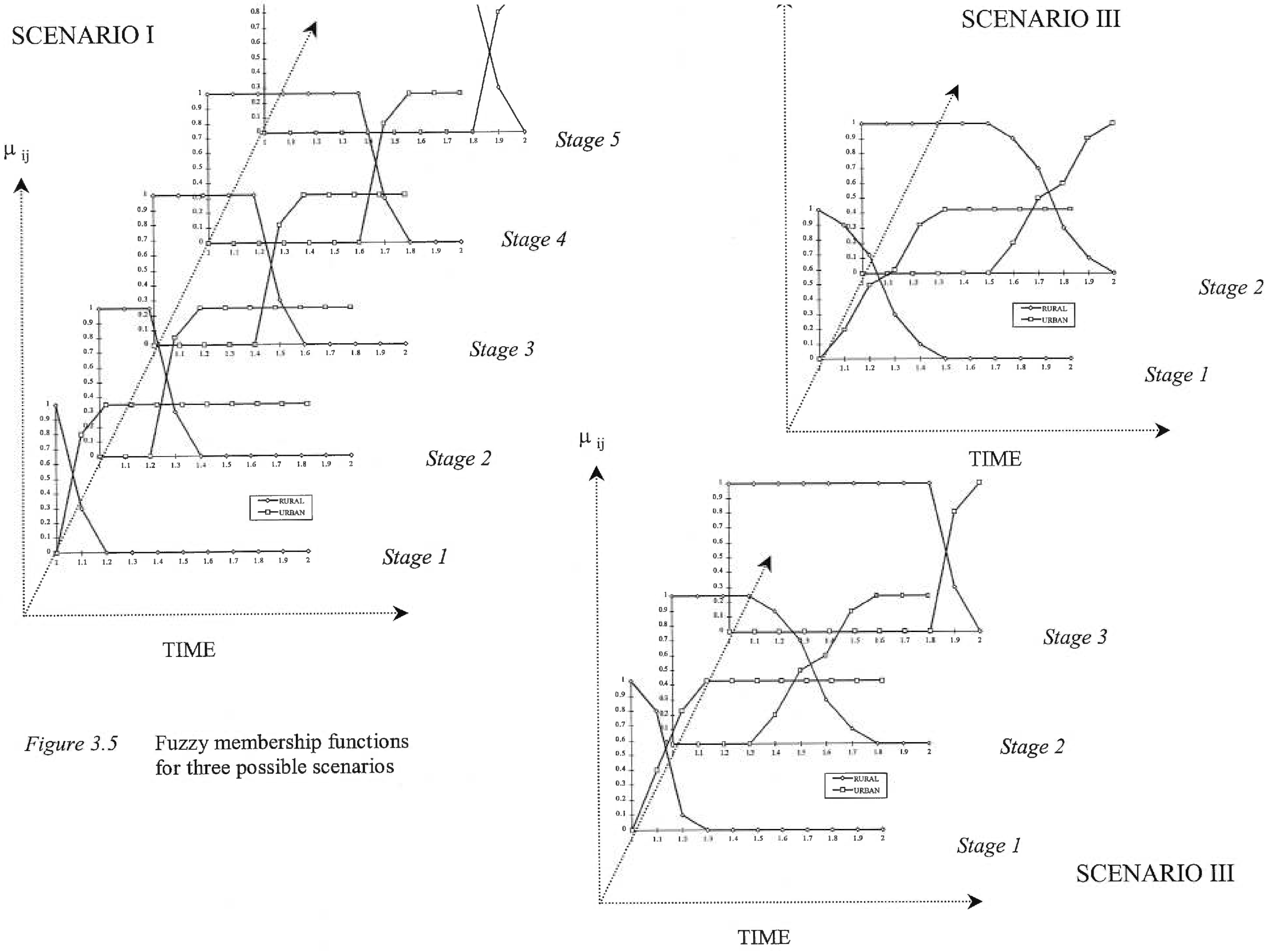


Figure 3.5 Fuzzy membership functions for three possible scenarios

3.5. RESULTS

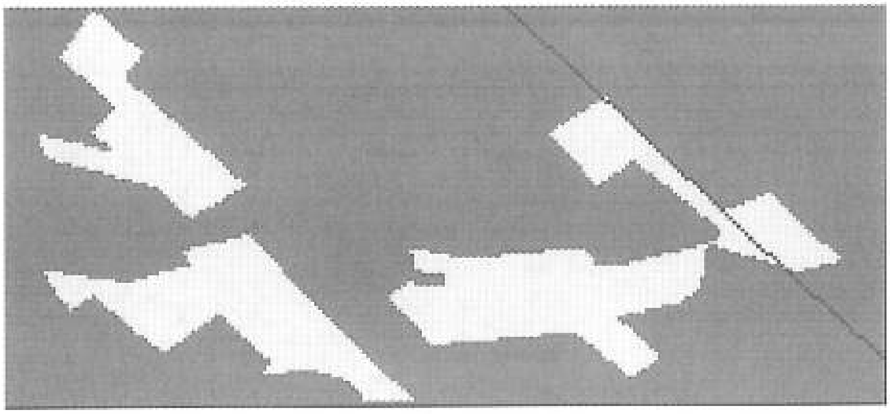
The following section discusses in more detail the results obtained through the implementation of FUZZY_TEMP and its function named *Fuzzy_Interpol.* In order to illustrate the results, two specific sub-areas of Montreal Metropolitan area have been chosen because of their significant land-use changes which occur in the period from 1956 to 1986.

The sub-area 1 is centred at $73^0 50^{'}$W and $45^0 38^{'}$N in the municipality of Ste-Thérèse and covers 9.49 km^2 (Figure 3.3). The simulation of urban growth according to the model of spatial interpolation is performed on the town of Ste-Thérèse-de-Blanville.

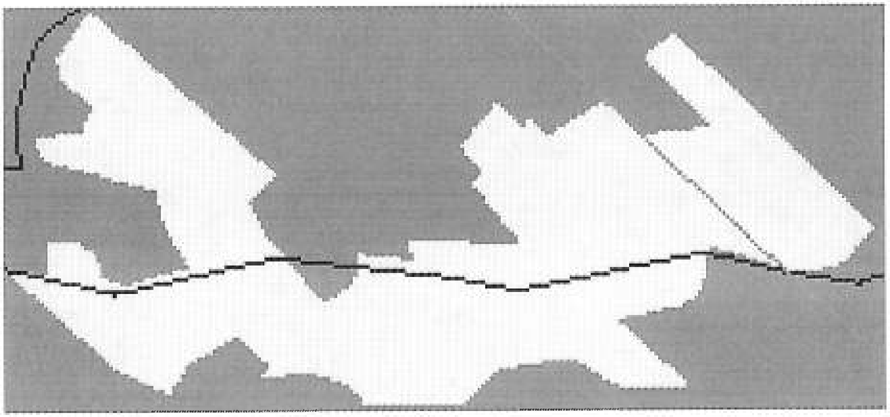
Figure 3.6 (a) and (b) outlines the maps of two characteristic snapshot layers in 1956 and 1966 which are stored in the database. Figure 3.6c shows the generic layer with its ten belts representing the boundaries of urban land-use corresponding to an annual temporal resolution. Each belt indicates the surface which will be occupied by newly constructed urban areas in the intermediate period between 1956 and 1966. For example, the boundaries of the belt 5 correspond to the boundaries of the urban body which is attained in the year 1961.

In order to illustrate the change which appears in 1958 and 1963, the resulting maps generated by *Fuzzy_Interpol* functions are presented in Figure 3.7 and Figure 3.8 respectively for all three possible scenarios. The basic results shown in Table 3.1 are category contents for the generated intermediate fuzzy layers in the transition from rural to urban land use. Each stage of the urban development for each scenario and for each consecutive year is presented in this table. For example, as depicted in Figure 3.7a, the stage 1 of the transformation is already finished according to the first scenario which corresponds to the shortest duration of change which in turn lasts only two years. Thus, the corresponding category content in Table 3.1 is as follows: 0 degree of belonging to rural and 1 degree of belonging to urban land-use for the first two interpolation belts

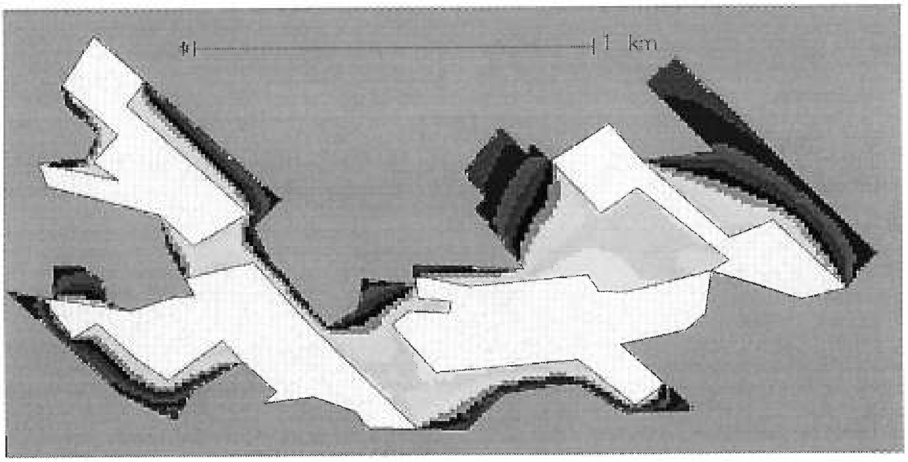
Figure 3.6 Resulting maps of sub area 1:



(a) snapshot layer in 1956



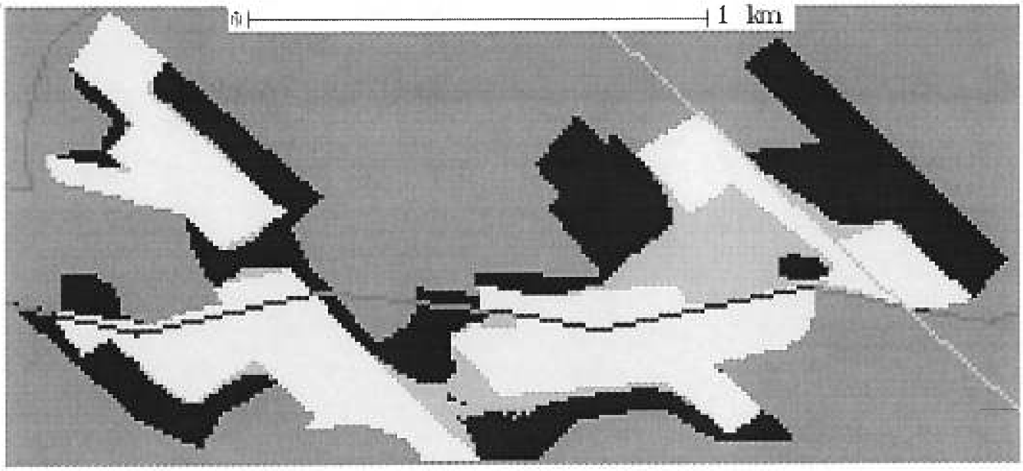
(b) snapshot layer in 1966



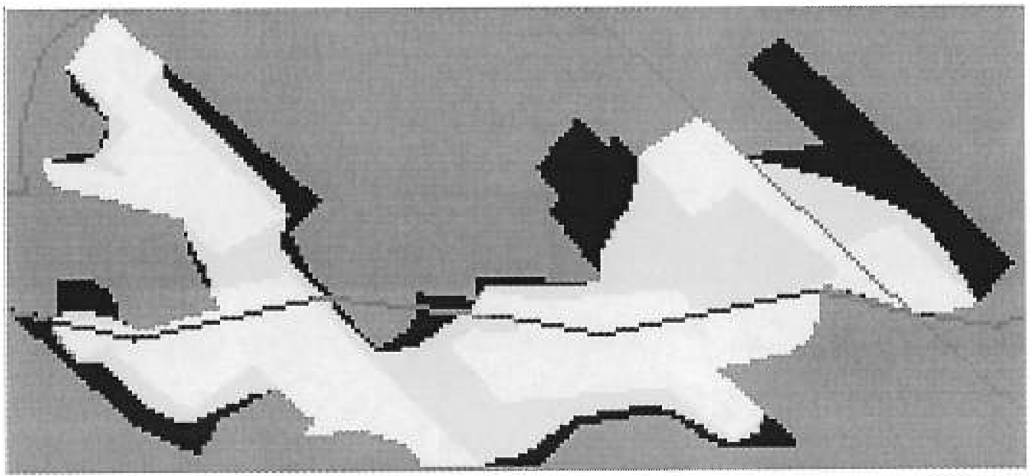
(c) generic layer with surface interpolation distribution of rural-urban transformation

▨ Rural land-use □ Urban land-use □ Belt 1 ▨ Belt 2 □ Belt 3 □ Belt 4

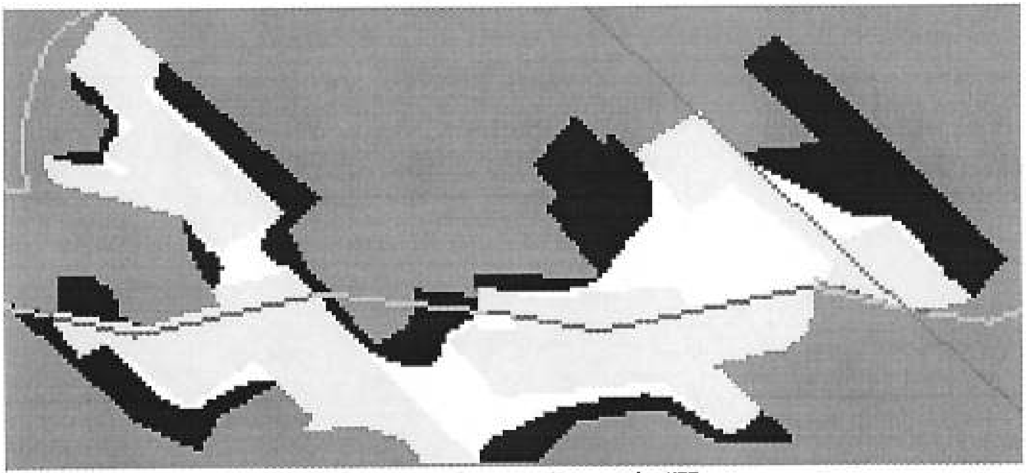
▨ Belt 5 ■ Belt 6 ■ Belt 7 ■ Belt 8 ■ Belt 9 ■ Belt 10



(a) according to Scenario I



(b) according to Scenario II



(c) according to Scenario III

▨ Rural land-use

☐ Urban land-use

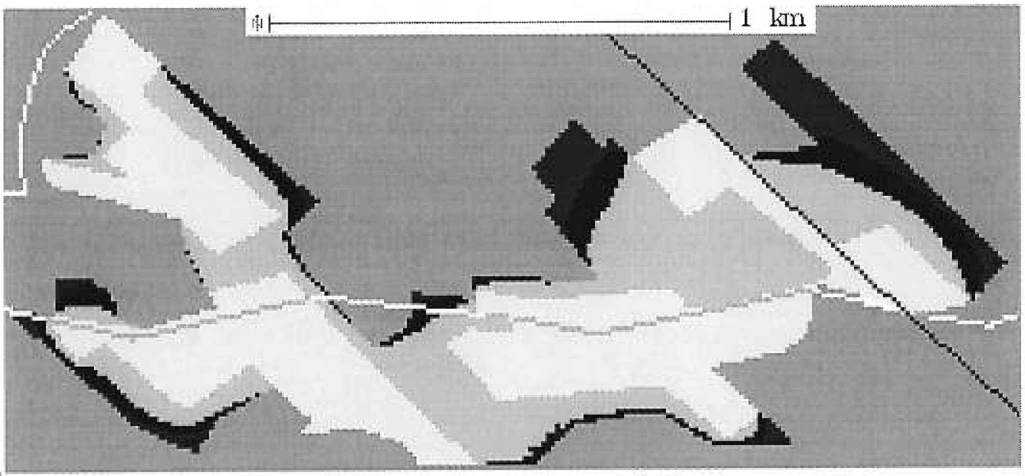
▨ R -> U, possibly 1.0/U

■ R -> U, possibly 1.0/R

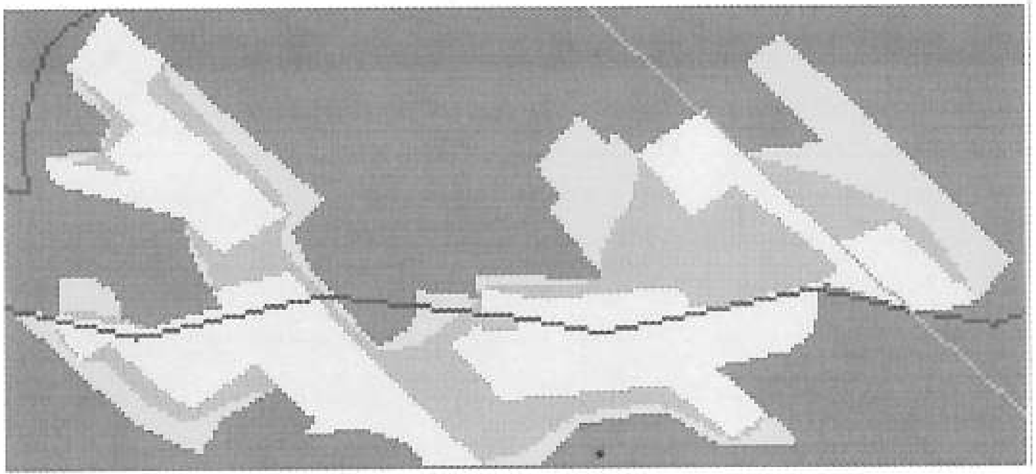
▨ R -> U, possibly 0.7/R + 0.5/U

☐ R -> U, possibly 0.1/R + 0.8/U

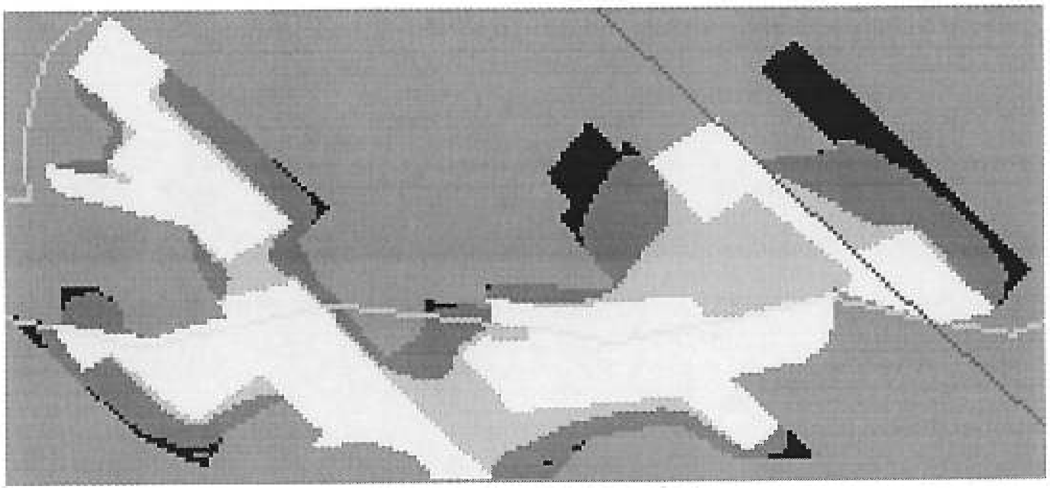
Figure 3.7 Generated fuzzy layers of sub-area 1 in 1958



(a) according to Scenario I



(b) according to Scenario I



(c) according to Scenario I

▨ Rural land-use □ Urban land-use ▨ R -> U, possibly 1.0/U ■ R -> U, possibly 1.0/R

■ R -> U, possibly 0.3/R + 0.8/U □ R -> U, possibly 0.7/R + 0.5/U ▨ R -> U, possibly 0.1/R + 0.9/U

Figure 3.8 Generated fuzzy layers of sub-area 1 in 1963 which make one class. Consequently, other interpolation belts will belong to the class of rural land-use with the corresponding category content of: 1 degree of belonging to rural and 0 degree of belonging to urban land-use. According to the scenario II which conforms to the longest duration of change (Figure 3.7b), the change is still not finished in the year 1958 hence *Fuzzy_Interpol* generates 0.7 degrees of belonging to rural and 0.5 degrees of belonging to the urban land-use for the belts in transition. Other interpolation belts will belong to the class of rural land-use. Finally, the scenario III which models the possible variable duration of change (Figure 3.7c), indicates 0.1 degrees of belonging to rural and 0.8 degrees of belonging to urban land-use and is located in the first stage of the urbanisation process. Other interpolation belts will also belong to the class of rural land-use.

The same analysis has been performed for the year 1963 and the obtained results are now discussed. According to the scenario I (Figure 3.8a), the evolution of the rural-urban change is in the stage 4 and the corresponding category content from Table 3.1 is 0.3 degrees of belonging to rural and 0.8 to urban land use. As for scenario II, the evolution is located in the stage 2 with category content of 0.3 to rural and 0.6 to urban land-use as depicted in Figure 3.8b. Finally, the scenario 3 indicates that the transition from rural-to-urban is closer to the end of the stage 2 (Figure 3.8c) with 0.1 degrees of belonging to rural and 0.9 to urban. According to this scenario, the latest change will start in stage 3 in the year 1965. Other interpolation belts in all scenarios are in some cases already achieving the class of urban land-use, or in other cases, still remaining the rural land-use.

