LINKING LAND CAPABILITY/SUITABILITY ANALYSIS WITH
ENVIRONMENTAL MODELS USING GEOGRAPHIC
INFORMATION SYSTEMS: AN ITERATIVE
MODELING APPROACH

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
School of the Ohio State University

By
Ruslan B. Rainis, Dipl.URP, B.A, MCRP

The Ohio State University

1991

Dissertation Committee:
Dr. Steven I. Gordon, Chairman

Dr. Jean-Michel Guldmann

Dr. C.Dana Tomlin

Dr. John G. Lyon

Approved by

Adviser
Department of City and Regional Planning
Copyright by
Ruslan B. Rainis
1991
To my parents, wife, and son
ACKNOWLEDGEMENTS

I would like to acknowledge and express my sincere appreciation for the help and support of many individuals and organizations without whom this research could not have been completed.

First, my sincere thanks and appreciation are due to Dr. Steven I. Gordon, my major adviser, for his advice, guidance, and support in bringing this research to fruition. I shall never forget the encouragement and moral support that Dr. Gordon provided when my hopes for this research flagged. I would also like to thank Dr. Gordon for giving me permission to use the Big Darby Creek Watershed data base for this research. I am also indebted to Dr. Gordon for providing financial support during the various stages of my education at the Ohio State University.

My thanks and appreciation are also due to Dr. Jean-Michel Guldmann, whose different outlooks on my work improved its balance. I would like to thank Dr. Guldmann for clarifying and providing the computer program of his algorithm on the convex combinations of non-linear programming used in this research.

It was also to my benefits to have Dr. C. Dana Tomlin in my dissertation committee. Dr. Tomlin was very helpful and willing to provide the computer programs of his Map Analysis Package (MAP), some of which were modified and used in this research. Dr. Tomlin also granted me permission to use the computer facilities at the Natural Resources Information System Laboratory, where most of the analyses for this research were undertaken. I am very much grateful to Dr. Tomlin for serving in my dissertation committee.

My sincere thanks are also due to Dr. John G. Lyon for his kindness, suggestions, and comments.
The technical assistance of Dick Haller of the Ohio Supercomputer Center, and Ed Beranek of the Natural Resources Information System Laboratory is gratefully acknowledged.

My deepest gratitude goes to my wife Noresah for her love, encouragement, patience, and sacrifice, and for taking care of our son. To my son, Azhar, I thank you for understanding my frequent absences.

I also express my appreciation to my fellow Malay friends at the Ohio State University for their kindness and friendship during all my stay at Columbus, Ohio.

Finally, thanks go to my parents, my brothers and sisters for their love, and encouragement during all my education in the United States.

The computer funds for performing this research were provided by the Instructional and Research Computer Center, The Ohio State University. The computer funds were also provided by the Ohio Supercomputer Center, through a research grant to Dr. Steven I. Gordon. The financial support from the Malaysian government and the University of Science Malaysia are also appreciated.
VITA

September 16, 1960................................. Born - Negeri Sembilan, Malaysia

1981.................................................. Diploma in Urban and Regional Planning, University Technology Malaysia, Malaysia

1981.................................................. Technical Assistant, Urban Division, Federal Town and Country Department, Malaysia

1983.................................................. B.A., Miami University, Ohio

1985.................................................. Master of City and Regional Planning, Ohio State University, Ohio

Summer 1985............................... Graduate Teaching Associate, Department of City and Regional Planning, Ohio State University, Ohio

1985/1986......................................... Graduate Program in Digital Cartography, Department of Geography, Ohio State University, Ohio - Incomplete

1986/1989......................................... Graduate Teaching Assistant and Graduate Research Associate, Department of City and Regional Planning, Ohio State University, Ohio

1990.................................................. Graduate Teaching Associate, Department of City and Regional Planning, Ohio State University, Ohio

FIELDS OF STUDY

Major Field: City and Regional Planning

Studies in Environmental Planning: Prof. Steven I. Gordon, Prof. Jean-Michel Guldmann
<table>
<thead>
<tr>
<th>Studies in Quantitative Methods</th>
<th>Prof. Jean-Michel Guldmann, Prof. Oscar Fisch, Prof. Emilio Cassetti</th>
</tr>
</thead>
<tbody>
<tr>
<td>Studies in Geographic Information System</td>
<td>Prof. Duane F. Marble, Prof. C. Dana Tomlin, Prof. Michael Demers, Prof. Douglas Way, Prof. Granville Barnes</td>
</tr>
<tr>
<td>Studies in Cartography</td>
<td>Prof. Hal Moellering, Prof. Joseph Loon, Prof. Nina Lam</td>
</tr>
<tr>
<td>Studies in Remote Sensing</td>
<td>Prof. John G. Lyon, Prof. Carolyn Merry, Prof. Scott Smith</td>
</tr>
</tbody>
</table>
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DEDICATION</strong></td>
<td></td>
<td>ii</td>
</tr>
<tr>
<td><strong>ACKNOWLEDGEMENTS</strong></td>
<td></td>
<td>iii</td>
</tr>
<tr>
<td><strong>VITA</strong></td>
<td></td>
<td>v</td>
</tr>
<tr>
<td><strong>LIST OF TABLES</strong></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td><strong>LIST OF FIGURES</strong></td>
<td></td>
<td>xii</td>
</tr>
</tbody>
</table>

## CHAPTER

1. **INTRODUCTION** | 1 |

1.1 Introduction | 1 |

1.2 Objectives and hypothesis of study | 5 |

2. **LITERATURE REVIEWS OF RELATED RESEARCH** | 9 |

2.1 Land Capability/Suitability Analysis | 9 |

   History of land capability/suitability analysis | 9 |

   Review of existing land capability/suitability analysis methods | 12 |

   Gestalt methods | 13 |

   Combination methods | 14 |

   Mathematical combination methods | 14 |

   Nominal/binary combination | 14 |

   Ordinal combination | 16 |

   Linear combination | 18 |

   Nonlinear combination | 22 |

   Explicit identification of regions | 24 |

   Factor combinations | 24 |

   Numerical taxonomy methods | 25 |

   Logical combination methods | 27 |

   Rules of combination | 27 |

   Hierarchical combination | 28 |

   Summary | 29 |

   Recent development in land capability/suitability analysis | 33 |
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2</td>
<td>Geographic Information System (GIS)</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>GIS components and operations</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>GIS as modeling tools</td>
<td>42</td>
</tr>
<tr>
<td>2.3</td>
<td>Review of Land Use Allocation Models</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>Predictive/descriptive land use models</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>Prescriptive land use models</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>Summary</td>
<td>53</td>
</tr>
<tr>
<td>2.4</td>
<td>Review of Nonpoint Pollution Models</td>
<td>54</td>
</tr>
<tr>
<td>III</td>
<td>THE CONCEPTUAL BASIS OF THE PROPOSED METHODOLOGY</td>
<td>59</td>
</tr>
<tr>
<td>3.1</td>
<td>Introduction</td>
<td>59</td>
</tr>
<tr>
<td>3.2</td>
<td>The Environmental Impact Model</td>
<td>61</td>
</tr>
<tr>
<td>3.3</td>
<td>Descriptive Modeling</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>General description</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>Model Formulation</td>
<td>69</td>
</tr>
<tr>
<td>3.4</td>
<td>Prescriptive Modeling</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>General description</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>Model Formulation</td>
<td>80</td>
</tr>
<tr>
<td>IV</td>
<td>IMPLEMENTATION OF THE PROPOSED METHODOLOGY</td>
<td>96</td>
</tr>
<tr>
<td>4.1</td>
<td>The Study Area</td>
<td>96</td>
</tr>
<tr>
<td></td>
<td>Demographic trends in Big Darby Creek</td>
<td>98</td>
</tr>
<tr>
<td></td>
<td>Delineating the study area boundary</td>
<td>101</td>
</tr>
<tr>
<td>4.2</td>
<td>Spatial Database</td>
<td>101</td>
</tr>
<tr>
<td></td>
<td>Geographic information systems used in the study</td>
<td>103</td>
</tr>
<tr>
<td></td>
<td>Data elements</td>
<td>104</td>
</tr>
<tr>
<td></td>
<td>Topography</td>
<td>104</td>
</tr>
<tr>
<td></td>
<td>Soils</td>
<td>105</td>
</tr>
<tr>
<td></td>
<td>Land uses</td>
<td>109</td>
</tr>
<tr>
<td></td>
<td>Roads</td>
<td>116</td>
</tr>
<tr>
<td></td>
<td>Public facilities</td>
<td>116</td>
</tr>
<tr>
<td>4.3</td>
<td>Environmental Data</td>
<td>116</td>
</tr>
<tr>
<td>4.4</td>
<td>Descriptive Modeling</td>
<td>123</td>
</tr>
<tr>
<td></td>
<td>Industrial land suitability analysis</td>
<td>126</td>
</tr>
<tr>
<td></td>
<td>Commercial land suitability analysis</td>
<td>133</td>
</tr>
<tr>
<td></td>
<td>Residential land suitability analysis</td>
<td>140</td>
</tr>
</tbody>
</table>
4.5 Prescriptive Modeling ........................................................................ 148
  Land use demands............................................................................. 148
  Population projection........................................................................ 148
  Demands estimation........................................................................... 151
  Cluster analysis.................................................................................. 153
  Implementation and evaluation of the proposed methodology on a
test sub-basin.................................................................................... 159
  Comparison of the proposed methodology with the traditional
  and capability/suitability analysis...................................................... 171
  Comparison of the proposed methodology with the random
generation method........................................................................... 177
  Comparison of the proposed methodology with the convex
  combinations of non-linear programming method........................... 189
  Discussion of results.......................................................................... 196
  Implementation of the proposed methodology on the Big Darby Creek
  study area.......................................................................................... 198

V - CONCLUSIONS AND RECOMMENDATION........................................ 201

5.1 Summary............................................................................................ 201
5.2 Toward implementation.................................................................... 203
5.3 Possible extensions........................................................................... 205

BIBLIOGRAPHY..................................................................................... 207

APPENDICES

A. GEOMETRIC CHARACTERISTICS AND PARAMETERS OF THE
   SEVEN REACHES IN THE STUDY AREA........................................... 224

B. COMPUTER PROGRAM OF THE ENVIRONMENTAL MODEL.......... 227

C. COMPUTER COMPUTER FOR THE CONVEX COMBINATIONS OF
   NONLINEAR PROGRAMMING MODEL............................................ 255
# LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Advantages and Disadvantages of Vector and Raster GIS Data Formats</td>
<td>41</td>
</tr>
<tr>
<td>2. Pollutant Concentrations of Stormwater Runoff for Selected Land uses</td>
<td>64</td>
</tr>
<tr>
<td>5. Population Growth of Selected MCDs in Big Darby Creek Watershed for 1980-1986</td>
<td>100</td>
</tr>
<tr>
<td>7. The Average BOD Concentrations for Each Land use Used in the Simulation Modeling</td>
<td>124</td>
</tr>
<tr>
<td>8. Land use and Hydrologic Soil Group Combination (Matrix) to define Curve Number</td>
<td>124</td>
</tr>
<tr>
<td>9. The Existing (Simulated) Environmental Quality of the Study Area</td>
<td>125</td>
</tr>
<tr>
<td>10. Industrial Land use Siting Criteria</td>
<td>127</td>
</tr>
<tr>
<td>11. Commercial Land use Siting Criteria</td>
<td>135</td>
</tr>
<tr>
<td>12. Residential Land use Siting Criteria</td>
<td>142</td>
</tr>
<tr>
<td>13. Projected Population of MCDs in the Study Area 1990-2010</td>
<td>152</td>
</tr>
<tr>
<td>14. Projected Population of the Study Area 1990-2010</td>
<td>154</td>
</tr>
<tr>
<td>15. Projected Number of Households in the Study Area for 1990-2010</td>
<td>154</td>
</tr>
<tr>
<td>16. Projected Land use Demand for the Study Area 1990-2010</td>
<td>155</td>
</tr>
</tbody>
</table>
17. Projected Industrial Land use Demand for Each Sub-basin in the Study Area 1990-2010 ................................................................. 155

18. Projected Commercial Land use Demand for Each Sub-basin in the Study Area 1990-2010 ................................................................. 156

19. Projected Residential Land use Demand for Each Sub-basin in the Study Area 1990-2010 ................................................................. 156

20. The Distribution of Sample for Each Environmental Group in the Test Sub-basin - Sub-basin 13 ................................................................. 163

21. The Distribution of Land use Allocated at Each Iteration for the Test Sub-basin - Sub-basin 13 ................................................................. 172

22. The Environmental Impacts of the New Land uses in Sub-basin 13 for Iteration 1 Allocated Using the Proposed Methodology ......................... 173

23. The Environmental Impacts of the New Land uses in Sub-basin 13 for Iteration 1 Allocated Using the Traditional Land Capability/Suitability Analysis ........................................................................... 179

24. The Environmental Impacts of the New Land uses in Sub-basin 13 for Iteration 1 Allocated Using the Random Generation Method - Solution 1 ................................................................. 185

25. The Environmental Impacts of the New Land uses in Sub-basin 13 for Iteration 1 Allocated Using the Random Generation Method - Solution 2 ................................................................. 186

26. The Environmental Impacts of the New Land uses in Sub-basin 13 for Iteration 1 Allocated Using the Random Generation Method - Solution 3 ................................................................. 187

27. The Environmental Impacts of the New Land uses in Sub-basin 13 for Iteration 1 Allocated Using the Convex Combinations of Nonlinear Programming ........................................................................... 191

28. The results of the regression analysis of the proposed methodology and the optimal solutions ........................................................................... 194

29. The Environmental Impacts of the New Land uses in Study Area for Iteration 1 Allocated Using the Proposed Methodology ........................................ 199

30. The Environmental Impacts of the New Land uses in Study Area for Iteration 5 Allocated Using the Proposed Methodology ........................................ 199
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Basic Components of Geographic Information System</td>
<td>38</td>
</tr>
<tr>
<td>2. GIS Conceptualized as Map Layers</td>
<td>40</td>
</tr>
<tr>
<td>3. Schematic Diagram of the Proposed Methodology</td>
<td>60</td>
</tr>
<tr>
<td>4. Conceptual Descriptive Model for Industrial Land Use</td>
<td>72</td>
</tr>
<tr>
<td>5. Conceptual Descriptive Model for Commercial Land Use</td>
<td>74</td>
</tr>
<tr>
<td>6. Conceptual Descriptive Model for Residential Land Use</td>
<td>77</td>
</tr>
<tr>
<td>7. The Flow Diagram of the Proposed Methodology</td>
<td>87</td>
</tr>
<tr>
<td>8. Location of Big Darby Creek Watershed</td>
<td>97</td>
</tr>
<tr>
<td>9. The Big Darby Creek Study Area</td>
<td>102</td>
</tr>
<tr>
<td>10. Topographic Aspect of the Study Area</td>
<td>106</td>
</tr>
<tr>
<td>11. Topographic Slope of the Study Area</td>
<td>107</td>
</tr>
<tr>
<td>12. Soil Erodibility (K) Factor of the Study Area</td>
<td>108</td>
</tr>
<tr>
<td>13. Soil Hydrologic Group of the Study Area</td>
<td>110</td>
</tr>
<tr>
<td>14. Flooding Potential in the Study Area</td>
<td>111</td>
</tr>
<tr>
<td>15. Soil Drainage Class of the Study Area</td>
<td>112</td>
</tr>
<tr>
<td>16. Soil Bearing Capacity of the Study Area</td>
<td>113</td>
</tr>
<tr>
<td>17. Land Uses of the Study Area (1965)</td>
<td>114</td>
</tr>
<tr>
<td>18. Land Uses of the Study Area (1979)</td>
<td>115</td>
</tr>
<tr>
<td>19. Road Network in the Study Area</td>
<td>117</td>
</tr>
<tr>
<td></td>
<td>Title</td>
</tr>
<tr>
<td>---</td>
<td>-----------------------------------------------------------------------</td>
</tr>
<tr>
<td>20.</td>
<td>Locations of Selected Public Facilities in the Study Area</td>
</tr>
<tr>
<td>21.</td>
<td>Hydrology of the Study Area</td>
</tr>
<tr>
<td>22.</td>
<td>Division of Big Darby Creek into Stream Reaches</td>
</tr>
<tr>
<td>23.</td>
<td>Site Suitability Model for Industrial Land Use</td>
</tr>
<tr>
<td>24.</td>
<td>Site Suitability for Industrial Land Use</td>
</tr>
<tr>
<td>25.</td>
<td>Site Suitability Model for Commercial Land Use</td>
</tr>
<tr>
<td>26.</td>
<td>Site Suitability for Commercial Land Use</td>
</tr>
<tr>
<td>27.</td>
<td>Site Suitability Model for Residential Land Use</td>
</tr>
<tr>
<td>28.</td>
<td>Site Suitability for Residential Land Use</td>
</tr>
<tr>
<td>29.</td>
<td>Result of the Cluster Analysis of the Study Area</td>
</tr>
<tr>
<td>30.</td>
<td>Distribution of the Environmental Groups in the Study Area</td>
</tr>
<tr>
<td>31.</td>
<td>Initial Location of Samples in Test Sub-basin 13</td>
</tr>
<tr>
<td>32.</td>
<td>Cartographic Model for Allocating Industrial Land use</td>
</tr>
<tr>
<td>33.</td>
<td>Candidate Sites for Industrial Land use in Sub-basin 13 at Iteration 1</td>
</tr>
<tr>
<td>34.</td>
<td>Cartographic Model for Allocating Commercial Land use</td>
</tr>
<tr>
<td>35.</td>
<td>Candidate Sites for Commercial Land use in Sub-basin 13 at Iteration 1</td>
</tr>
<tr>
<td>36.</td>
<td>Cartographic Model for Allocating Residential Land use</td>
</tr>
<tr>
<td>37.</td>
<td>Candidate Sites for Residential Land use in Sub-basin 13 at Iteration 1</td>
</tr>
<tr>
<td>38.</td>
<td>Distribution of New Land uses for Iteration 1 Allocated using the</td>
</tr>
<tr>
<td></td>
<td>Proposed Methodology</td>
</tr>
<tr>
<td>39.</td>
<td>Environmental Impacts of the Land uses Allocated Using the</td>
</tr>
<tr>
<td></td>
<td>Proposed Methodology for Sub-basin 13</td>
</tr>
<tr>
<td>40.</td>
<td>Distribution of New Land uses for Iteration 1 Allocated using the</td>
</tr>
<tr>
<td></td>
<td>Traditional Land Capability/Suitability Analysis</td>
</tr>
<tr>
<td>41.</td>
<td>Comparison of the Environmental Impacts of the Land uses Allocated</td>
</tr>
</tbody>
</table>
using the Traditional Land Capability/Suitability Analysis and the Proposed Methodology

42. Distribution of New Land uses for Iteration 1 Allocated using a Random Generation Method (Solution 1)................................. 180

43. Distribution of New Land uses for Iteration 1 Allocated using a Random Generation Method (Solution 2)................................. 182

44. Distribution of New Land uses for Iteration 1 Allocated using a Random Generation Method (Solution 3)................................. 183

45. Comparison of the Environmental Impacts of the Land uses Allocated using the Random Generation Method and the Proposed Methodology.................................................................................. 184

46. Comparison of the Environmental Impacts of the Optimal Land use Allocation with the Proposed Methodology.............................................................. 188

47. Scatter Distribution of the Environmental Impacts of the Proposed Methodology and the Optimal Solution.............................................. 192

48. Overall Comparison of the Environmental Impacts of the Land uses Allocated using the Proposed Methodology and Other Methods........ 195

49. Distribution of New Land uses for Iteration 5 Allocated using the Proposed Methodology for the Study Area................................. 199
CHAPTER I
INTRODUCTION

1.1 Introduction

One of the major tasks in land use planning is the process of determining the location of various land use activities that best achieve certain specified objectives. Many of these land use activities contribute to the modification of the chemical, physical, and biological environment, which is detrimental to our land, water, and air resources. Thus the process of selecting suitable locations for these land uses is very important because poor siting decisions can have far-reaching effects on the environment, on individuals and community, as well as the economy (Diamond and Wright, 1988; Williams et al., 1983).

Prior to the 1960s, most land use decisions were made mainly on the basis of social acceptability and economic efficiency. Externalities affecting environmental quality were often not properly taken into consideration. This began to change during the 1960s with the sudden shift in societal values regarding environmental quality. Since then, numerous pieces of legislation have been introduced by federal, state, and local governments concerning land and water resources. Most of this legislation explicitly requires consideration of environmental factors in all planning processes and land use decision making. This requirement, together with the dissatisfaction with the traditional land use planning approach, has resulted in considerable exploration of more systematic methods for inventorying natural features and for incorporating environmental values into planning and decision making. Of these methods, one that is most widely and commonly used by the design/planning profession is what has come to be known as land capability/suitability analysis.

Land capability analysis and land suitability analysis are two methods often used interchangeably in the literature, but each has slightly different meaning. Land capability analysis is a method of evaluating the natural physical ability or capacity of a given location to support a specific land use (Anderson, 1987; Steiner, 1983; and Gordon, 1978). Land
suitability analysis, on the other hand, is a method of evaluating the appropriateness of a given tract of land for specific use on the basis of its economic, social, and environmental characteristics (Anderson, 1987; Steiner, 1983; McDonald and Brown, 1984). In practice, both of these methods are usually used in conjunction with each other. It has also been given various names including resource suitability analysis, natural resource evaluation, land impact analysis, map overlay, land availability analysis, potential surface analysis, or environmental suitability analysis (McHarg, 1969; Steiner, 1983; Ortolano, 1984; Gordon, 1985; Bailey, 1987; Forbes, 1969; Zetter, 1974; and Chapin and Kaiser, 1979).

This approach has now become a standard part of planning analysis at many scales (Hopkins, 1977). Planners usually use land capability/suitability analysis when they want to delineate the relative suitability of each location in a geographic area for various land uses or facilities. The results from this analysis are usually used as input to the land allocation process in preparing comprehensive land use or zoning plans. This approach is seen as an appropriate way to quantify land development constraints and opportunities, and thus help planners cope with the "supply side" of the land use plan design problem (McDonald and Brown, 1984). The justification for using this approach in plan design is based upon one commonly stated principle that land should be allocated to the use to which it is most suited (McDonald and Brown, 1984).

The use of land capability/suitability analysis is not new to land use planning. It can be traced back to the early 1900s (Ortolano, 1984; Steinitz, Parker, and Jordan, 1976). The method was however not widely used for integrating environmental factors into land use planning until the 1960s. This has been due largely to the works of Ian McHarg (1969). McHarg (1969) eloquently demonstrated the merit of this approach through a series of land use planning projects. Hand-drawn transparent maps of each environmental and other siting criteria were overlaid to produce a set of maps showing the relative suitabilities or vulnerabilities of each land parcel for the proposed land uses. The rationale behind this method is that significant environmental or ecological response could be captured by synthesizing, or integrating the available factor maps.

This method has undergone several enhancements since it was first popularized by McHarg. Though widely used, the method is known to have various shortcomings. The method suffers from the implicit, hence subjective, nature of judgements regarding land
homogeneity and suitability, and the weighing of factors (Westman, 1985; Gordon, 1985; Hopkins, 1977). This limitation sometimes makes it difficult for others to replicate, scrutinize, or confirm the land suitability generated using this method. This method is also static and deterministic in an environment that is dynamic and probabilistic (Itami, 1988a; Itami, 1988b; Nichols and Hyman, 1982; Simpson, 1987; Smith and Robinson, 1983). It fails to adequately quantify environmental impacts, making linkage with environmental models difficult (Canter, 1977; Gordon, 1985). Finally, the outputs of this method do not yet constitute an implementable land use plan, rather they only serve as the information input for plan design (Hopkins, 1977; Chapin and Kaiser, 1979). Some of these problems were due to the limitations of the traditional manual approach which is analytically limited.

The recent advent in computerized geographic information systems (GIS) opens up new opportunities to automate the method and helps eliminate some of its limitations. These systems have various capabilities (primitive operations) that provide a practical and logical means of compiling, processing, evaluating, and displaying large arrays of spatially-referenced data collected over a period of time for a large geographic regions (Johnston, et. al, 1988; Svatoss, 1979; and Diamond and Wright, 1988). By combining these primitive operations in a logical manner, it is possible to develop an approach to cartographic modeling (Tomlin, Berry, and Tomlin, 1981; Tomlin, 1983; and Berry, 1987). Cartographic modeling, which was first formalized by Tomlin (1983), is a general but well-defined methodology to formally synthesize geographic information as part of decision making. It can help planners to analyze temporal change, provide an area-wide (regional) perspective, and evaluate the importance of landscape position (Johnston, et. al, 1988). These operations allow planners to vary the weights associated with different variables (maps) or the scores associated with the attributes of particular variables (Gordon, 1985). The ability to consider larger numbers of map layers (factors) allows the analysis of more complicated problems. Though some limitations have been overcome, the use of the new technology still fails to change the quality of the outcomes from the analysis. Many of the fundamental limitations of the traditional approach still remain.

To date, the use of land capability/suitability analysis integrated in a geographic information system is progressing at a much faster rate than the methodological improvements necessary for optimal use in land use planning (Hepner, 1984). This is
partly because the use of the method in the new setting is merely a direct adoption of the traditional approach rather than advancing the state of the art. Furthermore, the uses of the present geographic information systems in land use decision-making still focus on supportive rather than active roles (Tomlin and Johnston, 1988). Of the remaining limitations of the method, its static and deterministic nature and inability to predict environmental impacts or to link with existing environmental models are of particular concern to its future roles in land use and environmental planning.

Land capability/suitability analysis is said to be static (temporally and spatially) because it does not take into account the interdependencies of land units over time and space. It is temporally static because of the practical necessity to use available maps characterizing existing situations (Bailey, 1988; Simpson, 1987; and Simpson, 1988). This inherently limits its ability to depict environmental changes once any development is in place. In order to capture the environment's complexity and dynamism, land capability/suitability analysis needs to be dynamic, i.e., the analysis should not only consider existing conditions, but it should also consider the future characteristics of the proposed land uses, and their relationship with each other as well as with the existing land uses. Land capability/suitability analysis is also spatially static because it is usually carried out on a location-by-location (atomistic) rather than on an holistic basis. Often overlooked is the fact that there exist geographical associations among different ecological factors, and "geographical associations do not always imply the same ecological mechanisms of cause and effect" (Gordon, 1985). Research in this direction has recently gotten some attention from the planning and geographic information system community. The works of Steinitz and Rogers (1974), and Tomlin and Johnston (1988) illustrate a few attempts in this direction.