The most significant land-use transformation which occurs during the period of observation can be instantaneously quantified from intermediate fuzzy layers. The common GRASS4.1 command is used to calculate the surface area of change in percentage (%) or using other units of measure (ha, km^2). Figure 3.9c presents the histogram showing the percentage values of the surface area under urban and rural-land use in the specific snapshots corresponding to the years 1956 and 1966. As an example, histograms (a) and (b) from Figure 3.9 present the percentage change in surface area in

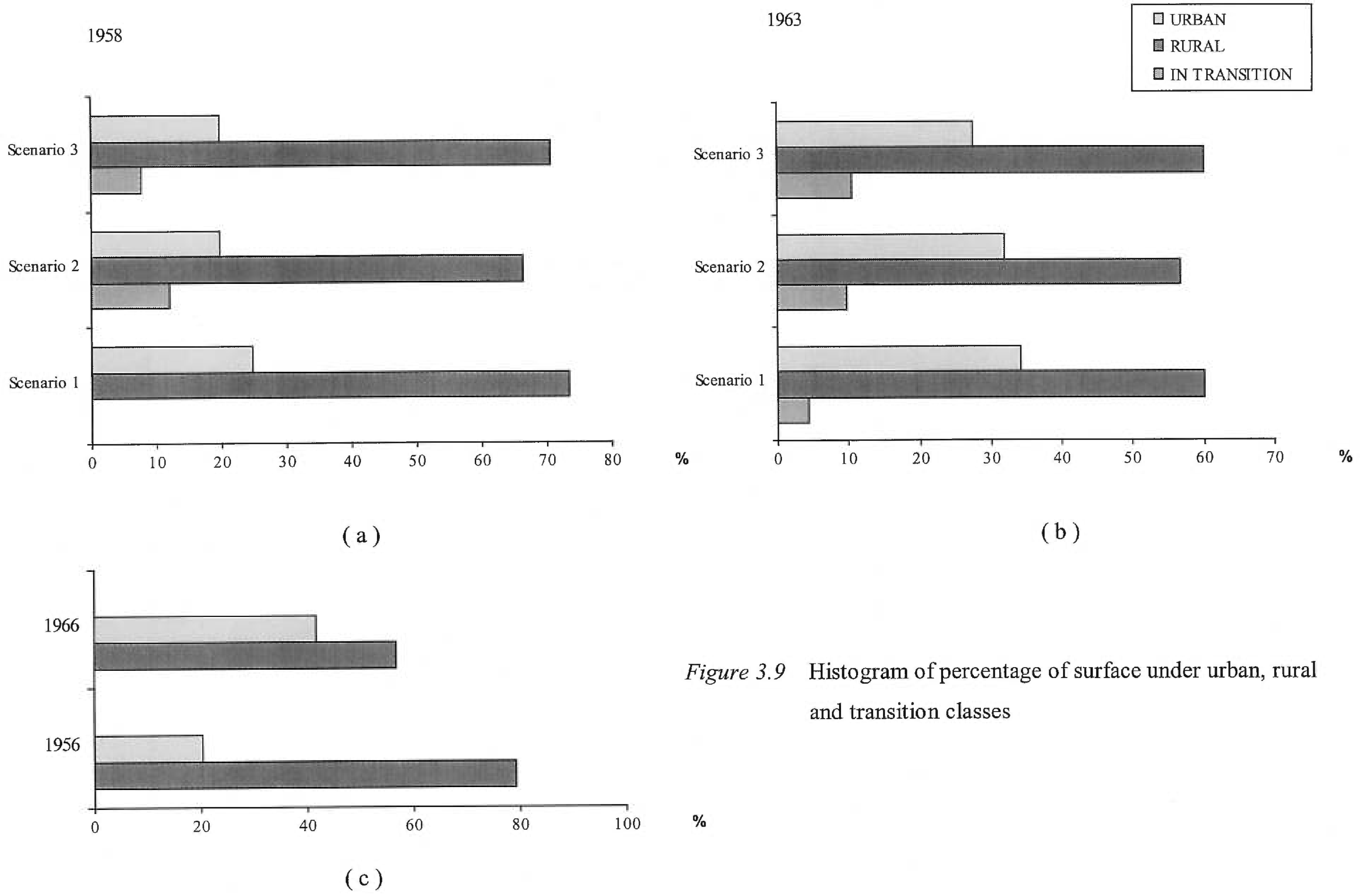


Figure 3.9 Histogram of percentage of surface under urban, rural and transition classes

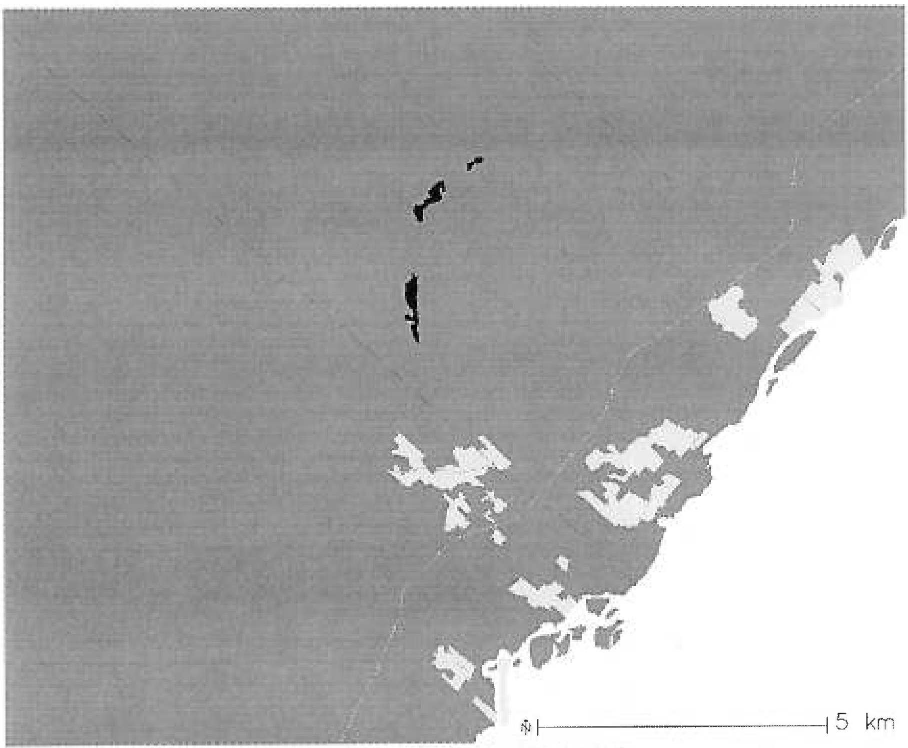
Table 3.1 Category contents for fuzzy layers generated for every intermediate year between two snapshots in 1956 and 1966 and according to all three possible scenarios

TRANSITION	1957	**1958**	1959	1960	1961	1962	**1963**	1964	1965
RURAL → URBAN	*Possible*	***possible***	*possible*	*possible*	*possible*	*possible*	***possible***	*possible*	*possible*
The Shortest Possible Scenario									
Stage 1	0.3/R+0.8/U	**0.0/R+1.0/U**	0.0/R+1.0/U	0.0/R+1.0/U	0.0/R+1.0/U	0.0/R+1.0/U	**0.0/R+1.0/U**	0.0/R+1.0/U	0.0/R+1.0/U
Stage 2	1.0/R+0.0/U	**1.0/R+0.0/U**	0.3/R+0.8/U	"	"	"	"	"	"
Stage 3	"	"	1.0/R+0.0/U	1.0/R+0.0/U	0.3/R+0.8/U	"	"	"	"
Stage 4	"	"	"	"	1.0/R+0.0/U	1.0/R+0.0/U	**0.3/R+0.8/U**	"	"
Stage 5	"	"	"	"	"	"	**1.0/R+0.0/U**	1.0/R+0.0/U	0.3/R+0.8/U
The Longest Possible Scenario									
Stage 1	0.9/R+0.2/U	**0.7/R+0.5/U**	0.3/R+0.6/U	0.1/R+0.9/U	0.0/R+1.0/U	0.0/R+1.0/U	**0.0/R+1.0/U**	0.0/R+1.0/U	0.0/R+1.0/U
Stage 2	1.0/R+0.0/U	**1.0/R+0.0/U**	1.0/R+0.0/U	1.0/R+0.0/U	1.0/R+0.0/U	0.9/R+0.2/U	**0.7/R+0.5/U**	0.3/R+0.6/U	0.1/R+0.9/U
The Mixed Possible Scenario									
Stage 1	0.8/R+0.4/U	**0.1/R+0.8/U**	0.0/R+1.0/U	0.0/R+1.0/U	0.0/R+1.0/U	0.0/R+1.0/U	**0.0/R+1.0/U**	0.0/R+1.0/U	0.0/R+1.0/U
Stage 2	1.0/R+0.0/U	**1.0/R+0.0/U**	1.0/R+0.0/U	0.9/R+0.2/U	0.7/R+0.5/U	0.3/R+0.6/U	**0.1/R+0.9/U**	"	"
Stage 3	"	"	"	1.0/R+0.0/U	1.0/R+0.0/U	1.0/R+0.0/U	**1.0/R+0.0/U**	1.0/R+0.0/U	0.3/R+0.8/U

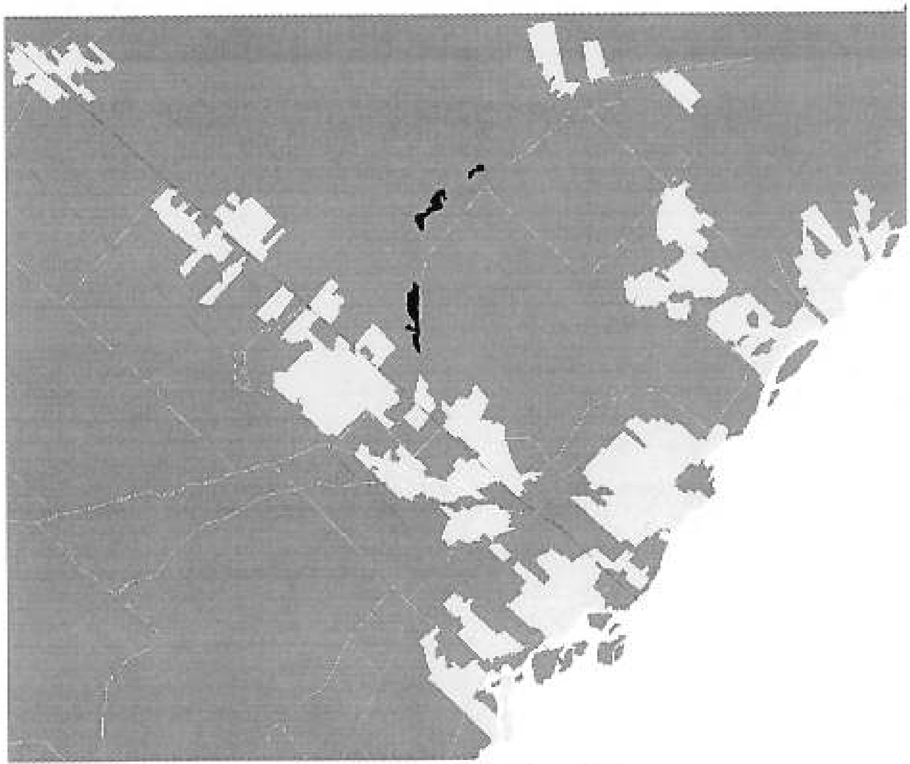
years 1958 and 1963 for all three scenarios. It is clearly demonstrated that there exist a percentage increase of the surface area under urban land-use and a decrease in surface area under rural land-use. Furthermore, the third bar in the histogram conforms to the surface area "*in transition*" from rural to urban land-use indicating the amount of percentage variation under the change.

The sub-area 2 is located at the same place as the sub-area 1 but covers 197.89 km^2 (Figure 3.3). It encompasses neighbouring municipalities of Ste-Thérèse, such as Blanville, Rosemère, Lorraine, Boisbriand, Terrebonne, Bois-de-Filion, St-Eustache and Mirabel, which joint Montreal metropolitan area by the year 1986. In the period between 1976 and 1986, a significant increase in urbanisation process has occurred in this area and the highway 15N and other new regional roads have been constructed. In this case, the spatial model of urban spread is based on road influence, and is developed using the common buffer operation around a road network for the snapshot layer in the year 1976. Figures 3.10 (a) and (b) show database snapshots which correspond to years 1976 and 1986 respectively.

Figure 3.11a presents buffer zones having a width of 90 m and which conform to the possible annual growth of urban body from the road network. For example, the boundaries of buffer zone 8 correspond to the boundaries of the urban land-use which is attained in the year 1984. The same tool *Fuzzy_Interpol* was used to generate all three scenarios using the different spatially distributed models of urban spread. Figure 3.11b depicts the generated intermediate fuzzy layer for the year 1982 according to the scenario III. The change is now in the second stage. Three main classes are displayed in Figure 3.11. The first class corresponds to the buffer zones which already finished its transformation and which became the urban area. Its category contents is: *« R→U, possibly 0.0/R+1.0/U »*. The second class corresponds to the buffer zones in second stage of transition and its category content for the year 1982 is *« R→U, possibly 0.3/R+0.6/U »*. Once this transformation is finished, the changes in the third class will



(a) snapshot layer in 1976



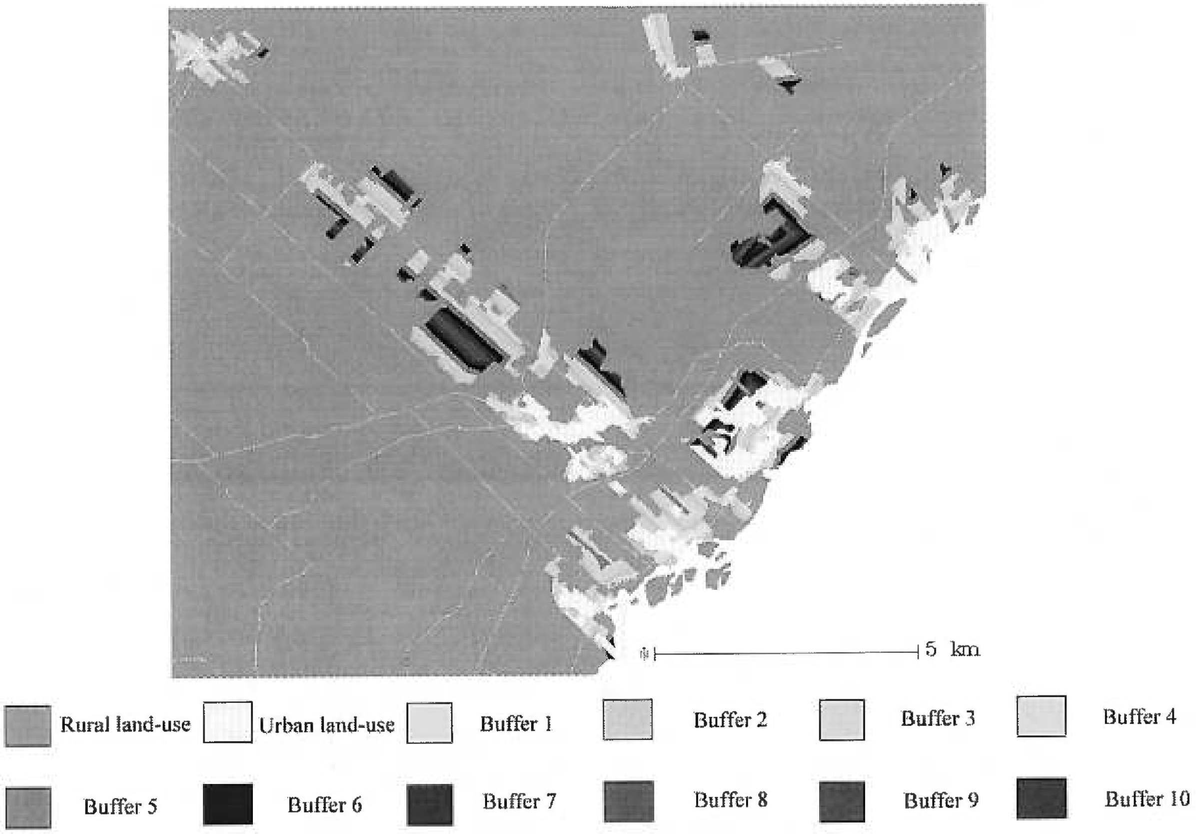
(b) snapshot layer in 1986

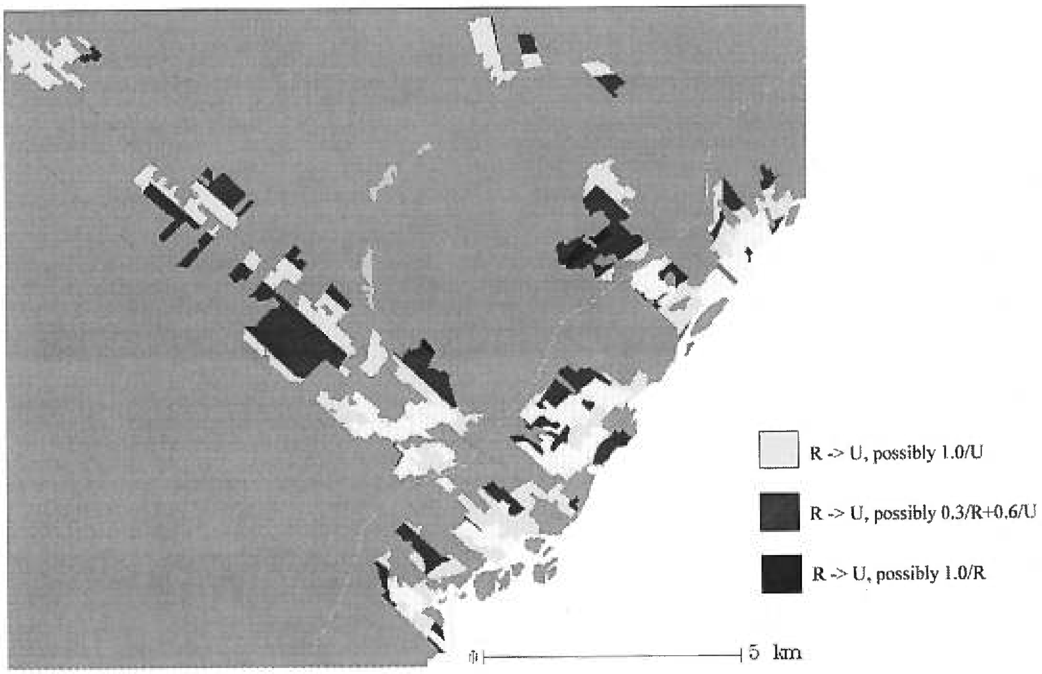
▨ Rural land-use □ Urban land-use ■ Lake

Figure 3.10 Resulting maps of sub-area 2

Figure 3.11 Generated layers of sub-area 2:

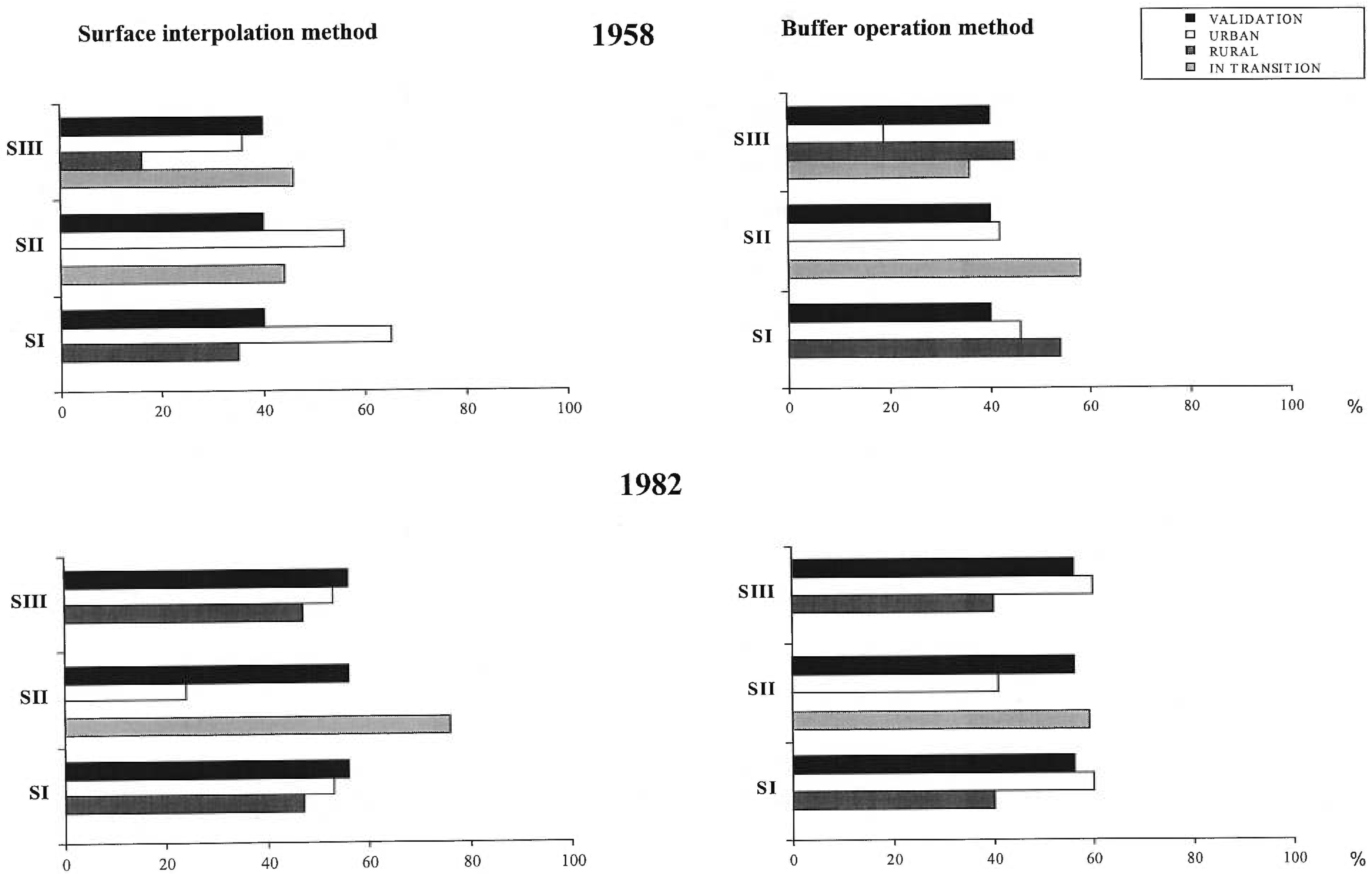
(a) generic layer with road influence distribution of rural to urban transformation





(b) fuzzy layer in 1982 and according to the Scenario III start and that is in the year 1985. However the third class still rural, is in the year 1982 hence having the category content for its buffer zones: *«R→ U, possibly 1.0/R+0.0/U »*.

The validation of the proposed approach was performed by comparing data layers generated by *Fuzzy_Interpol* and available aerial photographs acquired in years 1958 and 1982 for the sub-area 1 and at the scale 1: 40 000. These aerial photographs were digitized, geometrically corrected and interpreted using standard GRASS4.1 modules. Figure 3.12 represents histograms showing the percentage (%) of the surface areas in transition for each scenario and for both interpolation methods. In 1958, the scenario II and the buffer operation method provide the best estimation of the urban surface compared to the reference aerial photograph data. The surface interpolation method has a tendency to overestimated the percentage of urban land-use. In 1982 the best results are obtained with the first interpolation method for scenarios I and III. The buffer method results provides as well good results for the same scenarios. The scenario II for both interpolation method, slightly underestimates the urban surfaces. These results suggest that the urbanisation process had different dynamics and morphology of change in different periods of time. In the period 1956-1966 it could be estimated that urban expansion was guided by the regional road network. In the period 1976-1986 urban expansion showed a more concentric morphology.



Surface interpolation method

1958

Buffer operation method

1982

Figure 3.12 Histogram of obtained percentage of surfaces by validation and simulation

3.6. CONCLUSION

In this paper, a fuzzy logic approach is used to model spatio-temporal change in a raster snapshot GIS database. The rural-urban transformation was used in order to illustrate the methodology developed. It is based on the simultaneous utilisation of a series of fuzzy membership functions which generate intermediate layers between consecutive snapshots layers. It is also based on the use of a spatial generic layer which models spatial change of rural-urban transformation during the period of observation.

The advantage of this model is in the flexibility of development of fuzzy membership functions, in the possibility to choose the desired temporal resolution as well as to select a different model of spatial evolution related to the phenomenon under study. The user can create, through the consultation with experts in the domain and based on his own experience, various scenarios in order to better understand the dynamic process which flows between the known states which are registered in the database. The personal judgement which is involved in the choice of membership functions may represent a disadvantage of this model as well as the imperfection in spatial simulation of chosen methods of urbanisation processes. On one hand, this opens a possibility of creation of customised method used to design the GIS algorithm for better simulation of rural-urban transition which could replace the standard GIS methods of surface interpolation and buffer operations used in this paper. On the other hand, the proposed methodology could play an important role in the GIS advancement of temporal data visualization techniques as described in Acevedo and Masuoka, (1997). It may serve as a tool for the animation of urbanisation process or other spatial features in transition, creating fuzzy or smoother intermediate data frames.

There is a possibility to analyse the dynamic geographic phenomena on different scales such as regional, municipal or local. This implies that a number of classes in the database can be refined in a way that it is possible to replace rural land-use by agricultural, fallow, recreational land-use as well as a forest while within urban land-use it is possible to have commercial, industrial or residential land-occupation. This method could be also implemented for all above-mentioned classes given that all needed membership functions are developed.

All the above-mentioned advantages facilitate the analysis of spatial and temporal distribution of land-use This methodology could be employed in modelling gradual urban expansion dynamics which could support land-use planners in performing the urbanisation management tasks.

Le chapitre 3 vise à répondre au premier et deuxième objectif de la recherche et il élabore en détail la technique d'interpolation spatio-temporelle. Il présente des simulations des changements qui se déroulent à travers les étapes successives dans lesquelles un changement peut débuter et se terminer au complet. Les trois scénarios présentés sont conçus pour simuler différentes possibilités de durées des changements. Le premier scénario illustre que la transformation des classes d'utilisation du sol est rapide et ne dure que deux ans. Le deuxième scénario assume que le changement est le plus lent possible. Finalement le troisième scénario décrit que la transition entre les classes peut être conçue avec des durées de changements différents, soit de trois, cinq et deux ans respectivement. Pour des raisons de simplicité, les résultats sont produits uniquement pour les transitions entre les classes rural et urbain.

Les résultats des chapitres 2 et 3 sont obtenus en utilisant le module Fuzzy_Temp qui a été développé afin de pouvoir tester l'approche de la logique floue incorporée dans l'interpolation spatio-temporelle. Le chapitre 4 est consacré à décrire plus en détail le module développé dans le langage C et implanté dans l'environnement UNIX de GRASS4.1. La même méthodologie est présentée avec une emphase sur la modélisation des processus dynamiques sur un seul site d'étude en utilisant le logiciel développé. Tous les résultats obtenus sont présentés sous forme de figures qui montrent clairement l'interface graphique. Les principales fonctions développées sont expliquées afin de démontrer leurs capacités avec plusieurs classes et leurs transitions mutuelles ainsi que la transition unique de rural vers urbain. De plus, une session de travail avec Fuzzy_Temp est présentée via la description des menus principaux qui logiquement démontre comment on peut procéder à des simulations et produire des résultats pour les années intermédiaires choisies.

An Application of Fuzzy Logic Reasoning for GIS Temporal Modeling of Dynamic Process

4.1. ABSTRACT

The analysis and modeling of dynamic processes require the consideration of both spatial and temporal attributes of data and their integration into a GIS database. However, current GIS raster databases have severe limitations related to the temporal component of data. Data are generally stored through a series of snapshot layers associated to particular instants in time. If the interval between two consecutive snapshots is too long the essential information about the change may remain undetected. In this study, spatio-temporal interpolation based on fuzzy logic theory was applied in order to model the missing information about change that happened between consecutive snapshots. Three different scenarios of rural-to-urban land-use transformation were conceived to simulate different dynamics of change using module FUZZY_TEMP integrated in the GRASS4.1 environment. The obtained results were validated through a comparison of the urban boundaries obtained from aerial photographs and those which were generated using the proposed methodology. The results confirm the potential of the approach to produce realistic simulations of the dynamics of the urbanization process.

4.2. INTRODUCTION

Factors such as the availability of spatio-temporal data, the exponential growth of computational power and the new improvements in the area of geographic information systems (GIS) widely open the opportunity for the development of numerical models and simulation tools to investigate dynamic processes (Mitas *et al.*, 1997). Simulation models represent simplifications of the real world embodying diverse sets of rules that describe the human perception of the processes (Deursen, 1995). The application of various sets of input parameters through the use of simulation models create the possibility of building different scenarios which could be used to assess the effects of management options in the real world. GISs represent a great potential for the implementation of different numerical models. The incorporation of spatial and temporal variables in current GISs is necessary to enable the modeling of dynamic phenomena and to provide a means to better understand cause and effect relationships (Kelmelis, 1998).

However, current GISs have severe limitations related to the temporal component of data. The representation of time still relies on conventional cartographic models where it is usually depicted as a static attribute of space (Langran and Chrisman, 1988). In a raster GIS database, data are stored in a series of instantaneous pictures of the geographic space, called "snapshots", which carry the information about entities and their attributes at a particular moment in time (Chrisman, 1998). If the interval between two consecutive snapshots registered in the database is not adequate for the dynamics of the process under observation, the essential information about the change remains undetected. The capability to analyze dynamic geographic processes is also strongly influenced by the availability and quality of historical data. Data usually relies on a series of remote sensing/airborne images or maps acquired in the past. Unfortunately in such cases, the verification of the data in the field is almost impossible, hence missing information cannot be acquired.

This study addresses the problem of completing the lacking information between a series of historical snapshots registered in a GIS raster database, based on spatio-temporal interpolation and fuzzy logic reasoning, in order to model the dynamics of urban expansion. Other various approaches for simulations of the urbanization process have been developed but they are also implemented in future prediction models (Meaille and Wald,1990; Batty and Xie, 1994; Landis, 1994; Clarke *et al.*, 1997; Allen, 1997; Acavedo and Masuoka, 1997). These models use large number of parameters which are not adequate for the interpolation problem where "prediction" of change is performed between the known states stored in the database and when most accurate information related to the change is not available.

Markov chain theory has also been tested for analysis of urban development (Bell, 1974; Bourne, 1974; Robinson, 1978). The essence of the Markov chain theory lies in the assumption that the probability of a unit of land moving from one state characterized by one land-use class at time *ti* to another state characterized with another land-use class at time *tj* is conditional upon the state at time *ti*, where *ti<tj*. Thus, the Markov chain analysis can be useful as an efficient short-range forecasting method when studying the short-term behavior of change processes (Robinson, 1980). However, the problem addressed in this paper consists of determining the state at the exact time between two known snapshots in the historical database. Statistical data such as the frequency of change which are necessary for the Markov model are not available for the problem addressed in this paper.

4.3. METHODOLOGY

4.3.1. Study area and data set

The proposed approach is tested on the North Shore of the Montreal Metropolitan area in Quebec, Canada (Figure 4.1). This area, covering a surface of 1320 km^2, went through a radical transformation during the last forty years due to considerable and fast expansion of urban population. The main source of data was 32 topographic maps produced from 1956 to 1986 by the Survey and Mapping Branch of the Department of Energy, Mines and Resources, Canada, at the scale 1:50 000. Data were digitized using MapInfo3.0 desktop software and incorporated in the GRASS4.1 raster database in four snapshots with a final spatial resolution of 10 m and a temporal resolution of 10 years. Major land-use classes defined are urban area, forested area, agricultural land, principal road and hydrographic network, airport, national park and Indian reserve. In order to simplify the illustration of the methodology presented in this study, the main effort is focused on the simulation of the transformation from rural to urban land-use.

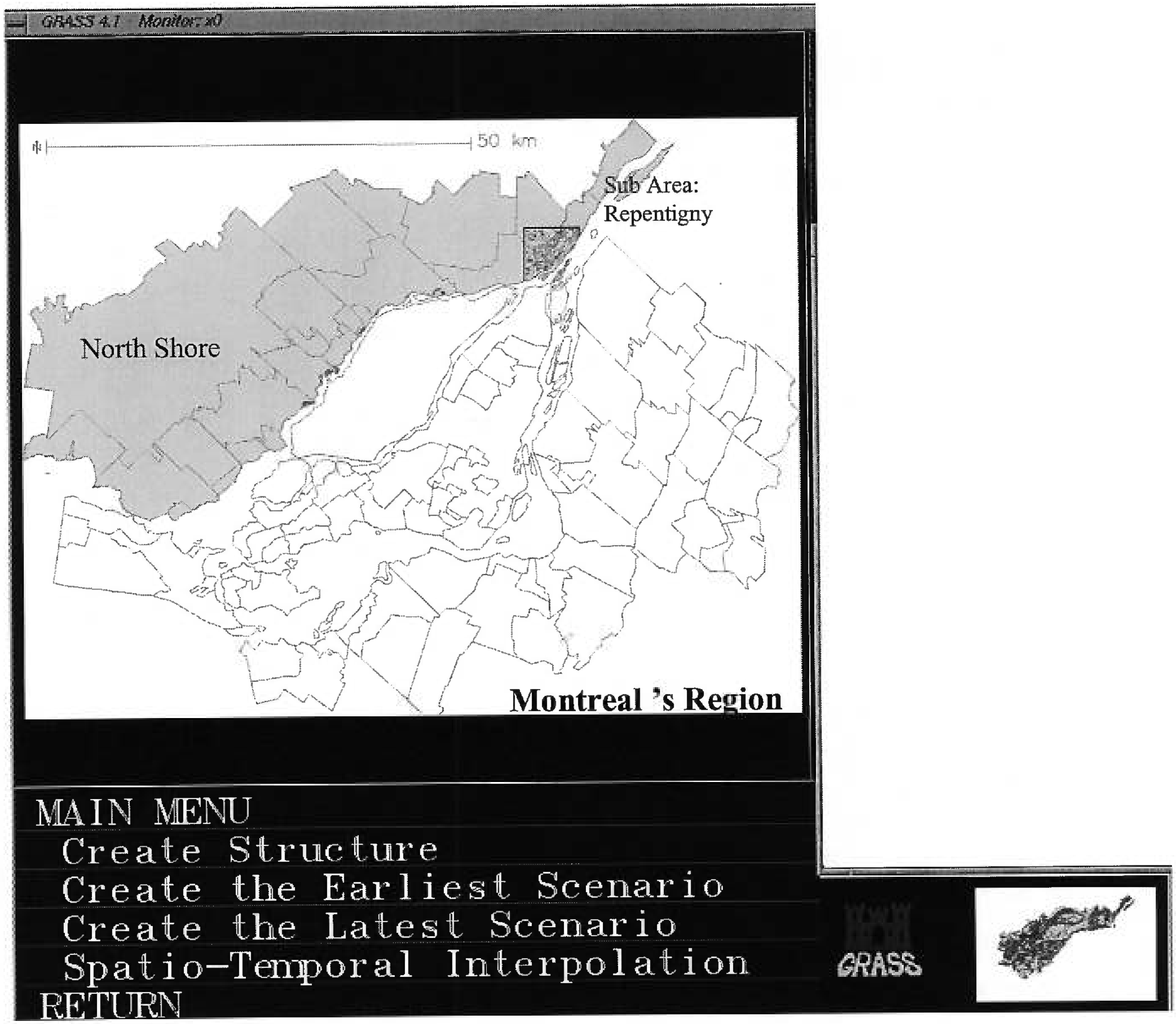


Figure 4.1 The Montreal Metropolitan area with all municipality limits, The North Shore and the chosen sub-area of Repentigny in FUZZY_TEMP graphical context

4.3.2. Linking fuzzy logic and spatio-temporal interpolation in a raster GIS database

The basic concepts related to fuzzy logic theory were postulated by Zadeh in 1965 and 1978. The application of fuzzy logic is aimed at creating a set of intermediate layers to simulate the evolution of a geographic entity between consecutive snapshots. The objective of the proposed approach of spatio-temporal interpolation is to model the gradual change of a geographic entity by defining its spatial and temporal evolution simultaneously. This simulation is then accomplished in three steps.

The first step is to determine the appropriate temporal resolution which yields the exact number of intermediate layers i.e. the temporal intervals between two consecutive snapshot layers. These layers correspond to the shortest possible transition time for each cell in the initial layers to change from one geographic class to another (one thematic value to another). The second step is to determine the generic layer which contains the information about the change of spatial boundaries for the given number of temporal intervals. This generic layer is defined using standard GIS methods such as surface interpolation. The third step consists of applying the fuzzy membership functions in order to generate the missing information about the change of the geographic entity for each cell of the initial snapshot layer.

The membership function are defined by using the semantic import model (Robinson, 1988; Burrough, 1989) where the user *a priori* assigns the membership grade based on his own experience or throughout the consultation with experts in the related domain. The fuzzy membership degrees are based on the realistic estimation of time needed for a possible duration of change for aerial surfaces under urban development. The selection of different membership functions is not an arbitrary process but it may provide different results (Kollias and Voilotis, 1991). Therefore, three possible scenarios with tree different sets of fuzzy membership functions are conceived in order to simulate the different possible outcomes of urbanization process.

In this study, the creation of the generic layer is performed using the inverse square distance method of surface interpolation (U.S.Army Cerl, 1993). Two boundaries of urban land-use from two consecutive snapshots registered in the database are overlaid in one single auxiliary layer. Since the difference between two ultimate boundaries corresponds to the interval of ten years and since an annual temporal resolution is chosen for modeling the dynamic urbanization process, ten intermediate belts are generated. The standard GRASS4.1 surface interpolation module creates the interpolation limits. Each limit corresponds to a belt of the annual spatial change of the rural-urban boundaries. Generally, it takes several years for the urbanization process of one part of the city to be completed. So in the proposed model, one stage represents one completed phase of the urbanization process. Several rural-urban boundaries from a generic layer can constitute one stage of the evolution. Figure 4.2 presents an example of the generic layer for the transition period 1966-1976 and for the town of Repentigny. The black line outlines the urban boundaries in 1966 and 1976. Ten zones identify the intermediate annual boundaries of urban land-use.

An example of rural to urban land-use transition based on the concept of fuzzy spatio-temporal interpolation is illustrated on Figure 4.3. When the cell value is the same in the initial snapshot layers (t_1 and t_2), the value in the corresponding cell in any generated intermediate layer at time t_{1i} will stay unchanged with the highest degree of belonging to rural or urban land-use class. If the value in the cell examined is different at the time t_1 and t_2, this means that the geographic entity is in transition and is therefore represented in the intermediate layers which are generated according to the model developed in this study. The value of the cell at time t_1 indicates 1.0 membership to the class R named rural land-use while the value in the same cell at the time t_2 indicates 1.0 degree of belonging to the class U named urban land-use. A new intermediate layer is created at the time t_{1i} with the membership degree $\mu_C(t_i)$ calculated according to the fuzzy functions which model the transition between classes R (rural) and U (urban) for the particular stage of

Figure 4.2 Generic layer with surface interpolation determination of rural-urban boundaries from 1966 to 1976 transition represented in FUZZY_TEMP graphical context

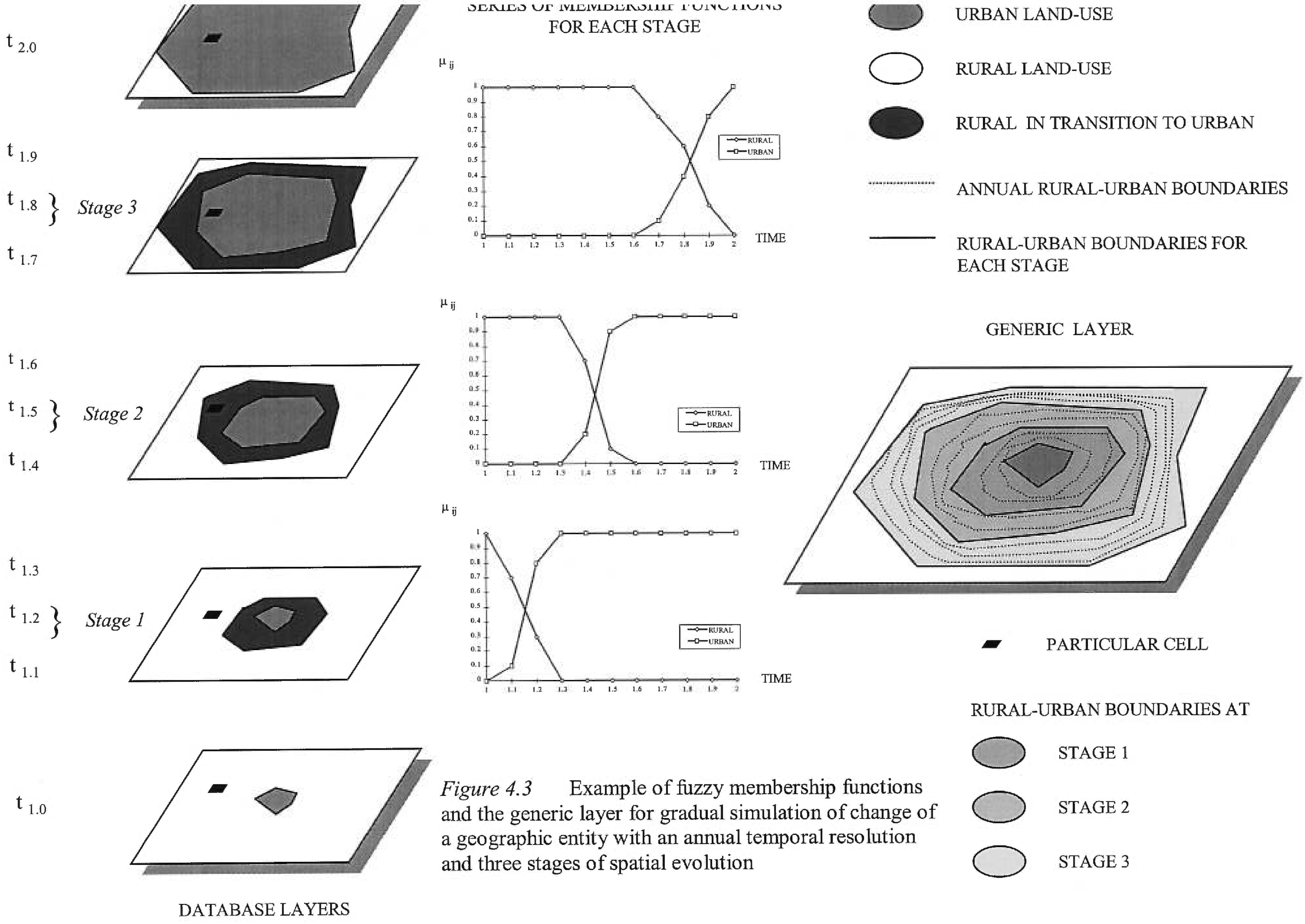


Figure 4.3 Example of fuzzy membership functions and the generic layer for gradual simulation of change of a geographic entity with an annual temporal resolution and three stages of spatial evolution

spatial evolution determined from the generic layer. For the chosen temporal resolution of one year the adopted fuzzy set notion is:

$$C = \sum_{i=1}^{n} \mu_C(t_i) / t_i \qquad \text{(Equation 4.1)}$$

where C is class R or class U, and n is the interval between two consecutive snapshots which is 10 years for this study.