Many of the existing geographic information systems are still limited in scope and analytical capabilities (Gordon, 1985; Sen and Radhakrishna, 1988; Armstrong, 1989). For instance, it is surprising that almost none of these systems have attempted to link the encoded data with any of the more analytical environmental models (Gordon, 1985). Some attempts have been made to use GIS for environmental modeling (e.g., Steinitz and Rogers, 1974; Fabos and Caswell, 1977; Berry and Sailor, 1987; Gilliland and Baxter-Potter, 1987; and Kittleson and Kruska, 1987 - to mention a few). Yet few of these attempts integrate such analysis with land capability analysis or the land-use allocation process. This
means that environmental analysis and the siting of the future land uses are still done independently of one another. Most often the environmental analyses are carried out only after the land use plans have been formulated.

To be effective for land use and environmental planning purposes, there is a need to integrate such environmental analysis with land capability/suitability analysis in a land use allocation process. The importance of such integrated analysis is obvious - the fact that environmental impacts are spatial phenomena and cumulative in nature. Impacts which may be individually insignificant can accumulate over space and time to cause significant environmental degradation (Johnston, et. al, 1988). They are strongly influenced by the location of the land uses, the land use mix and the spatial relationships between these land uses. Thus, the suitability of land to accommodate a given land use is not only the function of the characteristics of the land itself, but also its location in relation to other land uses as well as the overall pattern of the land uses (Fabos, 1981). It is the lack of a thorough understanding of these interactions that has been the roots of many present environmental problems (Guldmann, 1979; Johnston et. al, 1988). Although various technical or structural after-the-fact solutions are presently available to correct these problems, it is becoming recognized that they are costly, inefficient, and often ineffective (Chapin and Kaiser, 1979; Lynard et al., 1979). Hence, it is much wiser to anticipate and avoid them through land use design, planning, and control.

The prospect for integrating land capability/suitability analysis, environmental models, and land use allocation models using geographic information system has received little attention to date (e.g Fabos and Caswell, 1977; Steinitz, et al., 1974), thus more research efforts need to be expended in this direction. It is these concerns that motivate the proposal of this dissertation research.

1.2 Objectives and hypothesis of study

In order to deal with the concerns described above, this dissertation will have the following objectives:

(1). to develop a modeling approach that links land capability/suitability analysis with environmental models using geographic information systems.

(2). to evaluate the performance of the proposed approach in land use allocation involving environmental quality.
(3). to demonstrate the use of the proposed approach for urban nonpoint water pollution control.

In order to achieve the above objectives, this research will be comprised of two parts. In the first part, an iterative technique linking land use decisions to their impact on urban nonpoint water pollution levels is developed. The technique simulates the impacts of urban runoff from residential, commercial, and industrial land uses on biochemical oxygen demand (BOD) and dissolved oxygen (DO) concentrations using the Soil Conservation Service runoff model, and the Streeter-Phelps DO model. The resulting environmental quality is compared to a set of preset standards for dissolved oxygen (DO). If the standards are not met, a new tentative land use plan is developed in the next iteration. Otherwise, if the standards are met, the iteration stops, and the resulting land use plan will constitute a preliminary plan. The improvement in water quality is quantified by comparing the DO level at each iteration with the one from the previous iteration. The significance of the differences can be tested using statistical techniques for hypothesis testing. The hypothesis is that each subsequent iteration will produce an environmentally better land use allocation. If the hypothesis is accepted, meaning that the improvement is significant, then the iteration continues, otherwise it will stop.

The purpose of this research is to propose a modeling approach that links land capability/suitability analysis with environmental models using a geographic information system as an alternative approach to the formulation of a good land use plan in terms of environmental impacts. For this reason, improvement in water quality alone is insufficient to prove that the methodology is reliable. Therefore, the second part of the research will compare the results of the proposed methodology to the optimal solutions as well as to other solutions generated randomly, and using the traditional land capability/suitability analysis method. The optimal solutions are generated by solving the same problem using a mathematical optimization technique adapted from the convex combination method of nonlinear programming. The evaluation will be based on the overall environmental impacts that each technique produces. A linear regression analysis is used to analyze the technical relationship between the results of the proposed approach and the optimal solutions.

Urban nonpoint source pollution is used as an example because it is one of the environmental concerns recently receiving much worldwide attention. Water quality can be
impacted either by point or nonpoint source pollution. Unlike point sources, nonpoint source (NPS) pollution enters the environment from diffuse (intermittent) sources mainly associated with surface runoff, thus related to land use/cover. The major nonpoint pollutants include sediment, nitrogen, phosphorous, biochemical oxygen demand (BOD), chemical oxygen demand, and organics. Nonpoint pollution is often difficult to measure and does not lend itself to a straightforward control action. This kind of pollution is greatly influenced by the characteristics and locations of different land uses as well as their relationship with each other. For this reason, it is essential to recognize the interrelationship among existing and future land uses and their environmental consequences in order to recognize the impacts of nonpoint source pollution. Lynard et al. (1980) have suggested that land use planning should play an important role and perhaps should be used as the first step in controlling nonpoint pollution during development. In this regard, land capability/suitability analysis can play an important role in controlling nonpoint pollution as it is the method commonly used in land use planning. Yet this method at present lacks the ability to project environmental impacts and has no links to existing environmental models.

The proposed methodology is intended to be used for formulating preliminary land use alternatives before designing a plan with more detailed and expensive methods of analysis. It is hoped that the proposed approach will allow better decisions to be made regarding future environmental control (in this case nonpoint pollution control). Although the environmental focus will be on nonpoint pollution, the proposed methodology is applicable to any other form of pollution whose impact can be modeled analytically over space. It is also hoped that this approach will help increase the capability and utility of existing geographic information systems.

Before the objectives and problems described above can be considered in depth, an extensive literature review of research related to those objectives and problems is presented in the next chapter. These include the literature on land capability/suitability analysis, geographic information systems, land use allocation models, and urban non-point source water pollution.

In chapter three, the conceptual background and the solution strategy for linking land capability/suitability analysis with environmental models using geographic information systems are explained.
In chapter four, the results of implementing the proposed methodology on a test site and on the study area are examined. The environmental impacts of land use plans derived using the proposed methodology are compared to those produced by random generation methods, traditional land capability/suitability analysis method, and the convex combination method of nonlinear programming.

In the final chapter, the implication of the study, and the implementation strategy and future extension to the proposed methodology are discussed.
CHAPTER II
LITERATURE REVIEW OF RELATED RESEARCH

The present research is related to several research areas, namely land capability/suitability analysis, geographic information systems, land use allocation, and urban nonpoint water pollution. Thus, to accommodate this research, literature on these areas are reviewed in this chapter. The first section reviews literature on land capability/suitability analysis, followed by a brief review on geographic information systems. Next a review of several representative land use allocation models is presented. The last section provides a review on urban nonpoint source pollution.

2.1 REVIEW ON LAND CAPABILITY/SUITABILITY ANALYSIS.

The literature on land capability/suitability analysis is sparse. There is no doubt that land capability analysis may have been in use since humans first searched for suitable sites for various activities (Burneson, 1988). However, many of the works that have been done have not been published, or even if published no explicit mention was made on the method used (Gordon, 1985). There was relatively little work done in the subject that could be said to have a definite methodology (Lyle & Stutz, 1983). For instance, there is evidence that ecologically-based planning methods already existed during the latter part of the last century, an indication that there is "a respect of available natural resources accompanied by much concern for the quality of the environment" (Naveh & Lieberman, 1984).

Historical Development of Land Capability/Suitability Analysis

Land capability analysis has undergone considerable evolution, redefinition, and development since the turn of this century. Trowbridge (1979) indicates that trial-and-error techniques were among the early clearly identifiable regional methods of the 20th century. In these methods, planning decisions were made partially from common sense and experience as well as through a series of related actions and reactions. It was difficult to specifically relate two complex series of decisions because these approaches were nonreproducible. It was also difficult to arrive at agreement about the existence of the same
environmental qualities in a particular region because of partial or biased observations and the coloring of human judgements by an individual's experiences (Naveh & Lieberman, 1984). As planning decision-making at the regional level became more complex, the need for a more comprehensive land use approach increased. As a result hand-drawn overlay methods were introduced to address this problem. These methods are widely known today, and their histories have been traced by Steinitz et. al (1976) and Zube (1986), and are summarized below.

The earliest evidence of the use of data overlays as an analysis technique was found in a study done by Warren Manning in 1912 for the town Billerica, 22 miles northwest of Boston (Steinitz et. al, 1976). Manning used soil and vegetation information together with topography, and their combined relationship to land use to prepare at least 4 different data maps of the town and one plan showing recommendations and changes in the town's circulation routes and land use pattern. After Manning, there were indications that the overlay technique was applied in several studies (e.g. the City Plan for Dusseldorf in 1912, and The Doncaster Regional Planning Scheme in 1922). No notable advances in the technique were realized until the development of the sieve mapping technique in England (Lyle and Stutz, 1983). The sieve mapping technique was first described by Jacqueline Tyrwitt (1950). This survey probably provides the first explicit discussion of the "overlay technique" (Steinitz et al., 1976). According to Tyrwitt, all maps are drawn on transparent papers to the same scale, and referenced to common control features. Maps are combined and analyzed into one map which defines land areas that, for various reasons, should not be developed. This technique was widely used in the large-scale planning of the British new towns and other development projects after World War II (Lyle and Stutz, 1983).

During the 1950s there was again little development in the overlay technique for land planning and design purposes. This trend was then changed considerably in the 1960s, where many more examples of using overlay analysis techniques were later observed. In 1961, G. Angus Hills, a Canadian forester developed a plan for Ontario Province, which is an early North American example of employing a more sophisticated data overlay technique (Naveh and Lieberman, 1984). Beginning in the 1940s, Hills was concerned with ecologically-oriented planning for forestry, fish, wildlife, and recreational land management (Steinitz et al., 1969). He developed an approach to a land classification system which is based on physiographic characteristics. In Hills' technique, regions are
broken down hierarchically into consecutively smaller units of physiographic differentiation based on a gradient scale of climate (macro and micro) and landform features (e.g. landform, soil and geology). The smallest unit and first phase of classification is the physiographic site type, which is then compared to a predetermined set of general land use categories to determine its potential use (Harvard University, 1967). The potential uses are ranked at two levels: local and community. At the local level, i.e. the second phase of the system, the land units are "ranked on a scale of values corresponding to the degree of potential or limitation for each use or activity" (Harvard University, 1967). The ranking is based on the highest intensity and quality of use that can be accommodated without deteriorating the site. This ranking also indicates the capability class of each unit. Based upon this capability classification, these units are then regrouped into larger geographic areas called landscape units. The resulting units are again ranked to determine their relative potentials for dominant and multiple uses.

Philip Lewis, a landscape architect at the University of Wisconsin-Madison, is another individual who was active in land use and resource analysis using the land overlay analysis technique (Gordon, 1985). All these factors are mapped on transparent overlays and combined to produce a composite map that reflects the major patterns of land suitable for a particular purpose. Lewis assigned points to those areas that possessed the resources necessary for a particular use reflecting the values of those resources. These points were then totalled depicting areas of prime environmental importance.

Further advancement in the overlay technique is the ecological inventory process of Ian McHarg, a landscape architect and planner from the University of Pennsylvania. McHarg's approach requires the gathering of information on the basic natural as well as man-made attributes of the study area (Gordon, 1985). Each element of the area is mapped and photographed as a transparent overlay. Each land area is then ranked relative to its suitability for one or more land uses. The rankings are given on a scale of 1 to 7, and are represented on overlay maps where the lightest shading or color indicates the most suitable ranking for that resource for the particular land use under consideration and the darkest shades indicate the most suitable locations. The overlays are then combined to obtain the overall rankings, showing those areas with the most suitable conditions.
The hand-drawn overlay method has limitations too. It has been frequently criticized for the practical difficulties of superimposing a large number of maps, or also known as the "blob" problem (Gordon, 1985). It is also difficult to update/revise the maps for other analyses using different criteria. These problems have been greatly eliminated by recent methods as well as with the introduction of computer-assisted planning methods such as the geographic information system (GIS) to be discussed in later sections.

Existing Land Capability/Suitability Analysis Methods

Land capability/suitability analysis has been used since early in the 20th century. It has since then undergone considerable evolution, redefinition, and development. At the present time, there exists a wide variety of land capability/suitability analysis techniques. McAllister (1980) classifies these techniques into 2 groups: qualitative and quantitative. According to McAllister (1980), the qualitative approach classifies "land into ecological types to which land use principles are applied determining suitability", while the quantitative approach uses the conventional method of assigning ratings and calculating a grand index of land suitability.

Hopkins (1977), in his comprehensive review of land capability/suitability analysis techniques, on the other hand, divides these techniques into 2 broad classifications: gestalt and combination. The gestalt techniques are generally the earliest versions of land capability/suitability analysis. The combination techniques, which reflect the evolution of more sophisticated techniques, are further broken down into categories which includes: mathematical combinations (ordinal, ordinal with ordinal indices, linear, and nonlinear), the explicit identification of region (factor combinations and cluster analysis), and logical combinations (rules of combination and hierarchical combination). Chapin and Kaiser (1979) identify land capability/suitability analysis techniques based upon Hopkins’s classification. In contrast to gestalt methods, Chapin and Kaiser (1979) identify the simplest suitability analysis as the one based on single environmental characteristics such as the detailed soil classifications.

A more recent review of land capability/suitability analysis techniques is given by Anderson (1987). He reviews seven techniques: pass/fail screening method, penalty point assignment method, graduated screening, weighted factors, composite rating, direct assignment, and weighted composite rating method. All of these techniques can actually fall
under the combination methods of Hopkins' classification, although they were given different names by the author. For reasons of simplicity, the review of land capability/suitability analysis techniques that will follow will be largely based upon Hopkins' broad classification systems and his elucidating review.

**Gestalt methods**

The gestalt method views a region or site as a whole whose properties and reactions to development cannot be derived through consideration of its individual characteristics. The basic principle of this method is that the analyst divides the region into homogeneous areas by analyzing the internal relationship of the whole region directly through field observation, implicitly using clues such as topography, vegetation and substrate to establish distinct units. It is not possible to combine the individual factors (e.g. topography, soil, vegetation, etc.). This method has also been known as the landscape or "holistic" approach (Westman, 1985) to land capability/suitability analysis. This method can be described in 3 steps (Hopkins, 1977). The study area is first partitioned into homogeneous regions based on implicit judgement. Then a table is developed that verbally describes the effects or problems that will occur in each of the areas if each of the potential land uses is located there. The third step is to draw a set of maps, one for each land use, that show the homogeneous regions in terms of their suitability.

Several of the earlier land capability/suitability studies may have used the gestalt method. These include the works of Warren Manning, Angus Hills, Philip Lewis, and Abercrombie and Johnson. The works of the first 3 authors have been reviewed in the previous section, and will not be repeated here. Abercrombie and Johnson (1922) used this method in a study involving the mapping of circulation patterns, accessibility, and topographic areas such as "lowlands". Abercrombie and Johnson then synthesized this information by some technique, possibly map overlay, and recommended the general land use and circulation patterns. The map overlays did not produce direct suitability results. Instead they facilitated the mental synthesis and analysis of relationships typical of the gestalt method (Steinitz, Parker, and Jordan, 1976).

The gestalt method is relatively simple since it is based on direct observation and does not require the consideration of individual factors such as slope, soils, vegetation, etc. It views the site as a whole, thus has the capability to handle interdependence among
factors. The method however suffers from the implicit, hence subjective, nature of judgements regarding land homogeneity and suitability (Westman, 1985). It requires the planner to have longstanding local experience. Since it views a region as a whole without identification of individual factors, it is difficult for others to scrutinize or confirm the land suitabilities generated using this method. It may also be difficult for the planner to convince others or decision makers of the validity of suitability results (Hopkins, 1977). Due to these limitations and the frequent necessity to present and communicate results from planning analysis to other professionals and the general public, it was necessary to devise more explicit methods of combining factors in order to discover land suitabilities. The combination methods presented in the next section were derived in response to this need.

**Combination Methods**

The combination methods, which are parametric in nature, reflect the evolution of more sophisticated techniques. In these methods, individual landscape/environmental parameters or attributes are separately mapped and rated for suitability, which are then combined into a grand (composite) index of suitability (Westman, 1985). The basic assumption is that these methods yield valid suitability ratings because of the properties of the methods (Hopkins, 1977). The methods can be further broken down into 3 categories which include: mathematical combinations (nominal, ordinal, ordinal with ordinal indices, linear, and nonlinear), the explicit identification of region (factor combinations and cluster analysis), and logical combinations (rules of combination and hierarchical combination).

**Mathematical combination methods**

The premise of the mathematical combination methods is that they allow the use of the four different scale of measurement (nominal, ordinal, ratio, and interval), thus the generation of land suitability maps by mathematical operations. They simultaneously identify homogeneous regions and determine suitability ratings. There are basically 4 general methods of generating suitability maps by mathematical operations. These include the nominal, ordinal, ordinal with ordinal indices, linear, and nonlinear combination methods.
Nominal/binary mathematical combination method

These methods are based on a binary classification of factors in a form like "suitable or unsuitable", "good or bad", or "pass or fail" (Cornwell and Rohardt, 1983). This classification reflects only qualitative, not quantitative differences between mutually different levels of suitability. The sieve techniques (Tyrwitt, 1950), and pass/fail procedures (Anderson, 1987) fall under this category. For each factor, criteria are established to identify the minimum acceptable ratings which serve as cut-off points (Anderson, 1987). All sites with a rating below the minimum acceptable rating fail or are unsuitable, while all sites with a rating at or above the minimum rating pass or are suitable for that particular use.

The final suitability depends on the combination of all the factors. If an area meets all the criteria, it is given a score of pass (suitable), but if it fails to meet any of the criteria, it is considered as failing or unsuitable for a particular land use. This method can easily be implemented using graphic (map) analysis or with mathematical computations (Anderson, 1987). Graphically, each of the factors can be mapped on a mylar and marked with solid colors or shades. The land areas that fail to meet the minimum criteria are masked out, while those areas that meet or exceed the criteria are left unmasked so that the map is still visible through the overlay. The final suitabilities are then determined when the overlays of all factors have been completed. All those areas that meet all of the rating criteria will remain visible, thus are considered as suitable for that particular use. On the other hand, all those areas that fail any of the criteria will be masked out and are considered unsuitable.

Mathematically, this method can be easily used by assigning 1 and 0 to those areas that pass and fail to meet the criteria respectively. The final suitability is obtained by multiplying all maps (layers) together. The areas that meet all the criteria will have a value of 1 in the final map. This procedure can be easily implemented in and is suitable for analysis using a computerized geographic information system.

This technique is easy to understand and can usually be carried out rather quickly either graphically or mathematically (Anderson, 1987). It is useful in screening out land areas that should not be given any further consideration, before a more sophisticated

---

1. These methods are not part of the Hopkin's classification.
analysis is made of the study area. The basic limitation of this technique is that all factors are given equal importance (Anderson, 1987). This might not be necessarily true in real world applications, where the degree of importance does vary among factors, depending on the intended uses. Similarly, this technique generally oversimplifies real-world variations in suitability (Cornwell and Rohardt, 1983). In addition, the technique is unable to handle and examine the interrelationship among the factors being considered. Another limitation of this technique is the possible subjectivity involved in setting the minimum acceptable rating.

Ordinal mathematical combination method

The basic concept of this method is the use of ordinal ratings that are assigned to different categories (types) of land characteristics (e.g. soil, vegetation, slope, etc.) that reflect their relative suitability for a particular land use. These ratings can be assigned either using shades of grey level (graphically) or numerical indices (mathematically). Graphically, the lightest shade is used to indicate those areas with few (or no) limitations while the darkest shade (or black) is used for areas with serious limitations. Numerically, similar ratings are represented as numerical indices, such as on a 1 to 5 scale, where 1 and 5 are equivalent to the lightest and darkest shades respectively.

The general procedures for this method involve 4 major steps (Hopkins, 1977). The first step is to map the locational pattern of different types (slope classes, soil types, etc.) for each of a set of land characteristics (e.g. slope, soil, vegetation, etc.). The second step is to assign, by informed judgement, a rating that shows the relative suitability of each category of each factor for each land use for which suitability is being estimated. The rating is expressed as degree of gray shades or cross-hatching. Based upon the rating established in step 2, the third step involves making a suitability map for each land use. Every type on each factor map is assigned the appropriate gray level corresponding to its suitability for a particular land use. The final step is to overlay the individual factor suitability maps to create a composite suitability map of varying shades of gray, one map for each land use under consideration. Theoretically, all those areas that have few limitations in all factors will be lighter in shade, while those areas having most limitation will be darkest. Numerically, the equivalent technique is represented as ordinal numerical suitability ratings

---

2. This method is referred to as the "Graduated Screening Procedure" by Anderson (1987a & 1987b).
instead of gray levels. The composite suitability maps are then determined by adding (or other valid mathematical operations) the individual suitability maps.

An excellent example of this method is the works of Ian McHarg in the late 1960s and early 1970s. Perhaps this method is more commonly referred to as McHarg's method (Hopkins, 1977). Two of the McHarg's studies are the Richmond Parkway study in the 1960s and the Staten Island Study in 1970s. In the later study, McHarg maps variables such as bedrock, geology, hydrology, existing vegetation and tidal inundation in light and dark tones representing suitabilities for various land uses. These maps were superimposed over each other to create the necessary composite suitability maps for conservation, urbanization and recreation. These composite suitability maps were further combined to produce an overall composite map. This final map is displayed graphically in 4 different colors and 8 different tones within each color. Interpretation of each color and tone rely on individual judgement more than on any straightforward objective analysis (Burneson, 1988). This technique has also been used by Hobbs (1974) in a study to determine the least cost corridor for ANZA Road in San Diego County (California).

Examples of studies using the ordinal combination with numerical indices include those reported by Barnett et. al (1986), and Burneson (1988). Barnett et. al (1986) used this technique to choose potential sites for sanitary landfills for a number of counties in Kentucky. The state's Natural Resources Information System (KNRIS) was used for this study.

The ordinal combination method is simple and easy to understand (Anderson, 1987). The process can be completed using either graphic (map) or numerical techniques. However, both techniques suffer from several limitations. First, both techniques assume that the ratings of each characteristic are on the same scale and may be added like any numbers. This addition is not a valid mathematical operation since the ratings are in ordinal scale, where the ordinary mathematical properties do not hold (Hopkins, 1977). To be valid, the ratings must be in interval scale. The second limitation is that the techniques implicitly assume that the ratings of each factor are independent and can simply be added (Hopkins, 1977). In reality, many of the factors may not only be dependent but also interdependent and multiplicative in interrelation (Westman, 1985). The suitability may be a nonlinear and nonseparable function of the combination of types. Thus, adding the factors
together is inappropriate both because of the non-additivity of ordinal scale ratings and the interdependence of and characteristics contributing to suitability.

The techniques also assume that all factors are of equal importance (Anderson, 1987). This may also not be true in real world applications because some factors are usually of greater importance than others, depending on the land use (development) being considered. The graphical method also suffers from other problems. It is difficult to manually overlay more than 5 or 6 maps, thus limiting the numbers of factors that can be considered. This problem limits the use of this method only to small problems which fall short of more complex real world applications (Gordon, 1985).

**Linear mathematical combination method**

This method arose out of the recognition by analysts of the limitations of the ordinal combination method. To deal with this problem, the ordinal scale can be converted to a common interval scale by transforming the ordinal scale so that the intervals on each factor are equal to those other factors (Westman, 1985). This transformation can be done by expressing the ratings values for each factor to a range of interval scale that is common for all factors (Westman, 1985; Hopkins, 1977). This transformation will make all factors equally influential in determining the resultant variation in suitability among land units. Thus, the operations of addition and multiplication can be applied validly. Then a weight of interval scale is assigned to each factor and multiplied by the ratings of each type to obtain the composite rating. The effect of this multiplication implicitly transform the unit of measure of the ordinal numerical indices on each factor by the ratio of the multipliers so that all of the ratings are put on the same interval scale.

The basic procedures for this method usually involves 4 steps. The first step is similar to the ordinal combination method described above. Step 2 involves rating each type of each factor on an interval scale and assigning a weight to each factor. If all factors are measured on a common scale and range, there is no need to make any transformation. On the other hand, if each factor is originally rated on its separate and different scale, it is necessary to convert the rating values to a range common to all factors. One way to convert these ratings is to divide the rating of each type to the maximum rating of each factor, i.e.:

---
3. This method is referred to as the "Weighted Factors Procedure" by Anderson (1987a & 1987b).
\[ r_{ijk}'' = \frac{r_{ijk}}{r_{k\text{max}}} \]  

where:

- \( r_{ijk}'' \) - the transformed rating of kth factor for the jth category of the ith land unit;
- \( r_{ijk} \) - the original rating of kth factor for the jth category of the ith land unit;
- \( r_{k\text{max}} \) - the maximum rating for any rating of factor \( k \).

Some authors have also attempted to transform these ratings into other common cardinal units such as the dollar value (e.g. Laird, et al. (1979); Roberts et. al 1979; Fabos, et al. (1977)).

The third step is to map the relative suitability of each factor for each land use. This is accomplished by multiplying the rating of each category of each factor by the assigned factor weight. The final step is to add together the individual suitability maps to form the composite suitability map for each land use. Mathematically, this can be represented as:

\[ C_{ij} = \sum_{k=1}^{N} w_k \cdot r_{ijk} \]  

where:

- \( C_{ij} \) - the composite suitability rating of jth category for ith unit;
- \( w_k \) - the weight of factor \( k \);
- \( r_{ijk} \) - as defined above (it should be \( r_{ijk}'' \) in case of transformed rating);
- \( N \) - number of factors \( k \).