The membership functions used are of the asymmetric right or left range type. The functions are piecewise linear and the points corresponding to temporal interpolation intervals are connected by linear segments.

In each moment in time t_{1i}, the i-th intermediate database layer is calculated on the basis of the exact number of layers corresponding to one particular stage in the rural-urban transition process. Thus, as shown in Figure 4.3, at the time instant $t_{1.4}$, the created intermediate layer is in *stage 2* and cells which are not in the transition are assigned the values which they had in the initial snapshot layer that is either *Urban* or *Rural.* Only cells in the transition belt whose boundaries are defined in the generic layer receive the degrees of membership to classes R and U of *0.7* and *0.2* respectively. The corresponding thematic values could then be derived for each cell in the transition at the time $t_{1.4}$. Each defined thematic value matches one particular category content and must be different for each possible combination of degrees of membership. For example, the thematic value calculated for (*0.7, 0.2*) degrees related to classes R and U must be different from the thematic value obtained for (*0.7, 0.2*) degrees of membership to some other transitions (like *Rural* to *Road*). The user should adopt a new thematic value for any new membership combination thereby ensuring that the above condition is met. The most important task is to fill the database, layer by layer, with the fuzzy category contents associated with each cell value in question.

Considering the particular cell in Figure 4.3 which is in the transition from class *R* to class *U*, different degrees of belonging for different time instances are assigned from layer to layer. At the initial time $t_{1.0}$, the cell is belonging to the rural land-use, i.e. class *R*, and at the ending time $t_{2.0}$ to the urban land-use, i.e. class *U*. The category contents of this particular cell varies from intermediate time instants $t_{1.i}$ that is from stage to stage. In *stage 1* for the time instants $t_{1.1}$, $t_{1.2}$ and $t_{1.3}$, the category contents of the cell is: «*R*→ *U*, *possibly 1.0/R + 0.0/U*», because the urban boundaries do not yet include the cell in question such that it still remains in rural area. In *stage 2*, the cell is located in the belt showing the transition from rural to urban land-use. Therefore, the category contents for the same cell vary and are at time instant $t_{1.4}$: «*R*→ *U*, *possibly 0.7/R + 0.2/U*»,, at the time instant $t_{1.5}$: «*R*→ *U*, *possibly 0.1/R + 0.9/U*» and finally at time instant $t_{1.6}$: «*R*→ *U*, *possibly 0.0/R + 1.0/U*». In *stage 3*, at the time instants $t_{1.7}$, $t_{1.8}$ and $t_{1.9}$ the category contents of the same particular cell are: «*R*→ *U*, *possibly 0.0/R + 1.0/U*» because the cell already achieved the transition in the urban land-use and its category contents still remain the same. One stage is considered finished when all cells belong to the urban land-use; then the new stage of urbanization process can begin.

4.3.3. Generation of possible scenarios

The methodology proposed in this study allows the application of different scenarios for the simulation of urban expansion. The urbanization process could have been characterized by different dynamics in different periods of time in the past. Therefore, three possible scenarios are conceived in order to model various duration and speed of change within the ten year interval between the initial snapshots. Figure 3.5 indicates three sets of membership functions corresponding to the possible scenario developed in the study. The first scenario assumes that the dynamics of change is the fastest possible transition from rural to urban and is modeled in five regular stages, each having a duration of two years. Therefore, five successive sets of membership functions are developed in that purpose. The second scenario is slower and the dynamics of change is completed through two stages of five years and are characterized with two sets of membership functions. The third scenario assumes the irregular urban expansion process which unfolded in three stages, each of which having the different duration of three, five and two years respectively. Therefore, three sets of membership functions are developed for this scenario. The number of series of membership functions always corresponds to the number of stages in order to simulate three possible speeds of urbanization dynamics. For example, as seen at Figure 3.5, for the cell in transition at the time instant $t_{1.7}$, which corresponds to the seventh year after the instant corresponding to the initial snapshot layer, the following category content is obtained according to the first scenario: «$R \rightarrow U$, *possibly* $0.3/R + 0.8/U$ ». When the second scenario is considered the category content is as follows: «$R \rightarrow U$, *possibly* $0.7/R + 0.5/U$». Finally, the third scenario yields: «$R \rightarrow U$, *possibly* $0.1/R + 0.9/U$ ».

4.3.4. Description of the new GRASS4.1 fuzzy logic application module

An automated tool named FUZZY_TEMP was designed to support the practical implementation of fuzzy logic and spatio-temporal interpolation into a raster snapshot database. FUZZY_TEMP encompasses a set of routines developed using C programming language and integrated into the GRASS4.1 environment. The corresponding call frame structure distinguishes three main groups of functions. The first group is intended to enable data manipulation and data conversion, and converts, returns, and stores the GRASS4.1 data structures in the format accessible to FUZZY_TEMP routines such as *CreateStructure, EditMatrix.* The second group of functions perform fuzzy logic calculations according to the chosen scenarios. The functions *CreateNewMatrixEarly* and *CreateNewMatrixLately* were developed to perform all possible transitions between all major land-use classes in the initial database such as transition from forest to agricultural land-use, from agricultural land-use to regional road or forest to urban land-use explained in Dragicevic and Marceau, 1997. These routines are used to calculate the estimated degree of membership using fuzzy set functions derived for all classes and according to two possible scenarios. These scenarios simulate the earliest and the latest possible beginning of the change. In the case of transition from rural to urban land-use three other possible scenarios are created in order to model different dynamics of change. Therefore, the functions *CreateNewMatrixInterpol* and *ReturnId* were added to handle spatio-temporal interpolation based on the information contained in the cells of the generic layer. The function *FuzzySystemInterpol* performs the comparison of two cells from two consecutive layers, and based on their values, determines the type of the transition, the cell value in the intermediate layer and the identification number from the generic layer. This is accomplished using predefined fuzzy logic functions which model each possible transition. For example, the function *FuzzyLogicRU_Interpol* models rural-to-urban transition using a spatio-temporal interpolation approach while function such as *FuzyLogicFA* models forest-to-agricultural transition using other major land-use classes generated in the database (Dragicevic and Marceau, 1997). The function *CreateCatsFile* assigns a corresponding category content to a particular cell generated in the intermediate layers. It enables the access and display of the category content information (*«R→ U, possibly 0.6/R +0.2/U»*) from the graphical display. The third group of functions support the user interface functionality, examples of which are *Main_Menu, Display_Menu* or *Fuzzy_Functions_Menu.*

4.3.5. Validation procedure

Validation of the interpolation results were performed by comparing data layers generated by FUZZY_TEMP and digitized aerial photographs acquired at the corresponding years. The aerial photographs, at the scale 1:40 000, were geometrically corrected using a minimum of ten control points per photo with the standard GRASS4.1 imagery modules (U.S.Army Cerl, 1993). The modified Gaussian elimination method of first polynomial order was used to calculate the transformation matrix which converts the coordinates of image to standard map coordinates for each pixel in the image. Thereafter, a photo-interpretation was performed to establish the boundaries between rural and urban land-use. The calculation of urban land-use surface was then accomplished, and the results were compared with simulated urban land-use areas using a GRASS4.1 functionality.

4.4. RESULTS

To illustrate the results, a sub-area showing considerable land-use changes and growth of population through the last 50 years was chosen. It is located in the municipality of Repentigny, centered at $45^0$44'N and $73^0$27'W and it covers 51.21 km^2 (Figure 4.1). The comparison of urban boundaries data obtained from aerial photographs with the corresponding data provided by simulations is performed for the years 1958, 1975 and 1982.

Figure 4.4 outlines the map of a typical snapshot layer corresponding to the year 1976 which is stored in the database and used to create the generic layer as well as the resulting intermediates layers. The generic layer for the transition from 1966 to 1976 is presented in Figure 4.2 containing ten belts representing the boundaries of urban land-use with an annual temporal resolution. For example, belt 4 represents the estimated urban boundaries reached in the year 1970. The resulting map for the year 1975 generated by FUZZY_TEMP using the first scenario and its generated classes is presented in Figure 4.5. The tiny black lines represent the urban boundaries determined from the aerial photograph in 1975. According to the first scenario which corresponds to the shortest duration of change lasting only two years, in the year 1975, the stage 4 of the transformation is already finished and the stage 5 is in course. Therefore, four classes are distinguished with different cell values and its category contents. The two major classes such as *Rural* and *Urban* are denoting with cell values *50* and *30* respectively. Their category contents *«Rural -> Rural»* and *«Urban -> Urban»* respectively, point out that these cells were not in the transition, they remain the same in all intermediate layers. The third class with the cell value of *38* represents the urban surface which already finished the transition. Its category content indicates *«R→ U, possibly 1.0/Urban»*. The fourth class with cell value *211* represents the surface whose transition still lasts and its category content is *«R→ U, possibly 0.3/RU + 0.8/U»*.

```
+-----------------------------------------+
|        Use mouse on graphics monitor    |
|        to make selection on the menu    |
+-----------------------------------------+


Enter the new epoha name
Enter 'list' for a list of existing raster files
Enter 'list -f' for a list with titles
Hit RETURN to cancel request
> epoha1975
<epoha1975>
 Introduse the Scenario number
-  1 for the shortest possible scenario;
-  2 for the longest possible scenario  or
-  3 for the mixted duration possible scenario.
1
Enter first epoha:
epoha1966
```

Figure 4.4 Snapshot layer of study area in 1976 in a FUZZY_TEMP graphical context and the command line window for generation of an intermediate layer in 1975

```
Buttons
 Left:  what's here
 Right: quit

620395(E) 5064555(N)
epoha75_R_S1 in PERMANENT (0)

620165(E) 5066475(N)
epoha75_R_S1 in PERMANENT (50)RURAL -> RURAL, RURAL AREA

619155(E) 5064475(N)
epoha75_R_S1 in PERMANENT (30)URBAN -> URBAN, URBAN AREA

619505(E) 5065355(N)
epoha75_R_S1 in PERMANENT (38)RURAL -> URBAN possibly 1.0 URBAN

619755(E) 5066045(N)
epoha75_R_S1 in PERMANENT (211)RURAL -> URBAN, possibly 0.3/RU + 0.8/U
```

Figure 4.5 Generated intermediate layer of study area in 1975 according to the first scenario shown in graphical context of FUZZY_TEMP along with its category contents

Table 4.1 presents more detailed results representing calculated surfaces obtained using spatio-temporal interpolation technique for all three possible scenarios of change and for three different dates. The urban land-use surfaces calculated from digital aerial photographs are also shown for comparison purposes. Three classes are distinguished showing the surfaces which already achieved the urban land-use, which are in transition and which still remains in rural land-use.

Table 4.1 The comparison of surfaces covered by rural, urban and classes in transition generated with the spatio-temporal interpolation method (using three scenarios of change and three different dates) and surfaces of urban land-use calculated from digital aerial photographs

SUB AREA: Repentigny	**Surface Interpolation Model**			**Aerial photograph**
Scenario	*S1*	*S2*	*S3*	*Urban land-use*
1958	*ha*	*ha*	*ha*	*ha*
Possible 1.0/Urban	26.07	37.12	17.09	33.78
Possible x/Rural + y/Urban	-	79.58 0.9/R+0.2/U	55.18 0.3/R+0.6/U	
Possible 1.0 /Rural	90.63	-	44.43	
1975	*ha*	*ha*	*ha*	*ha*
Possible 1.0/Urban	272.48	191.58	272.48	258.12
Possible x/Rural + y/Urban	107.31 0.3/R+0.8/U	188.21 0.1/R+0.9/U	107.31 0.3/R+0.8/U	
Possible 1.0 /Rural	-	-	-	
1982	*ha*	*ha*	*ha*	*ha*
Possible 1.0/Urban	274.62	111.46	274.62	269.75
Possibly x/Rural + y/Urban	-	362.66 0.3/R+0.6/U	-	
Possibly 1.0 /Rural	199.50	-	199.50	

According to the Table 4.1, in 1958, the second scenario provides the best estimation of the urban surface compared to the reference aerial photograph data. The first and third scenario underestimate the surface of urban land-use for 7% and 14% of total surface, respectively. However, for the year 1975 the best results are obtained with the first and third scenario providing similar results, slightly overestimating the urban expansion for 4% of the total surface. The second scenario significantly underestimates the urban surface. In 1982, the best results are obtained with the first and the third scenario showing a very good concordance with the urban surface obtained for the aerial photography. The second scenario considerably underestimates the change of the urbanization process.

The results obtained using the proposed approach suggest that the dynamics of change was slower in the first observation period from 1956 to 1966 since it is based on the premise that five years are required to complete the change. A gradually faster urbanization dynamics is observed in the period 1966-1976; and the change was possibly slower than two years but faster than five years. In the period from 1976 to 1986 the obtained results indicate that the urban growth occurred rapidly since it is based on the premise that two years are required to complete the transformation.

These results are in accordance census and population density data (Statistics Canada, 1951-1986). The community of Repentigny had a low population and high population density in 1951. Since 1961 the population started to significantly increase but the population density decreased till 1986. This indicates that urban expansion was slow in the first observation period and considerably faster from 1966 to 1986.

4.5. CONCLUSION

In this study, an application of fuzzy logic theory and spatio-temporal interpolation for GIS temporal modeling of a urban expansion process is presented. The main advantage of the proposed methodology is its capability to build various scenarios and to choose the desired spatio-temporal resolution which offer to the user the flexibility to test different simulations related to the dynamic phenomenon under study. The obtained results reveal that spatio-temporal interpolation based on fuzzy logic can generate realistic scenarios of the urban expansion process and could provide interesting clues about the dynamics of change which happened in the past.

A user-friendly software package named FUZZY_TEMP was developed in order to implement spatio-temporal interpolation based on fuzzy logic as an integrated module of GRASS4.1 GIS. The flexibility of its functions offers high level of reusability allowing easy addition of new scenarios, which in turn permits the application of this tool to any other study area under different spatial and temporal resolutions.

It is possible to customize the fuzzy set functions through the refinement of the existing classes of rural and urban land-use into sub-classes, and by introducing other various land-use classes. This implies the consideration of transitions from agricultural, fallow, recreational land use as well as forest to commercial, industrial or residential land-use. In that way, the new fuzzy set functions have to be developed to include a larger number of transitions and possible scenarios. In the case of larger temporal intervals the simulation of more complex situations such as cyclical and sequential changes is needed.

Furthermore, the surface interpolation technique could be replaced with more realistic models of urbanization process taking into account the urban morphology, human and socio-economic factors or the influence of local and regional transportation network. This research is extended to include a buffer operation method performed along the local road network to evaluate the impact of the road network on the urbanization process (Dragicevic and Marceau, 1999).

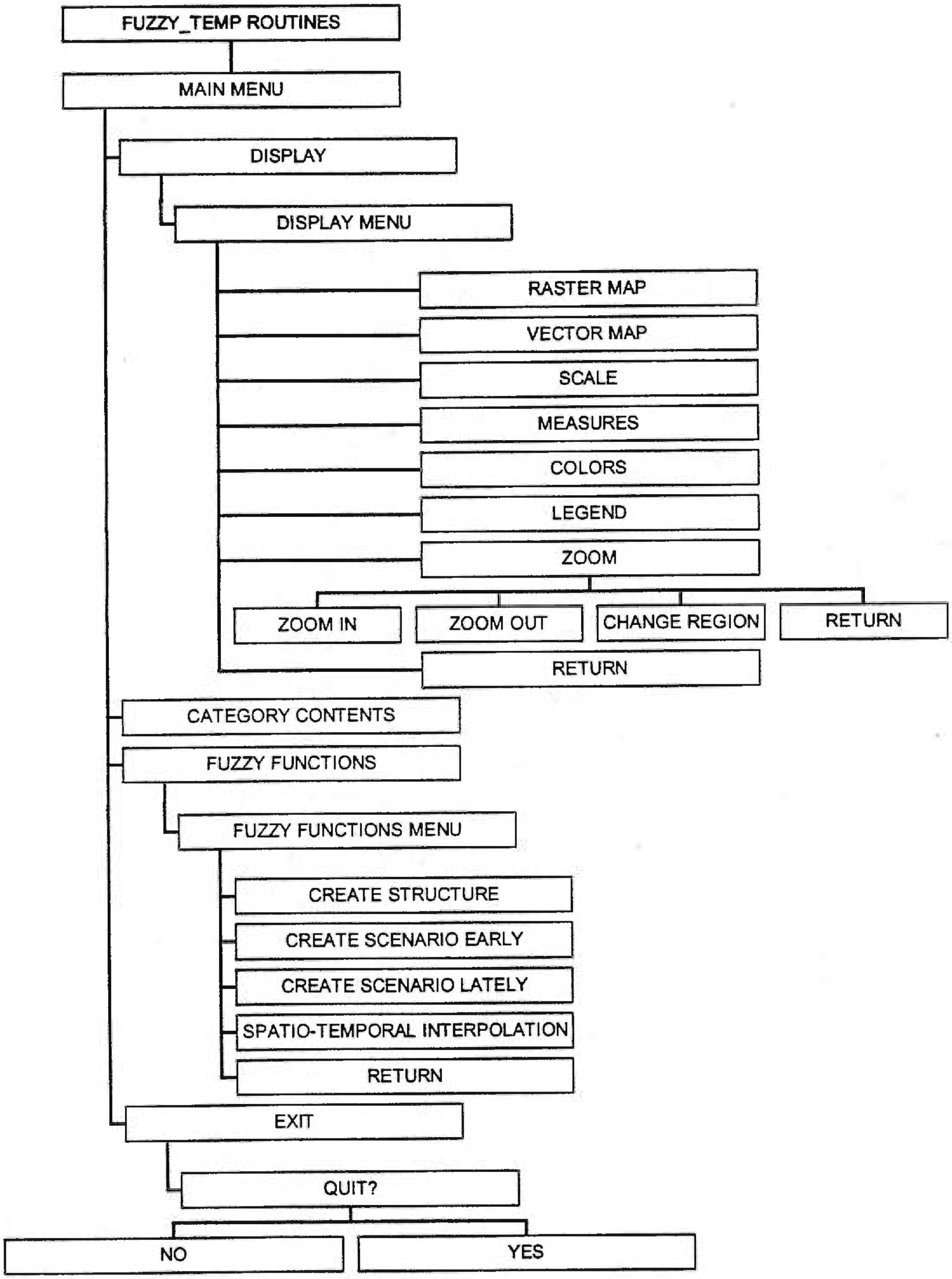
The proposed approach and the software package developed are flexible enough to be implemented using various models related to other dynamic processes and could help urban planners to improve historical databases for management purposes.

4.6. APPENDIX

The example of a FUZZY_TEMP **session**:

From the main menu shown in Figure 4.2, the *DISPLAY MENU* is entered first and the desired raster map is selected from the existing snapshot layer. The *FUZZY FUCTION MENU* is entered next and the preferred type of a fuzzy function is chosen. Two choices are possible: (i) the functions which perform all possible transitions between major database classes and (ii) the functions which perform the spatio-temporal interpolation for rural-to-urban transition (Figure 4.1). In order to generate one intermediate layer, the snapshot layer corresponding to the initial instant of time must be displayed first. The *CREATE STRUCTURE* option is then activated on the menu therefore generating the data related to the initial snapshot layer and storing them in the format accessible by the fuzzy functions. The more recent snapshot layer (e.g. for year 1976), is then displayed (Figure 4.4). The year for which the intermediate layer is to be created is entered (e.g. 1975) as well as the chosen scenario (e.g. first scenario) and the year corresponding to the initial snapshot layer which is used for comparison (1966). Once the aforementioned required information is entered, the fuzzy routines will perform the necessary comparisons and will generate the intermediate fuzzy layer. Upon termination of the processing, FUZZY_TEMP will return to the main menu. The user can now display the new generated intermediate layer and examine its category contents. The new category content classes and their corresponding cell values also can be displayed in the separate window (Figure 4.5) using the *CATEGORY CONTENT* option. Since FUZZY_TEMP relies on the generic layer during the creation of the intermediate layer, the former must be created before any FUZZY_TEMP processing and it must be a file with the same dimension as the corresponding snapshot layers in the study. The organizational chart of FUZZY_TEMP graphical user interface is given in Figure 4.6.

Figure 4.6 Organizational chart of FUZZY_TEMP graphical user interface for GRASS4.1



Le chapitre 4 est de nature technique et explique en détail les fonctions principales du module Fuzzy_Temp. Il démontre les capacités de tester le concept d'interpolation spatio-temporelle intégré avec la logique floue dans un SIG matriciel. Pourtant, les résultats présentés dans ce chapitre indiquent le besoin de développer des techniques de simulations spatiales plus proches de la réalité et également la nécessité d'appliquer une procédure de validation du modèle développé sur différents sites.

L'argumentation scientifique concernant ces problèmes est présentée dans le chapitre 5. Également ce chapitre présente une discussion générale des résultats obtenus en appliquant la méthode de l'interpolation spatio-temporelle basée sur la logique floue pour des simulations de changements. Une méthode de validation est appliquée sur trois sites d'étude. Il s'agit d'une comparaison des limites des zones urbaines obtenues lors des simulations avec des photos aériennes pour des dates intermédiaires entre celles enregistrées dans la base de données. Les résultats obtenus démontrent qu'il est possible de modéliser le phénomène d'étalement urbain. Les scénarios de différents changements donnent des indications réalistes sur la dynamique possible des changements du rural vers l'urbain. Deux variables de mesure de la dynamique sont utilisées pour démontrer la vitesse et le mécanisme des changements des trois zones urbaines en question.