The composite rating may also be normalized by dividing the rating by the total weight of all the factors, thus giving a rating that falls within the original data range. Another approach to computing and normalizing the final suitability rating was developed by Roberts et. al (1979). In this approach, the final rating for each land use is the weighted root mean square of the ratings of all environmental variables. For each proposed land use, the rating for each variable is first squared, and then multiplied by a user-defined coefficient (weight) for that variable. All of the products are added together and divided by the sum of the weights. The final suitability rating is then the square of that quotient (Roberts et. al
The root mean square is used as an averaging device which emphasizes the larger values in the set to be averaged at the expense of the smaller values. The reasoning for this approach is that "values of environmental variables that have negative implications for suitability often exercise their effects in a manner out of proportion to their apparent arithmetic significance" (Roberts et al., 1979, p. 348). Thus, using the root mean square will make those variables with high ratings much greater in importance than those with lower ratings.

This method is the most commonly used among the many land capability/suitability analysis methods, especially with the recent advent of computer tools such as geographic information systems. It has been used in the study for Palo Alto (California) by Livingston and Blavey (Ortolano, 1984), the studies by Lyle and von Woodtke (1974), Hartsook (1973), Steinitz and Rogers (1974), Gordon (1978), Lane and McDonald (1983), Buckley and Hendrix (1986), Hammond and Walker (1984), Fabos et al. (1977), Williams, et al. (1983), Gordon and Gordon (1981), Roberts, et al. (1979), Hollenbaugh (1987), and Tomlin and Johnston (1988). In the Palo Alto study, land capability/suitability analysis was performed to assess the impacts of alternative land use patterns. In that study, the area was divided into a rectangular grid consisting of 330 cells of 20 acres each. Land capability/suitability was based upon the analysis of 25 factors. Each factor was rated on a 5 point rating scale where 5 represents the greatest suitability for a particular development. Weights were assigned to each of the factors reflecting its importance in land development. For example, soil erosion potential was judged to be 6 times more important than the proximity to present development, and 3 times as important as air pollution. The final step in the analysis was to compute total suitability scores for each grid cell. The relative suitability of cells for each land use were determined by dividing the resulting ratings into classes that have approximately equal numbers of cells in each class. The results were used to examine various scenarios of future land use development patterns.

The strengths of the linear combination technique are that it corrects the measurement problem of the ordinal combination method, and allows the assignment of individual weights for each factor that reflect its relative importance for the development under consideration. The latter is important because in real world applications, the importance of factors in an analysis vary with the kind and geographic location of the development being considered. For example, time distance from freeway interchange is
very important to commercial and industrial development, but less so for low-density residential development. Thus, the use of a weighting system provides a means of making tradeoff decisions among various factors affecting suitability (Williams, et al., 1983, p.103).

Though it is claimed that this technique has no measurement problem as in the ordinal combination technique, Dobson (1979), and Alexander and Manheim (1962, p. 93) caution that this may not be true. The ordinal numbers from which the interval ratings were derived may not be linear and thus may not be transformed by simple multiplication, division, addition, or subtraction. It also relies on an unacceptable assumption about the comparability of rating scales among different factors (Alexander and Manheim, 1962 - pp. 90). Some of the factors are interdependent, which this method also fails to take into account, thus cannot be transformed separately. This problem is complex, and no systematic technique to transform these different rating scales into a common one has yet been developed. However, Alexander and Manheim (1962) have proposed the use of a hierarchical (tree-like) procedure as one way to deal with this problem, which will be described further in a later section.

The linear combination method, as suggested by Hopkins (1977), cannot deal with the situation where the relative suitability for a given land use of a type of one factor depends on the type of any other factors. For this reason, Hopkins (1977) warns that "the linear combination method cannot be applied appropriately across the board to all combinations of factors". This problem is analogous to the problem of non-additivity and interdependence of land characteristic of the ordinal methods as described in the preceding sub-section. Thus, adding the factors together may not be a valid assumption since it may result in "double counting" (Westman, 1985). There also remain problems of subjectivity with the selection of weights, and division of composite suitability ratings into various suitability classes. Weights for each factor are commonly selected arbitrarily by the analyst without any well defined procedures. The process can easily be manipulated by the analyst such that the weights chosen may reflect his preferences or biases.

The problem dealing with the classification of the composite ratings into different classes may be less severe than the selection of weights. To date, various data classification techniques do exist that can help the analyst classify the composite ratings. The only
problem then is to select which classification techniques are to be used, since different techniques will produce different progression in the suitabilities. Cornwell and Rohardt (1983) present an interesting study on the effects of classification and measurement scale on the progression (differentiation) of suitability levels. They use 3 different scales: ordinal/interval, ratio, and pseudo-log. In the ordinal/interval scale, all ascending levels of suitability from least to most suitable increase by equal numerical intervals. In the ratio and pseudo-log scales, the progression of suitability is expressed as a constant ratio of difference between successive suitability levels and the log of number in the interval scale respectively. In a study for the government of Nigeria to locate manufacturing facilities based upon 17 variables, they found that the nominal/interval scale yields the least differentiation in the range of suitability levels. The pseudo-log scale, on the other hand, offers only slightly greater differentiation, while the ratio scale offers far greater differentiation than the two other scales. As a result, the ratio scale produces the greatest resolution in the high end of the range in suitability. In contrast, the pseudo-log scale causes greater aggregation on this end, thus is more appropriate in analysis to highlight the unsuitable areas (Cornwell and Gohardt, 1983).

Nonlinear mathematical combination method

This method is similar to the linear combination method except that interdependence among factors is taken into account. Hopkins (1977) notes that if the appropriate relationships among factors are known and can be expressed as mathematical functions, then the ratings of types for all factors can be plugged into the nonlinear functions and suitability results are obtained analytically. Most of the nonlinear functions are usually used to generate suitabilities regarding generation of impacts such as soil loss and runoff, rather than suitabilities for land uses. Recently, Anderson (1987) suggested that this method can be used to calculate land capability/suitability. There are 2 possible ways of doing this. The first one is what Anderson (1987) called a "composite rating procedure", which can be considered as non-weighted nonlinear method. The suitability of any land unit is calculated simply by multiplying the ratings of each factor together, which can be expressed mathematically as:

\[ S_i = r_1 \times r_2 \times r_3 \times r_4 \ldots \ldots \times r_n \]  \hspace{1cm} (3)

4. This method is referred to as the "Composite Rating Procedure" by Anderson (1987a & 1987b).
where

\[ S_i = \text{suitability score for land unit } i; \]

\[ r_j = \text{rating of the } j \text{th factor for land unit;} \]

\[ n = \text{the number of factors used in the study.} \]

Anderson (1987) also developed another nonlinear combination method for land use suitability analysis which he called "weighted composite rating procedure". This procedure is similar to the composite rating procedure with the distinction that the relative importance of each factor is weighted. By assigning factor i a weight \( W_i \), this procedure can be mathematically expressed as:

\[
S_i = (r_1 \times W_1) \times (r_2 \times W_2) \times \ldots (r_n \times W_n).
\]

(4)

This method is supposedly capable of overcoming the problem of interdependence among factors, however only a few studies have attempted to use this method. These include studies reported by Fabos, et al. (1977), Svatos (1979), and Warren et al. (1989). Though Anderson (1987) has suggested two mathematical formulas to compute land capabilities, he provides no justification nor examples of their uses.

Warren et al. (1989) used the Universal Soil Loss Equation (USLE) to estimate soil loss and to create a land classification for use by military trainers and land managers to minimize the environmental impacts of military training activities. They compared the estimated soil loss to the soil tolerance values to estimate the erosion status of each land unit. Lands with erosion status values of less than 90 percent are considered as lands with varying degrees of satisfactory soil erosion status, while lands with values greater than 110 percent are considered as areas with increasingly unsatisfactory conditions. Warner et al. (1989) also calculated the soil erodibility index (EI) of each land unit based upon the inherent erosion potential and the tolerance values. Areas with an erodibility index greater than 8 are considered highly erodible lands. The maps produced from the analysis are used to aid military trainers and land managers in scheduling the kinds and intensities of military training activities appropriate to their environmental impacts.
The major strength of this method is that it does consider the interrelationship among factors being considered (Hopkins, 1977 and Anderson, 1987). Anderson (1987) also indicates that the way this method works is easy to understand. It is probably less subjective and arbitrary once the functional relationship among the factors are found. This method can also quickly weed out land units that have a low rating for any factor.

Though this method overcomes the problem of interdependence among factors, it is not likely to be possible because the interaction between factors are rarely sufficiently understood or simple enough to be confidently represented by mathematical functions (Chapin and Kaiser, 1979 and Hopkins, 1977). Furthermore, most nonlinear equations that are widely used to generate suitability are based upon the generation of impacts (e.g. runoff, soil erosion, etc.), which constitute only a few factors that are required for an overall land capability/suitability analysis (Chapin and Kaiser, 1979). The main and most serious drawback of this method is that the results produced are very difficult to interpret without extensive experience.

Explicit Identification of Regions

The explicit identification of homogeneous regions is another approach of handling the problem of interdependence among factors. By explicitly identifying the homogeneous regions, it is possible to make implicit judgements about the suitability ratings of those regions as a whole. Factor combination and numerical taxonomy techniques are 2 groups of methods that fall under this category.

Factor combination method

This method is a modification of the gestalt method. In this method, all types of all factors are combined in an overlay process to obtain a composite map of regions that are homogeneous with respect to all factors (Hopkins, 1977). Then, each combination of factors and types are rated (through implicit judgements) for its suitability, consciously taking into account the relationship between factors. These composite suitability ratings are made without assigning suitability ratings to the individual types, or without attempting to weigh or add the ratings together.

5. This method is referred to as the "Direct Assignment Procedure" by Anderson (1987a & 1987b).
An example of the use of this method is Ian McHarg's study of the Valleys in the Baltimore, Maryland region (McHarg, 1971). McHarg used 2 factors, i.e. forest cover and topography, to generate 5 factor combination: valley floor, unforested valley walls, forested valley walls, forested plateau, and unforested plateau. McHarg (1971) then prescribed the management principles or verbal description of the types and intensity of development which should be permitted.

The factor combination method requires that the interdependence among factors be taken into account. If properly done, it will probably produce a more valid result than will any of the methods described earlier. However, this method has several shortcomings. First, like the gestalt method, "the ratings of regions in terms of suitability relies entirely on implicit judgement for the transformation of the types in the combination into a rating for the combination as a whole" (Hopkins, 1977). As a result, it will be very difficult to convince and communicate the results to decision makers. It is impossible for an outside observer to replicate the many decisions required in the analysis, unless voluminous documentation exists (Anderson, 1987). This method is suitable only for studies involving a few factors because, as the number of factors becomes large, it is infeasible to determine the suitability ratings for each combination (Chapin and Kaiser, 1979; Westman, 1985). The greater the number of factors and the types in each factor, the greater will be the number of unique combinations. Thus, the potential number of combinations becomes enormous, i.e. equal to the number of types per factor raised to the power of the number of factors. For example, if there are ten (10) factors that have to be considered, and each factor has 5 types, then are potentially 100,000 different combinations that would have to be rated. Though not all of these combinations may be necessary in any particular application, the example presented does illustrate the nature of the problem. This method also requires the analyst(s) to have a very thorough knowledge of all the factors being considered and the interrelationship among them (Anderson, 1987).

**Numerical Taxonomy Techniques.**

Numerical taxonomy techniques are a group of multivariate statistical techniques that are used to classify individuals in a large data set into a manageable number of

---

6. This is an extension of Hopkin's classification. In his review, Hopkins (1977) only described cluster analysis. But other numerical taxonomy techniques such as factor analysis or discriminant analysis have also been used in land capability studies.
classes/groups. Thus, these methods provide a possible remedy for the combination problem of the factor combination method described above. Examples of these techniques include factor analysis, cluster analysis, and discriminant analysis. Many of these techniques were originally used in biological classification. Classification of objects into different groups is based upon their similarities with respect to selected characteristics rather than their differences (Gordon, 1985; Omi et. al, 1979).

The general concept of numerical taxonomy can be applied to land capability/suitability analysis since this analysis involves a classification of land units into different capability/suitability groups (Gordon, 1985). For a given group of land units with a set of attributes, these techniques successively calculate a measure of similarity among all the land units and then link them together to form homogeneous groups as measured against a numerical criterion (Gordon, 1985; Hopkins, 1977). The resulting set of groups have mean values which may then be transformed into some aggregate rating by implicit judgement. These methods have an important characteristic that homogeneous regions are identified based on objective measurements of natural characteristics rather than by the analyst's judgement (Burneson, 1988).

Several researchers have experimented with these techniques in their land capability/suitability studies. These include Sharpe and Williams (1972), Gordon (1978), Rowe and Sheard (1981), Omi et al. (1979), Jenkins, et al. (1981), and Burneson (1988).

A study for Louisville Airport (Kentucky) by Sharpe and Williams (1972) provides an example of using this method for land capability/suitability analysis. They performed the cluster analysis across 13 hazard and resource factors on 1350 cells of 35 acres each. The 1350 cells were reduced to 25 clusters, each with its own distinct characteristics relating to development. By examining the mean and standard deviation for each factor of each cluster, Sharpe and William (1972) make recommendations on the types and intensity of development for each cluster of sites.

The numerical taxonomy approach has several potential advantages for land capability/suitability analysis including (Gordon, 1985; Hopkins, 1977, Sharpe and William, 1972): (1). assumptions concerning the final classification or grouping need not be made a priori; (2). the methods help to generalize a large, complex, numerical data set in
an explicit and objective way; (3) the methods are able to handle large amounts of numerical data, thus minimizing the loss of information; (4) the results are replicable when the same statistical technique and input data are used; and (5) the methods derive explicit quantitative measures of the interrelationships among the input variables. However the methods have several limitations. The use of such methods requires significant cost of computation (Hopkins, 1977). The results also require careful interpretation and implicit (subjective) judgement since it is not possible to use such results in actual scoring (Stutz and Lyle, 1983).

**Logical Combination Methods**

Unlike the methods previously described, the logical combination methods are based on verbal descriptions of principles or rules for combining factors (Burneson, 1988). These rules/principles are derived from an understanding of the underlying natural system being described rather than on a single set of relationship repeated for all combination requirements of the specific types and factors under consideration (Diamond and Wright, 1988). For this reason, it is not necessary to evaluate every combination individually or to express relationships among factors mathematically. The two types of logical combination methods are the rules of combination, and the hierarchical combination methods, and they are reviewed below.

**Rules of combination**

This method is a merging of the nonlinear combination and factor-combination methods (Chapin and Kaiser, 1979). The rules are generally policy statements or general values on the importance of each factor. The logic behind this method is that the more important factors will override the ratings of all other factors. Under this method, different land units having similar landscape/environmental attribute levels will be given the same suitability rating. Like other methods, it begins by mapping categories of individual factors first.

Examples of the rules of combination method are provided by Keifer (1965), Imgrime and Patri (1971), Fabos et al. (1977), and Butler et al. (1977).

The rules of combination method determines suitabilities more explicitly than many other methods. The rules are usually explicit, thus can easily be understood and scrutinized
by others. If properly devised, such rules can also take interdependence of factors into account (Chapin and Kaiser, 1979). Furthermore, this method also does not require the use of numerical ratings, thus avoiding the difficulty of converting verbal (symbolic)/qualitative ratings (e.g. poor, fair, good, slight, severe, etc.) into numerical ratings as required in most of the methods described earlier. One obvious example of this nature is the difficulty in converting information from soil survey (which is usually represented as verbal ratings such slight, moderate, and severe) into numerical ratings.

Due to its nature, this method is suitable and can be applied to construct composite suitability maps without having to deal with each possible combination separately (Hopkins, 1977), i.e. for solving problems involving principles/rules derived from non-formal procedures such as rules-of-thumbs, personal judgement, intuition, or personal experiences. However, rules for combining some factors may sometimes not be so obvious especially in complex projects where the number of factors to be considered is large. The determination of which factors are more important than others is based upon implicit judgement, and is thus subjective. This may raise the question of who determines the validity of the result, and how it is determined. It may also be difficult to handle complex rules manually. However, the recent advances in the field of computer science may solve this problem to a certain extent. The use of techniques from the field of artificial intelligence such as expert systems, rule-based language, and knowledge acquisition, may not only ease this problem but also allow further development in the method. Some of the recent developments in this direction have been reported by several researchers including Chandra and Goran (1986), Han and Kim (1987), Sun et al. (1986), and Lolonis and Armstrong (1988).

Hierarchical combination method

The basic concept of this method is that composite rating can be generated hierarchically. It evaluates and rates combinations of types from subsets of highly related (interdependent) factors. The combinations are further combined into higher order combinations and then given overall ratings.

An excellent example of the use of the hierarchical combination method is the study for a highway corridor by Alexander and Manheim in 1962 (Alexander and Manheim, 1962). Alexander and Manheim use 26 different factors (criteria) depicting the desirability
for highway location of each specific requirement of the highway study. They propose a formal "tree" (hierarchical) procedure for combining and weighing of factors. The implication of the tree structure is that "the designer starts with the groups of requirements at the lowest level of the tree, and then proceeds upwards, gradually considering each of the groups at higher levels" (Alexander and Manheim, 1962 - p. 28). The factors were first combined to produce smaller subset of maps representing overall suitability for that combination. These subsets were further combined to produce yet another smaller subset of maps, and the process continued until a final composite map was developed.

This method shares most of the strengths and problems of the rules of combination method described earlier. However, it has the advantage that fewer factor combinations ultimately need to be rated (Westman, 1985), and partly avoid the problem of non-comparability of rating scales in the linear combination methods described earlier (Alexander and Manheim, 1962).

Summary

This section has reviewed various methods of land capability/suitability analysis which generally fall into 2 broad categories: gestalt method, and combination methods. Each method has its own strengths and weaknesses. The progression and evolution from one method to another can in fact be associated with the search for a better method of doing land capability/suitability analysis. From this review, the weaknesses of the land capability/suitability analysis methods can be summarized as: subjectivity, inability to handle interdependence of factors, inability to explicitly determine homogeneous regions, the use of invalid mathematical operations, inability to explicitly determine ratings, the problem with determining classes of suitability, static and deterministic in nature, inability to predict environmental impacts and to link with existing environmental models, and the result does not constitute a land use plan. Since each method is unique, Hopkins (1977) suggested that the best approach is to use the methods in combination (i.e. hybrid) such as in hierarchical sequence of combinations. For instance, the simpler methods may be used in early stages of the analysis proceeding to the more complex in the later stages. McDonald and Brown (1986), and Buckley and Hendrix (1980) provide examples of studies employing this combined approach.
The recent advance in computerized geographic information systems (GIS) opens up new opportunities to automate the methods and helps eliminate some of the limitations. These systems permit large areas of geographical data on large geographic regions to be quickly and efficiently quantified, weighted, aggregated, stored, or presented in graphic form (Svatoss, 1979; Diamond and Wright, 1988). They allow planners to vary the weights associated with the attributes of particular variables (Gordon, 1985). The ability to overlay larger number of map layers (factors) eliminates the "blob" problem of the manual approach. Though this new development has been able to eliminate some of the limitations implicit to each method, many of the fundamental shortcomings of the methods as a whole still remain. These shortcomings include subjectivity, static and deterministic in nature, inability to predict environmental impacts and to link with existing environmental model, and the results does not constitute a land use plan.

The problem with subjectivity still remains even with the use of GIS. This is not surprising as Lyle and Stutz (1983) suggest that "given the present state of the art, suitability modeling involves a variety of factors far too complex to be described entirely by absolute values". Thus it is unlikely that the processes will soon be able to abandon the human judgmental factors. The use of GIS can however provide a convenient tool for dealing with relative numbers in a more systematic and orderly way. Similarly, though the problem of subjectivity may not be totally removed, a number of existing decision analysis techniques do exist such as the Delphi and pairwise comparison methods, that may potentially be used to reduce such problems (Lyle and Stutz, 1983).

Land capability/suitability analysis methods have been criticized as being static (Simpson, 1987; Simpson, 1988; Itami, 1988; McDonald and Brown, 1984). They do not incorporate interdependencies between land units in a temporal sense. This is partly because of their reliance on static mapping units. This inherently limits their ability to depict environmental changes once any development is in place. As a result, the analyst is only able to view a single frame of the environment's infinite complexity and dynamism (Simpson, 1987).

Another problem that is common to most methods is related to the assumptions underlying the approaches. They do not consider any cause and effect relationships among factors (factor interdependence), and between spatial units (spatial interdependence). This
is what Gordon (1985) called "ecological naivete". Often overlooked is the fact that there exist geographical associations among different ecological factors (variables). As Gordon (1985) states "geographical associations do not always imply the same ecological mechanisms of cause and effect". Interdependencies between spatial units may give rise to positive and negative relations between preferred uses (McDonald and Brown, 1984). Some uses are supportive of neighboring uses while others are in conflict. The former case may be as a result of economies of scales, or due to linkages between uses, while the latter case is primarily as a result of environmental effects. Furthermore, the "determination of suitability requires an understanding of effects of management practices and prescriptions on the quantity and quality of resource outputs" (Bailey, 1988). The understanding of these relationships requires sound knowledge of ecological processes. Information about the nature of the various combinations (integrations) of factors and related processes, and their variations from places is required in order to make predictions about ecological behavior (Bailey, 1988). Without this information and understanding, a very real possibility for unintended environmental impacts remains (Gordon, 1985). Though attempts to deal with factor interdependence are reasonably well developed, attempts to deal with spatial interdependence are still lacking (Westman, 1985). One approach to deal with the latter problem, which is becoming commonly used, is to define the study area based on a natural ecological boundary that is appropriate to the study of interest, such as watershed for a water pollution study, or "airshed" for air pollution study. Individual land units may also be combined into larger, ecologically homogenous areas using any of the numerical taxonomic techniques described earlier.

Land capability/suitability analysis methods have also been criticized for their missing links with environmental models (Gordon, 1985) and inability to predict environmental impacts (Canter, 1977; Chapin and Kaiser, 1979). Though various authors have attempted to use GIS for environmental modeling in recent years (e.g. Steinitz and Rogers, 1974; Fabos and Caswell, 1977; Berry and Sailor, 1987; Gilliland and Baxter-Potter, 1987; Kittleson and Kruska, 1987; Moreno and Seigel, 1988 - to mention a few), few (e.g. Steinitz and Rogers, 1974 and Fabos and Caswell, 1977) have attempted to link/integrate these models with land capability analysis, or to use them as the basis for land use allocation process. This is not surprising as many of the geographic information systems are still limited in scope and analytical capability (Gordon, 1985; Sen and Radlakrishna, 1988).
Environmental impacts/factors have been included in most previous land capability/suitability studies. However, the method does not explicitly predict impacts, rather they are implied by scientific data on land characteristics such as slope, hydrology, soils, geology, etc. (McAllister, 1980). It is also a common approach to use proximity as surrogate for environmental impacts. Though proximity between different land uses does influence environmental impacts, it only considers the interaction between land uses that are adjacent to each other, and not the combined interactions between different locations of land uses. It is these combined interactions that are important in environmental planning because of the cumulative nature of environmental impacts such as air pollution dispersion or surface water runoff. For example, the water quality at any watershed outlet is greatly influenced by the quality of surface water runoff from upland areas. Thus the suitability of a piece of land to accommodate a given land use is not only a function of the characteristics of the land itself but also its location in relation to other land uses (Fabos, 1981) as well as the overall pattern of the land uses.

Land capability/suitability analysis methods have been criticized for their many shortcomings, yet they are still commonly used by planners for various planning studies. This is not surprising, as noted by Simpson (1988), because they are the only practical methods available for such purposes, thus will remain to be used in the future. Though it may not be possible to eliminate many of the problems inherent to the methods, several improvements may still be introduced to their general methodology, so that they may be used more effectively for environmental planning purposes. One approach to go about some of the common problems described above is to integrate land capability/suitability analysis with land use activity allocation models and environmental models in a dynamic (interactive) manner (Fabos, 1985; Chapin and Kaiser, 1979). Such an integrated system would enable a planner to predict not only changes in the spatial pattern of land use activities but also the effects of these changes on the environment (Fabos and Gross, 1981; Gross, 1979). If the impacts are unacceptable, then the planner can change the policy attributes, or take several control measures, and repeat the whole process. If land capability/suitability analysis is to play a more important role in environmental planning, then there is a great need for such an integrated system, and more research efforts needs to be expended in this direction (Gordon, 1985).
Recent Development in Land Capability/Suitability Analysis

Several new developments have been made on land capability/suitability analysis in recent years. These include the works of Rogoff et al. (1980), Lyle and Stutz (1983), Anjomani (1984), Diamond and Wright (1988), and Tomlin and Johnston (1988).

Rogoff et al. (1980) developed a set of procedures to numerically rate soil potential for several urban land uses. Unlike the approaches reviewed earlier, they apply (introduce) different corrective measures to soils with severe limitations. By applying these measures, they found that the land suitable for these uses may be increased. The implications of this study is that land originally thought unsuitable for urban development may actually be suitable provided that certain corrective measures are applied to overcome such limitations. This raises the question of the possible impacts of new, innovative technologies upon the existing land capability/suitability analysis. This approach can also be extended to other factors such as slope, etc.

Lyle and Stutz (1983) propose a land suitability method that is defined by analyzing the interactions among three sets of factors: location, developmental actions, and environmental effects. This means that given certain developmental actions to be carried out and the specified environmental effects to be controlled, one can then find the most or least suitable location (sites) for those actions. This approach considers ecological factors as the fundamental determinants of land use patterns. The concept of the approach incorporates a close connection between land suitability analysis and environmental impact prediction.

The interaction describing the developmental actions is basically human activities occurring on the land which may bring changes to the environment. This can be divided into 2 categories: capital and operational. Capital actions are those that invest energy and natural resources in physical alterations and additions to the landscape. The developmental actions were listed and described in a series of charts or tables to provide simplified comparisons of environmental effects brought about by different methods of producing the developmental actions.

Information describing environmental effects is analyzed using a flow diagramming technique which is based on the symbolic language developed by Howard T. Odum for
tracing energy use. The interactions among factors are identified by means of a transformation key chart. This chart lists the developmental actions with which each transformation interacts. Lyle and Stutz (1983) have successfully used this approach in several real life projects such as the San Diego Coastal Plain project, and the Vandenberg Air Force Base project.

Land capability/suitability analysis has been criticized for not producing an optimal land use plan as its output. Anjomani (1984) and Diamond and Wright (1988) formulated their models as land use optimization models in an attempt to overcome this problem. Anjomani (1984) formulated his capability model as a linear assignment model based on the model developed by Koopmans and Beckman (1957). The objective function of the model is to minimize negative effects by maximizing the overall development suitability.

Diamond and Wright (1988) developed a decision support system that consists of three distinct decision making technologies: a geographic information system (GIS); a rule-based system (RBS); and a multiobjective programming model (MPM) that are linked together in the form of an integrated spatial information system (ISIS). The role of the GIS is to provide information to the decision models in the form of composite suitability maps depicting the relative suitability of any given parcel or region for achieving a particular objective. A separate suitability map is generated for each objective.

The suitability maps are generated based upon a combination of 3 methods: the linear, and nonlinear combination in conjunction with the rule of combination methods. The authors observed that the suitability-assessment process has 3 major characteristics: 1). The task of selecting meaningful ratings, weights, and methods of combination is too complicated and tedious to be done manually, 2). "Expert judgement and knowledge are common and necessary ingredients of the assessment process", and 3). "factor combination is often best achieved through the use of an explicit set of rules and verbal logic". The problems with these characteristics are resolved using rule-based expert systems (RBS), a computer program designed to use domain-specific knowledge gathered from human experts to perform problem-solving tasks in a manner similar to humans. In this case, the role of the RBS is to provide recommendations on the set of ratings, weights, and combination strategies to be used in the land capability/suitability analysis. This recommendation is derived from an interactive question and answer session with the user.
The resulting suitability maps serve as data for the multiobjective programming models, the third component of the ISIS.

The multiobjective programming models are used to define the geographic areas best suited for a single facility or land use. The model is based on the assumption that parcels of land are of the same size and shape, and arranged in a regular grid configuration, which is well suited for implementation in a grid-based GIS. The "best" site is identified by first finding an initial non-inferior solution. Depending upon the preference of the decision-maker, another noninferior solution can also be identified by improving the value of one objective at the expense of deteriorating the value of another objective. The procedure continues moving from one noninferior solution to another until a solution is found that is consistent with the preferences of the decision maker.

Tomlin and Johnston (1988) develop a dynamic modeling approach to land capability/suitability analysis and land use allocation using geographic information systems as part of the ORPHEUS project sponsored by Prime Computer Inc. The approach is in the form of a cartographic model, i.e. a series of map transformation proceeding from basic data and siting criteria to a general land use plan. The model is organized on a land-use-by-land-use basis, and comprised of 2 components: the descriptive component, and the prescriptive component. The purpose of the descriptive component is to describe the characteristics of different sites and situations in terms of their relative suitability for the location of a particular land use. The purpose of the prescriptive component is then to move from a description of locational suitability to a prescription of how best to achieve the land use allocation.

In order to describe the suitability for the location of each land use, the model makes an explicit distinction between two sets of criteria: the site criteria, and the situation criteria. Site criteria are "those that involve relationships between a proposed land use and the characteristics of the existing study area". Situation criteria, on the other hand, are "those that involve relationships between a proposed land use and the other proposed land uses".

The first step is to create the relative suitability map for each proposed land use. Unlike the site criteria, the situation criteria cannot be initially expressed in the form of
suitability maps because they involve relationships between proposed but not-yet-located land uses. This information is not available until the land use allocation decisions have been made. Initially, only the rules by which such maps should be constructed can be described. For each proposed land use, these rules are expressed in terms of the desired distance (minimum, maximum, or both) from any other proposed land use to which it has a strong relationship.

The next step is to transform the descriptive statements into prescriptive form. This process is analogous to mathematical optimization or the inversion of an algebraic equation in solving for an independent variable. This component of the cartographic model begins by allocating each proposed land use independently based solely on the site suitability map. Only areas with suitability ratings above some specified level are chosen as candidate sites. The land use plan derived at this stage constitutes an initial land use allocation, regarded as tentative, and is used to initiate an iterative process. Based upon this plan the distances to tentative land-use locations are calculated and are transformed into maps of proximity (minimum, maximum, or both) constraints according to the situation criteria already established for each land use. These maps are combined with the existing suitability maps to create new suitability maps that reflect the present site as well as situation concerns. Using these adjusted suitability maps, the land use allocation process is repeated in its entirety to generate a new set of tentative allocations. The process continues until the conflicts between different land uses are resolved. From each iteration, new information is available on the tentative but likely locations of the other proposed land uses, thus each land use is able to make a "more informed decision" about its own desired location. Furthermore, the iteration process allow the study team to intervene to adjust criteria and resolve conflicts when necessary. This approach has been successfully applied on a hypothetical program of land use allocation problem at a study area in Illinois for the siting of a research and development facility.

The approaches developed by Rogoff et al. (1980), Lyle and Stutz (1983), Anjomani (1984), Diamond and Wright (1988), and Tomlin and Johnston (1988) described above have obviously brought some new development to land capability/suitability analysis. However, the approach by Lyle and Stutz (1983) is static, and the results of the analysis are not linked to any land use allocation model. Though the approach of Diamond and Wright (1988) does incorporates land use allocation, it is still relatively static and does
not attempt to explicitly consider environmental impacts. The approach developed by Tomlin and Johnston (1988) does handle the static and land use allocation problems, but only implicitly considers environmental impacts (i.e. through proximity). This latter approach is unique and several improvements can still be made to it. One possible improvement is to integrate it with environmental models.

2.2 GEOGRAPHIC INFORMATION SYSTEMS

The main purpose of geographic information systems is to process spatial/geographic information. It can provide a framework to store, manage, manipulate, and display various spatial information in a more efficient manner. A GIS is capable of integrating spatially-oriented data from many sources into a location-specific data base. Fundamental to the understanding of a GIS are its functional components and its capabilities for modeling purposes, which will be further described in the next few subsections.

Functional Components of GIS

The functional components of GIS can be divided into 4 major groups (Marble, 1984; Guptill, 1989): data input/creation, data management/storage, data manipulation and analysis, and data display and reporting (Fig. 1).

The data input/creation component collects and/or processes spatial data derived from diverse sources such as existing maps, aerial photography, remote sensing satellites, census statistics, and other sources. In order to use GIS for modeling and management purposes, every mappable characteristics associated with any given geographical location should be organized as a series of spatially-registered computer-compatible map layers, or 'overlay' (Tomlin, 1990; Berry, 1987) (Fig. 2). Each overlay represents one and only one thematic attribute (i.e. mutually exclusive in space) such as topography, roads, water, health facilities, etc. These map layers can be stored in either raster or vector (line) format. Each of these data formats has its own strengths and limitations (Table 1).

The data management/storage component provides the environment within which the GIS functions and the means by which the data are controlled. It organizes the spatial data in a form which permits it to be quickly retrieved by the user for subsequent analysis,
FIG. 1. AN IDEALIZED GEOGRAPHIC INFORMATION SYSTEM (Adapted from Cracknell, 1986).
as well as permitting rapid and accurate updates and corrections to be made to the spatial database.

The GIS data manipulation and analysis component provides spatial analysis techniques/operations to be used for modeling, making predictions, and reaching conclusions about problems of interest. GIS can have numerous analytical operations/functions (see Burrough, 1986; GIS World, 1989; Tomlin, 1990 for comprehensive examples of commonly available GIS functions). The definitions of GIS functions have not been standardized, thus the number of these operations vary a great deal from one system to another. They do, however, have one common characteristic, i.e. the levels at which these functions operate. Tomlin (1990, 1983) divides the fundamental GIS analytical functions into 3 classes: local or point-characterizing operations, focal or neighborhood-characterizing operations, and zonal or region-characterizing operations. Point-characterizing operations are spatially myopic where each geographical unit is considered independently. In other words, these operations are aspatial in nature. They compute new values on a point-by-point (or location-by-location/cell-by-cell) basis, without taking into account any relationship between one location and another. Examples of these operations are add, subtract, multiply, divide, maximize, minimize, average, and cover. Neighborhood-characterizing operations, on the other hand, operate on a set of points defined by some neighborhood forming function. Neighborhood processing depends upon the spatial arrangements of values, i.e. the values for processing are identified by specified distance, connectivity, and directional criteria. Examples of these operations include: scan which computes summary statistics for each neighborhood; differentiate, orient, and profile which measure surficial slope, aspect, and cross-sectional characteristics, respectively; spread which measures proximity; drain simulates surficial flow; and radiate which delineates viewsheds. Zonal or region-characterizing operations compute new values for each location as a function of existing values associated with the region containing that location.

The data display and reporting component of the GIS is capable of displaying part of the original databases as well as manipulated data and the output from spatial models. The displays may range in complexity, from tabular reports and simple monochrome plots to publication quality three-dimensional color graphics.
FIG. 2 A GEOGRAPHIC INFORMATION SYSTEM CONCEPTUALIZED AS A SET OF GEOGRAPHICALLY REGISTERED DATA LAYERS. (Adapted from FAO, 1986).
Table 1:  
Advantages and Disadvantages of Raster and Vector 
GIS Data Structures

Vector methods

Advantages
- "Good representation of phenomenological data structure"
- Data structure is compact
- "Topology can be completely described with network linkages"
- Produce/display accurate graphics
- Allow retrieval, updating and generalization of graphics and attributes

Disadvantages
- Data structures are complex
- Difficult to combine/overlay several polygon maps or polygon and raster maps
- Difficult to use for simulation because each unit has a different topological form
- The technology is still relatively expensive especially for the more sophisticated software and hardware especially for display and plotting
- Impossible (very difficult) to do spatial analysis and filtering within polygons

Raster methods

Advantages
- Data structures are simple
- Easy to combine and overlay mapped data with remotely sensed data
- "Various kinds of spatial analysis are easy"
- "Simulation is easy because each spatial unit has the same size and shape"
- The technology is relatively cheaper, and continue to be developed

Disadvantages
- Require large volume of graphic data
- There will be a serious loss of information and phenomenologically recognizable structures as the cell size become larger
- Raster maps can be considerably less beautiful than maps drawn with fine lines
- "Projection transformation are time consuming unless special algorithms or hardware are used"
- Difficult to establish network linkages

Source: Adapted from Burrough, 1986.
GIS as Modeling Tools

Given the set of arithmetic and logical operations described above, it is possible to develop a general approach to "cartographic modeling" (Tomlin, 1990). Cartographic modeling is a general but well-defined geographical data-processing methodology that can be used to address diverse applications in a clear and consistent manner. This can be done by decomposing data-processing tasks into standardized components, components that can be recombined with ease and flexibility. This approach can be conceptualized as a 'map algebra' in which the maps of individual characteristics such as topography or land use are treated as variables that can then be transformed or combined into new variables through specified operations (Tomlin, 1990). The logical order of the map operations is similar to solving algebraic equations to find the unknowns. Many of the natural resource modeling procedures already existing can be implemented in the GIS environment.

Like other conventional models, these cartographic models can be developed either for descriptive or prescriptive purposes. The descriptive modeling efforts attempt to describe in geographic terms "what is" or "what could be" (Tomlin, 1990). A variety of cartographic models can be developed to represent facts, express judgement, or simulate processes. Given a set of problems, the descriptive model will present the objectives and constraints associated with those problems. It describes how the objectives (e.g. minimizing environmental impacts) arise from the existing conditions (e.g. demographic pattern, land suitability, soil types, etc.). Though descriptive modeling is a useful beginning in any modeling processes, it can only answer questions ("what is") but not solve them ("what should be done"). The latter is a prescription, thus requiring prescriptive models. The problems addressed by prescriptive models generally involves some form of geographic allocation, the process of selecting locations in order to satisfy stated objectives. For example, this type of model can be used to address the question of "where development should be located" in order to minimize the impacts on water quality.

2.3 REVIEW OF LAND USE ALLOCATION MODELS

Urban planners have been using land use models for many years. The first attempts to develop land use models began in the 1920s and 1930s (Sharpe, 1986; Chapin and Kaiser, 1979). These include the works of Reilly (1931), Losch (1944), and Christaller (1973). Since then, many more attempts have been made to develop a model for land use plan design, especially with the advent of powerful computers in the early 1960s. The
major purpose of these models is to allocate a scarce resource, land, between competing and often conflicting land use activities (Schlager, 1965). Land use models can be classified in many ways. In general, land use models can be divided into 2 groups: predictive and prescriptive models (Sharpe, 1986). The basic difference between these two types of models is that predictive models say "what is" or "what would be", while prescriptive models say "what should be". As their names imply, predictive models attempt to predict or simulate urban growth processes, allowing planners to observe the likely outcomes over time. These models were mainly developed empirically based on judgmental basis, or statistical techniques. The most popular model of this type was developed by Lowry (1964) using an economic base approach (Sharpe, 1986).

The prescriptive models (or also called normative models), on the other hand, attempt to "prescribe or optimize urban land use patterns to meet desired planning goals subject to various physical, environmental, economic, and social constraints" (Sharpe, 1986). In other words, prescriptive models typically have objective function(s) which provide the criterion for optimizing a system (Goldner, et. al, 1972). These models are usually developed using various mathematical programming techniques (e.g. linear or non-linear programming, integer programming, etc.). Unlike the predictive models which assume that the planner's role is largely passive, the prescriptive models assume a more active planning role in determining future land use patterns (Sharpe, 1986).

To date, numerous urban land use models have been developed, some of which will be reviewed in this section. Further reviews on these models may also be found in various texts/reports including those by Brown et al. (1972), Gordon and Fisch (1976), and Kilbridge et al. (1969).

**Predictive Models**

The most commonly known predictive model was developed by Lowry (1964). Other subsequent predictive models are mostly derivatives of the Lowry model, including those developed for the Puget Sound Regional Transportation Study, Detroit Regional Transportation and Land Use Study, Bay Area Transportation Study, Bay Area Simulation Study, Harvard Land use Allocation Model, the Oak Ridge Model, and Atlanta Region Metropolitan Planning Study. This section will review the Lowry model, and some of its derivatives.
The Lowry Model.

The Lowry model was developed as an analytical model capable of assigning urban activities to sub-areas of a bounded region in accordance with those principles of locational interdependence that can be reduced to quantitative form. In order to be treated by this model, urban activities are divided into 3 broad groups: 1). a basic sector, which include industrial, business, and administrative establishments whose clients are relatively unconstrained in local site-selection by problems of access to local markets. The amounts and distributions of basic employment and basic land use are determined outside the model, that is, are treated as exogenous to the model. 2). a population-serving sector, which include retail, administrative, and other establishments which deal predominantly and directly with the local population. The locations and levels of employment in this sector are determined endogenously to the model. 3). a household sector, which consists of the resident population. The level of employment in this population sector depends directly on the number of basic and population-serving jobs available at any given time. The level and location of this sector's employment are also determined endogenously to the model. The essence of the model construct involves the projection of a long-run equilibrium spatial distribution of population and certain types of employment and assumptions about the behavior of urban trip-makers.

The model is iterative in nature. Given the information on the amounts and distributions of basic employment and basic land use, the model generates appropriate amounts of retail employment and residential population, and distributes these employees and households among the sub-areas of the metropolitan region. This is done by means of algebraic functions which relate places of residence to places of work and the locations of various types of retail activity to the accessible market of consumers. The competition for sites among retail establishments and households is determined by calculating the "potential" of each location as a residential and/or population-serving site. Specifically, the Lowry model first generates a spatial distribution of the residences of the basic employment employees. This spatially distributed residential population along with assumptions about "shopping-trip" behavior are then used as the basis for locating the population-serving activities. Using this information, it is then possible to generate the locations of the residences of the population-serving employees. This event changes the distribution of the residential population, as does the market potentials. Thus, the solution of the model
proceeds in an iterative manner through successive allocations of residences and population-serving employment until stable distributions are obtained or a "stopping-point" for the algorithm is reached.

Bay Area Simulation Study (BASS).

The BASS model was developed to analyze the impact of employment and transport on the structure and distribution of urban land uses in the San Francisco Bay Area (Brown et. al, 1972). The model utilizes economic projections as inputs and produces the effects of economic changes in land absorption as the output.

The basic assumption of the BASS model is that development in the region is driven by changes in industrial employment. Given a set of employment projections by industry, the first step of the model is to allocate industries to census tracts. This is done through a combination of 2 methods. The first method is to develop a number of regression equations that relate industrial location of each industry to a series of industrial location factors. Among the factors considered were the location of the other industrial firms in the area, freeway access, rail access, restaurants, libraries, and tract density. The second method is to obtain the opinions of local industrialists and real estate brokers as to the importance of different factors in the industrial location process. Based upon these 2 pieces of information, each census tract is tested for each new industry. These tests are binary tests that simply determine whether each tract has the "essential" characteristics for the location for a particular industry. If the tract fails the tests, no industry will be located there. Otherwise, if the tract passes the binary tests, a group suitability score for the industry is calculated. The tract with the highest score for one industrial group receives an average size firm. The amount of land allocated for the industry is determined by a land absorption coefficient derived from the literature.

The next step of the BASS model is to allocate retail employment. The proportion of new retail employment locating in any census tract is a function of the percentage of the region's new employment locating in the tract, the percentage of the area's total population residing in that tract, and the tract's relative attractiveness. The relative attractiveness of the tract is a function of its potential demand for retail trade, and its commercial site suitability. The potential demand is determined based on a gravity model formulation. Commercial site suitability is estimated by a regression equation relating the amount of retail employment to
population accessibility, consumers access, industrial access, tract density, and the amounts and location of other types of employment.

The final step in the model is to allocate the residential sites. This allocation is based on a complex algorithm related to existing housing units, demolition of older units, density of development, and demand by employment in industrial and commercial employment.

The most interesting feature of the BASS model is the introduction of filtering and demolition into the model of the residential housing market (Brown et al., 1972). However no attempt has been made to model the behavior behind filtering and demolition. In addition, BASS repeatedly used arbitrary equations in the allocation of employment and households (Brown et al., 1972). These equations are defined judgmentally rather than estimated via statistical techniques (Brown et al., 1972). Gordon and Fisch (1976) criticize the model based on the fact that a number of subjective, unconfirmed, and unvalidated decisions are made at each step in the industrial allocation process. The coefficients of the regression equations are not reported. Thus, it is not possible to determine either the statistical significance or the variability of the estimates of the equations. Furthermore, the reason for choosing a particular form of relationship is also not clear (Brown et al., 1972). Finally, no account of competition between different land uses for the same finite land supply has been made in the allocation process.

*The Harvard Land Use Allocation Model*

Another major attempt at land use modeling has been undertaken by a research team at Harvard University. In a study for the National Science Foundation, the Harvard University Landscape Architecture Research Office has developed a series of discrete, yet inter-related major model components that analyze the process of urban development in a region (Steinitz and Rogers, 1974). The study area included in this project consists of 756 square kilometers area located in the southeast sector of the Boston Metropolitan Area. The area is divided into 75,600 one hectare grid cells. The model begins with exogenous forecasts of population and employment of the study area (Gordon and Fisch, 1976). This set of models is primarily driven by the changes in industry and housing. Other land uses (e.g. commercial, schools, recreation and utilities) are located in response to the locational choices made by these prime movers.
The Industrial Allocation Model consists of three basic components: (1) determination of demand for industrial sites; (2) determination/ranking of available sites; and (3) allocation of demand to sites (Steinitz and Rogers, 1974). The demand for industrial sites is determined by disaggregating the exogenous employment forecasts to the employment categories, and then converting these forecasts into demand for industrial sites. Industries are classified into eight categories based on their pollution potential, that is, the level of water and air pollution and solid waste generation. The distribution of new firms is determined based on data of the distribution of firm and site size within each of these categories. The sites available for industrial development are determined based on their attractiveness. Each site available for development is "ranked on the basis of the site characteristics important for that particular industrial site selection". The final step in the model is to allocate the demand to the sites available which is accomplished by using site characteristic ranking and the weighting factors derived through interviews.

The Housing Allocation Model starts with "the identification of the amounts and types of new residential development which can be expected within the study area", and then "locates the various housing types at particular sites on the basis of developer's profit". The basic assumption of the model is "that developers choose sites which maximize the profits from the development". In order to determine the profits, the model requires two major inputs: the estimates of the full building cost, and the expected selling price for each structure type in every available and useable cells. No equation was given for estimating the full building cost. The expected selling prices are estimated based on econometric (regression) analysis that relates housing prices with such things as the difference in distance to commercial center, highways and highway interchanges, neighborhood income, town tax rate, distance to school, distance to industry, and noise and visual quality of the site.

The Commercial Allocation Model simulates the location of new commercial facilities due to the increase in residential population. The commercial activities are classified into four groups: neighborhood centers, community centers, regional centers, and strip development. The spatial distribution of the new commercial activity is "determined by comparing the distribution of commercial expenditure against the distribution of existing commercial facilities". This new activity is located in those districts where expected sales volume is largest, and on sites that minimize the cost of constructing
the commercial facility. The commercial expenditure is estimated using an equation
developed based on expenditure data from the Bureau of Labor Statistics. The sales
potential for each enumeration district is then estimated using a gravity model. Sites suitable
for commercial development is determined by "a screening process which clusters usable
contiguous cells into commercial sites". A site is considered suitable if it meets the following
criteria: (1) it is physically suitable for development, (2) it is not currently being used,
(3) it is nearby a major road, and (4) it is zoned for commercial development.
Development costs are computed for each cluster of developable sites. Then the amortized
costs are subtracted from the estimated sales, and the results are used to rank the sites
accordingly.

The Harvard project presents an early attempt to comprehensively relate
urbanization trends to changes in land use. The set of models developed in this project can
be characterized as performing either allocation, or evaluation (not discussed in this section)
functions. One major improvement of the allocation model is explicitness. Most model
components are clearly defined. It however still share some of the pitfalls found in previous
work. Some of the model components are still based on qualitative judgement. The
competition among land uses for the same site was also not taken into consideration.

Atlanta Region Metropolitan Planning Study

The objective of this study was to predict the demand for transportation and land
use in 1983. The Atlanta model is based on a series of steps employing judgements from
empirical analyses rather than a mathematical model (Brown et al., 1972).

The model starts with "the determination of areawide totals for employment,
population, mean family income, and the age distribution of the population". Given this
information, the next step of the model is to allocate the industrial employment. The
industrial employment is divided into 13 groups. Each of these groups is assigned to one of
four types of employment location based on an analysis of each group's location
orientation. The 4 types of employment locations are: central places, industrial districts and
parks, population-linked areas, and special areas. Employment in those industries attracted
to the 2 area types is allocated to subareas that most closely satisfy the groups' preferences
for certain locational factors. The employment attracted to special areas (e.g. airports and
hospitals) is allocated exogenously.
The allocation of retail land use depends on the transportation system and the spatial distribution of demand for retail purchases. The total space requirements for retail are estimated using the total retail sales. The sales are estimated from the population and income projections. The total retail sales are distributed to the five counties in the study area on a judgmental basis. Similarly the allocation of retail space to tracts and zones is also made on a judgmental basis.

The next step is to allocate the population. The population is first allocated to built-up rural areas on the basis of current urban renewal plans, planned private projects, probable installation of utility services to outlying areas, and recommendations of planning staff. The remaining population is allocated to expansion areas using a predefined formula as follows:

\[ p_i = \frac{P_1 A_i H_i K_i}{\sum_m A_i H_i K_i} \]  

where \( p_i \) is the predicted population in tract \( i \), \( P_1 \) is the predicted total population, \( A_i \) is accessibility by auto and transit to employment, \( H_i \) is tract holding capacity, and \( K_i \) is an adjustment factor.

Once the land use pattern of the area is determined, the final step is to derive the transportation requirements of the new spatial form. This is based on the physical characteristics of the area as well as the economic and demographic characteristics of its inhabitants.

The Atlanta model relies heavily on judgements. Though this may be good for short-term planning, it is insufficient for a continuing planning program (Brown et al., 1972). In this situation, it is very difficult to introduce new information or new personnel into the planning process, unless careful specification of the basis for the judgement is made. Further, the determination of the location of industry is based on the locational characteristics of all rather than only the recently moving firms. This introduces biases that tend to perpetuate the historical locational pattern.
Prescriptive Land Use Models

Prescriptive land use models are basically mathematical optimization models. The earliest attempts to use mathematical optimization techniques in land use modeling were in the forms of linear programs. A comprehensive land use optimization model was initially developed by Schlager (1965). He developed the model using the linear programming technique. The objective function relates to the minimization of land development cost for a given land use pattern (CT) and is represented as:

$$CT = \sum_{k=1}^{K} \sum_{i=1}^{N} c_{ki}x_{ki}$$  \hspace{1cm} (6)

where the variables $x_{ki}$ represents the amount of land use $k$ (e.g. residential, industrial, etc.) assigned to area (cell) $i$, $c_{ki}$ represents the cost of developing area (cell) $i$ for land use $k$, and $N$ is the number of land use types.

The constraints for the model can be either in the form of equality or inequality. Schlager considers 3 constraints:

1. Equality constraint dealing with the total demand requirement for each land use category:

$$\sum_{i=1}^{N} d_{i}x_{ki} = E_{k}$$  \hspace{1cm} (7)

where $E_{k}$ is the regional land use demand requirement for land use $k$ and the parameters $d_{i}$ are the service ratio coefficients corresponding to the supporting service land requirements (e.g. streets)

2. Inequality constraints dealing with the maximal (minimal) limits on land uses within a zone:

$$\sum_{k} x_{ki} \leq F_{i}$$  \hspace{1cm} (8)

where $F_{i}$ is the upper limit on land use $k$ in zone/area $i$.

3. Inequality constraints for interzonal or intrazonal land use relationship constraints:

$$x_{ki} \leq G_{i}x_{lj}$$  \hspace{1cm} (9)

where $G$ is the ratio of land use $k$ allowed relative to land use $l$, with land uses $k$ and $l$ in the same or different zones.
Constraints (8) and (9) relate to design standards which may vary in form. This model requires 4 primary sets of input data to operate: (1) the current land inventory (e.g. land use and soil characteristics), (2) the unimproved land and land development costs for each primary land use activity for each type of soil, (3) the aggregate demand for each primary land use activity, and (4) the design standards. These models were tested in the South-eastern Wisconsin Regional Planning Study.

Schlager’s models were extended by various authors, including Ben-Shahar et al. (1969), Lundquist (1973), Hartwick and Hartwick (1974), Ripper and Varaiya (1974), Hopkins (1977), Los (1978), and Elmes and Harris (1986). Most of these models were in the forms of linear or quadratic programs. Hopkins (1977) and Los (1978) introduce heuristic procedures to solve their quadratic models. The models described thus far are mainly based on single objective function, and do not include any environmental factors. More recent development in land use optimization models either include environmental concerns, or are based on multiple objective mathematical programming techniques.