Les points forts de la méthodologie sont soulignés en indiquant la flexibilité de l'approche permettant de confronter des scénarios de l'évolution du territoire avec les dynamiques réelles. Les limites de la méthodologie proposées sont aussi présentées. Ces limites concernent surtout la simplicité du modèle utilisé dans la propagation spatiale de l'expansion urbaine. Le potentiel d'utilité de la méthodologie proposée pour la visualisation de la dynamique des changements est aussi discuté, ce qui ouvre des perspectives pour la cartographie animée, une composante importante dans un SIG temporel.

Space, Time and Dynamics Modeling : A Fuzzy Logic Approach

5.1. ABSTRACT

In this paper, an approach of spatio-temporal interpolation for GIS modeling of urban growth dynamics is proposed. It is based on fuzzy logic theory using three proposed scenarios for temporal simulation, and two techniques for spatial simulation of urban change patterns. The notion of stages in the urban growth are taken into consideration as well as variables describing the speed and the mechanism of change. The simulation results are presented for three study sites from the north shore of Montreal Metropolitan area in Quebec, Canada, covering the period from 1956 to 1986. The modeling approach is validated by comparing the simulation results with aerial photographs of the study area taken for the years 1958, 1971, 1975 and 1982. The potential of this approach as a visualization technique is also discussed.

5.2. CONTEXT AND OBJECTIVES

Space and time are apparently well-known notions but to explain them they must be connected to other fundamental concepts such as change or process (Hazelton *et al.*, 1992). Space and time can be defined according to an absolute or a relative framework. According to the absolute view, space is a container in which objects are located, and its structure is best described with the familiar three-dimensional Euclidean geometry. The relative view focuses on objects as the subject matter, and space is measured as relationships between objects. While the former view involves measurement referenced to some constant base with non-judgmental observations, the later implies interpretation of patterns and processes within specific contexts (Peuquet, 1994; Marceau, 1999). Time can be described as the absolute linear line on which events occur and on which intervals between events can be measured. However, as stated by Blaut (1961), since relative space is inseparably fused to relative time, nothing in the physical world is purely spatial or temporal; everything is process. Change must be seen as a composite of processes that occur on a wide band of time scale in space. Therefore, the link between space and time is through the process itself, where specific processes determine specific temporal and spatial conceptualization (Chrisman, 1998; Frank, 1998).

Geography and cartography both deal with space and time, and their relationships with various phenomena under study. If there is no understanding of time and its effects, geographers could not analyze and understand the spatial change nor cartographers could represent it on maps (Vasiliev, 1998). Geographic space and time concept confront with different metrics and scales in their representations of large-scale environments, relationships and interactions between humans and environment (Kelmelis, 1998). In the later 20th century, geographers started to systematically analyze the concept and representation of time as well as its effects on geographic phenomena. Time was used as a measure of human activity in the new born discipline time geography (Hagerstrand, 1970; Thrift, 1977) and was introduced as a necessary variable in other disciplines like historical, quantitative or cultural geography. At the same time, with the powerful growth of computer capabilities, geographical information systems (GIS) were becoming a new geographical tool capable to use space and time components of geographical data.

The issue of time in GIS usually involves the question of how to store and manipulate temporal information with spatial information in a digital database (Vasiliev, 1998). The incorporation of the time component in GIS and the ability to reason about change are strongly influenced by three major factors.

The first factor is the cartographic influence on the GIS representation of geographic data. Cartographers usually maintain the representation of the continually changing world by making static maps. This practice has been transferred from the analog to the digital world, and the data structures in use today are designed for and limited to the static GIS representation of dynamic geographic phenomena (Langran and Chrisman, 1988). Therefore, the time component in a GIS database remains just an attribute of space.

The second factor stems from the nature of historical data. The available data is typically non-ideal because data volumes may be large, coming from different sources, expressed using different spatial and temporal scales, and finally determined by circumstances that are initially and possibly beyond the analysts' control (Vrana, 1989; Openshaw, 1994). The change is not registered at the time when the real change occurs but rather when a new product like a geographic map is needed (Langran, 1993). If data are collected from a series of images or maps acquired in the past, there is no possibility to check these data in the field or complete the missing information about the change (Marceau and Dragicevic, 1998).

The third factor consists of traditional database models, such as the relational model, commonly used in the current GIS, which is atemporal. Due to the nature of digitized geographic data stored in a database, dynamic phenomena have to be dealt with discrete form (Kemp and Kowalczyk, 1994). The current GIS are not yet capable to store change in a continuous manner and is represented as a series of discrete events. Time is represented as an attribute through a series of snapshots corresponding to instantaneous pictures of a geographic area at particular moments. Information about change is derived and based on difference calculations between snapshots. Several problems arise with the use of this model. First, emphasis is put on the rate of change rather than on the process inducing the changes (Schlagel and Newton, 1996). However, to be complete, an analysis of change should focus on the dynamics, i.e. the processes evolving through time that induce changes (Chrisman, 1998; Stead, 1998). Second, some changes may not be detected due to inappropriate sampling; if the interval between snapshots is too long a whole cycle of events may go undetected (Chrisman, 1998). This also means that some information may be lost causing an inaccurate picture of the real world to be stored. Finally, the unchanged data are redundant for each snapshot produced at each time instant. In a more efficient database, only the changed data should receive new representation (Langran, 1993). In that case the time intervals should be variable and determined by events. The temporal resolution should not be arbitrarily chosen but should be settled by the requirements imposed by the geographic phenomenon or process under study.

In order to analyze dynamic geographic phenomena, one must manage current GIS atemporal capabilities, snapshot databases and the nature of historical data. This study has been undertaken to address these challenges. More specifically, it attempts to solve the problem of missing information about change when the time intervals between consecutive snapshots are too long, and when there is no available information between them. The proposed solution is to apply a spatio-temporal interpolation to simulate changes which occurred between snapshots registered in a GIS database. The temporal resolution is then chosen in accordance with the rate of change of the process under study.

This approach incorporates the concept of branching time (Snodgrass, 1992; Frank, 1998). Branching models of time can be used in planning to develop scenarios describing alternative sequences of events that could occur in the future depending on the decisions that are taken. The results of the scenarios represent possible future states, only one of which will be actually achieved. Branching models can also be applied to investigate possible sequences of past actions that have led to a known situation. In such a case, scenarios are built to simulate alternative sequences of changes that occurred between two known states. These scenarios can considerably increase the information content of historical databases, and can lead to the testing of hypothesis related to the dynamics of the phenomenon of interest when other sources of data are impossible to obtain.

The spatio-temporal interpolation method developed in this study is based on the fuzzy logic theory and is described in the following section.

5.3. METHODOLOGY

5.3.1. Study area

The proposed approach is tested on the North Shore of the Montreal Metropolitan area in Quebec, Canada (Figure 5.1). This area, covering a surface of 1320 km^2, went through a radical transformation during the last forty years due to considerable and fast expansion of urban population. The main source of data was 32 topographic maps produced from 1956 to 1986 by the Survey and Mapping Branch of the Department of Energy, Mines and Resources, Canada, at the scale 1:50 000. Data were digitized using MapInfo3.0 desktop software and incorporated in the GRASS4.1 raster database in four snapshots with a final spatial resolution of 10 m and a temporal resolution of 10 years. Major land-use classes defined are urban area, forested area, agricultural land, principal road and hydrographic network, airport, national park and Indian reserve. In order to simplify the illustration of the methodology developed in this study, the paper focuses on rural to urban land-use transformations.

An automated module FUZZY_TEMP was designed and incorporated in the GRASS4.1 GIS database to support the spatio-temporal interpolation and to manage fuzzy membership functions. The description of the module is given in more detail in Dragicevic and Marceau (1999a).

5.3.2. Fuzzy logic in dynamics modeling

The basic concepts of fuzzy logic theory were postulated by Zadeh in 1965. This theory was extended and found diverse applications in different scientific fields such as image processing, robotics, operational research, linguistics, expert systems, meteorology, quantum mechanics and decision making (Dubois and Prade, 1980; Zimmermann, 1985; Terano, 1992). In geography, the majority of applications of fuzzy logic are focused on the problems related to the spatial component of data in order to solve fuzzy aspects of

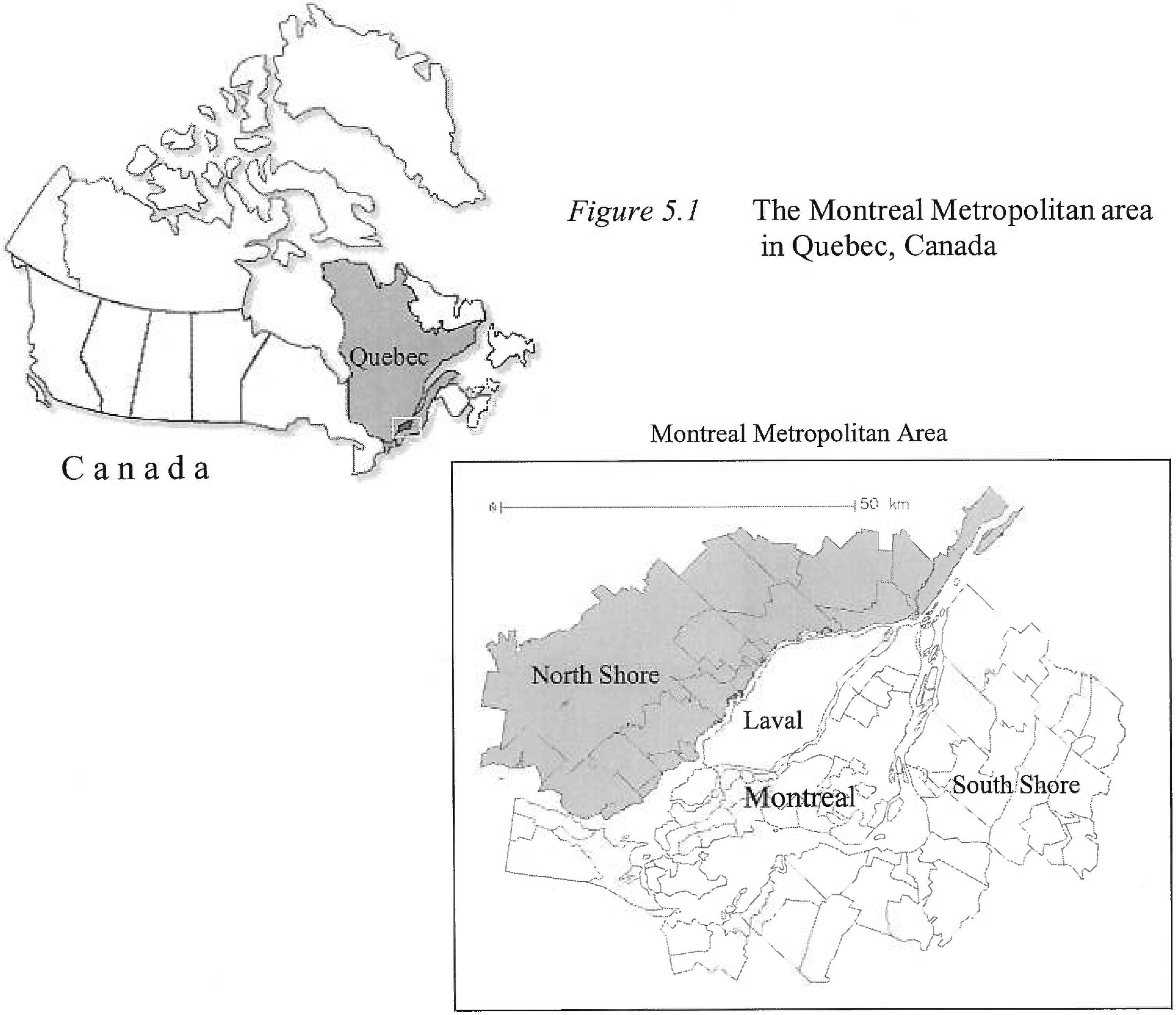


Figure 5.1 The Montreal Metropolitan area in Quebec, Canada

land use classification, and geographic boundaries (Burrough, 1989; Kollias and Voliotis, 1991; Burrough *et al.*, 1992; Sui, 1992; Hall *et al.*, 1992; Davidson *et al.*, 1994; Wang and Hall, 1996). Recently, Dragicevic and Marceau (1997) applied fuzzy logic to solve the problem of missing temporal information in a historical GIS database. The theoretical background of fuzzy spatio-temporal interpolation is explained in more detail in Dragicevic and Marceau (1999b). In brief, fuzzy spatio-temporal interpolation is employed to simulate gradual land-use change between consecutive snapshots. According to the chosen one year temporal resolution, the generation of intermediate layers is based on the series of membership functions used as a rule for generating lacking information between consecutive database snapshots. In this study, the spatial propagation of change is performed using two techniques that are enhanced, applied and validated on different urban areas. The first technique is guided by a surface interpolation GIS module in order to better represent the diffusive mechanism of urban growth. The second technique is built to represent urban growth influenced by the road network, and is a mixture of buffer operation and surface interpolation generated by standard GIS modules. For each transition period between consecutive snapshot layers, generic layers are created using each of these techniques. Information from the generic layer is then combined in the simulation process with fuzzy membership functions in order to generate intermediate layers.

The simulation of urban change dynamics is also guided by the notion of stage. A temporal stage is defined as an interval between the dates in which the structural configuration of an urban area is considerably modified. The stages of the urban morphology are determined on the basis of a direct correspondence between form and function in some components that are taken to characterize the overall urban configuration at a particular time period. The temporal definition of a stage depends on the starting and ending points of a set of actions performed on urban morphology (Campari, 1998).

The transition from rural to urban land-use is performed throughout multiple stages. Each stage is subject to a possibility of change which is defined throughout a series of fuzzy logic functions with the membership grades adjusted to reflect its spatial and temporal context. Therefore, three possible scenarios are conceived in order to model different duration of change on the basis of two proposed techniques simulating spatial development of urban area. The first scenario assumes that the dynamics of change is the fastest possible transition from rural to urban and is modeled in five regular stages, each having a duration of two years. Therefore, five successive sets of membership functions are developed for that purpose. The second scenario is slower and the dynamics of change is completed through two stages of five years and are characterized with two sets of membership functions. The third scenario assumes the irregular urban expansion process which unfolded in three stages, each of which having the duration of three, five and two years respectively. Therefore, three sets of membership functions are developed for this scenario. The number of series of membership functions always corresponds to the number of stages in order to simulate three possible speeds of urbanization dynamics.

5.3.3. Validation procedure

Discussions of validation in the literature are often contradictory. In some cases validation is deemed essential while in other cases it is considered impossible. Some scientists believe that models can only be invalidated (Rykiel, 1996). The validation should provide insurance that the model used to simulate the phenomenon under study performs capacity to correctly predict the behavior of the phenomenon (Power, 1993). Therefore, validation is defined as the demonstration that the proposed model possesses a satisfactory range of accuracy consistent with the intended application of the model (Rykiel, 1996). It is not always possible to determine if the model is in fact the best model possible. There is no absolute criteria for model validation and the process of validation depends on the applications and the users of the model (Mayer and Butler, 1993).

According to the list of validation procedures proposed in Rykiel (1996), a predictive validation procedure is used in this study. Validation was performed to compare how the fuzzy spatio-temporal interpolation model simulates the dynamics of urban expansion in the reality. The procedure of validation consists of comparing simulated data layers generated by FUZZY_TEMP with digitized aerial photographs acquired at some corresponding years. The aerial photographs, at the scale 1:40 000, were geometrically corrected using a minimum of ten control points per photo with the standard GRASS4.1 imagery modules (U.S.Army Cerl, 1993). The modified Gaussian elimination method of first polynomial order was used to calculate the transformation matrix which converts the coordinates of image to standard map coordinates for each pixel in the image. Thereafter, a photo-interpretation was performed to establish the boundaries between rural and urban land-use. The calculation of urban land-use surface was then accomplished, and the results were compared with simulated urban land-use areas using a GRASS4.1 functionality.

5.3.4. Measures of dynamics of urban change

Different variables may be used to describe the process of urban expansion. In order to "measure" the dynamics of urban change occurring in the study areas two basic variables are chosen. They steam, in one hand, from the proposed methodology and its scenarios chosen for modeling change. For another hand, they are chosen for simplicity reasons and because they reflect clearly the urban land-use progress.

The first variable is named the "*speed of change*" and could be defined based on the time required for the completion of change. A change can be categorized as *rapid* if the first scenario is chosen to represent the urban growth. The urbanization process takes two years for its completion. When the third scenario is chosen, where duration of change is more than two but less then five years, change is characterized as *accelerated*. The next category is the *slow* change, which needs five years to terminate when the second scenario is chosen for modeling the urban growth.

The second variable is entitled the "*mechanism of change*" and it defines the manner in which the urban growth was carried out. This variable depends on the interpolation technique that is chosen to represent the urban expansion process. Therefore, it is possible to distinguish two basic forms: *the diffusive mechanism* and *the road influence mechanism*. The former occurs when the surface interpolation technique is chosen for modeling change. This mechanism appears as a consequence of the well-centered boundaries between older and more recent snapshot layers. However, the surface interpolation technique cannot accurately simulate the urban expansion that occurred as isolated patches in the study area since the interpolation function cannot recognize the utmost boundaries of isolated patches. Thus, another technique based on the road influence mechanism is considered more appropriate to handle isolated patches. Nonetheless, if the development of the urban area was too fast, the local road network from the previous snapshot layer does not sufficiently cover the territory where the changes are supposed to happen hence the aforementioned technique provides results of lower quality.

5.4. RESULTS

The following section discusses in more detail the results obtained through the implementation of the proposed methodology. Three sub-areas of the Montreal Metropolitan area (Figure 5.2) are chosen in order to illustrate the simulated dynamics of peri-urban land use and to validate the proposed model of urban expansion. The sub-area 1 is in the municipality of Ste-Thérèse; it covers 9.48 km^2, and is centered at the 72^{0}58'W and 45^{0}42'N. The simulation of the urban growth according to the model of spatio-temporal interpolation was performed on the town of Ste-Thérèse-de-Blanville and was compared with the aerial photographs of the area acquired in 1958 and 1982. The second sub-area is located in the municipality of Terrebonne; it covers 10.76 km^2, and is located at 73^{0}50'W and 45^{0}38'N. The simulation results were compared with aerial photographs acquired in 1958, 1971 and 1982. The third sub-area is located in the municipality of Repentigny; it is located at 73^{0}27'W and 45^{0}44'N, and it covers 51.21

km². The comparison of urban boundaries data obtained from aerial photographs of the town of Repentigny with the corresponding data provided by simulations was performed for the years 1958, 1975 and 1982.