The models developed by Shefer and Guldmann (1973, 1975), and Guldmann and Shefer (1977) provide some early examples of land use optimization models that take environmental concerns into consideration. They developed static optimization models for land use allocation and air pollution control, with emphasis on industrial pollution. Guldmann (1979) later developed an integrated urban development optimization model to deal with long-run, intertemporal decisions concerning environmental (i.e. air) pollution control and allocation of urban land uses. The author used air pollution generated by the industrial, residential, and transportation sectors as representative of the urban environmental quality problem. A mixed-integer linear programming technique was used in this model with the objective of minimizing total discounted costs of urban development and operation subject to various constraints such as urban development targets and environmental quality standards.

The models described thus far use environmental criteria on a location-by-location basis, i.e. for impacts from point source. These models are not suitable for non-point source pollution, which is cumulative and combinatorial in nature. This kind of pollution is greatly influenced by the interactions (combination) between different land uses (Guldmann, 1986). This combinatorial problem is difficult to solve, and no algorithm
exists for solving it. As suggested by Guldmann (1979), the objective function of this problem is not only non-linear but also cannot be expressed analytically. The objective function is the output of a complex simulation process/model, that cannot be expressed in a closed mathematical form F(X). Thus it cannot be solved by the classic gradient algorithm of non-linear programming. However, Guldmann (1979) was able to develop a computational algorithm adapted from the method of convex combination of non-linear programming. He has successfully demonstrated the use of the algorithm in allocating new structures/land uses that minimize visual impacts. The basis of the algorithm is to approximate the first derivatives of the objective function, which are the changes in visual impacts resulting from increments in the amount of structures to be allocated at each site. These results are used to seek the optimal direction of improvements in the objective function. This algorithm produces only local optima, thus it was applied to a sufficiently large number of initial solutions so as to get a maximal sample of local optima. The solution to the problem is then the best among these local optima.

Land use optimization models using multiple objective mathematical programming techniques have been recently developed by a number of authors such as Bammi et al. (1976), Bammi and Bammi (1979), Gilbert et al. (1985), Diamond (1988), and Diamond and Wright (1988). Bammi and Bammi (1979) developed a land use optimization model for Du Page County (Illinois) to determine the acreage to be allocated to each land use type that simultaneously considers multiple objectives and constraints on desired growth pattern.

Gilbert et al. (1985) developed a multiobjective integer programming model for allocating an area of land for development. Three objectives were considered in the model: the cost of land acquisition and development, the proximity to desirable and undesirable land features, and the shape of the allocated land area. The authors use an interactive multiobjective optimization algorithm to generate a subset of efficient solutions. At each iteration the solutions are generated with some guidance from the decision maker as to what constitutes a "preferred" efficient point. The authors tested the model and algorithm in locating potential sites for residential development in a study area near Norris, Tennessee. A more recent multiobjective land use model was developed by Diamond and Wright (1988). This model has been reviewed in Section 2.
Apart from the predictive and prescriptive modeling approaches described above, there have also been several attempts to use random generation methods for generating different alternatives of land use plans. The major motivation for using this approach was that land use planning problems are usually too complex to be fully represented by a mathematical model (Chang, Brill, and Hopkins, 1982). Many planning issues are ill-defined and cannot be explicitly modeled (Hopkins, 1984); objectives are qualitative and conflicting; and many constraints may not be clearly defined. Sinha, Adamski, and Shlager (1973), and Chang, Brill, and Hopkins (1982) provide some examples of the use of this approach.

Summary

This section has reviewed some of the existing land use models. It is evident from the above discussion that the predictive/empirical modeling approach has several limitations. Most of them were developed based upon subjective decisions. All the models allocate changes to different uses sequentially, thus they also failed to consider the complex competition among land uses in urbanizing areas (Gordon and Fisch, 1976). The land use models developed using mathematical optimization techniques, on the other hand, were able to take into consideration such problems. However, only a few models directly take environmental impacts into consideration. With the exception of the models by Diamond (1988), Diamond and Wright (1988), Diamond and Wright (1989), and Elmes and Harris (1986), most of these models have not been integrated with geographic information system. GIS provides a framework for the storage, analysis and manipulation, as well as display of large volume of spatially/geographically referenced data. It may be "linked with a land use model at both pre- and post-optimization phases of the model structure", and could potentially overcome several difficulties in most model applications including:

1). "the identification and implementation of appropriate data organization and management program for spatial data manipulation, as input to and output from a land use design model."

2). the representation of existing land use activities and the change in land use activities following optimal allocation, and

3). the generation of input data (e.g. estimated costs, land use compatibility weighting, distance over specified networks), and the relative weighting of such data according to the different forces influencing the planning process" (Elmes and Harris, 1986).
A large number of public and private agencies (local, state, regional, or federal) already own these geographic information systems, and their numbers are still increasing. However, these systems have not yet been used extensively for land use or environmental modeling. This is partly due to the fact that the present uses of GIS in land use decision making are still focused on supportive rather than active roles (Tomlin and Johnston, 1988). It may be also because many of the existing GIS are still limited in scope and functional capabilities (Gordon, 1985; Sen and Radhakrishna, 1988; Armstrong, 1988). There are however several improvements in GIS capabilities as well as modeling techniques in recent years. For instance, Tomlin and Johnston (1988) developed a modeling approach to land use allocation using geographic information systems. The approach is heuristic in nature, but is quite similar to an optimization technique. This approach has brought some light to the land use modeling efforts, but need to be extended so that environmental impacts can be modeled explicitly rather than just implicitly (for example through proximity analysis).

2.4 REVIEW OF NONPOINT POLLUTION MODELS

Numerous models have been developed for estimating nonpoint pollution. Their complexity and data requirements vary from one another. Most of these models are actually runoff models embedded with water quality components. This is because of the very nature of nonpoint pollution which is mainly associated with surface runoff. The literature on these models is quite extensive, and can be found in many books related to hydrology, stormwater runoff, or environmental planning, including those by Gordon (1985); Viessman et al. (1989); Novotny and Chesters (1981); and Overton and Meadows (1976). To mention a few, these models include the Stormwater Management Model (SWMM); the Storage, Treatment, Overflow, Runoff Model (STORM); the Batelle Urban Runoff Management Model; the Agricultural Chemical Transport Model (ACTMO); the Nonpoint Simulation Model (NPS); and the Overland Flow and Pollution Generation Model (LANDRUN). These models will not be used directly in this study and so will not be reviewed here. Only the runoff models will be reviewed further.

Numerous storm runoff models exist to date. Two of these models which have gained wide acceptance for use in predicting runoff and have been incorporated in many
stormwater/water quality models are: the rational method and the Soil Conservation Service (SCS) method. The rational method is represented as (Viessman, et al., 1989):

\[ Q = CIA \]  \hspace{1cm} (10)

where

- \( Q \) - the peak discharge in cubic feet per second (cfs)
- \( C \) - the runoff coefficients
- \( I \) - the average rainfall intensity
- \( A \) - the size of the drainage area (acres).

The rationale for the method lies in the concept that application of a steady rainfall intensity will cause runoff to reach its maximum rate when all parts of the watershed are contributing to the outflow at the point discharge (Viessman et al., 1989). It assumes a linear relationship between runoff and the three parameters. Since the rainfall is assumed constant for the watershed, runoff is mainly determined by the runoff coefficients. These coefficients vary with respect to land use and soil types, but are the same for storms of different frequencies. The drainage characteristics are also assumed the same for all portions of the watershed. The method is only based on empirical approximation of runoff rather on the treatment of the processes.

Another runoff model, which is more comprehensive than the rational method is the SCS runoff model. This model relaxes some of the assumptions of the rational method. It provides a fairly detailed adjustment of runoff data. It is based on empirically derived relationships of soil type, land use/cover, and hydrological conditions, with runoff represented as runoff curve number-CN (SCS, 1986). A composite curve number for an entire drainage basin is computed by determining the area-weighted average of the curve numbers of sub-basin units. This curve number is used to calculate direct runoff volume for a given rainfall event. For a small watershed, the runoff can be computed as follows:

\[ Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \]  \hspace{1cm} (11)

where

- \( Q \) = the actual direct runoff volume (inches)
- \( P \) = the total storm rainfall (potential maximum runoff excess)
- \( S \) = the potential maximum retention (abstraction)

The potential maximum abstraction, \( S \), can be estimated from:
\[ S = \frac{1000}{CN} - 10 \]  \hspace{1cm} (12)

In order to calculate the final amount of runoff for each soil group, one only needs to define the hydrology characteristics, land cover, and the amount of rainfall. The model assumes that the initial abstraction of rainfall (i.e. surface storage) that occurs prior to runoff is relatively constant, and that storms over the basin are uniform in distribution.

Besides the volume of runoff, the SCS model can also predict a runoff hydrograph for a given timing characteristic of water flow within a basin. This hydrograph illustrates runoff flows versus time. The timing characteristics depend on spatially-related conditions such as the slope, size, surface roughness (land cover types), and shape of the drainage basin, but the SCS method lumps these effects into one parameter known as time of concentration \((T_c)\). The time of concentration is the time required for water to travel from the hydraulically most distant point of the watershed to a point of interest in the watershed (e.g. watershed outlet). It is the sum of all travel times for the consecutive components of the drainage flow systems (SCS, 1986).

The travel time \((T_i)\) is the time it takes for runoff (or water) to travel from one location in a watershed to another location downstream (SCS, 1986). It is the ratio of flow length \((L)\) to flow velocity \((V)\) and can be calculated using the following equation:

\[ T_i = \frac{L}{(3600V)} \]  \hspace{1cm} (13)

where 3600 is the conversion factor from seconds to hours. Thus, the time of concentration \((T_c)\) can be computed as follows:

\[ T_c = \sum_{i=1}^{m} T_i \]  \hspace{1cm} (14)

where \(m\) is number of flow segments.

The time of concentration \((T_c)\) influences the peak as well as the shape of the runoff hydrograph (SCS, 1986). Besides time of concentration, peak runoff/discharge is also influenced by the drainage area of the watershed, the runoff volume, the location of
developments, and the effects of any flood control mechanisms. Urban development usually increases peak discharges because of its influence on the factors affecting travel time and time of concentration. Urbanization reduces retardance to flow, thus increases flow velocity (SCS, 1986). Similarly, it also reduces overland flow lengths and modifies the land slopes. As a result, the travel time, and therefore time of concentration ($T_c$) through the watershed is generally decreased (SCS, 1986). Using the relationship between these parameters, the peak runoff (discharge) can be estimated as follows:

$$Q_p = \frac{(484AQ)}{T_p}$$  \hspace{1cm} (15)

where $Q_p$ is the peak runoff (cubic feet per second), $A$ is the drainage area of the watershed (square miles), $Q$ is the runoff volume (inches), and $T_p$ is the time to peak (hours). The time to peak ($T_p$) can be estimated using the following relationship:

$$T_p = \frac{\Delta D + L}{2}$$  \hspace{1cm} (16)

where $\Delta D$ is the duration of unit excess rainfall (hours), and $L$ is the lag time. The duration of unit excess rainfall ($\Delta D$) is related to the time of concentration and can be derived from it as follows:

$$\Delta D = 0.133\ T_c$$  \hspace{1cm} (17)

The lag time ($L$) is the time delay after a brief heavy rain before the runoff reaches its maximum peak, and is also related to the time of concentration. It can be estimated as follows:

$$L = 0.6\ T_c$$  \hspace{1cm} (18)

Thus, on the average, the time to peak ($T_p$) is related to the time of concentration ($T_c$) in the following manner:

$$T_p = \frac{0.133\ T_c}{2} + 0.6\ T_c = \frac{2T_c}{3}$$  \hspace{1cm} (19)

Therefore, by substituting (19) in (15), it is possible to express the peak discharge ($Q_p$) in terms of $T_c$, rather than $T_p$, with:
\[ Q_p = \frac{726.4A}{\text{T}_e} \]  

(20)

The above equations show the relationship of peak runoff (discharge) to various watershed parameters only in general terms. The SCS method, however, is also capable of providing much detailed information on the distribution of runoff over time, which may be useful for various design purposes.

The SCS method provides a simple and straightforward means of calculating storm runoff impacts, that is particularly suitable for making planning decisions in rural or semi-urbanizing watershed (Gordon, 1985).

This chapter has reviewed several research areas related to the present study. With these foundations, it is then possible to develop the conceptual framework of the proposed methodology, and is described in the next chapter.
CHAPTER III
THE CONCEPTUAL BASIS OF THE PROPOSED METHODOLOGY

In the previous chapter, the research areas related to this study were reviewed. In this chapter, the conceptual basis and the procedure to implement the proposed methodology are formalized. The first section briefly introduces the major components of the methodology. Then the environmental models used in this research are described. The next two sections provide the detailed formulation of the methodology.

3.1 Introduction

The proposed methodology attempts to integrate/link land capability/suitability analysis with an environmental model in urban land use modeling using a geographic information system (Fig. 3). Urban nonpoint water pollution is used as the example of environmental impact to demonstrate the methodology. The main objective is to allocate future land uses to sites that are not only physically suitable but also environmentally acceptable. Rather than undertaking an analysis in a linear (static) form, the methodology will be dynamic in the sense that it follows an iterative process. The environmental quality criteria to be achieved will be used to determine whether the land allocation at each iteration is acceptable or not.

The general approach of this methodology is based upon the land use suitability/allocation model initially developed by Tomlin and Johnston (1988), and the optimization model developed by Guldmann (1979a), but extend them on several respects. It extended Tomlin and Johnston's model in that it attempts to explicitly quantify and use the magnitude of environmental impacts in determining land suitabilities, and in locating land uses to different sites. It is different from Guldmann's model in that land uses are allocated sequentially rather than simultaneously, and implemented mainly in the form of cartographic models. Cartographic modeling is now a common convention used in
FIGURE 3. SCHEMATIC DIAGRAM OF THE PROPOSED METHODOLOGY
reference to the act of formally synthesizing geographic information as part of a decision-making process. In the present context, it will be a series of map transformations proceeding from basic data and siting criteria to a preliminary land use plan. The approach will be comprised of two modeling components: descriptive and prescriptive. This is basically analogous to the two types of traditional urban models - predictive and prescriptive models (as reviewed in Chapter 2). The main difference between these two approaches is that in the present context, the models are implemented as cartographic models, i.e. in the form of maps.

The descriptive modeling component attempts to describe a problem in terms of "what is" or "what could be" (Tomlin, 1990; Sharpe, 1986). In land suitability analysis, it is concerned with describing the characteristics of different sites and situations in terms of their relative suitability for the location of a land use (Tomlin and Johnston, 1988). The prescriptive model (component), on the other hand, attempts to solve the problem, that is, it encompasses concern for "what should/ought be done" (Tomlin, 1989; Sharpe, 1986). Thus, the purpose of the prescriptive model (component) is to move from a description of a problem to a prescription of its solution. This is to move from a description of locational suitability to a prescription of how best to achieve certain specified objectives. The role of environmental planning is prescriptive rather than descriptive (Tomlin, 1983), thus it is the prescriptive model that is of particular importance to the present research. In this context, the prescription generally involves some form of land use allocation that best achieves the stated environmental quality criteria.

Before the descriptive and prescriptive modeling components of the approach are described in further detail, the environmental impact model to be used will be described first. This is to help better understand the proposed methodology.

3.2 The Environmental Impact Model.

The environmental impact of concern in this study is nonpoint source water pollution. The water quality measure (indicator) selected is the dissolved oxygen (DO) level. DO concentration has long been one of the most important indicators of the health of water body (EPA, 1976; Keifer, 1979; Gordon, 1985). Thus, it has historically been a major focus of water quality investigations. In the past, dissolved oxygen has been
associated mainly with point source pollution. However, with the recent advance in abatement technology, more and more BOD (which impacts the DO level) from point sources has come under control. It has now become evident that nonpoint sources are also significant sources of DO depletion. DO has been generally considered as significant in the protection of aesthetic qualities of water as well as for the maintenance of fish and other aquatic life (EPA, 1976). Lack of DO in the water columns causes an anaerobic decomposition of any organic materials present in the water. This causes the formation of noxious gases such as hydrogen sulphide and the development of carbon dioxide and methane in the sediments (EPA, 1976).

Dissolved oxygen is also a desirable indicator of a satisfactory water quality in terms of low residuals of biologically available organic materials, which is important if the water is to be used for municipal water supplies. Furthermore, DO in the water column is also important in predicting the chemical reduction and subsequent leaching of iron and manganese from the sediments (EPA, 1976). DO is also required for the biochemical oxidation of ammonia, and ultimately of nitrate in natural water. Such reduction of ammonia is important as it reduces the chlorine demand of waters, and increases the disinfection of chlorination (NAS, 1974). Thus, it is obvious that the maintenance of the minimum DO level is an important concern in every water quality investigation. It affects the cost of water treatment and the welfare of water users by causing taste, and staining plumbing fixtures and other surfaces which contact the water in the presence of oxygen (NAS, 1974).

The delivery of nonpoint source (NPS) pollutants from discrete upstream contributing areas to a particular downstream location can generally be separated into two distinct phases: the site-to-stream delivery (or loading) phase, and the downstream delivery (or fluvial transport) phase (Philips, 1989). The loading phase is mainly characterized by overland flow, while that of fluvial transport phase by channelized flow.

To comply with the above requirement, estimating the impact of urban nonpoint sources on DO levels will require two separate models. The first model, which is used for the site-to-stream delivery phase, is the runoff model that estimates the runoff quantity (discharge) and the quality of biological oxygen demand (BOD) of surface runoff from nonpoint sources. BOD is one of the major parameters in estimating DO level (other major
parameters include atmospheric aeration, photosynthesis, plant and animal respiration, benthal demand, nitrification, salinity, and temperature). The second model is the water quality model for estimating the DO level on the receiving stream.

There are a number of existing models for estimating urban NPS pollutants. Most of these models do not explicitly consider the spatial nature of NPS pollution. Therefore, this research will not make use of any particular urban NPS models for determining the generation of NPS pollutants. Instead, a more general approach will be used. This is possible due to the fact that any model that deals with the generation and washoff (as well as downstream transport) of NPS pollution can be generalized to a simple spatial model (Philips, 1989). Therefore, the estimation of runoff volume and quality for this research is based on the Soil Conservation Service (SCS) runoff model. This model is more comprehensive than the rational method, and is suitable for urbanizing areas. The quality of the runoff is estimated based upon a set of average pollutant concentration coefficients/multipliers derived from the literature. Table 2 shows the range of values for different land uses and pollutants obtained from other studies of nonpoint source pollution from urban runoff. The pollutant concentrations vary significantly between different areas and land uses depending upon the population density, degree of development, and impervious characteristics. In general, highly impervious areas such as industrial and commercial areas yield relatively high runoff volume, thus high pollutant concentrations. For residential areas, pollution level usually increases with population density and degree of development (Lager et al., 1977).

Using the selected average values (multipliers), the pollutant concentration for each land use category can then be assigned to the corresponding runoff volume of each site. The runoff volume must first be converted to peak runoff/discharge (cubic feet per second) before it can be used to estimate the runoff concentration. In order to adequately model the spatial effect of different land use pattern on NPS pollutants, it is also necessary to treat the spatial dynamics explicitly. Thus, it is necessary to route the pollutant from one site to sites downstream and eventually to the watershed outlet. The weighted concentration of any pollutant immediately downstream of a runoff input is a function of the concentration and flow in the runoff, and the concentration and flow in the runoff coming from upstream (Di Toro, 1984; Philips, 1989). This can be estimated as follows (Amy et al., 1974; Di Toro, 1984; Philips, 1989):
Table 2: Pollutant Concentrations in Runoff for Several Land uses.

<table>
<thead>
<tr>
<th>Land Uses</th>
<th>Suspended solids</th>
<th>BOD$_5$</th>
<th>Total N</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>General forest</td>
<td>8.7-66</td>
<td>0.5-2.5</td>
<td>0.2-1.35</td>
<td>0.06-0.1</td>
</tr>
<tr>
<td>Agriculture</td>
<td>180</td>
<td>3.0-7.0</td>
<td>2.58</td>
<td>0.46</td>
</tr>
<tr>
<td>Recreation/natural</td>
<td>48</td>
<td>0.6</td>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td>Low density residential</td>
<td>27-664</td>
<td>2.0-9.0</td>
<td>0.6-7.1</td>
<td>0.3-0.84</td>
</tr>
<tr>
<td>Medium density residential</td>
<td>54.4-489</td>
<td>0.8-11.0</td>
<td>0.6-8.4</td>
<td>0.28-0.5</td>
</tr>
<tr>
<td>High density residential</td>
<td>249</td>
<td>-</td>
<td>0.7-3.0</td>
<td>0.3-0.8</td>
</tr>
<tr>
<td>High rise residential</td>
<td>-</td>
<td>1.0-9.7</td>
<td></td>
<td>0.2-0.3</td>
</tr>
<tr>
<td>Commercial</td>
<td>101-773</td>
<td>8.0-12.0</td>
<td>0.01-11</td>
<td>0.02-1.3</td>
</tr>
<tr>
<td>Industrial</td>
<td>195-2052</td>
<td>11.0-19.0</td>
<td>0.54-14</td>
<td>0.3-1.02</td>
</tr>
</tbody>
</table>

\[ C_{w_i} = \frac{C_i Q_i + C_{w_{i-1}} Q_{w_{i-1}}}{Q_i + Q_{w_{i-1}}} \]  \hspace{1cm} (21)

where

- \( C_{w_i} \) - the weighted pollutant concentration at site \( i \) after the routing.
- \( C_i \) - the pollutant concentration at site \( i \) prior the routing (dependent on land use type).
- \( C_{w_{i-1}} \) - the weighted pollutant concentration at upstream site \( (i-1) \).
- \( Q_i \) - the runoff discharge (cfs) at site \( i \).
- \( Q_{w_{i-1}} \) - the weighted (cumulated) runoff discharge from upland sites \( (i-1) \).

Thus the weighted concentration at the sub-basin or watershed outlet is the sum of the concentrations from all upland/upstream areas weighted by the sum of the runoff discharges. This model assumes that the pollutant concentrations routed to downslope sites are constant. This is reasonable because the pollutants are soluble, thus once they reach concentrated flow, they are usually assumed to remain (Young et al., 1987). The input data required to use this model are soil types, land use/cover (for runoff estimation), topography (for runoff routing), and the pollutant multipliers which are functions of land uses (for runoff quality estimation). All of these input data are spatial variables, and can be represented as map layers. Thus, given a geographic information system that has the appropriate primitive neighborhood operations, it may be possible to implement this runoff model as a cartographic model.

The stream water quality model used for estimating DO concentration is the Streeter-Phelps model as described by Liu (1986). This model was selected because it is relatively easy to implement. As mentioned earlier, DO level is greatly affected by BOD concentration. BOD in wastewater consists of two materials: carbonaceous and nitrogenous (Liu, 1986). Of these materials, the carbonaceous is normally more important and exerted first because of a lag in the growth of the nitrifying bacteria necessary for oxidation of the nitrogen form (Lui, 1986). For the present research, it is assumed that the DO level is affected only by CBOD, which can be estimated from BOD$_5$. 
According to this model, the distribution of dissolved oxygen deficit (D) in a receiving stream can be estimated as follows:

\[ D = D_1 + D_2 \]  

(22)

where

\[ D_1 = D_0 \exp(-K_2t) \], is the point source DO deficit (initial value of DO deficit),

\[ D_2 = \frac{K_r L_{cp} \left[ \exp(-K_r t) - \exp(-K_2 t) \right]}{K_2 - K_r}, \]

is the deficit due to the point source of CBOD,

\[ t = \frac{1}{K_2 - K_r} \ln \left\{ \frac{K_2}{K_r} \left[ 1 - \frac{K_2 \cdot K_r}{K_r} \frac{D_0}{L_{cp}} \right] \right\}, \]

is the time to the critical D.O. point,

\[ L_{cp} \] - concentration of point source CBOD (mg/L)

\[ K_r \] - CBOD removal (deoxygenation) rate, temperature dependent, \((d^{-1}, \text{ base } e)\)

\[ K_2 \] - the rate of atmosphere reaeration, temperature dependent \((\text{day}^{-1})\)

The distribution of carbonaceous oxygen demanding \((L_C)\) material at any point downstream can then be computed as follows (Liu, 1986):

\[ L_C = L_{cp} \exp(-K_r t) \]  

(23)

As can be seen from the above equation, most of the parameters are temperature and time dependent, and can be assumed constant in a steady-state modeling. However, since most of these parameters can vary greatly with seasons, it is ideal to simulate the DO level under different seasonal conditions. The other alternative is to choose the set of conditions that is representative or critical. The latter option is used in this research, where the DO level will be simulated under the summer low flow condition, the condition where the worst DO level generally occur. All the parameters, except BOD concentration \((L)\), are assumed to be given. These data are usually available from the state Environmental Protection Agency.
(EPA). The BOD concentration will be derived from the runoff quality model described earlier, which changes with land uses.

3.3 **Descriptive Modeling**

**General description**

This modeling is mainly concerned with the land capability/suitability analysis, a process of describing the characteristics of different locations in terms of their relative suitability for a particular land use. It deals with the supply aspect, and the task involves mapping the implications of the siting/location principles and standards on the existing spatial pattern describing the land supply (Chapin and Kaiser, 1979). In determining the suitability of a given location for a particular land use, it is important to distinguish between 2 sets of criteria (characteristics): site (static) criteria and situation (dynamic) criteria (Golany, 1976; Tomlin & Johnston, 1988). They are the guiding principles and standards for the placement of activities on land, which are derived based on the statement of goals and objectives; the statement of problem structure; the need for interaction among residents, firms, and institutions; and the need for a compatible relationship between urbanization and natural environment (Chapin and Kaiser, 1979). Thus, they involve the consideration of the economic-technical, physical-biological (environmental), and socio-cultural issues of land uses allocation.