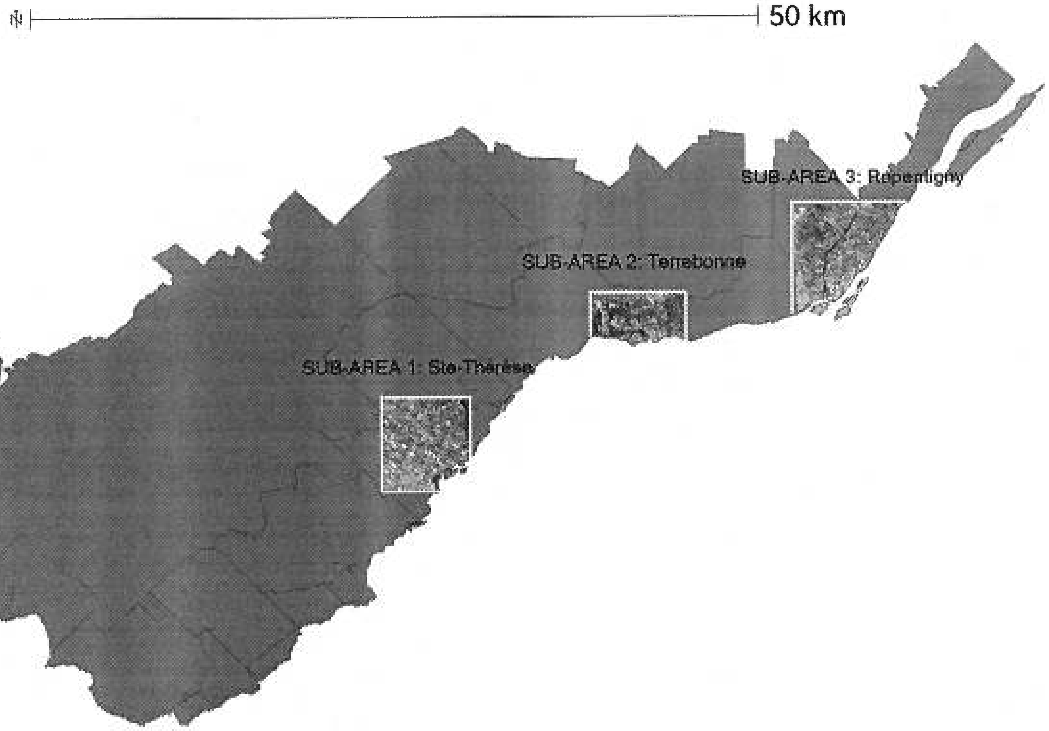
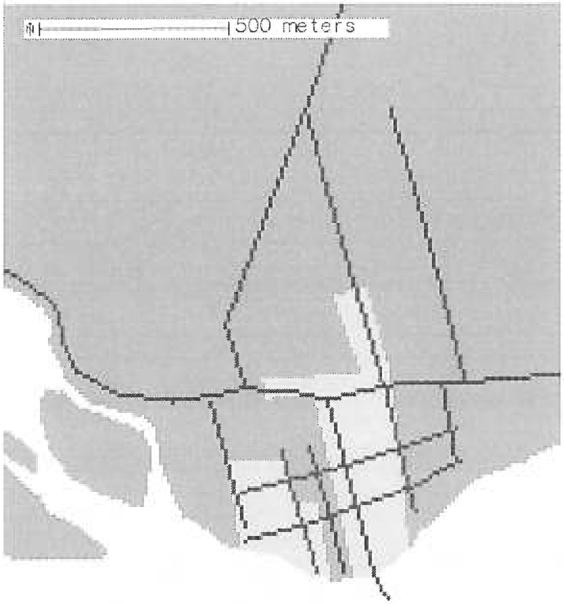


Figure 5.2 The North shore of Montreal metropolitan area with three study areas

The obtained results are presented using generated maps of the town of Terrebonne as an example. Figures 5.3 (a) and (b) outline the maps of two typical snapshot layers corresponding to the years 1956 and 1966 respectively. These maps were stored in the database and used to create the generic layer as well as the resulting simulated intermediates layers. The local road network is presented as well as the principal classes such as rural and urban land-use. The generic layers for the transition from 1956 to 1966 are presented in Figure 5.4 where (a) represents the layer obtained with surface interpolation (diffusive mechanism), and (b) represents the layer obtained using mixed

Figure 5.3 Database initial snapshot layers of Study area 2 – city of Terrebonne :

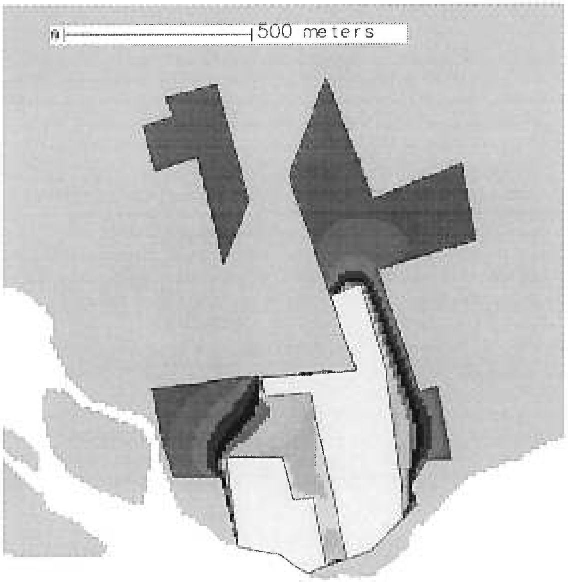


(a) snapshot layer in 1956

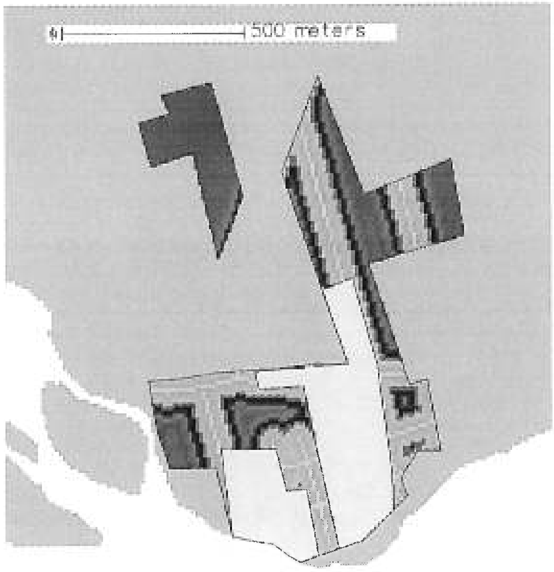
(b) snapshot layer in 1966

▨ Rural land-use □ Urban land-use ━ Local roads

Figure 5.4 Generic layers of Study area 2 for the transition period 1956-1966 :



(a) diffusive technique



(b) road influenced technique

▨ Rural land-use □ Urban land-use □ Belt 1 ▨ Belt 2 ▨ Belt 3 □ Belt 4

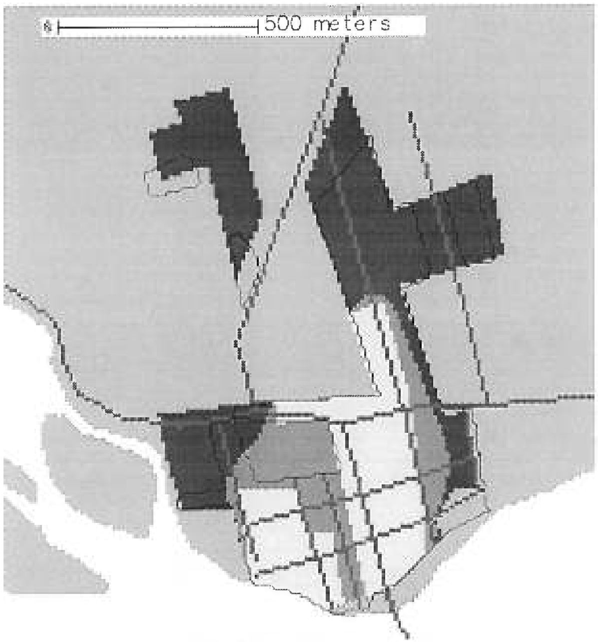
▨ Belt 5 ■ Belt 6 ■ Belt 7 ▨ Belt 8 ■ Belt 9 ▨ Belt 10 interpolation technique (road influenced mechanism). Both generic layers contain ten belts representing the boundaries of urban land-use with an annual temporal resolution. For example, belt 3 represents the estimated urban boundaries reached in the year 1959.

The resulting maps for the year 1958 generated by FUZZY_TEMP using the first scenario and both interpolation techniques are presented in Figure 5.5. The tiny black lines represent the urban boundaries of the town of Terrebonne delineated from the aerial photograph in 1958. Thus, according to the first scenario which corresponds to the shortest duration of change of two years, the stage 2 is completed in the year 1958. Therefore, four classes are distinguished with different cell values and category contents. The two major classes such as *Rural* and *Urban* land-use denote that these cells were not in the transition, but they remain the same in all intermediate layers. Their category contents are *«Rural -> Rural»* and *«Urban -> Urban»* respectively. The third class represents the urban surface which already finished the transition. Its category content indicates *«R→ U, possibly 0.0/R+1.0/U»*. The fourth class represents the surface that is still in rural land-use with the category content of *«R→ U, possibly 1.0/R + 0.0/U»*.

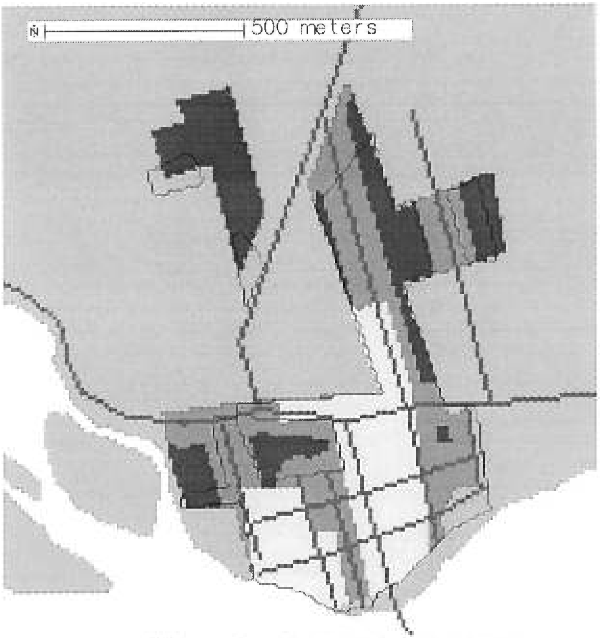
Two other resulting maps which are presented in Figures 5.6 (a) and (b) show simulations for the second and third scenario respectively that are generated with the second technique. Other classes are then distinguished between usual, rural an urban land-use classes, and are characterized with fuzzy category contents. Figure 5.6 (a) shows the class representing the area which is possibly more rural than urban, with 0.9 degree of belonging to rural and 0.2 degree of belonging to urban land-use, and with the category content *«R→ U, possibly 0.9/R + 0.2/U»*. Figure 5.6 (b) outlines the generated map where another class is represented with fuzzy content *«R→ U, possibly 0.3/R + 0.6/U»* showing that there is a surface which is possibly more urban (0.6 degree of belonging) than rural land-use (0.3 degree of belonging).

Table 5.1 shows more detailed results expressed as the percentage of calculated surfaces obtained using spatio-temporal interpolation technique for three study areas, for all three

Figure 5.5 Generated intermediate maps of Study area 2 in 1958 for the first scenario :



(a) diffusive technique



(b) road influenced technique

▢ Rural land-use

▢ Urban land-use

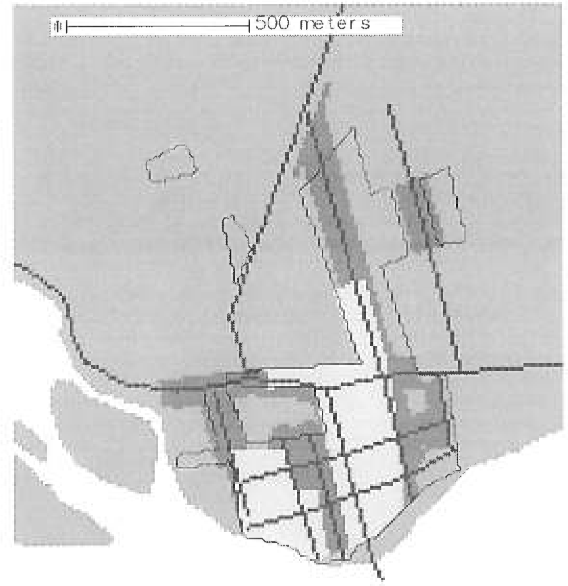
— Local roads

■ R -> U, possibly 1.0/R

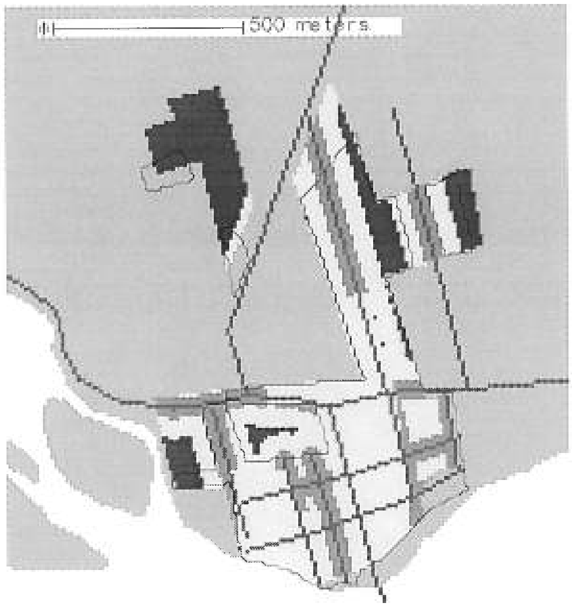
▨ R -> U, possibly 1.0/U

— Urban boundary

Figure 5.6 Generated intermediate maps of Study area 2 in 1958 with road influenced technique :



(a) second scenario



(b) third scenario

Table 5.1 Comparison of percentages of surfaces covered by rural, urban and classes in transition and percentages of surfaces of urban land-use calculated from digital aerial photographs

SUB-AREA 1 : Ste-Thérèse	**Diffusive Technique**			**Road Influenced Technique**			**Aerial Photograph**
Scenario	*S1*	*S2*	*S3*	*S1*	*S2*	*S3*	*Urban land-use*

1958							
Land-use classes	%	%	%	%	%	%	%
Possible 1.0/Urban	64.9	56.0	37.4	46.1	**41.9**	18.7	**40.0**
Possible x/Rural + y/Urban	-	44.0 0.9/R+0.2/U	46.3 0.3/R+0.6/U	-	58.1 0.9/R+0.2/U	58.5 0.3/R+0.6/U	
Possible 1.0 /Rural	35.1	-	16.3	53.9	-	44.8	

1982							
Land-use classes	%	%	%	%	%	%	%
Possible 1.0/Urban	**52.6**	23.6	**52.6**	59.8	41.1	59.8	**55.9**
Possible x/Rural + y/Urban	-	76.4 0.3/R+0.6/U	-	-	58.9 0.3/R+0.6/U	-	
Possible 1.0 /Rural	47.4	-	47.4	40.2	-	40.2	

(a)

SUB-AREA 2 : Terrebonne	Diffusive Technique			Road Influenced Technique			Aerial Photograph
Scenario	*S1*	*S2*	*S3*	*S1*	*S2*	*S3*	*Urban land-use*
1958							
Land-use classes	%	%	%	%	%	%	%
Possible 1.0/Urban	26.9	22.2	13.4	**57.6**	50.1	17.6	**56.4**
Possible x/Rural + y/Urban	-	77.8 0.9/R+0.2/U	26.1 0.3/R+0.6/U	-	49.9 0.9/R+0.2/U	47.2 0.3/R+0.6/U	
Possible 1.0 /Rural	73.1	-	60.5	42.4	-	35.2	
1971							
Land-use classes	%	%	%	%	%	%	%
Possible 1.0/Urban	**85.5**	48.2	**85.5**	**85.4**	69.9	**85.4**	**87.4**
Possible x/Rural + y/Urban	14.5 0.3/R+0.8/U	51.8 0.1/R+0.9/U	14.5 0.3/R+0.8/U	14.6 0.3/R+0.8/U	30.1 0.1/R+0.9/U	14.6 0.3/R+0.8/U	
Possible 1.0 /Rural	-	-	-	-	-	-	
1982							
Land-use classes	%	%	%	%	%	%	%
Possible 1.0/Urban	63.9	22.8	63.9	**68.2**	50.8	**68.2**	**77.4**
Possible x/Rural + y/Urban	-	77.2 0.3/R+0.6/U	-	-	49.2 0.3/R+0.6/U	-	
Possibly 1.0 /Rural	36.1	-	36.1	31.8	-	31.8	

(b)

SUB-AREA 3 : Repentigny	**Diffusive Technique**			**Road Influenced Technique**			**Aerial Photograph**
Scenario	*S1*	*S2*	*S3*	*S1*	*S2*	*S3*	*Urban land-use*

1958							
Land-use classes	%	%	%	%	%	%	%
Possible 1.0/Urban	22.3	**31.8**	14.6	36.1	24.5	7.5	**30.0**
Possible x/Rural + y/Urban	-	68.2 0.9/R+0.2/U	47.3 0.3/R+0.6/U	-	75.5 0.9/R+0.2/U	51.7 0.3/R+0.6/U	
Possible 1.0 /Rural	77.7	-	38.1	63.9	-	40.8	

1975							
Land-use classes	%	%	%	%	%	%	%
Possible 1.0/Urban	**71.7**	50.4	**71.7**	76.7	44.3	76.7	**68.0**
Possible x/Rural + y/Urban	28.3 0.3/R+0.8/U	49.6 0.1/R+0.9/U	28.3 0.3/R+0.8/U	23.3 0.3/R+0.8/U	55.7 0.1/R+0.9/U	23.3 0.3/R+0.8/U	
Possible 1.0 /Rural	-	-	-	-	-	-	

1982							
Land-use classes	%	%	%	%	%	%	%
Possible 1.0/Urban	**57.9**	23.5	**57.9**	59.5	29.7	59.5	**56.9**
Possibly x/Rural + y/Urban	-	76.5 0.3/R+0.6/U	-	-	70.3 0.3/R+0.6/U	-	
Possibly 1.0 /Rural	42.1	-	42.1	40.5	-	40.5	

(c)

possible scenarios of change and for three different dates. The percentage of urban land-use surfaces calculated from digital aerial photographs are also shown for comparison purposes. Three major classes are distinguished: the surfaces which already achieved the urban land-use, these which are in transition and these that still remain in rural land-use.

For the first study area, town of Ste-Thérèse, the best results in 1958 are obtained using the road influence technique and the second scenario (Table 5.1(a)). The accordance of urban surface with that obtained from the aerial photograph data is within 2%. However, for the year 1982 the best results are obtained using the diffusive interpolation technique. The first and the third scenario provide similar results, slightly underestimating the urban expansion by 3% of the total surface. The second scenario significantly underestimates the urban surface.

For the second study area, town of Terrebonne, in 1958, the best results are obtained with the road influenced technique since the diffusive technique significantly underestimates the urban surface compared to the reference aerial data (Table 5.1(b)). The first scenario is the most suitable to represent the simulation of duration and the speed of change that occurred in that period. For the year 1971, the two interpolation techniques provide similar accurate results for the first and third scenario which are in accordance with urban surface obtained with the aerial photograph within 2%. In 1982, both interpolation techniques underestimate the urban expansion but the first and the third scenario provide the best estimate with an error of 13.5% for diffusive technique and 9.2% for road influenced technique.

For the third study area, town of Repentigny, the diffusive technique provides the best results for all observed years (Table 5.1 (c)). In 1958, the second scenario gives the best estimation of the urban surface compared to the reference aerial photograph data. The first and the third scenario underestimate the surface of urban land-use by 7% and 14% of the total surface, respectively. However, for the year 1975, the best results are obtained with the first and third scenario which provide similar results and slightly overestimate the urban expansion by 4% of the total surface. The second scenario significantly underestimates the urban surface. In 1982, the best results are obtained with the first and the third scenario showing a very good accordance with the urban surface obtained from the aerial photograph. The second scenario considerably underestimates the change of the urbanization process.

Table 5.2 summarize the dynamics of change for the three study areas in three observed periods in the last 30 years. The descriptive variables are used to indicate the speed and mechanism of the change. Table 5.2 is build in accordance with the results stemming from Table 5.1. The best results obtained through validation procedure for each study area are chosen as the indicators of the best scenarios and then, the choice of variables for measures of dynamics of urban change was made.

The results obtained indicate that the possible dynamics of change shown in Table 5.2 for the town of Ste-Thérèse in the first observation period 1956-66 were characterized with slow urban growth since five years were needed to complete the change. In the period 1966-76 there was no registered changes in the urban boundaries according to the information in initial snapshots layers in the database. In the period 1976-86 an accelerated urban growth is estimated since the possible speed of change was assessed to be slower than 2 years but faster then 5 years. The mechanism of urbanization process is more road influenced in the first observation period, but more diffusive in the last observation period.

The possible dynamics of urban land-use transformation for the town of Terrebonne (Table 5.2) can be described as follow. In the first observation period from 1956 to 1966, the growth was rapid since only two years are needed to complete the change. An accelerated dynamics characterized with the speed of change slower than 2 years but faster then 5 years is shown in the period from 1966 to 1976. In the last period (1976-1986), the obtained results indicate that urban expansion was rapid since the best simulation results underestimated the surface obtained by the aerial photograph. The

Table 5.2 Overview of the dynamics of change for all three study areas in three observation periods

Study area	Urban Change Variables	1956-1966	1966-1976	1976-1986
Ste-Thérèse	*speed*	Slow	-	Accelerated
	mechanism	Road Influenced	-	Diffusive
Terrebonne	*speed*	Rapid	Accelerated	Rapid
	mechanism	Road Influenced	Road influenced & Diffusive	Road influenced
Repentigny	*speed*	Slow	Accelerated	Accelerated
	mechanism	Diffusive	Diffusive	Diffusive

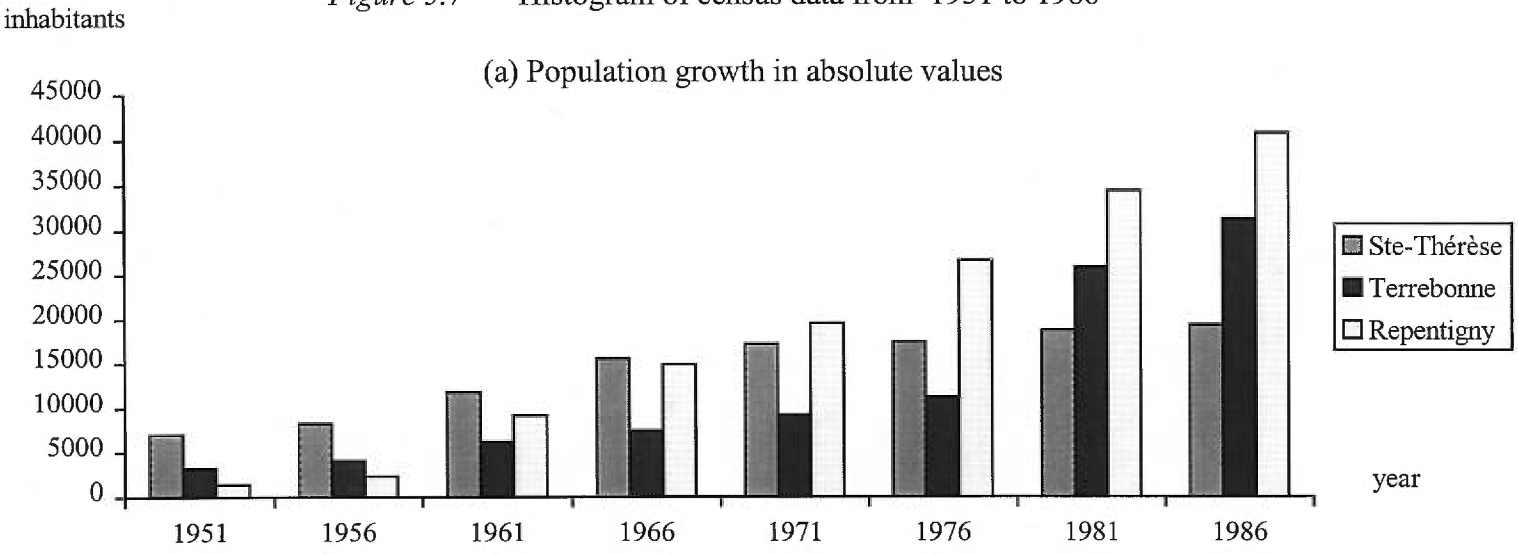
change needed possibly to be simulated with another scenario which use less than two years for change to be completed. The mechanism of urban expansion can be characterized by road influenced in the first and the third observation period, but in the interval between 1966 and 1976, both forms yield good results. This can be explained by the relatively concentric mechanism of urban boundaries in 1966 and 1976 that also follow the radial expansion of the local road network which symmetrically emerges from one central avenue in the town of Terrebonne.