The site criteria are those that are concerned with the relationship between the proposed land use and the existing characteristics of the study area. Thus they are relatively static. These include those concerns such as the economic feasibility of developing particular units of lands for particular uses considering the physical characteristics of the site (e.g. topography, slope, soils characteristics); the pattern of land values; the susceptibility and vulnerability of important environmental processes to urban development practices and urban activities; the danger from floods and other health and safety hazards; and the livability of the site and physical and social conditions in built-up areas (Chapin and Kaiser, 1979).

The situation criteria, on the other hand, are those that are concerned with the relationships between the proposed land use and other proposed land uses and the impacts of the proposed land uses on environmental quality (e.g. water). These include those concerns such as the social, economic, and cultural compatibility of adjacent uses in order
to support the need for interaction among residents, firms, and institutions. For the purposes of this research, i.e. land use planning involving environmental impact, it may be desirable to distinguish between two types of situation criteria: those that express the relationship between different land uses on a location-by-location (atomistic) basis, and those that express the relationship on the basis of geographic "wholes" (holistic). The first type, i.e. the atomistic criteria, is the most commonly used criteria in representing this situation. It describes the situation in terms of the desired proximity, either in time, cost, or distance, of one land use to any other proposed land uses with which it has a strong relationship, designated either as amenities or detractors (see for example Diamond, 1988; Diamond and Wright, 1989). The objective is to minimize and maximize the proximity to the land units considered as amenity and detractor respectively. Thus, the closer one land unit to an amenity land unit will the better solution, while the farther one land unit away from a detractor land unit the better solution. For example, an ideal location for residential developments should be within three-quarters of a mile from local shopping centers, one mile from grade school, two and a half miles from high school, four miles from major shopping centers, less than thirty minutes travel-time to centers of employment (ULI, 1978), and 1600 feet away from heavy industrial areas.

The atomistic situation criteria address the situation on a location-by-location basis, thus is usually insufficient to capture/represent the cumulative and combinatorial nature of NPS pollution and most other environmental impacts. Therefore, a second way of representing the situation is in terms of the relationship of each site to other sites (locations) having influence upon the paths of the impacts (e.g. flow path of runoff) to a point of reference (e.g. watershed outlet, or receptors). This will require that the situation be described in terms of geographic "wholes". Taking nonpoint source pollution as an example, what this means is that the suitability of a particular location is not only dependent upon its own characteristics, but more importantly on the characteristics and the proposed land uses of all sites upstream as well as those downstream that are located along the flow path of the surface runoff to the watershed outlet. This type of situation is less straightforward than the first (proximity) one. It is much more difficult to describe and model explicitly. There are no specific or explicit rules that can be used to relate one location with another location. One potential approach is to derive these rules explicitly through trial-and-error or simulation modeling (Guldmann, 1986). The experience using this approach as a basis for land suitability analysis or land use allocation is at present
rather limited (see e.g. Guldmann, 1979a). For this reason, it is recommended that this
type of situation suitability be treated as a separate and distinct type of data (i.e. as an
objective function), against which suitability derived from the site and other situation
characteristics may be tested and modified. The above classification of situations has been
chosen specifically to highlight the environmental holistic situation, which has been
receiving little attention in previous land suitability studies. Therefore, for the rest of this
research, the atomistic situation criteria will be simply referred to as situation criteria, and
will be used to generate situation suitability map(s). The holistic situation criteria will be
referred to as environmental situation criteria, and used to generate the environmental
suitability map(s). It will be described further in the prescriptive modeling sub-section
because it is very closely related to that type of modeling.

The site and situation criteria, and environmental quality criteria provide the basis
for defining the factors (variables) to be considered, and the corresponding data needs.
Ideally, they should reflect local values and local conditions. However, in practice most of
them are similar from one place to another. Thus, for the present study, they will be
compiled based upon the existing literature and will be described next.

**Model formulation**

Having described the conceptual definition of the descriptive model, the next step is
to formulate the model for each land use under consideration. At this stage, the model is
formulated based upon the existing literature and theoretical background without much
regard to data availability. The task basically involves identifying the locational
requirements of different land uses. The literature on land use suitability analysis is quite
extensive. Various factors and criteria have been used to derive the suitability of different
land uses. These factors and criteria are usually defined at different level of abstraction, and
depend upon the level of analysis (regional, local, or individual site). One reasonable
approach to structure the problem is to organize it into a hierarchical order. This involves
identifying the elements of the problem, decomposing the elements into homogeneous sets,
and arranging these sets in different levels of abstraction (Saaty, 1980). The hierarchies can
be developed either inductively or deductively. In the inductive approach, one begins from
particular instances (e.g. available data) to general principles (e.g. objective). In the
deductive approach, one begins from general principles to particular instances. Each of
these approaches has its own merits and weaknesses. The deductive approach is, however, much better and more commonly used in the decision making process, and will be used in this project.

This research will involve allocating three basic land uses: industrial, commercial, and residential. Two additional land uses - agriculture, and forestry, are considered as residual land uses, those land uses to be affected by urban development. The hierarchies for determining the suitability of each land use will be broken down into 4 levels: purpose/objective, major land use requirements, land quality, and diagnostic criterion. This breakdown is similar to those used by Food and Agricultural Organization (FAO, 1978). Land use requirements are "the conditions of land necessary or desirable for the successful and sustained practice of a given use type" (FAO, 1978). A land quality is "a complex attribute of land which acts in a manner distinct from the actions of other land qualities in its influence upon the suitability of land for a specified kind of use" (FAO, 1978). Examples of land qualities include land availability, moisture availability, topographic suitability, and availability of utilities. A diagnostic criterion is "a variable, which may be a land quality, a land characteristic or a function of several land characteristics, that has an understood influence on the output from, or the required inputs to, a specified kind of land use, and which serves as a basis for assessing the suitability of a given type of land for that use" (FAO, 1978). For every diagnostic criterion, there will be a critical value or set of critical values which are used to define suitability class limits. For example, the set of critical values for land slope (in percent) used to define the class limits for residential development may be: 0-3% as "most suitable", 3-8% as "suitable", 8-15% as "moderately suitable", 15-25% as "marginally suitable", and more than 25% as "least suitable".

While the factors and ratings affecting the suitability of sites for each land use are usually different, the major requirements are, in most cases, common to all land uses. For instance, Chapin and Kaiser (1979) suggest that the requirements be broken into 3 groups: physical/environmental, and social-economic. In this research, the land use requirements are simply grouped into 3 classes: those related to development costs, environmental impacts, and effective land utilization (function). Figures 4 to 6 show the conceptual descriptive models for the industrial, commercial, and residential land uses. Using these models it is then possible to define the general locational principles/guidelines for each land use. These principles/guidelines are given below. They were primarily derived from

**Industrial land use**

1. Land must be physically suitable for industry. Site should be inexpensive, level, well drained and accessible. Land slope should not be over 5 percent and preferably 3 percent. Steep slope can pose severe limitations to development due to limited accessibility, erosion, and slippage hazard. Swampy, hilly, remote, or inaccessible land, and land within floodplain areas does not constitute a usable industrial site. Building in poorly drained soils may result in wet basements, cracked foundations, flooded lawns. Unique natural areas such as rare or endangered plants and animals, and special geologic formations are irreplaceable and should be avoided for development.

2. Sites should not have soil with high shrink/swell potential. Changing soil volume can damage pavements and foundations, thus affect cost of maintenance. Sites should be able to be tolerate heavy load, i.e. high bearing capacity. Soils with the greatest bearing strength - gravels, sands, and sandy silts- are best suited to large-scale development. Least suited to large-scale developments are clay, silt, and organic soils.

3. Utilities (e.g. sewer, water, telephone, gas, and electric) and services (e.g. police and fire protection) should be available or feasible. Large industrial establishments often drill wells for water supply, construct their own water and sewage treatment facilities, and are large consumers of power. Availability of ample groundwater in excess of 100 gallons per minute is usually desirable. Small industrial plants are, however, not self-sufficient and must rely upon the community for the services. Absence of these utilities and services can greatly increase the cost of development.

4. Sites should be accessible to commercial transportation network (e.g. freeways, railroads, airport, and harbor). Sites should have direct access to major freeways, and preferably within 2.5 miles from an interchange. Sites should be visible from major freeways. Industries seek the advertising advantage of a prominent site for their attractive new plants, as well as the economy of an unencumbered route for employees driving to and from work. They also seek the availability of the freeway for truck service. Highway sites can vary in depth from a minimum of approximately 600 to 800 feet up to 2,000 feet or more. Railroad sites continue to
FIG. 4 - CONCEPTUAL DESCRIPTIVE MODEL FOR INDUSTRIAL LAND USE
be vital to many industries. Sites along the railroad should be no less than 1,00 feet in depth and preferably between 2,000 feet and 3 miles.

5). Sites should be within easy commuting time of residential areas of labor force and accessibility to transit and major thoroughfares directly connected with housing areas.

6). The location of the sites should be compatible with the environmental quality criteria such as the air quality management criteria, especially in "nonattainment areas" of the Air Quality Control Region in which the sites fall.

7). Sites should be compatible with surrounding areas. Prevailing winds, possibilities of protective greenbelts of open space, development of "industrial parks", and other amenity factors within the manufacturing area and in relation to adjoining land uses must be considered. In order to minimize the noise effect from heavy industrial land use, it should be located at least 1600 feet away from residential areas.

8). Environs of industrial sites must be attractive, not blighted. Industry does not want to build next to blighted areas, whether residential or industrial. A location overlooking a public park provides neighboring industry with both prestige sites and protected open space.

9). Size of industrial tracts should vary, usually five acres as a minimum, with some sites ten, twenty-five, fifty, or one hundred or more acres depending on the size of the urban area and economic outlook for extensive manufacturing. An average industrial site in the United States is about 35 acres (Lynch, 1984).

Commercial land use

1). Paramount importance in the success of all types of shopping centers is the site location. A site must be suitable in terms of its trade area characteristics, the income level of the households in the area, competition, highway access, and visual exposure. It must be easy to reach and its roads must have the extra capacity to avoid congestion during periods of high traffic volumes. Good visibility also improves a center's accessibility.

2). Recommended distances between shopping centers cannot be precisely established. However, the following theoretical distances for site location may be used as guidelines:

- neighborhood centers draw customers from a distance of approximately one and one-half miles or 5 minutes driving time, depending on the density and character of
FIG. 5 - CONCEPTUAL DESCRIPTIVE MODEL FOR COMMERCIAL LAND USE
the residential area. Walking distance is not a valid criterion, especially in suburban locations.

- **community centers** draw customers from an area within three to five miles of the site or 10 minutes driving time.
- **regional centers** draw customers from distances of eight miles or more. The center's area of influence is better determined by driving time rather than distance. The recommended driving time is between 20 to 30 minutes.

3). **Neighborhood centers** should be located to have direct access from collector streets. Minor residential service streets should not be used as their principal access.

**Community centers** should be located to have access from major thoroughfares. However, these centers do not need to be accessible from an extended trade area via high-speed freeways.

**Regional centers** are usually located on a site that is easily accessible from interchange points between expressways and freeways. Access to public transportation is equally important to these centers. Depending on local circumstances, the distance from an interchange may range from one-half mile to a mile. The site for a regional center should offer ease of access and should be a reasonable distance from a radial highway leading to the city and from a circumferential highways that taps the urbanized residential periphery of the metropolitan areas. The ideal site for a regional center would be ringed by major traffic routes having access points and traffic control devices carefully designed to disperse traffic over a major street system and to handle the peak loads generated by such centers.

4). **Site should be regular in shape** (i.e. no acute angle, odd projection, or indentations) and should all be in one piece, undivided by highways or dedicated streets. This is very important for two reasons: (i). trafficways through a site impede the flow of pedestrians, complicate car movements within the parking areas, and contradict with the basic principle of a unified shopping facilities, and (ii). regular shape lends itself best to an efficient layout.

5). **Land must be physically suitable for commercial use.** This is important because it determines the layout, design and construction costs of a building. Site should be inexpensive, level, well drained and accessible. Land slope should not be over 5 percent. Low-lying areas and poor drainage can complicate subsurface
construction. An ideal site would have minimal subsoil complications and neither solid rock nor a high water table.

6). The availability of utilities is an asset. The cost of off-site improvement is a critical part of capital costs and a location close or easily accessible to water, sewers, gas, telephone, and electricity will keep down the costs of such development.

7). The sites should be compatible with the surrounding areas. Adjacent land uses are important in evaluating/determining a site suitability for development. They also influence the approval of a rezoning application, if it is necessary to do so. For instance, apartments or office uses adjacent to a shopping center provide an excellent transition zone between a shopping center location and a single-family residential areas.

*Residential land use*

1). Sites should be accessible to places of employment, the central business district, shopping centers, schools, churches, and recreational places by both private and public transportation. Accessibility (usually measured in time of travel) by major roads is critical to the overall location suitability of a site. High-density development must have collector and/or arterial street access, while lower density developments require less elaborate provisions for access. Ideally, a new development should have a point of access to a thoroughfare. A site location is considered good when travel time to centers of employment is less than 30 minutes, fair when travel time is between 30 and 45 minutes, and poor when travel time is over 45 minutes. An ideal location for residential development should also be within 0.75 mile from local shopping center, 1 mile from grade school, 2.5 miles from high school, 3.5 miles from churches, and 4 miles from major shopping center.

2). The site should preferably be located on the established residential side of town, or on the recent direction of city growth.

3). The availability of utilities is an increasingly important locational consideration. Permission to develop a site is greatly dependent upon the availability of water and sewer lines. Lack of utility capacity not only increases development cost, but may also delay construction.

4). The suitability of a site for development is greatly influenced by the nature and intensity, as well as the compatibility with surrounding areas. Good sites are those
FIG. 6 - CONCEPTUAL DESCRIPTIVE MODEL FOR RESIDENTIAL LAND USE
that are adjacent to public open space and cultural facilities such as parks, recreation areas, museums, libraries, and similar amenities. The suitability is also dependent upon the economic and social character of surrounding areas. For instance, high-income areas tend to attract new developments of a similar character. Sites adjacent to existing residential areas are desirable for new residential developments.

5). New residential areas should be developed away from conflicting land uses. Primary among those uses include railroad tracks, rundown commercial development, noxious industrial uses, and shoddy, poorly subdivided residential development. Residential development should also be free from any adverse effects of through traffic. Sites that are close to large storage tanks of gas, oil, and other flammable materials should be avoided. A site should be free from smoke and offensive odors emanating from nearby or distant uses. Low-lying sites can adversely be affected by air pollution. Potential sources of air pollution include nearby manufacturing industries, electric power generating plants, and garbage-burning installations. Long-distance transmission of sound is greatly affected by the prevailing direction and speed of wind. In general, sites located upwind from the source of noise are preferable than sites downwind. The nuisance of noise as well as air pollution make it undesirable to locate residential development nearby an airport. A common approach for development is to place higher density residential areas closest to commercial and industrial districts so that the residential areas can benefit from proximity to the higher capacity system and the more extensive shopping facilities and employment areas required for heavier population densities.

6). The site must be physically suitable for residential uses. This is influenced by the topography, hydrology, geology, soil and vegetation, and microclimate of the site. Moderately sloping sites are preferable to either steep or flat land. Improvement costs rise sharply on flat land and land with slopes over 10 percent. Flat land presents numerous problems of sewer and storm drainage. The shape of the site should be compact.

A site should have good natural surface drainage. Clay loam, sand, gravel, or other porous material contributes to good soil drainage, thus minimize construction cost. Standing water causes foundation problems around buildings. Sites with underlying rock close to the surface or high groundwater are more expensive to develop. Development on groundwater recharge areas and floodplains should be
avoided. Protection of recharge areas is important for keeping the quality of the groundwater intact.

A site should have good soil characteristics. A good soil is the one that is more than 5 feet deep, moderately pervious to water, free from the hazards of periodic flooding or a high water table, and level to gently sloping. Shallow soil over rock costs 10 to 20 times more to excavate than deep soil. As a general rule, sites with deep, well-drained soils found on ridge tops and gently sloping hillsides are best for development. These areas have minimal surface and subsurface water management and load-bearing problems. Mature native vegetation and ground cover, the natural habitat and food supply of wildlife should be retained as integral parts of development.

The underlying bedrock of an area is important as source of raw materials, reservoirs for water, possible waste disposal sites, and as the support necessary to accommodate any heavy structure. Development on special mineral resource and geologic hazard areas should be avoided. Development should not be placed on or near areas of active faulting. Areas with landslides, rockfalls, mudflows, as well as gentle but persistent soil creep should also be avoided.

Using the site and situation criteria, maps of relative site suitability and situation suitability are created for each proposed land use. The site characteristics are static, thus the site suitability map is generated only once. Unlike the site characteristics, the situation characteristics are spatially and temporally dynamic, thus the situation criteria cannot be initially expressed in terms of a suitability map because they require the information on the future impacts of the land use on environmental quality as well as the relationship between the proposed but not-yet-located land uses. This information will be available only after the land use allocation decisions have been made (Tomlin and Johnston, 1988). Every location in the study area is characterized by way of a numerical suitability score. There are numerous land capability/suitability methods that can potentially be used for this purpose (see review in Section 2). In this study, the suitability maps will be derived using the rules of the combination (exclusion), and the weighted linear combination methods. The rating and weighting for each factor and land use will be derived mainly through literature review.
The output of this modeling will be suitability maps which show the gradations of suitability of each land unit for each land use type to be allocated in the land use plan. These maps do not yet constitute a design, rather they only serve as the information input for the plan design (Chapin and Kaiser, 1979), i.e. for the prescriptive modeling to be discussed next.

3.4 Prescriptive Modeling

General description

Once the site suitability maps are created, they need to be transformed to a prescriptive form, i.e. how to allocate the land uses to best achieve the stated objectives. For the purposes of this research, i.e., land use planning for nonpoint source (NPS) water pollution, this objective is to achieve the desired water quality, which can be stated in either of 2 ways: the pollution concentration must be within a specified level (standard), or it must be as low as possible. This land use allocation problem is complicated due to the cumulative and combinatorial nature of NPS pollution (and most other environmental impacts). There are many possible land use combinations and conflicts that can occur. It is not possible to independently determine the contribution of each individual site (location) to the overall impacts. In other words, this problem cannot be addressed by considering locations one at a time. Instead, all (or groups) of the locations have to be treated as integrated wholes (Guldmann, 1979a; Guldmann, 1986; Tomlin, 1990).

This problem will require an holistic rather than atomistic (location-by-location) approach to land use allocation. The solution approach to this kind of allocation problem relies on heuristics rather than algorithms (Tomlin, 1990). A heuristic, unlike an algorithm, is a set of guidelines by which a problem can be explored. It provides advice/directions that can be used along the way toward a solution that is likely close to the optimum but never fully guaranteed to be optimum.

Model formulation

To help formulate the approach for solving this problem using a geographic information system, it will be helpful to describe it in terms of a mathematical programming formulation. This simple model is similar to one of the models formulated by Guldmann (1979a). For reasons of simplicity, just assume that the problem is concerned with only
one measure of water quality, i.e., dissolved oxygen (DO). Let us assume that the study area is made of C cells \((i,j=1,...,C)\), in which we want to locate \(K\) different types of land uses \((k=1,...,K)\). These land uses are assumed to be divisible and the total stock of land use \(k\) to be located is \(X_k\). Each unit of land use \(k\) has a land input (minimum size) requirement \(l_k\). Each cell \(j\) has an amount \(A_j\) (its size) of land available for the location of any of these land uses. We also consider a set of receptor (outlet) cells \(R \in C\), and assume that the impact coefficients for any couple of cells and any land use are given. Let \(e_{ijk}\) be the impact coefficient of locating land use \(k\) at cell \(j\) with respect to receptor (outlet) \(i\). The decision variables to this problem are the amount of land use \(k\) to be located at cell \(j\), \(x_{kj}\). The objective is to allocate land uses among cells of a grid that minimize the total environmental impact \((E)\) at the watershed outlet cell \(i\), thus we have the following objective function:

Minimize 

\[
E = \sum_{i=1}^{C} \sum_{k=1}^{K} e_{ijk} x_{kj} \quad i \in R
\]  

(24)

subject to:

\[
\sum_{j=1}^{C} x_{kj} = X_k \quad (k=1,...,K)
\]  

(25)

\[
\sum_{k=1}^{K} l_k \cdot x_{kj} \leq A_j \quad (j=1,...,C)
\]  

(26)

Equations (25) and (26) are the total land requirement and total land availability constraints, respectively.

Since the impact coefficients \(e_{ijk}\) are related to the land uses to be located along the path of the pollutant to the outlet, they should be determined endogenously to the allocation model. If \(X\) be the vector of the decision variables \(x_{kj}\), the impact function to be minimized then becomes:

Minimize 

\[
E(X) = \sum_{i=1}^{C} \sum_{k=1}^{K} e_{ijk} (X) x_{kj} \quad i \in R
\]  

(27)
As suggested by Guldmann (1979a), the above function is not only non-linear but also cannot be expressed analytically because the elementary impact functions \( e_{ik}(X) \) can only be computed as outputs of a complex simulation model. This combinatorial problem is difficult to solve. It is not possible to express the partial derivatives of the function analytically, and to use the classic gradient algorithm of non-linear programming to solve the problem. However, Guldmann (1979a) has developed a computational approach adapted from the method of convex combinations of nonlinear programming which has yielded encouraging results.

The basis of Guldmann's solution approach is to approximate the marginal changes in the total impacts at the receptor(s) as a result of a small change in the land use pattern, using the environmental impact simulation model. This gives an approximation of the derivatives of the objective function. Once all the derivative approximations have been computed, it is then possible to apply the convex combination algorithm step, and get a new land use allocation. With this new allocation, the procedures are repeated until the objective function can no longer be improved.

Although it is possible to solve this problem using the above optimization approximation technique, unfortunately most existing geographic information systems do not yet have the same analytical capabilities for solving general mathematical optimization problems (Gless, 1988). A limited number of geographical information systems (e.g. MAP, OSU MAP-for-the-PC, and ARC/INFO) do however have some capabilities for solving optimization problems, but mainly for facility location problems. Therefore, in order to solve this kind of allocation problem using geographic information systems, a new set of procedures is proposed. The basic idea of the solution approach is adapted from that used by Guldmann (1979a) but was simplified as seen appropriate to suit the GIS database environment.

---

7 GIS procedures for solving facility location problem may not be applicable to the land use allocation problem. This is because facility location models treat optimal locations as points in a plane or along a network, but land use allocation models treat optimal locations as 2 dimensional areas (Diamond, 1988 - p.8).
The first simplification is that the decision variables $x_{i,j}$ become integer variables, and each cell can only accommodate a single land use. To distinguish these new variables from the continuous variables $x_{i,j}$, let denote them as $x_{k_{ij}}$, and the vector as $X$. This simplification is necessary because of the general requirement of GIS that each geographic location in a map layer (overlay) can have one and only one thematic attribute, i.e. mutually exclusive in space (Tomlin, 1983; Berry, 1987).

The second simplification is that the land use allocation problem is solved sequentially rather than simultaneously as commonly used in mathematical optimization technique \(^8\). As mentioned earlier, this is in part because no geographical information system procedures have yet been developed that can solve simultaneous equations similar to those existing mathematical programming procedures. The use of a sequential technique also seems reasonable because even the traditional optimization techniques will have difficulties solving optimization problems involving geometric (spatial) constraints. This kind of problems is suspected to be NP-complete, that is, the complexity of the solution increases at a rate much faster than the increase in the number of decision variables in the problem (Chen, 1988). Sequential allocation can be done in several ways, depending upon the objectives to be achieved such as economic, social, or environmental quality. Chapin and Kaiser (1979) suggested that, in general, land use should be allocated in the following sequence: open spaces, regionally oriented activity centers and facilities (e.g. manufacturing, wholesale, retail, highway, etc.), and residential and community areas (e.g. housing, schools, local shopping, etc.). In the present study, land uses are allocated sequentially with respect to the magnitude of their environmental impacts. This approach is justified because different land uses usually produce different level of impacts. Furthermore, the need to rank the pollutant potential of different areas as a function of land use, and the need to project pollution loading for future growth options is important to areawide characteristics studies (Lager et al., 1977). Projection of future pollution potential by land use allows planners to direct potentially damaging activities away from environmentally sensitive areas. In terms of water quality, the order of magnitude is generally as follows: industrial, commercial, residential, agricultural, and natural/forest

---

\(^8\) An exception to this is the dynamic programming, which solves an optimization problem using a sequential allocation procedure (Haith, 1982). The solution procedure requires that all possible combinations of the decision variables be evaluated, but the number of possible combinations reduces after each iteration.
areas (refer to Table 3). Thus, land use with the greatest impact (industrial) will be allocated first, followed by the next greatest (commercial), and so on.

The third simplification is that the changes in the overall impacts are approximated only for a small number of land use combinations at sample sites selected using locationally stratified random sampling methods. The study area is stratified with respect to the major parameters used in the impact model, with exception of land uses which are dynamic. In this research, these parameters are the hydrologic soil group, slope, and flow length from each site to the outlet. This sampling strategy will partition the study area into homogeneous groups that are environmentally significant. This simplification assumes that sites with similar characteristics will contribute the same amount of impacts to the overall impacts at the outlet. These parameters will be different if other NPS models are used. This simplification/grouping is important in order to reduce the number of possible combinations since it is practically impossible to simulate the impacts of each possible land use combinations that can potentially exist in real world application involving large areas such as a watershed.

With these simplifications, and in line with the objective of this research, the simple mathematical model presented earlier can be extended to account for land suitability of each cell for various land uses such that a land use k can only be located at cell j if the cell is suitable for that purpose. For reason of simplicity, let us assume that this land suitability is a 0-1 parameter, where 0 and 1 represent unsuitable and suitable for development respectively. Let us denote this parameter as $s_{jk}$. As mentioned earlier, the overall land suitability is comprised of two components: site suitability, and situation suitability, or $r_{jk}$, and $r_{yjk}$ (j=1,...,C; k=1,...,K) respectively. To generate these two suitability scores, we must first identify the set of factors (characteristics) relevant to each suitability. Let suppose that there are M1 site factors, $\{a_1,a_2,\ldots,a_{M1}\}$ and M2 situation factors, $\{y_1,y_2,\ldots,y_{M2}\}$. Thus, the suitability models/methods reviewed in Section 2

---

9 It is also possible to represent land suitability as an objective function, i.e. to maximize land suitability. However, this will not be attempted in this research as it will make the problem a multiobjective optimization problem, which requires a different set of solution approach. Refer to Diamond (1988), and Diamond and Wright (1989) for examples of multiobjective discrete (0-1 integer variable) single land use optimization model, in which land suitability is used as one of the objective functions.
can then be used to determine the two suitability ratings. The general form of the suitability models are:

\[ r_{Ajk} = F_{Ak} \left( a_{j1}, a_{j2}, \ldots, a_{jM1} \right), \]  
and \[ r_{Yjk} = F_{Yk} \left( y_{j1}, y_{j2}, \ldots, y_{jM2} \right) \]

where \( F_{Ak} \) is the rating function/model to generate site suitability for land use \( k \), and \( F_{Yk} \) is the rating function/model to generate situation suitability for land use \( k \). These two suitability scores can then be combined to generate the composite suitability scores, \( r_{jk} \)

\[ r_{jk} = F_k \left( r_{Ajk}, r_{Yjk} \right) \]  

where \( F_k \) is the rating function to normalize the suitability scores to a common scale. Using the weighted linear combination suitability model, these suitability scores can be calculated as follow:

\[ r_{jk} = \sum_{u=1}^{M1} r_{Ajku} \cdot w_{Auk} + \sum_{v=1}^{M2} r_{Yjkv} \cdot w_{Yvk} \]

where

- \( r_{Ajku} \) - the site suitability rating of factor \( u \) for the \( j \)th cell and \( k \)th land use,
- \( r_{Yjkv} \) - the situation suitability rating of factor \( v \) for the \( j \)th cell and \( k \)th land use,
- \( w_{Auk} \) - the weighting of site factor \( u \) for land use \( k \), and
- \( w_{Yvk} \) - the weighting of situation factor \( v \) for land use \( k \).

Suppose that the highest suitability score is the best. Suppose further that all areas with suitability scores \( r_{jk} \) at or above some specified level, \( R_{k\text{max}} \) be selected/considered as the suitable (candidate) sites. Therefore,

\[ s_{jk} = \begin{cases} 1 & \text{if } r_{jk} \geq R_{k\text{max}} \\ 0 & \text{otherwise} \end{cases} \]

Therefore, the land suitability constraint can be represented as:

\[ x_{jk} \leq s_{jk} \quad (k=1, \ldots, K; \ j=1, \ldots, C) \]
This constraint will force $x_{jk}$ to be set to 0 when cell $j$ is not suitable for land use $k$. However, the situation characteristics are dynamic, i.e., they are dependent upon the decision variables $X$, thus $s_{jk}$ must be determined endogenously to the model. Therefore, Eqs. (32) and (33) become:

$$s_{jk}(X) = \begin{cases} 1 & \text{if } r_{jk}(X) \geq R_{k\text{max}} \\ 0 & \text{otherwise} \end{cases}$$  \hspace{1cm} (34)

and $x_{jk} \leq s_{jk}(X)$ \hspace{1cm} (k=1,...,K; j=1,...,C)  \hspace{1cm} (35)

Given the above formulation, it is now possible to formulate the solution approach to the problem. Suppose that the existing (initial) land use pattern, the existing overall impacts at the watershed outlet located at cell $i$, the land use demand, and the characteristics of each site are given (i.e., determined exogenously to the model). It is assumed that land uses are categorized into 5 major groups: industrial, commercial, residential, agricultural, and forested/natural areas, and are allocated in that sequence. Let us define 2 related terms to be used in the following discussion, namely stage and iteration. Stage refers to the sequence of allocating land uses in each iteration, e.g., land use 1 (i.e., industrial) as stage 1, land use 2 as stage 2, etc. It may also be referred to as sub-iteration, and will be used interchangeably. Iteration refers to a complete sequence of stages, i.e., when all the land uses have been allocated. Let $k$ and $t$ be the indices in reference to the stages (also land use types) and iterations, respectively. Further let $H$ be the number of years in the planning time frame (e.g., 25 years), and $X_{k}^{H}$ be the total land demand for land use $k$ at the end of the planning horizon $H$. The notations of other variables to be used in the following discussion will be similar to those defined earlier, with exception to iteration-specific variables, in which case they will be superscripted with the index $t$.

The proposed approach consists of the following steps (Fig. 7):
**Step 1:** Generate the site suitability map for each land use $k$ (k=1,...,K) using the weighted linear combination method, i.e.

$$r_{Ajk} = \sum_{u=1}^{M1} r_{Aju} \cdot w_{Auk} \quad \text{(from Eq. 31)}$$
FIG. 7 - THE FLOW DIAGRAM OF THE PROPOSED METHODOLOGY
**Step 2:** Stratify the study area into homogeneous groups based on the major parameters of the environmental model, i.e. hydrologic soil groups, slope, and flow length. This task can be accomplished using various classification methods. One of the most common method, and used in this study, is cluster analysis. Cluster analysis is a multivariate statistical technique for grouping objects (land units) based on their similarity/dissimilarity over the characteristics which describe them. Suppose we have a data matrix \( U \), where \( U = (u_{ij}) \) \((j=1,\ldots, C; \ i=1,\ldots, 3)\) representing the \( C \) objects, each with the 3 parameters. The objective then is to group these objects into \( N \) \((m=1,\ldots, N)\) clusters, so that the objects in any one cluster differ from one another as little as possible, while objects in different clusters are as dissimilar as possible. Let us suppose that distance is used as the measure of similarity. Let \( D_W \) be the distance between objects within a cluster, and \( D_B \) be the scatter of clusters (i.e., between-clusters scatter). Then the objective is to minimize \( D_W \) and simultaneously maximizing \( D_B \), which is also equivalent to the following criteria (Swain, 1978).

\[
\text{MIN } \text{SSE} = \sum_{i=1}^{N} \sum_{U \in C_m} |U - M_m|
\]

(36)

where \( M_m \) is the mean vector for the \( i \)th cluster, \( C_m \) is the set of objects belonging to the \( m \)th cluster, \( |U - M_m| \) is the distance (or other measure of similarity) between \( U \) and \( M_m \), and \( \text{SSE} \) is the "sum-of-squared error".

**Step 3:** Determine the minimum sample size, \( \eta \), required to achieve a desired statistical level of significant \( \alpha \), and level of precision (error) \( \varepsilon \),

\[
\eta = \frac{(z_{\alpha}/2 \sigma)^2}{\varepsilon}
\]

(37)

where \( \sigma \) is the standard deviation of the population BOD level. Using the sample size \( \eta \), determine the number of samples required for each group, \( O_m \) \((m=1,\ldots, N)\). It is assumed that this sample size \( O_m \), is proportional to the number of objects in each group \( m \), i.e.
\[ O_m = \eta \times (C_m/C) \]  

(38)

where \( C_m \) is the number of cells in group \( m \), and \( C \) is the total number of cells in the study area. For each group \( m \), selection of samples \( p_{mj} \) (\( m=1,\ldots,N \), \( j=1,\ldots,C_m \)), are made using a random sampling method.

**Step 4:** For each sample site \( p_{mj} \), predict the overall impacts (DO level), \( w_{mk}(X)^t \), at the watershed outlet resulting from land use \( k \) to be allocated at iteration \( t \). Since some groups may have more than one sample site, the impact level assigned to each group will be the average impacts of all samples within that group. Let us denote this impact as \( w_{mk}(X)^t \), referring to the impact coefficient of group \( m \) for land use \( k \).

**Step 5:** Using the impact coefficient matrix, classify all sites in the study area into different impact categories for land use type \( k \) to be allocated, that is, assign \( w_{mk}(X)^t \) to cell \( j \) if \( j \) is a member of group \( m \). Algebraically,

\[ e_{jk}(X)^t = w_{mk}(X)^t \quad \text{if} \quad j \in C_m \quad (j=1,\ldots,C; \ m=1,\ldots,N; \ k=1,\ldots,K) \]  

(39)

The results from this classification will be transformed into map layers in the geographic information system. These map layers, referred to as "environmental impact suitability" maps, show the impact levels/suitabilities of each location.

**Step 6:** Generate the situation suitability \( r_{Yjk}(X)^t \) for the land use \( k \) to be allocated using the weighted linear combination suitability model,

\[ r_{Yjk}(X)^t = \sum_{v=1}^{M2} r_{Yjvk} \cdot w_{Ysk} \]  

(40)

This map is generated using the information on the locations of the land use(s) that have been allocated in the previous stage(s) or iteration(s). This is done to take into account the cumulative effect of the land use(s) already being allocated on the locations of the land use to be allocated. This suitability map is then combined with the site suitability map generated in Step 1, to generate the composite land suitability map, \( s_k(X)^t \), for land use \( k \), i.e.
\[ r_{jk}(X)^t = r_{Ajk} + r_{Yjk}(X)^t \]  \hspace{1cm} (41) \hspace{1cm} \text{and} \hspace{1cm} \\
\[ s_{jk}(X)^t = \begin{cases} 
1 & \text{if } r_{jk}(X)^t \leq R_{kmax}^t \\
0 & \text{otherwise} 
\end{cases} \]  \hspace{1cm} (42) \\

Skip this step if the land use type is the first one to be allocated.

**Step 7:** Using the land suitability (\(s_{jk}(X)^t\)) and impact suitability (\(e_{ijk}(X)^t\)) maps, start the land use allocation process. The objective is to minimize the overall environmental impact \(E_k^t\) with respect to the land use \(k\) to be allocated. The locations will be selected such that those with the lowest impact will be allocated first, and adding others in the order of increasing impacts, provided that the total amount of the space requirement for that land use and other constraints are met, i.e.

\[
\text{MIN } E_k^t = \sum_{j=1}^{C} e_{ijk}(X)^t \cdot x_{kj}^t 
\]  \hspace{1cm} (43) \\

subject to

\[
\sum_{j=1}^{C} x_{kj}^t = X_k^t 
\]  \hspace{1cm} (44) \\

In case of a tie, that is, if the number of available sites with the same impact category (suitability) is greater than needed, then several decision strategies could be used to break the tie. The simplest strategy is to select the sites arbitrarily. Another more objective strategy and recommended for this study is to first select the sites with the highest overall suitability (from Eq. 41 in Step 6), adding others in the order of decreasing suitability. If there is still a tie after this rule has been applied then sites that meet the most important siting criteria will be selected next. Further ties will be resolved in the same manner, taking one criterion at a time.

The output of this step will be tentative locations for the land use \(k\) that has been allocated.
Step 8: Readjust the sample sites to replace those that have already been selected. Repeat steps 4 through 7 for the next stage, i.e. land use $k+1$ to be allocated. Go to step 9 if all land uses have been allocated.

Step 9: Predict the overall environmental impact $E^i$ of the tentative land use plan generated in step 7 using the NPS model described earlier. The purpose is to consider the resulting land use pattern in a more holistic framework. Terminate the calculation if one of four conditions occurs. The first condition is when the impact is less or equal to the predefined standard (ES), i.e.:

$$
\sum_{j=1}^{C} \sum_{k=1}^{K} e_{ijk}(X)^i \cdot x_{kj}^i \leq ES
$$

The existing water quality criteria for selected pollutants is shown in Table 3.

The second condition is when the solution is stable, i.e. when no further reduction in environmental impacts is possible, i.e.:

$$
\sum_{j=1}^{C} \sum_{k=1}^{K} e_{ijk}(X)^i \cdot x_{kj}^i \leq \sum_{j=1}^{C} \sum_{k=1}^{K} e_{ijk}(X)^{i-1} \cdot x_{kj}^{i-1}
$$

In this case, it means that the area has reached its holding/carrying capacity.

The third condition is when the change in the overall impacts from the present iteration ($d^i$) is less than the change in the previous iteration ($d^{i-1}$), i.e.:

$$
d^i \leq d^{i-1}
$$

where

$$
d^i = \sum_{j=1}^{C} \sum_{k=1}^{K} e_{ijk}(X)^i \cdot x_{kj}^i - \sum_{j=1}^{C} \sum_{k=1}^{K} e_{ijk}(X)^{i-1} \cdot x_{kj}^{i-1}
$$

The fourth condition is when the amount of land allocated to each land use has reached the predefined minimum acreage ($X_{k_{min}}$), i.e.
Table 3: Water Quality Criteria for Selected Pollutants

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Water quality criteria (mg/l)</th>
<th>Domestic water supply</th>
<th>Aquatic life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suspended solids</td>
<td>80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total phosphorous (P)</td>
<td>0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrite-N</td>
<td>0.5</td>
<td>1.60</td>
<td></td>
</tr>
<tr>
<td>Nitrate-N</td>
<td>10.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dissolved oxygen</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cadmium (Cd)</td>
<td>0.01</td>
<td>0.012</td>
<td></td>
</tr>
<tr>
<td>Arsenic (As)</td>
<td>0.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead (Pb)</td>
<td>0.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iron</td>
<td>0.3</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Chromium (Cr)</td>
<td>0.05</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Mercury</td>
<td>0.003</td>
<td>0.00005</td>
<td></td>
</tr>
<tr>
<td>Fecal coliform bacteria</td>
<td>200**</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

** Coliform limit for bathing waters is expressed as MFFCC/100ml. MFFCC is membrane filter fecal coliform counts.

\[ \sum_{j=1}^{C} x_{kj} \geq X_{k_{\text{min}}} \quad (k=1, \ldots, K) \quad (48) \]

This is to ensure that the reduction level chosen is not too low, thus unrealistic.

Since the allocation procedures are partly based on sample data (which are statistical in nature), it is desirable to test whether there is any significant change in the overall impacts resulting from each iteration. This is done using a matched pair t-statistic to test the hypothesis of significance of change at a selected level of significance (e.g. 95%, 97%, etc.). The hypothesis is that the result of the new iteration is better than the result of the previous one. The t-statistic can be computed as follows:

\[ t = \frac{\bar{X} - U_d}{S / \sqrt{n}} \quad (49) \]

where

- \( t \) - t-statistic
- \( U_d \) - the hypothesized mean difference, i.e. zero,
- \( \bar{X} \) - the mean difference between matched pairs,
- \( S \) - the standard deviation of the matched pairs,
- \( n \) - the number of pairs.

If none of the conditions is met, and the differences in result between iterations are statistically significant, then the methodology calls for some adjustments to be made to the land use allocation and the process is repeated. Otherwise, the allocation process stops.

These adjustments can be in many forms including the following:

i). reduce the intensity (i.e. amount) of the land uses to be allocated
   
   This can be accomplished by one of two approaches:
   
   a). reduce the land uses intensity proportionately, or
   
   b). reduce the land uses intensity sequentially in the same order they were allocated. Both of these reduction approaches can also be made on sub-
basin basis (if the study area is divided as such). The reduction can start at
the most critical proceeding to the least critical sub-basin.

ii). modify the weighting system, or the siting criteria.

iii). introduce structural control (e.g. sedimentation basins, seepage beds, treatment
facilities, etc.) to reduce the impact at the watershed outlet.

Among these 3 options, option 1 (i.e. reduction in land use intensity) is selected for this
research. This is in line with the objective of this research to demonstrate the role of land
use planning (i.e. non-structural control) in minimizing environmental impacts. The next
question to be addressed is how to determine the amount of land that should be reduced for
each uses after each iteration. At present, no definite technique (approach) is available to
address this problem.

One possible approach is to select some arbitrary amounts and test their impacts on
a trial-and-error basis. This could mean repeating the whole procedure for each possible
choice, and is time-consuming. The approach suggested for this study is to use the annual
changes (increments) in land requirement as the basis of the reduction. This means that the
land use allocation will begin with the end of the planning time horizon (H), e.g. 20 years.
If the land use plan generated for this period is unacceptable, then the land to be allocated in
the next iteration will be reduced to the (H-t)th year land requirements. Let \( \Delta X_k \) be the
annual increment of land demand for land use \( k \). For reason of simplicity, it is assumed that
the land demand changes equally throughout the planning time frame, thus \( \Delta X_k \) can be
calculated as \(^{10}\):

\[
\Delta X_k = \frac{X_k^H}{H}
\]

(50)

Thus the new land use intensity \( X_{k}^{t+1} \) can be calculated as follows:

\[
X_{k}^{t+1} = X_k^H - (\Delta X_k, t)
\]

(51)

\(^{10}\) It is also possible to use a linear programming model to find the optimal increment in land
demand, i.e. the optimal temporal allocation with respect to certain constraints, but will not be
attempted in this research.
This approach may be justified because one year is usually the smallest time frame for many land use planning activities. Furthermore, this approach could also provide the planners with temporal information at which the study area will reach its natural carrying/holding capacity.

**Step 10:** Determine the new land uses intensity \( X_{k+1} \) for the next iteration \((t+1)\) using Eq. (51). Go back to step 4 to start the next iteration, \( t = t+1 \).

The procedure described above may be considered as a heuristic, search-type procedure, thus there is no guarantee that the solution it produces is optimal. Different land use plans can be generated by varying the initial plan using different siting criteria or weighting system. The performance of this procedure will be evaluated by comparing the results it produces to the results from the traditional land capability/suitability analysis, the random generation method, and the "optimal" solutions, which will be described in the next chapter.
CHAPTER IV
IMPLEMENTATION OF THE PROPOSED METHODOLOGY

In the previous chapter, the conceptual basis of the methodology and solution approach to link land suitability/capability analysis with an environmental model using a geographical information system were developed. In this chapter, the results and analyses of the model are presented.

4.1 Study Area

The Big Darby Creek watershed, located in Central Ohio (Fig. 8) was chosen as a case study for this research. This watershed occupies a drainage area of about 372,500 acres or 580 square miles (Fig. 8). It stretches through 7 counties of Central Ohio, i.e. Champaign, Clark, Franklin, Logan, Madison, Pickaway, and Union counties. This watershed was chosen for several reasons. Westman (1985) has suggested that in order to deal with the problem of spatial interdependency, any land capability analysis should be based upon the appropriate natural ecological boundary suitable for the particular study of interest. For a water quality study such as in this research, this natural boundary is a drainage basin or watershed.

The Big Darby and its tributaries comprise one of the last free-flowing stream ecosystems remaining in Ohio (Betz, et. al, 1989). It has a very unique natural environment and has been named a Scenic River. Until recently the Big Darby Creek has not been under the pressure of urban development. Most of the areas in the watershed are still in agricultural uses. Portions of the watershed are expanding/urbanizing at a relatively rapid rate. This is especially true in those areas located in or nearby the Columbus Standard Metropolitan Statistical Area (SMSA). This development, together with the existing agricultural uses, have contributed a heavy load of nonpoint source pollutants to the creek. These pollutants threaten to destroy the existing wildlife habitat and other unique educational, historical and recreational resources of the creek. Compounding the Big Darby's pollution problems further is the fact that no regional plan is presently in existence.

FIG. 8 - LOCATION OF BIG DARBY CREEK WATERSHED.
to help reduce the pollution load to the stream or to limit the potential negative impacts of urban development (Betz, et. al, 1989). Therefore the preservation of this stream has become a major concern among Central Ohio communities in recent years. Thus the Big Darby Creek can provide an excellent area to demonstrate the application of the proposed methodology.

Another reason for choosing the Big Darby Creek watershed was because of data availability. Data availability is very important to any type of analysis and GIS operations. Data input and database creation are the most time-consuming and costly sub-system of any GIS. One way to save time and reduce this cost is to use existing databases wherever possible. In the case of the Big Darby Creek watershed, a geographic database has recently been created as part of an on-going pilot project for demonstrating the use of remotely sensed and other spatial data for developing land management strategies that will minimize the adverse impacts of agriculture on the Big Darby Creek. A great portion of the information in this database were useful for the present study.

**Demographic trends in the Big Darby Creek Watershed.**

In order to determine the potential impacts of development in the Big Darby Creek watershed, it is important to analyze the past demographic trends and potential future demographic events. The watershed is primarily rural. The population growth from 1970 to 1980 for the counties in the watershed varies between -4.4% and 24.2% (Table 4), with Union County having the highest rate (24.2 %) of growth.

At the township level, the variations in population growth between townships are considerable. Several townships are currently under the pressure of urbanization. The population of Darby (Union County), Brown, Jerome, Pleasant, Monroe and Allen townships increased by 29.4%, 41.9%, 31.1%, 44.9%, 68.1%, and 83.9% respectively between 1970 and 1980 (Table 4). These townships are located close to the Columbus and Marysville urban centers. Several townships on the other hand, were losing population. These include Zane, Pike, Darby (Madison County), Scioto, and Wayne. But recent estimates for the 1986 population indicate that several townships are experiencing a reversal in this demographic trend (Table 5). The populations of Prairie, Jefferson, Darby (Pickaway County), and Scioto townships were estimated to have increased 15.9%, 3.5%,
<table>
<thead>
<tr>
<th>PLACES</th>
<th>POPULATION</th>
<th>GROWTH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1970</td>
<td>1980</td>
</tr>
<tr>
<td>Champaign County</td>
<td>30491</td>
<td>33649</td>
</tr>
<tr>
<td>Goshen Twp</td>
<td>2856</td>
<td>3255</td>
</tr>
<tr>
<td>Rush Twp</td>
<td>1783</td>
<td>2055</td>
</tr>
<tr>
<td>Union Twp</td>
<td>1208</td>
<td>1529</td>
</tr>
<tr>
<td>Wayne Twp</td>
<td>941</td>
<td>1214</td>
</tr>
<tr>
<td>Clark County</td>
<td>157115</td>
<td>150236</td>
</tr>
<tr>
<td>Pleasant Twp</td>
<td>1791</td>
<td>2760</td>
</tr>
<tr>
<td>Franklin County</td>
<td>833249</td>
<td>869132</td>
</tr>
<tr>
<td>Brown Twp</td>
<td>1084</td>
<td>1538</td>
</tr>
<tr>
<td>Norwich Twp</td>
<td>13468</td>
<td>13258</td>
</tr>
<tr>
<td>Pleasant Twp</td>
<td>4187</td>
<td>6068</td>
</tr>
<tr>
<td>Prairie Twp</td>
<td>15704</td>
<td>16340</td>
</tr>
<tr>
<td>Washington Twp</td>
<td>3082</td>
<td>4322</td>
</tr>
<tr>
<td>Logan County</td>
<td>35072</td>
<td>39155</td>
</tr>
<tr>
<td>Monroe Twp</td>
<td>678</td>
<td>925</td>
</tr>
<tr>
<td>Perry Twp</td>
<td>933</td>
<td>872</td>
</tr>
<tr>
<td>Zane Twp</td>
<td>574</td>
<td>568</td>
</tr>
<tr>
<td>Madison County</td>
<td>28318</td>
<td>33004</td>
</tr>
<tr>
<td>Canaan Twp</td>
<td>1065</td>
<td>2210</td>
</tr>
<tr>
<td>Darby Twp</td>
<td>1968</td>
<td>2015</td>
</tr>
<tr>
<td>Deer Creek Twp</td>
<td>1061</td>
<td>1020</td>
</tr>
<tr>
<td>Fairfield Twp</td>
<td>1145</td>
<td>1293</td>
</tr>
<tr>
<td>Jefferson Twp</td>
<td>5747</td>
<td>7055</td>
</tr>
<tr>
<td>Monroe Twp</td>
<td>634</td>
<td>1066</td>
</tr>
<tr>
<td>Pike Twp</td>
<td>448</td>
<td>438</td>
</tr>
<tr>
<td>Pickaway County</td>
<td>40071</td>
<td>43662</td>
</tr>
<tr>
<td>Circleville Twp</td>
<td>13749</td>
<td>15039</td>
</tr>
<tr>
<td>Darby Twp</td>
<td>2116</td>
<td>1268</td>
</tr>
<tr>
<td>Jackson Twp</td>
<td>829</td>
<td>839</td>
</tr>
<tr>
<td>Muhlenberg Twp</td>
<td>543</td>
<td>734</td>
</tr>
<tr>
<td>Scioto Twp</td>
<td>5684</td>
<td>4458</td>
</tr>
<tr>
<td>Wayne Twp</td>
<td>637</td>
<td>531</td>
</tr>
<tr>
<td>Union County</td>
<td>23786</td>
<td>29536</td>
</tr>
<tr>
<td>Allen Twp</td>
<td>616</td>
<td>1133</td>
</tr>
<tr>
<td>Darby Twp</td>
<td>1212</td>
<td>1569</td>
</tr>
<tr>
<td>Liberty Twp</td>
<td>1141</td>
<td>1136</td>
</tr>
<tr>
<td>Millcreek Twp</td>
<td>624</td>
<td>834</td>
</tr>
<tr>
<td>Paris Twp</td>
<td>7721</td>
<td>10542</td>
</tr>
<tr>
<td>Jerome Twp</td>
<td>2509</td>
<td>3290</td>
</tr>
<tr>
<td>Union Twp</td>
<td>1627</td>
<td>1681</td>
</tr>
</tbody>
</table>

Table 5 - Population growth for selected townships in the Big Darby Creek (1980-86)

<table>
<thead>
<tr>
<th>Township</th>
<th>1986</th>
<th>1980</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Darby(Pick)</td>
<td>3,370</td>
<td>1,268</td>
<td>165.77</td>
</tr>
<tr>
<td>Jerome</td>
<td>3,640</td>
<td>3,290</td>
<td>1.00</td>
</tr>
<tr>
<td>Jefferson</td>
<td>7,300</td>
<td>7,055</td>
<td>3.50</td>
</tr>
<tr>
<td>Pleasant</td>
<td>6,450</td>
<td>6,068</td>
<td>6.30</td>
</tr>
<tr>
<td>Prairie</td>
<td>18,900</td>
<td>16,340</td>
<td>15.90</td>
</tr>
</tbody>
</table>

Source: County and City Data Book, 1988.

Table 6 - Population growth for selected cities close to the Big Darby Creek Watershed (1980-1986).

<table>
<thead>
<tr>
<th>City</th>
<th>1986</th>
<th>1980</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hilliard</td>
<td>9,050</td>
<td>8,131</td>
<td>11.30</td>
</tr>
<tr>
<td>Marrysville</td>
<td>11,050</td>
<td>8,694</td>
<td>27.10</td>
</tr>
</tbody>
</table>

Source: County and City Data Book, 1988.
3.1% and 18.2% respectively. Similarly, several cities that are close to the Big Darby Creek were also experiencing relatively high population growth (Table 6).

Looking at the demographic trends of the watershed, it is highly likely that future development will have adverse impact on the water quality of the Big Darby Creek.