The results obtained using the proposed approach suggest that the dynamics of change was slow in the first observation period from 1956 to 1966 (Table 5.2) since it is based on the premise that five years are required to complete the change. The accelerated urbanization dynamics was observed in the period 1966-1976 because the change was possibly slower than two years but faster than five years. In the period from 1976 to 1986, the results indicate that the urban growth was rapid since it is based on the premise that two years are required to complete the transformation. The urban expansion was in diffusion mechanism for all three periods. This could be explained by the fact that Repentigny is a city stacked between two rivers and the space for the expansion is limited by the mechanism of land such that the road influence is not evident.

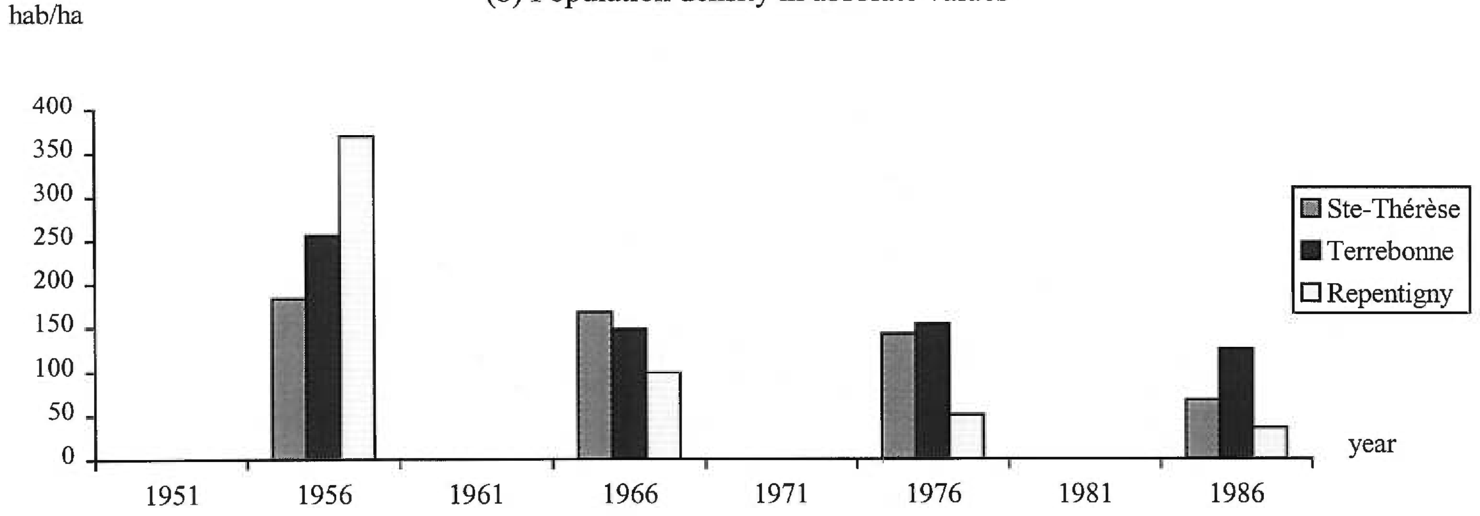
Urban growth could be influenced with the increase of population. Some parts of Montreal metropolitan area, usually urban fringes of north and south shore, had a remarkable population increase (Marois, 1998). Therefore, the results obtained in Table 5.2 are compared with census and population density data in order to find some possible concordance. Population growth for the period from 1951 to 1986 are shown on Figure 5.7 (a) (Statistics Canada, 1951-1986). Population density data are calculated for the urban surfaces obtained from the database snapshot layers and for each available date (Figure 5.7 (b)). The trends of simulated urban development and population density are compared with results presented in Table 5.2 for each study area.

Figure 5.7 Histogram of census data from 1951 to 1986

(a) Population growth in absolute values



(b) Population density in absolute values



(b)

The town of Ste-Thérèse had a very constant increase of population from 1961 to 1986. According to the census data, in 1961, Ste-Thérèse had 7 038 inhabitants while in 1986 the population attained 19336 inhabitants. Thus in the period of 35 years the population has grown only 2.7 times with no drastic jumps for any of the census years (Figure 5.7(a)). The population density was relatively constant in 1951, 1961 and 1976 but significantly lower in 1986 (Figure 5.7(b)). This is in accordance with the results of the model shown in Table 5.2: the speed of urban expansion was slower in the period from 1956 to 1966 whereas it was more accelerated in the period between 1976-86.

In Terrebonne, the population had a constant increase from 1951 till 1976, and shows an increase of 3.5 times for the whole period of 25 years (Figure 5.7(a)). However, a sharp increase in population from 11 204 inhabitants in 1976 to 25 941 inhabitants in 1981, and then to 31 310 inhabitants in 1986 indicates that an abrupt influx of the population has occurred in a short period of time. Furthermore, density data point out that the population density in 1951 was high but it started to fall since 1961 and then remained constant (125 habitants/ha) by the year 1986 (Figure 5.7(b)). It can be concluded that the simulation results mostly match the tendency driven by the density data thereby characterizing the first and third observation period of urbanization as rapid while the second period was characterized as slower. As the population in the last period drastically grew up and the density remained nearly unchanged, it can be concluded that a large spatial expansion has occurred thus keeping the population density constant.

The community of Repentigny had a low number of inhabitants and high population density in 1956 (Figure 5.7 (a) and (b)). Since 1961, the population started significantly to increase, 3.9 times till 1986. But, in the same period the population density is in a decline of 2.8 times. This indicates that the urban expansion was slow in the first observation period and accelerated in the period from 1966 to 1986.

5.5. DISCUSSION

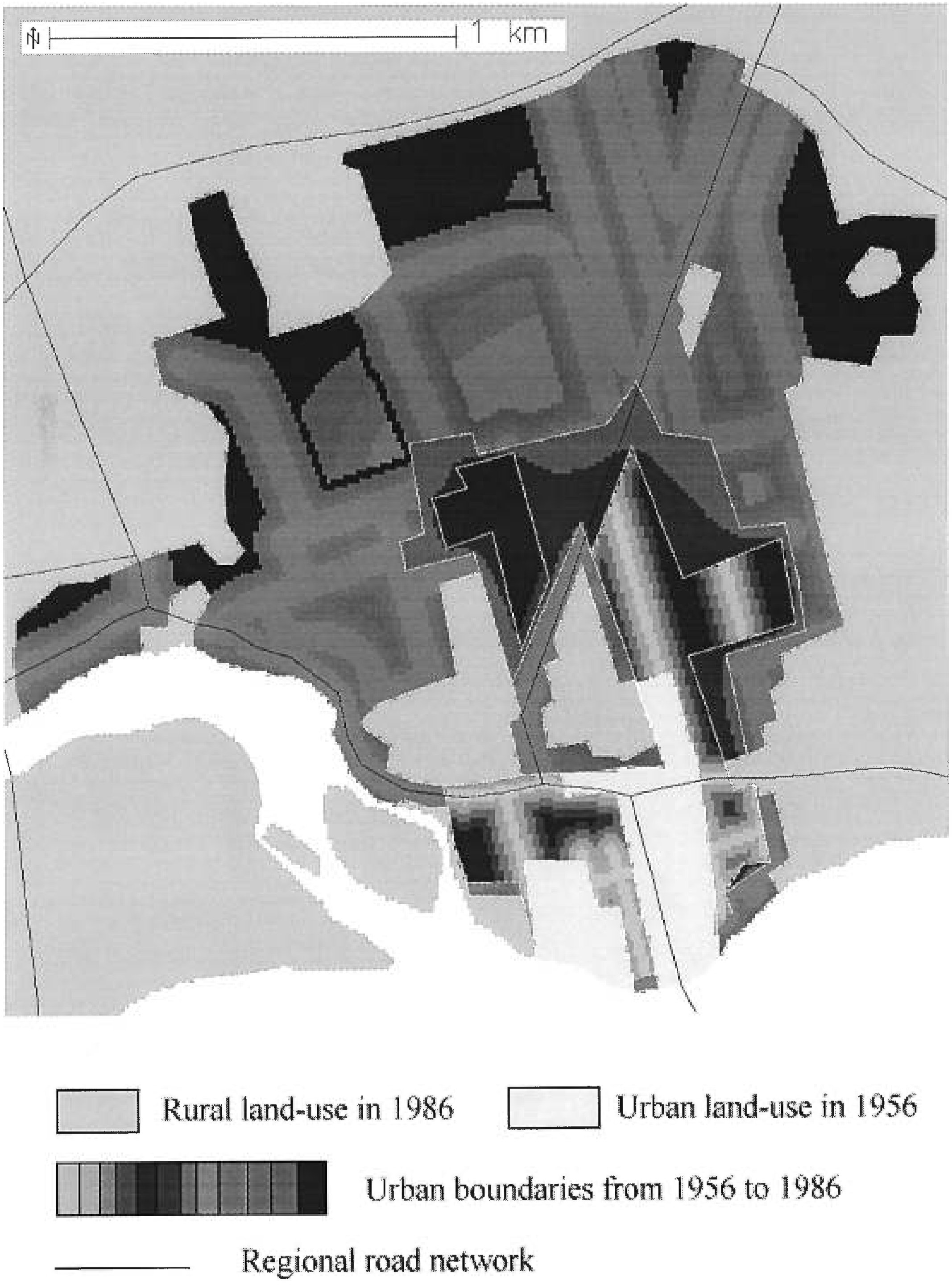
There exist more sophisticated models which simulates urban expansion (Batty and Xie, 1994; Kirtland *et al.*, 1994; Clarke *et al.,* 1996; Clarke and Gaydos, 1998). They are based on different factors which influence the behavior of the land-cover change process and are used for more realistic modeling of urban growth. These factors are determined depending on the urban morphology and are expressed in terms of diffusion, breed and spread coefficient. Some of the factors such as slope can be used to describe the physical environment as well as the influence of the road network on the urban growth (Clarke *et al.*, 1997). Other factors such as the role of zoning, local and regional transportation network, socio-economic and demographic data are also included in some urban expansion models (Landis, 1994; Portugali and Beneson, 1995; Xie and Batty, 1997; Allen, 1997; Wu and Webster, 1998). All these models are useful in a short and long range forecasting since they are based on a large amount of data stemming from snapshots where the probability of transition is extracted from current trends of urban change.

The approach proposed in this study does not explicitly provide causal factors, thus it is not an explanatory model. The main advantage of the fuzzy spatio-temporal interpolation approach lies in its flexibility to create various temporal scenarios of urbanization process and to choose the desired temporal resolution. Thus, if the chosen resolution assumes smaller time period between generated snapshots, the more accurate representation of the real world can be achieved. In this way, the representation of time as a continuous flow of changes can be closely simulated thereby significantly enhancing the existing GIS capabilities.

Another advantage of the proposed methodology lies in its great potential to be used as a visualization technique. Visualization is a sophisticated procedure which, based on a series of transformations, converts raw simulation data into a displaying map understandable by the human perceptual system (Haber and McNabb, 1990; MacEachren and Monmonier, 1992; Dorling and Openshaw, 1992; Kraak *et al.*, 1995). The benefit of visualization is in its productive coupling with geographic representational methods which enhances the policy analysis of dynamic processes and facilitates the understanding of spatial associations among environmental variables (Howard and MacEachren, 1996). There exist various types of visualization techniques related to time series geographic data such as two and three dimensional plots, two dimensional planimetric views, three dimensional perspective views and animation. The animation technique is often employed as a tool for representing the urban growth phenomena that occurred over time in a particular region (Bell *et al.*, 1995; Clark *et al.*, 1996; Acevedo and Masuoka, 1997). The animation of dynamic phenomena whose data are stored in a GIS raster database usually involves a number of steps and is based on the snapshots as well as on interpolation techniques (Masuoka *et al.*, 1996). The interpolation techniques make spatial changes smoother and better for animation. Frame-based raster animation uses a set of images or snapshots that are displayed sequentially to a computer screen or video recorder. The proposed fuzzy spatio-temporal interpolation can represent a great tool for time-series animation of geographic data in order to create "in-between" frames. The combination of different scenarios generated by this methodology can give different possible animations of phenomenon under study. Every generated stage may be used for each visualization frame since it represents an intermediate snapshot. For example, Figure 5.8 presents the overlaid best scenarios resulting from the validation procedures. They could be used to construct one possible series of frames which could be used in the visualization of urban growth of the city of Terrebonne (study area 2) from 1956 to 1986. The advantage of the fuzzy spatio-temporal technique is in the capability to visualize different dynamics of urban growth through the combination of various scenarios which flow in a consecutive manner with different temporal resolutions.

In order to maintain the concept of a continuous flow of processes and changes during time, the minimal temporal resolution for the study may be chosen to be less than one year as it was adopted in this study. This implies that the analysis of dynamics could be possibly implemented in studying larger spatial scales such as municipal or local. This

Figure 5.8 Visualization of one possible succession of urban boundaries for the town of Terrebonne from 1956 to 1986 generated with the best combination of spatio-temporal interpolation techniques and scenarios



means that changes at the cadastre level of such as changes of land parcel ownership could be also modeled with the temporal resolution of one month. The database could be enriched with more land-use classes and new fuzzy membership functions can be developed to model all kinds of possible transitions. In the case of modeling dynamic phenomena such as fire or disaster occurrences which require the observation over a long period of time entailing a higher temporal resolution (50 years and more), it is necessary to account for cyclic or sequential changes when generating the scenarios of possible changes.

In conclusion, the proposed methodology can generate realistic scenarios of urban expansion process and could provide interesting insights into the dynamics of change which happened in the past. There is a potential for enhancement of the proposed fuzzy spatio-temporal technique in order to make it a more powerful tool for modeling changes as well as using it as a visualization technique.

Conclusion

6.1. DISCUSSION GÉNÉRALE DE L'ENSEMBLE DES RÉSULTATS

Cette recherche traite du problème global de l'intégration de la composante temporelle dans un SIG. L'ensemble des résultats obtenus indique qu'il est possible, en utilisant la logique floue, d'apporter quelques éléments de solutions au problème de la gestion du temps dans une base de données historique d'un SIG matriciel. L'approche ne demeure pas seulement au niveau conceptuel, mais se démarque par une application orientée à un problème géographique particulier. Le concept d'application de la logique floue dans le temps pourrait aussi être appliqué pour traiter des problèmes similaires dans un SIG vectoriel. Les résultats obtenus avec la méthodologie proposée et appliquée sur la problématique de changement du sol d'un milieu périurbain démontrent qu'il est possible de produire des scénarios réalistes de processus d'expansion urbaine. L'avantage majeur de l'approche d'interpolation spatio-temporelle basée sur la logique floue réside dans sa flexibilité à créer différents scénarios d'évolution de processus.

La possibilité de choisir une résolution temporelle plus fine conduit à une représentation du phénomène dynamique plus proche de la réalité. De cette façon, la succession de changements devient un flux continu qui se déroule dans le temps et dans l'espace. Le raffinement de l'échelle spatio-temporelle peut contribuer à des applications dans d'autres régions d'étude avec une variété de classes d'utilisation du sol plus grande que celle proposée dans cette étude. Le rural peut être subdivisé en classes: agricole, recréationnel, friche ou forêt, et l'urbain peut être subdivisé en classes: résidentiel, commercial ou industriel. Cela peut permettre la modélisation de phénomènes plus complexes.

L'application de la méthodologie proposée à la modélisation des changements qui se déroulent d'une manière cyclique ou successive est possible pour des phénomènes qui peuvent être considérés à une échelle temporelle plus grossière. Donc il est possible de simuler, avec la méthodologie développée, les phénomènes géographiques dynamiques qui se déroulent au niveau de différentes échelles spatiales et temporelles, c'est-à-dire à l'échelle de processus local, municipal, régional ou global. Le raffinement des fonctions d'appartenance et le développement de nouvelles fonctions qui considèrent une plus grande gamme de transitions entre un plus grand nombre de classes peut être facilement ajouté dans le module Fuzzy_Temp.

Une autre contribution de cette recherche réside dans la capacité de fournir une indication de la dynamique d'étalement urbain. Le premier indicateur est la vitesse et le deuxième, le mécanisme des changements. Les scénarios proposés modélisent les différentes durées de changement indiquant ainsi la vitesse de l'étalement urbain. Les différentes techniques de propagation spatiale, comme la diffusion basée sur l'interpolation spatiale et celle de l'influence du réseau routier, basée sur les zones tampons, donnent une idée de la forme de propagation de l'étalement urbain. Les variables utilisées décrivent un comportement géographique spatial relié au champ précis d'application : la zone périurbaine avec toutes ses particularités de changement.

L'ensemble des résultats de validation de la méthodologie proposée indique que chaque zone urbaine montre une dynamique différente et est un système indépendant avec son comportement spatial et temporel particulier. Chaque zone étudiée utilisée dans cette recherche montre soit des vitesses, soit des mécanismes différents de changement reliés à des facteurs d'intervention humaine dans l'environnement physique. Cependant, ce modèle ne peut pas établir ou expliquer des liens de causalité parce qu'il n'est pas conçu comme un modèle explicatif.

L'approche développée dans cette recherche démontre un potentiel pour la visualisation des changements d'utilisation du sol. La visualisation et l'animation des phénomènes dynamiques représentent un champ de recherche récent qui se développe rapidement (Haber et McNabb, 1990; MacEachren et Montmonier, 1992; Dorlin et Openshaw, 1992; Howard et MacEachren, 1996). Il sert à animer les données géographiques brutes et statiques sur les changements dans le but de générer une représentation vive et acceptable pour le système de perception des humains. La visualisation peut aider à la compréhension des processus dynamiques qui se déroulent dans l'espace géographique. Les différentes techniques d'animation sont souvent utilisées pour représenter le phénomène d'expansion urbaine (Bell *et al.*, 1995; Clark *et al.*, 1996; Acevedo et Masuoka, 1997). Grâce à la méthodologie développée dans cette étude, les résultats obtenus par les simulations peuvent être intégrés dans l'animation visuelle des transformations de la frange périurbaine. De plus, la variété des scénarios utilisés et leurs mutuelles combinaisons peut résulter en plusieurs variantes du déroulement du changement.

6.2. CONCLUSION GÉNÉRALE

Il existe des modèles plus complexes de simulation de changements d'utilisation du sol et de simulation d'expansion urbaine qui sont basés sur des facteurs divers (Batty et Xie, 1994; Kirtland *et al.*, 1994; Clarke *et al.*, Clarke et Gaydos, 1998). Ce sont surtout des facteurs qui prennent en considération les influences de l'environnement physique, des données socio-économiques ou démographiques, du réseau de transport, des lois de zonage ou de la morphologie urbaine (Landis, 1994; Portugali et Beneson, 1995; Xie et Batty, 1997; Wu et Webster, 1998, Wu, 1998). Ces modèles sont basés sur un plus grand nombre de données ce qui permet également d'extraire les probabilités de changements et ils sont utilisés comme modèles de prédiction.

Le fait de ne pas utiliser tous les facteurs possibles qui peuvent intervenir dans la modélisation des changements d'utilisation du sol représente une limite de cette recherche. Pourtant il est possible d'introduire différents facteurs qui vont donner une simulation plus réaliste des changements de la zone périurbaine. Cette limite en même temps représente une ouverture vers une nouvelle piste de recherche. Par exemple, en combinant la théorie des automates cellulaires, qui prend en considération de nombreux facteurs qui influencent la dynamique des changements à la logique floue et l'interpolation spatio-temporelle, un modèle plus réaliste de simulation de changements pourrait être bâti. De même la présente approche pourrait être étendue de modèles historiques à des modèles de prédiction de changements d'utilisation du sol.

La méthode d'interpolation spatio-temporelle basée sur la logique floue développée dans cette recherche représente une nouvelle solution pour la génération et la simulation de l'information manquante dans une base de données d'un SIG. Elle considère des comportements réalistes d'un milieu géographique particulier comme est une zone périurbaine. Par conséquent, elle peut s'avérer utile dans la gestion du territoire pour la manipulation et l'utilisation de basées de données historiques en situation de limitations de données disponibles. En concluant, cette recherche a permis de faire avancer l'état présent des connaissances dans le domaine des SIG temporels et de la modélisation spatio-temporelle. Elle représente également un potentiel pour de futurs développements dans le domaine des sciences de la Terre.

Bibliographie

ACEVEDO, W., FORESMAN, T.W., and BUCHANAN, J.T., 1996, Origins and philosophy of building a temporal database to examine human transformation processes. In *Proceedings ASPRS/ACSM Annual Convention and Exhibition*, (Baltimore, MD), **1**, 148-161.

ACEVEDO, W., and MASUOKA, P., 1997, Time-series animation techniques for visualising urban growth. *Computers & Geosciences*, **4**, 423-435.

ALLEN, P. M., 1997, Cities and regions as evolutionary, complex systems. *Geographical Systems*, **4**, 103-130.

AL-TAHA, K.K., and BARRERA, R., 1990, Temporal data and GIS: an overview. In *Proceedings of GIS/LIS'90*, (Bethesda, Maryland), ASPRS/ACSM, 244-254.

ALTMAN, D., 1994, Fuzzy set theoretic approaches for handling imprecision in spatial analysis. *International Journal of Geographical Information Systems*, **3**, 271-289.

ARBIA, G., GRIFFITH, D., and HAINING, R., 1998, Error propagation modelling in raster GIS: overlay operations. *International Journal of Geographical Information Science,* **2**, 145-167.

BANAI, R., 1993, Fuzziness in geographical information systems: contributions from the analytic hierarchy process. *International Journal of Geographical Information Systems*, **4**, 315-329.

BATTY, M., and XIE, Y., 1994, From cells to cities. *Environment and Planning B: Planning and Design,* **21**, 531-548.

BELL, E.J., 1975, Stochastic analysis of urban development. *Environment and Planning A,* **7**, 35-39.

BELL, C., ACEVEDO, W., and BUCHANAN, J.T., 1995, Dynamic mapping of urban regions: growth of the San Francisco/Sacramento Region. In *Proceedings of Urban and Regional Information Systems Association*, (San Antonio, TX), 723-734.

BEZDEK, J. C., 1981, *Pattern Recognition with Fuzzy Objective Functions*. (New York: Plenum Press).

BLAUT, J.M., 1961, Space and Process. *Professional Geographer*, **13/4**, 1-7.

BOURNE, L.S., 1976, Monitoring change and evaluating the impact of planning policy of urban structure: A Markov chain experiment. *Plan Canada*, **16**, 5-14.

BURROUGH, P. A., 1989, Fuzzy mathematical methods for soil survey and land evaluation. *Journal of Soil Science*, **40**, 477-492.

BURROUGH, P. A., MACMILLAN, R.A., and VAN DEURSEN, W., 1992, Fuzzy Classification methods for determining land suitability from soil profile observations and topography. *Journal of Soil Science*, **43**, 193-210.

BURROUGH, P. A., and FRANK, P.A., 1995, Concepts and paradigms in spatial information: are current geographical information systems truly generic?. *International Journal of Geographical Information Systems*, **2**, 101-116.

CAMPARI, I., 1998, Analyzing temporal factors in urban morphology development. *Spatial and Temporal Reasoning in Geographic Information Systems*, edited by Egenhofer M.J., and Golledge R.G. (Oxford University Press), 220-237.

CANNON, R. L., DAVE, J. V., BEZDEK, J. C., and TRIVEDI, M. M., 1986, Segmentation of a Thematic Mapper images using the fuzzy c-means clustering algorithm. *IEEE Transactions on Geoscience and Remote Sensing*, **3**, 400-408.

CARVER, S.J., and BRUNSDON, C.F., 1994, Vector to raster conversion error and feature complexity: an empirical study using simulated data. *International Journal of Geographical Information Systems,* **3**, 261-270.

CASPARY, W., and SCHEURING, R., 1993, Positional accuracy in spatial databases. *Computers, Environment and Urban Systems*, **17**, 103-110.

CHRISMAN, N., 1998, Beyond the Snapshot: Changing the Approach to Change, Error, and Process. *Spatial and Temporal Reasoning in Geographic Information Systems*, edited by Egenhofer M.J., and Golledge R.G. (Oxford University Press) 85-93.

CLARAMUNT, C., and THERIAULT, M., 1995, Managing time in GIS: an event-oriented approach. In *Recent Advances in Temporal Databases*, edited by J. Clifford and A. Tuzhilin (Springer), 23-42.

CLARK S.C., STARR J., FORESMAN, T., ACEVEDO, W., and SOLOMON, C., 1996, Development of the temporal transportation database for the analysis of urban development in the Baltimore-Washington region. In *Proceedings ASPRS/ACSM Annual Convention and Exhibition*, (Baltimore, MD), **3**, 101-110.

CLARKE, K.C., HOPPEN, S., and GAYDOS, L., 1996, Methods and techniques for rigorous calibration of a cellular automaton model of urban growth. *Third International Conference/Workshop Integrating GIS & Environmental Modeling*, (Santa Fe, New Mexico), 21-25.

CLARKE, K.C., HOPPEN, S., and GAYDOS, L., 1997, A self-modifying cellular automaton model of historical urbanization in the San Francisco Bay area. *Environment and Planning B: Planning and Design,* **24**, 247-267.

CLARKE, K.C., and GAYODS, L.J., 1998, Loose-coupling a cellular automaton model and GIS: long-term urban growth prediction for San Francisco and Washington/Baltimore. *International Journal of Geographical Information Science*, **7**, 699-714.

CRAWFORD-TILLEY, J.S., ACEVEDO, W., FORESMAN, T., and PRINCE, W., 1996, Developing a temporal database of urban development for the Baltimore/Washington region. In *Proceedings of ASPRS/ACSM Annual Convention and Exhibition,* (Baltimore, Maryland, 22-24 April) **3**, 101-110.

DAVIDSON, D. A., THEOCHAROPOULOS, S. P., and BLOKSMA, R. J., 1994, A land evaluation project in Greece using GIS and based on Boolean and fuzzy set methodologies. *International Journal of Geographical Information Systems*, **4**, 369-384.

DAVIS, J.T., and KELLER, P.C., 1997, Modelling uncertainty in natural resource analysis using fuzzy sets and Monte Carlo simulation: slope stability prediction. *International Journal of Geographical Information Science*, **5**, 409-434

DAWSON, T. P., and JONES, C. B., 1995, Representing and analyzing fuzzy natural features in geographical information systems. In *Proceedings of GIS`95*, (Vancouver, Canada, March 27-30), 423-428.

DEURSEN, W.P.A, 1995, *Geographical Information Systems and Dynamic Models.* Netherlands Geographical Studies 190, (Utrecht), 198 p.

DOMBI, J., 1990, Membership function as an evaluation. *Fuzzy Sets and Systems*, **35**, 1-21.

DORLING, D, and OPENSHAW, S., 1992, Using computer animation to visualize space-time patterns. *Environment and Planning B: Planning and Design,* **19**, 639-650.

DRAGICEVIC, S., and MARCEAU, D. J., 1997, Fuzzy logic in spatio-temporal GIS database. *Proceedings of Annual Conference GIS/LIS'97.* (Cincinnati, Ohio, October 28-30).

DRAGICEVIC, S., and MARCEAU, D. J., 1999a, A fuzzy set approach for modeling time in GIS. *International Journal of Geographical Information Science*, in press.

DRAGICEVIC, S., and MARCEAU, D. J., 1999b, An application of fuzzy logic reasoning for GIS temporal modeling of dynamic processes. *Fuzzy Sets and Systems*, in press.

DRAGICEVIC, S., and MARCEAU, D. J., 1999c, Spatio-temporal interpolation and fuzzy logic reasoning for GIS simulation of rural-urban transition. *Cartography and Geographic Information Systems,* in press.

DRUMMOND, J., 1987, A framework for handling error in geographic data manipulation. *ITC Journal,* **1**, 73-82.

DUBOIS, D., and PRADE, H., 1980, *Fuzzy Sets and Systems: Theory and Applications.* (Academic Press), 393 p.

DUNN, R., HARRISON, A.R., and WHITE, J.C., 1990, Positional accuracy and measurement error in digital databases of land use: an empirical study. *International Journal of Geographical Information Systems,* **4**, 385-398.

EDWARDS, G., GAGNON, P., and BEDARD, Y.,1993, Spatial-temporal topology and causal mechanisms in time-integrated GIS: from conceptual model to implementation strategies. In *Proceedings of the Canadian Conference on GIS'93*, (Ottawa, Canada), 842-857.

FISHER, P. F., 1994, Probable and fuzzy models of the viewshed operation. *Innovations in GIS,* edited by Worboys M.B., (Taylor and Francis, UK), 161-175.

FOODY, G. M., 1996, Approaches for the production and evaluation of fuzzy land cover classifications from remotely-sensed data. *International Journal of Remote Sensing*, **7**, 1317-1340.

FRANK, A.U., 1998, Different Types of "Times" in GIS. *Spatial and Temporal Reasoning in Geographic Information Systems*, edited by Egenhofer M.J., and Golledge R.G. (Oxford University Press) 85-93.

GUINDON, L., 1997, Intégration de la dimension temporelle dans un SIG: application à l'analyse des transformation de l'utilisation du sol en milieu périurbain. Mémoire de maîtrise non publié. Université de Montréal, 104 p.

HALL, G. B., WANG, F., and SUBARYONO, 1992, Comparison of Boolean and fuzzy classification methods in land suitability analysis by using geographical information systems. *Environment and Planning A,* **24**, 497-516.

HABER, R.B., and MCNABB, D.A., 1990, Visualization idioms: a conceptual model for scientific visualization systems. *Visualization in Scientific Computing*, edited by Nielson, G, Shriver, M, Rosenblum, L., 74-94.

HAGERSTRAND, T., 1970, What about people in regional science?. *Papers of the Regional Science Association*, **24**, 7-21.

HAZELTON, N.W.J., LEAHY, F.J., and WILLIAMSON, I.P., 1992, Integrating dynamic modeling and geographic information systems. *Journal of the Urban and Regional Information Systems Association,* **2**, 47-58.

HEUVELINK, G.B., BURROUGH, P.A., and STEIN, A., 1989, Propagation of errors in spatial modelling with GIS. *International Journal of Geographical Information Systems,* **4**, 303-322.

HEUVELINK, G.B., and BURROUGH, P.A., 1993, Error propagation in cartographic modelling using Boolean logic and continuous classification. *International Journal of Geographical Information Systems,* **3**, 231-246.

HOOTSMANS, R.M., 1996, *Fuzzy sets and series analysis for visual decision support in spatial data exploration.* Netherlands Geographical Studies 202, (Utrecht), 168 p.

HOWARD, D., and MACEACHREN, M., 1996, Interface design for geographic visualization tools for representing reliability. *Cartography and Geographic Information Systems,* **2**, 59-77.

HUNTER, G.J., and GOODCHILD, M.F., 1993, Managing uncertainty in spatial databases: Putting theory into Practice. *Journal of the Urban and Regional Information System Association,* **2**, 55-62.

ISAAKS, E. H., and SRIVASTAVA, R. M., 1989, *Applied Geostatistics.* (Oxford University Press), 561 p.

JEANSOULIN, R., FONYAINE, Y., and WERNER, F., 1981, Multitemporal segmentation by means of fuzzy sets. *Symposium on Machine Processing of Remotely Sensed Data,* 336-339.

KELMELIS J.A, 1998, Process Dynamics, Temporal Extent, and Causal Propagation as the Basis for Linking Space and Time. *Spatial and Temporal Reasoning in Geographic Information Systems*, edited by Egenhofer M.J., and Golledge R.G. (Oxford University Press) 94-103.

KEMP, Z., and KOWALCZYK, A., 1994, Incorporating the temporal dimension in a GIS. *Innovations in GIS*, edited by Worboys M.F. (Taylor and Fransis), 89-103.

KENT, J. T., and MARDIA, K. V., 1988, Spatial classification using fuzzy membership models. *IEEE Transactions on Pattern Analysis and Machine Intelligence,* **10**, 659-671.

KIIVERI, H.T., 1997, Assessing, representing and transmitting positional uncertainty in maps. *International Journal of Geographical Information Science*, **1**, 33-52.

KIRTLAND, D., GAYDOS, L., CLARKE, K., DeCOLA, L., and JOHNSON, C.B., 1994, An analysis of human-induced land transformations in the San Francisco Bay/Sacramento area. *Resource Review*, **2**, 206-217.

KOLLIAS, V. J., and VOLIOTIS, A., 1991, Fuzzy reasoning in the development of geographical information systems FRSIS: a prototype soil information system with fuzzy retrieval capabilities. *International Journal of Geographical Information Systems*, **2**, 209-223.

KRAAK, M-J., MULLER, J.C., and ORMELING, F., 1995, GIS-cartography: visual decision support for spatio-temporal data handling. *International Journal of Geographical Information Systems*, **6**, 637-645.

LAM, N. S., 1983, Spatial Interpolation Methods: A Review. *The American Cartographer*, **2,** 129-149.

LANDIS, J. D., 1994, The California urban futures model: a new generation of metropolitan simulation models. *Environment and Planning B: Planning and Design,* **21**, 399-420.

LANGRAN, G., and CHRISMAN, N.R., 1988. A framework for temporal geographic information. *Cartographica,* **3**, 1-14.

LANGRAN, G., 1989, A review of temporal database research and its use in GIS applications. *International Journal of Geographical Information Systems*, **3**, 215-232.

LANGRAN, G., 1992, *Time in Geographic Information Systems.* (London: Taylor & Francis), 182 p.

LANGRAN, G., 1993, Issues of implementing a spatiotemporal system. *International Journal of Geographical Information Systems*, **4**, 305-314.

LOWELL, K., 1994, A fuzzy surface cartographic representation for forestry based on Voronoi diagram area stealing. *Canadian Journal of Forest Research*, **9**, 1970-1980.

MACEACHREN, A.M., and MONMOINIER, M., 1992, Geographic visualization: Introduction. *Cartography and Geographic Information Systems*, **4**, 197-200.

MARCEAU, D.J., MAROIS, C., and GUINDON L., 1995, Integrating multi-source spatial data in GIS to study the land-use change in a rural-urban fringe. In *Proceedings of GIS`95*, (Vancouver, Canada), 334-339.

MARCEAU, D.J., and DRAGICEVIC, S., 1998, Linking space and time to model dynamics of change in a rural-urban environment. *Proceedings of The modeling of complex systems Conference*, (New Orleans, Louisiana, 12-17 July).

MARCEAU, D.J., 1999, Scale: A problem or a new paradigm ?. Submitted to *Canadian Journal of Remote Sensing*.

MARK, D. M., and CSILLAG, F., 1989, The nature of boundaries on 'Area-Class' maps. *Cartographica*, **1**, 65-78.

MAROIS, C., DESLAURIERS, P., et BRYANT, C., 1991, Une revue de la littérature scientifique sur l'étalement urbain et sur les relations urbaines-agricoles dans la frange urbaine: le cas de la région métropolitaine de Montréal, dans le contexte nord-américain. *Espace, Population, Sociétés*, **2**, 325-334.

MAROIS, C., 1998, La population montréalaise. *Montréal 2001: Visage et défis d'une métropole*, publié par C. Manzagol et C. Bryant (Les Presses de l'Université de Montréal), 83-97.

MASUOKA, P., ACEVEDO, W., FIFER, S., FORESMAN, T., and TUTTLE, M.J., 1996, Techniques for visualizing urban growth using a temporal GIS database. *Proceedings ASPRS/ACSM Annual Convention and Exhibition* (Baltimore, Maryland), **3**, 89-100.

MAYER, D.G., and BUTLER, D.G., 1993, Statistical validation. *Ecological Modeling*. **68**, 21-32.

MCBRATNEY, A.B., and DE GRUIJTER, J.J., 1992, A continuum approach to soil classification by modified fuzzy *k*-means with extragrades. *Journal of Soil Science*, **43**, 159-175.

MÉAILLE, R., and WALD L., 1990, Using geographical information system and satellite imagery within a numerical simulation of regional urban growth. *International Journal of Geographical Information Systems*, **4**, 445-456.

MENDOZA, G. A., and SPROUSE, W., 1989, Forest planning and decision making fuzzy environments: an overview, and illustrations. *Forest Science*, **35**, 481-502.

MITAS. L., BROWN, W.B., and MITASOVA, H., 1997, Role of dynamic cartography in simulations of landscape processes based on multivariate fields. *Computers & Geosciences*, **4**, 437-446.

NCGIA, 1994, *Time in geographic space: Report on the Specialist Meeting of Research Initiative 10.* Technical report 94-9, 42 p.

NEWCOMER, J.A., and SZAJGIN, 1984, Accumulation of Thematic Map Errors in Digital Overlay Analysis, *The American Cartographer*, **1**, 58-62.

NEWELL, R.G., THERIAULT, D., and EASTERFIELD, M., 1992, Temporal GIS-modeling of the evolution of spatial data in time. *Computers & Geosciences*, **4**, 427-433.

OPENSHAW, S., 1994, Two exploratory space-time-attribute pattern analysers relevant to GIS. In *Spatial Analysis and GIS*, edited by S. Fortheringham and P. Rogerson, 83-104.

PEUQUET, D.J., 1984, A conceptual framework and comparison of spatial data models. *Cartographica*, **4**, 66-113.

PEUQUET, D.J.,1994, It's about time: a conceptual framework for the representation of temporal dynamics in geographic information systems. *Annals of the Association of American Geographers*, **3**, 441-461.

PEUQUET, D.J., and DUAN, N., 1995, An event-based spatiotemporal data model (ESTDM) for temporal analysis of geographical data. *International Journal of Geographical Information Systems*, **1**, 7-24.

PORTUGALI, J., and BENENSON, I., 1995, Artificial planning experience by means of a heuristic cell – space model: simulating international migration in the urban process. *Environment and Planning B: Planning and Design*, **27**, 1647-1665.

POWER, M., 1993, The predictive validation of ecological and environmental models. *Ecological Modeling*. **68**, 33-50.

ROBESON, S.M., 1997, Spherical methods for spatial interpolation: review and evaluation. *Cartography and Geographic Information Systems*, **1**, 3-20.

ROBINSON, V. B., 1978, Information theory and sequences of land use: An application. *Professional Geographer*, **2**, 174-179.

ROBINSON, V.B., 1980, On the use of markovian equilibrium distributions for land use policy evaluation. *Journal of Socio-Economic Planning Science*, **14**, 85-89.

ROBINSON, V. B., 1988, Some implications of fuzzy set theory applied to geographic databases. *Computers, Environment and Urban Systems*, **12**, 89-97.

RYKIEL, E.J., 1996, Testing ecological models: the meaning of validation. *Ecological Modeling*. **68**, 229-244.

SCHLAGEL, J.D., and NEWTON, C.M., 1996, A GIS-based statistical method to analyze spatial change. *Photogrammetric Engineering & Remote Sensing*, **7**, 839-844.

SMITH, P. N., 1992, Fuzzy evaluation of land-use and transportation options. *Environment and Planning B: Planning and Design,* **19**, 525-544.

SNODGRASS, R.T., 1992, Temporal databases. In *Theory and Methods of Spatio-Temporal Reasoning in Geographic Space,* edited by A.U. Frank, I. Campari, and U. Formentini, 22-64.

STATISTICS CANADA, 1951-1986, *Census Data.*

STEAD, S.D., 1998, Temporal dynamics and geographic information systems. *Spatial and Temporal Reasoning in Geographic Information Systems*, edited by Egenhofer M.J., and Golledge R.G. (Oxford University Press), 214-219.

SUI, D. Z., 1992, A fuzzy GIS modeling approach for urban land evaluation. *Computers, Environment and Urban Systems*, **16**, 101-115.

TERANO, T., 1992, *Fuzzy systems theory and its applications.* (Academic Press), 268 p.

THRIFT, N., 1977, An introduction to time geography. In *Concepts and Techniques in Modern Geography*, **13**, 36 p.

XIANG, W.N., GROSS, M., FABOS, G.J., and MACDOUGALL, E.B., 1992, A fuzzy-group multicriteria decision making model and its application to land-use planning. *Environment and Planning B: Planning and Design,* **19**, 61-84.

XIE Y., and BATTY, M., 1997, Automata-based exploration of emergent urban form. *Geographical Systems*, **4**, 83-102.

U. S. ARMY CERL, 1993, *GRASS4.1 User's Manual*, 550 p.

YOUCAI, H., and WENBAO, L., 1997, Building the estimation model of digitizing error. *Photogrammetric Engineering & Remote Sensing*, **10**, 1203-1209.

VAN DER KNAAP, W.G., 1992, The vector to raster conversion: (mis)use in geographical information systems. *International Journal of Geographical Information Systems,* **2**, 159-170.

VASILIEV, I.R.,1998, Mapping Time. *Cartographica*, Monograph 49, 51 p.

VEREGIN, H., 1989, A review of error models for vector to raster conversion. *The Operational Geographer*, **1**, 12-16.

VRANA, R., 1989, Historical data as an explicit component of land information systems. *International Journal of Geographical Information Systems,* **1**, 33-49.

WANG, F., HALL, B.G., and SUBARYONO, 1990, Fuzzy information representation and processing in conventional GIS software: database design and application. *International Journal of Geographical Information Systems*, **3**, 261-283.

WANG, F., 1990a, Fuzzy supervised classification of remote sensing images, *IEEE Transactions on Geoscience and Remote Sensing*, **28**, 194-201.

WANG, F., 1990b, Improving remote sensing image analysis through fuzzy information representation. *Photogrammetric Engineering and Remote Sensing*, **8**, 1163-1169.

WANG, F., 1994, Towards a natural language user interface: an approach of fuzzy query. *International Journal of Geographical Information Systems*, **2**, 143-162.

WANG, F., and HALL, B.G., 1996, Fuzzy representation of geographical boundaries in GIS. *International Journal of Geographical Information Systems*, **5**, 573-590.

WARCHOWICZ, M., and HEALEY, G., 1994, Towards temporality in GIS. *Innovations in GIS* edited by Worboys M.F., (Taylor & Francis) 105-115.

WU, F., 1998, An experiment on the generic polycentricity of urban growth in a cellular automatic city. *Environment and Planning B: Planning and Design,* **25**, 731-752.

ZADEH, L. A., 1965, Fuzzy sets. *Information and Control*, **8**, 338-353.

ZADEH, L. A., 1972, A fuzzy set theoretic interpretation on linguistic hedges. *Journal of Cybernetics*, **2**, 4-34.

ZADEH, L. A., 1978, Fuzzy sets as a basis for a theory of possibility. *Fuzzy Sets and Systems*, **1**, 3-28.

ZHU, A. X., 1997, Measuring uncertainty in class assignment for natural resource maps under fuzzy logic. *Photogrammetric Engineering and Remote Sensing*, **10**, 1195-1202.

ZIMMERMANN, H-J., 1985, *Fuzzy sets and its applications.* (Kluwer Academic Publishers), 363 p.