**Delineating the study area boundary**

The Big Darby Creek watershed covers an area of about 580 square miles. Formulation of a land use plan and establishment of planning criteria for this entire area is beyond the scope of the present study. The most critical areas to the water quality of the creek, and to this study about urban nonpoint sources pollution are the urbanizing areas. Since water pollutants degrade with distance, those portions of the watershed that are likely to produce the greatest problems are those areas which are adjacent to the creek. For this reason, only those urbanizing areas of Madison, Franklin, and Pickaway counties were chosen for further analysis in this study. As described in the preceding section, a number of townships in these counties have the biggest potential to grow. These include Prairie, Pleasant, and Brown townships of Franklin county; Jefferson township of Madison county; and Darby and Scioto townships of Pickaway county (Table 4 & 5). In a previous study (Gordon and Simpson, 1990), the watershed was divided into 19 sub-basins for analysis. Seven of these sub-basins are located within these areas (Fig. 9). These sub-basins covers an area of about 120,115 acres (188 square miles), and will constitute the study area for this research.

4.2 **Spatial Database**

The data needed for this research will mainly be in the form of physical and environmental data. The physical data includes information such as land uses/cover, topography, soils, zoning, geology, hydrology, and special uses (e.g. wildlife habitat, flood zones, sewer and water facilities, etc.). The environmental data includes data such as the concentration of in-stream and point source CBOD and DO at various reaches, the average flow, and other data to be used for the Streeter-Pheips DO model.

The primary types of data representation (encoding) used by a geographic information system (GIS) are vector and raster (grid). Each of these types of representation has its own strengths and limitations (refer to Section 2.2). To decide which data
LEGEND

- Other sub-basins
- Study area

FIG. 9 - THE BIG DARBY CREEK STUDY AREA.
representation to use in any particular application depends in part on the purpose, software availability, and the existing data sources. For this study, all the data were encoded in raster format. This is because raster-based GIS is commonly used and well-suited for natural resource and environmental management applications. It is also because a major portion of the physical data were derived from an existing geographic data-base recently developed for a demonstration project on nonpoint pollution of the entire Big Darby Creek watershed. Most of the data were organized as a series of map layers, originally encoded using the ERDAS image processing and geographic information system, a raster-based system. The study area was divided into equal size grids of 400 meters. Thus, the area (i.e. cell resolution) of each grid is approximately 40 acres. This grid size is not so large as to cause significant loss of information and appropriate for regional-based analysis as in the case of this study.

**Geographic information system used in the study**

The development and implementation of cartographic models in a GIS environment requires a GIS that is comprehensive as well as powerful in its capabilities. A number of geographic information systems are available at The Ohio State University. These include ARC/INFO, ERDAS, MIPS, OSU MAP-for-the PC, MAP II, MacGIS, SPANS, and IDRISI. None of these systems is superior to the others. They vary in capabilities, ease of use, and complexity. Two geographic information systems were chosen for this study: ERDAS, and MAP II. They were chosen due to the familiarity, capabilities, and ease of accessibility to the systems. The Earth Resources Data Analysis System (ERDAS) developed by ERDAS Inc. of Atlanta, Georgia, was used to digitize all additional maps. ERDAS provides a very easy and user friendly environment for digitizing. It however lacks some of the analytical capabilities needed for this research. Thus, all the digital maps were then imported into MAP II. The MAP II *map processor* (Pazner, Kirby, and Thies, 1989) was developed at the University of Manitoba to run on a Macintosh computer. It is based upon the Map Analysis Package (MAP) originally developed at Yale University by Dr. Dana Tomlin (now at Ohio State University). Though it lacks a formal input sub-system, the package does support a number of data input and output formats including Text (ASCII), TIFF, SYLK, and PICT. It is capable of handling a map size up to 64,000 by 64,000 grid cells, with map zones and layers limit of 32,000. Although the package can only handle integer data values, it can represent such numbers ranging from -2,147,483,647 to 2,147,483,647. It provides powerful analytical capabilities useful for
cartographic modeling described in Section 2.2. It also provides a very user friendly environment.

MAP II was running on Macintosh II computer, available at the Natural Resources Information System Laboratory in the School of Natural Resources. This computer has 8Mb of RAM, and two 3 1/2 inch floppy disk drives (720Kb and 1.4Mb). It was attached to a 600Mb hard disk drive for additional storage, and a 19 inch SuperMac RGB monitor for display purposes. Hardcopy output can be printed either on an Apple Laserwriter or Tektronics 4693D thermal wax printer.

**Data elements**

Using the grid system described earlier, several types of base data were tabulated. They were primarily derived from three sources: topographic, soil, and land use maps. Apart from the existing database, several other maps were digitized using ERDAS and added to the database. These maps include industrial land use, roads, and public facilities. All the maps in the database were registered to the Universal Transverse Mercator (UTM) coordinate system. Additional physical data were created by recoding the existing map layers using the GIS capabilities. The method of tabulations and results of the analysis for each of these types of data are discussed below.

**Topography**

Topography is a major determinant of a site suitability for different land uses. This is because topography influence the type and cost of development, controls the direction and rate of water runoff, adds variety to the landscape, influences the weather and climate, and affects the type of vegetation and wildlife (Meschenberg, 1970). Topographic information can be obtained from many sources. The common source is the topographic maps produced by the United States Geological Survey (USGS). These maps contain specific characteristics such as elevation, hydrography, roads, buildings, and features such as bogs, swamps, and marshes.

Two types of topographic information are useful to this study: slope and aspect. The only topographic information available in the existing database is the aspect data. The slope data was derived from soils information and will be discussed in a later section. Aspect represents the slope orientation of the surface of a cell, and is perpendicular to the
general direction of contours on topographic maps. This data was manually interpreted cell-by-cell from the USGS topographic maps. It can be very useful in locating sites for certain types of land uses sensitive to the direction of the prevailing wind of a region, or to solar radiation, especially during the winter. Maximum radiation is received by a surface that is perpendicular to the direction of the sun (Lynch, 1984). Lynch states that 10% southern slope receives as much direct radiation as flat land 6 degrees closer to the equator. Aspect data is also useful in determining the direction of surface water flows from one site to another and thus is important for nonpoint source water modeling.

Figure 10 shows the aspect of the study area. Most of the cells are oriented to the east (34%). This is because a large portion of the study area is located west of the Big Darby Creek, thus flowing east toward the creek.

**Soils**

The detailed soil map is one of the most important single source of information for land capability/suitability study. It provides information on the property/characteristics of various soil types and how they might affect various land uses. These properties include texture, permeability, flooding potential, slope, depth to water table, and erodibility factor. In terms of water quality, soils play a critical role in the erosion as well as runoff processes. For example, fine textured soils allow water to infiltrate at a lower rate than coarse textured ones. This will affect the amount of water which runs off over the land surface. Increases in runoff entail increases in the ability of the water to erode as well as transport soil particles. Under this condition, there will be greater potential for water pollution to occur.

The study area stretches over 3 counties. Thus over 100 different soil series are found in the study area. Several characteristics of these soils are important for this study. Slope, hydrologic soil groups, and the erodibility (k) factor are 3 physical parameters needed for the environmental modeling. Figure 11 shows the slope map of the study area. About 90 percent of the study area is located on relatively flat areas with slopes of less than 6%. Areas with high slope (> 25%) are relatively small (2%), located mostly along the Big Darby Creek and its tributaries. A large portion of the study area is located on soils with high erodibility factor ( > .37), thus highly susceptible to erosion problems (Fig. 12). Similarly, about 57 percent of the area is located on soils with hydrologic soil groups C and
FIG. 10 - TOPOGRAPHIC ASPECT OF THE STUDY AREA.
FIG. 11 - TOPOGRAPHIC SLOPE OF THE STUDY AREA.
FIG. 12 - SOIL ERODIBILITY (K) FACTOR OF THE STUDY AREA

**LEGEND**

- 0.01
- 0.02
- 0.24
- 0.28
- 0.32
- 0.37
- 0.43
D (Fig. 13). These soils have slow/very slow infiltration rates when thoroughly wet, and high surface runoff potential.

Other soil characteristics such as depth to water table, flooding potential, drainage class, frost action potential, corrosion potential, and bearing capacity are useful for the land suitability/capability study. The spatial distribution of some these characteristics are shown in Figures 14 to 16.

**Land uses**

The study of existing land use patterns is another important consideration in land use suitability analysis and modeling. Existing land use data show areas that have been developed, and those available for future urban development. Land use data are also useful in determining the compatibility of different land uses in order to maintain land use harmony and minimize conflicts (impacts). In addition, the analysis of land use data from different time periods can provide information on land use changes or urban growth. Land uses also affect the quantity and quality of nonpoint source pollution, and are critical input data to the urban nonpoint model to be used for this research.

Two sets of land use data were available for this study: 1965, and 1979. The land uses were originally classified into 4 broad classes: commercial/urban, residential, agricultural, and forests/open. The 1979 land use data were later edited to separate commercial from industrial land uses. This was necessary because the present study involves the allocation of industrial land use, which has different siting requirements and environmental impacts with regard surrounding land uses. The editing was made by digitizing only industrial land use from the existing analog land use maps. These data were then merged with the existing land use map layer to create a new layer comprised of 5 major land use classes: industrial, commercial, residential, agricultural, and forest.

Figures 17 and 18 show the distribution and composition of the 1965 and 1979 land uses in the study area. Only about 20% of the area was developed for industrial, commercial, residential, and other urban uses. A great portion (79%) is still undeveloped, occupied by agriculture and forest. However, the rate of rural to urban land conversion was relatively high for the past 15 years. A recent report by Gordon and Simpson (1990) indicates that the urban development in the Big Darby Creek watershed has quadrupled
FIG. 13 - HYDROLOGIC SOIL GROUP OF THE STUDY AREA.
LEGEND

- Not rated - Urban
- Not rated - Other
- None
- Occasional
- Frequent

FIG. 14 - FLOODING POTENTIAL OF THE STUDY AREA.
FIG. 15 - SOILS DRAINAGE CLASS OF THE STUDY AREA.
FIG. 16 - SOIL BEARING CAPACITY OF THE STUDY AREA.
FIG. 17 - LAND USES OF THE BIG DARBY CREEK STUDY AREA (1965)
LEGEND

- Industrial
- Commercial
- Residential
- Agriculture
- Forest

FIG. 18 - LAND USES OF THE BIG DARBY CREEK STUDY AREA (1979)
during the period of 1965-1988, at a rate of about 250 acres/year. The majority of the growth has occurred due to the growth of Columbus and Marysville urban centers.

Transportation

Another important data element for this study is the availability of different types of transportation facilities. This is useful in assessing site accessibility, which is an important locational factor for various urban land uses.

The two major types of transportation facilities available in this study area are roads and railroads. This data was derived by digitizing the topographic maps. Fig. 19 show the spatial distribution of these transportation facilities. Two interstate expressways pass through the study area; the Interstate Highway 75 on the north and Interstate Highway 70 on the south. Three railway tracks also pass through the study area on the north, center, and south respectively.

Public facilities

The suitability of any site for certain land use is in part influenced by its proximity to and the availability of public facilities. These facilities include hospital/health clinic, schools, library, fire and police protection, civic center, churches, and parks.

Public facilities information for this study was derived from the USGS topographic maps. Although these maps may not be the ideal data source for public facility location, they do provide useful information for this demonstration. These facilities were digitized using ERDAS and converted to MAP II. They include hospitals, schools, churches, and parks. Figure 20 shows the spatial distribution of these facilities.

4.3 Environmental Data

Several environmental data were needed for the urban runoff and dissolved oxygen modeling. The urban runoff (nonpoint source) modeling requires physical data (such as soil hydrologic group, slope, land uses) as well as the pollutant loading for each land use. The physical data have been discussed earlier, and Table 1 (page 62) shows the ranges of pollution concentration for selected land uses derived from the literature. The average concentrations were used in this study (Table 7).
LEGEND

- Non-road area
- Secondary road
- Primary road
- Highway
- Railroad

FIG. 19 - MAJOR ROADS IN THE BIG DARBY CREEK STUDY AREA.
LEGEND
- Other land uses
- Elementary school
- High school
- Church
- Hospital
- Park

FIG. 20 - SELECTED PUBLIC FACILITIES IN THE STUDY AREA.
To model the in-stream dissolved oxygen level using the Streeter-Phelps model, the Big Darby Creek and its tributaries (Fig. 21) were divided into seven reaches, each of which corresponds to a sub-basin in the study area (Fig. 22). The model also requires basic parameters such as the initial dissolved oxygen, initial BOD, initial discharge, BOD and discharge from point sources, stream deoxygenation (CBOD removal) and reaeration rates, water temperature, velocity, and reach length. To date no comprehensive D.O modeling has been done for the Big Darby Creek, thus very few data were available for that purpose. The only information available that is useful for this research is the initial(ambient) dissolved oxygen and BOD, and water temperature. These data were obtained from the Ohio Environmental Protection Agency. In the absence of any other data, most of the parameters for the modeling were approximated using equations available in the literature. These equations relate the selected parameters to channel characteristics such as depth, flow, cross-sectional area, and wetted perimeter which are readily available from topographic maps or aerial photographs. The parameters approximated using this procedure include stream velocity, discharge, and deoxygenation and reaeration rates.

The velocity (U) and channel flow (q) were estimated using procedures based on the hydraulic principles known as slope-area computation. The common formula for estimating velocity is the Manning equation (SCS, 1986):

\[
U = \frac{1.49 \ R^{2/3} \ S^{1/2}}{c}
\]

(52)

where

- \( R \) - hydraulic radius (ft) which is equal to \( A/P_w \)
- \( A \) - cross sectional flow area (sq.ft)
- \( P_w \) - wetted perimeter (ft)
- \( S \) - channel slope (ft/ft)
- \( c \) - Manning's roughness coefficient for open channel flow.

The accuracy of this equation largely depend upon \( c \), the Manning's coefficient. A value of 0.039 is usually used for a natural channel.

The above equation can also be used to estimate the channel discharge rate. The Chevy-Manning formula is ordinarily used for this purpose, which can be expressed as follows:
FIG. 21 - HYDROLOGY OF THE BIG DARBY CREEK STUDY AREA..
LEGEND
- Stream reach
- First order stream
- Second order stream
- Third order stream
- Fourth order stream
- Subbasin outlet

FIG. 22 - DIVISION OF BIG DARBY CREEK INTO STREAM REACHES
\[ q = 1.49 \ A \ R^{2.5} \ S^{1.2} \quad (53) \]
\[ = A \ . \ U \quad (54) \]

Several equations are also available for estimating the deoxygenation \((K_d)\) and reaeration \((K_r)\) coefficients. Tsivoglou and Wallace (1972) developed an equation for estimating reaeration coefficients that have been found to compare well to observed reaeration rates, especially for small streams. They assume that the reaeration coefficient for a reach is proportional to the change in elevation of the water surface in the reach and inversely proportional to the flow (travel) time through the reach (Brown & Barnwell, 1985). The equation has the following form:

\[ (K_r)_{20} = \frac{C_e \ H}{T_f} \quad (55) \]

where
- \( H \) - difference in water surface elevation between the beginning and end of a stream reach, ft
- \( T_f \) - flow time within reach, day·
- \( C_e \) - escape coefficient, ft\(^{-1}\)

This equation can also be represented as:

\[ (K_r)_{20} = (3600 \times 24) \ C_e \ S \ U \quad (56) \]

where \( S \) is the channel slope (ft/ft), and \( U \), the mean velocity in reach (ft/sec). The escape coefficient, \( C_e \) can be estimated as follows:

\[ C_e = 0.054 \ \text{ft}^{-1} \text{ (at } 20^\circ \text{ C) for } 15 \leq Q \leq 3000 \ \text{ft}^3/\text{sec} \quad (57) \]
\[ C_e = 0.110 \ \text{ft}^{-1} \text{ (at } 20^\circ \text{ C) for } 1 \leq Q \leq 15 \ \text{ft}^3/\text{sec} \quad (58) \]

The reaeration rate changes with temperature, thus for any given temperature, it can be determined as follows:

\[ (K_r)_T = (K_r)_{20}(\phi)^{T\cdot20} \quad (59) \]

where \( \phi \) is the temperature-correction factor, which generally ranges from 1.005 to 1.030, with a value of 1.024 often used (Thamann and Mueller, 1987).

Several attempts have also been made to correlate BOD decay, \( K_d \), to channel characteristics such as depth, flow and wetted perimeter. The formulation used in the present study is the one developed by Wright and McDonall (1979):

\[ (K_d)_{20} = 10.3Q^{-0.49} \quad (60) \]
The oxidation of the CBOD is a bacterially mediated process, thus the $K_d$ rate changes with water temperature. This process can be approximated by:

$$(K_d)_T = (K_d)_{20} \beta T - 20$$  \hspace{1cm} (61)

where $(K_d)_T$ and $(K_d)_{20}$ are the decay rate at water temperature, $T$ ($^\circ C$) and at $20^\circ$ C respectively. The value of $\beta$ is reported to range from 1.02 to 1.09 (Zison, et al., 1985). In practice, $\beta$ is usually assumed to be 1.047.

The geometric characteristics of the seven reaches used to estimate these parameters are shown in Appendix A. The existing ambient biological oxygen demand (BOD), dissolved oxygen, and temperatures were assumed to be the worst case summer condition. This is usually the period at which the stream dissolved oxygen concentrations are at the critical levels. The stormwater runoff was simulated using a 24-hour 25 year rainfall of 2.5 inches (SCS, 1985). The curve number for each land use was defined using the land use and hydrologic soil group combination (matrix) shown in Table 8.

Using all the parameters that have been defined, the impacts of the existing land uses on the stormwater runoff and the stream dissolved oxygen concentrations were simulated using the computer program developed for this research (Appendix B). The results of this simulation is shown in Table 9, and constitutes the initial water quality for this study. The table shows that the existing (simulated) water quality of the Big Darby Creek is relatively high. The dissolved oxygen concentrations at the watershed outlet and all reaches are above 6 mg/l, the minimum standard for a stream to be classified as an exceptional warm water habitat. Reach 3, which is one of the major tributaries of Big Darby Creek, has the lowest dissolved oxygen concentration. This reach is located in Subbasin 13, which is the most urbanized sub-basin in the watershed. Any further urban development in this sub-basin can further degrades the water quality of this reach, and the Big Darby Creek as a whole.

4.4 Descriptive Modeling

The conceptual framework of the descriptive models for the industrial, commercial and residential land uses have been described in Chapter 3. These models were formulated without regard to data availability. In order to implement these models, several modifications were made to suit the data available for this research.
Table 7 - **Average BOD concentrations used in the nonpoint source modeling**

<table>
<thead>
<tr>
<th>Land use type</th>
<th>Pollutant Concentration (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest/Open</td>
<td>1.50</td>
</tr>
<tr>
<td>Agriculture</td>
<td>5.00</td>
</tr>
<tr>
<td>Residential</td>
<td>7.00</td>
</tr>
<tr>
<td>Commercial</td>
<td>10.00</td>
</tr>
<tr>
<td>Industrial</td>
<td>15.00</td>
</tr>
</tbody>
</table>

Table 8 - **Land use and Hydrologic Soil Group Combination (Matrix) to Define the Curve Number Used in the Study**

<table>
<thead>
<tr>
<th>Land uses</th>
<th>Hydrologic Soil Group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Industrial</td>
<td>81</td>
</tr>
<tr>
<td>Commercial</td>
<td>89</td>
</tr>
<tr>
<td>Residential</td>
<td>51</td>
</tr>
<tr>
<td>Agriculture</td>
<td>66</td>
</tr>
<tr>
<td>Forest/Open</td>
<td>36</td>
</tr>
</tbody>
</table>

Source: SCS (1986).
Table 9. The Existing (Simulated) Environmental Quality of the Study Area.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2133.52</td>
<td>6.36</td>
<td>6.86</td>
<td>6.51</td>
</tr>
<tr>
<td>2</td>
<td>2598.46</td>
<td>4.90</td>
<td>7.01</td>
<td>6.51</td>
</tr>
<tr>
<td>3</td>
<td>2346.16</td>
<td>6.24</td>
<td>6.06</td>
<td>6.06</td>
</tr>
<tr>
<td>4</td>
<td>2012.78</td>
<td>5.42</td>
<td>6.98</td>
<td>6.51</td>
</tr>
<tr>
<td>5</td>
<td>1665.34</td>
<td>4.40</td>
<td>6.72</td>
<td>6.51</td>
</tr>
<tr>
<td>6</td>
<td>1381.38</td>
<td>6.30</td>
<td>6.55</td>
<td>6.51</td>
</tr>
<tr>
<td>7</td>
<td>1681.63</td>
<td>4.72</td>
<td>6.51</td>
<td>6.51</td>
</tr>
</tbody>
</table>
The suitability of the sites in the study area for each land use is determined using the linear weighted combination method. Under this method, suitability points were assigned to certain values (data classes) of each factor. Suitability points range from 1 to 5, where 1 is the least suitable and 5 is the most suitable. Each factor was also assigned a weight indicating its relative importance in determining the overall suitability for each particular land use. These weights also range from 1 to 5, where 5 indicates that a factor is 5 times more important than those with the lowest (1) weight. The suitability points were multiplied by the factor weight and then summed up to give a total (overall) suitability score. The suitability points and weights were assigned to the factors on the basis of the existing literature, and where information was lacking, by arbitrary assignment.

Each of the implemented suitability models and their results will be described below. However, with the exception of industrial land use, only the results of the site suitability can be described in this section as the situation suitability, thus overall suitability can only be determined after the allocation process has begun; and will be described in the prescriptive modeling section.

**Industrial land use suitability analysis**

The industrial sector plays an important role in every locality. It provides basic employment and tax revenue to the local economy. In terms of land use planning, industrial land use needs to be properly located in order to minimize its impacts on the environment as well as on the general public. This land use requires a different set of siting requirements as compared to the commercial and residential land uses. The conceptual land capability/suitability (descriptive) model and the general siting requirements for this land use have been described in the previous chapter. Table 10 shows the ratings and weighting of the factors used in the analysis.

Functional/locational factors were judged to be the most important determinant of the suitability of a land area for industrial development. These factors include the accessibility to transportation services, and compatibility with surrounding land uses. The most important location consideration for industrial development is the array of transportation services available at the site (ULI, 1975) and thus these were given the highest (5) weight. Interstate highways have a strong influence on the location of modern
Table 10: Siting Criteria for Industrial Land Use

<table>
<thead>
<tr>
<th>FACTOR</th>
<th>Suitability points *</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td><strong>COST</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil &amp; geologic suitability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth to bedrock **</td>
<td>&gt; 5 ft</td>
<td>2.5 ft</td>
</tr>
<tr>
<td>Flooding potential</td>
<td>Low</td>
<td>Low-Moderate</td>
</tr>
<tr>
<td>Drainage class</td>
<td>Well-drained</td>
<td>Moderately well-drained</td>
</tr>
<tr>
<td>Frost action potential</td>
<td>Low</td>
<td>Low-Moderate</td>
</tr>
<tr>
<td>Depth to water table **</td>
<td>&gt; 5 ft</td>
<td>3.5 - 5 ft</td>
</tr>
<tr>
<td>Shrink-swell potential</td>
<td>Low</td>
<td>Low-Moderate</td>
</tr>
<tr>
<td>Corrosion potential</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- steel</td>
<td>Low</td>
<td>Low-Moderate</td>
</tr>
<tr>
<td>- concrete</td>
<td>Low</td>
<td>Low-Moderate</td>
</tr>
<tr>
<td>Bearing capacity</td>
<td>Clean gravel &amp; sand</td>
<td>Silty &amp; clayey gravels</td>
</tr>
<tr>
<td>Soil erosion</td>
<td>&lt; 8 t/a</td>
<td>8 - 20 t/a</td>
</tr>
<tr>
<td>Limitation for landfill</td>
<td>Low</td>
<td>Low-Moderate</td>
</tr>
<tr>
<td><strong>Topographic limitation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Land slope</td>
<td>1 - 2 %</td>
<td>2 - 6 %</td>
</tr>
<tr>
<td>**Land availability *****</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Existing land uses</td>
<td>Forest, agriculture</td>
<td></td>
</tr>
<tr>
<td>Built-up areas &amp; water body</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>FUNCTIONAL</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accessibility to transportation network</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proximity to highway</td>
<td>&lt; 1 mile</td>
<td>1 - 3 miles</td>
</tr>
<tr>
<td>Proximity to primary roads</td>
<td>&lt; 1 mile</td>
<td>1 - 3 miles</td>
</tr>
<tr>
<td>Proximity to highway intersection</td>
<td>&lt; 1.5 miles</td>
<td>1.5 - 3 miles</td>
</tr>
</tbody>
</table>
Table 10 (continued)

<table>
<thead>
<tr>
<th>FACTOR</th>
<th>Suitability points *</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Proximity to railroad</td>
<td>.25 - 1 mile</td>
<td>1 - 3 miles</td>
</tr>
<tr>
<td>Proximity to supporting land uses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proximity to other **** industrial areas</td>
<td>&lt;1 mile</td>
<td>1 - 3 miles</td>
</tr>
<tr>
<td>Proximity to city center</td>
<td>&lt; 5 miles</td>
<td>5 - 10 miles</td>
</tr>
<tr>
<td>Proximity to hospital</td>
<td>&lt; 3 miles</td>
<td>3 - 5 miles</td>
</tr>
<tr>
<td>Accessibility to center of population</td>
<td>&lt;30 min</td>
<td>30 - 45 min</td>
</tr>
<tr>
<td><strong>ENVIRONMENTAL</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water - related impacts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance to water body</td>
<td>&gt; 2000 ft</td>
<td>1000 - 2000 ft</td>
</tr>
<tr>
<td>Noise/air-related impacts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance to commercial areas</td>
<td>&gt; 2600 ft</td>
<td>1300 - 2600 ft</td>
</tr>
<tr>
<td>Distance to residential areas</td>
<td>&gt; 3200 ft</td>
<td>1600 - 3200 ft</td>
</tr>
</tbody>
</table>

Note:  
* 5 - "most suitable"  4 - "suitable"  3 - "moderately suitable"  
2 - "marginally suitable"  1 - "least suitable"  
** Soil Conservation Service does not record soils information for depths below five feet.  
*** This factor is rated as 0 or 1, where 1 indicates the land is available, and 0 not available.  
**** These are the situation criteria used in this research. All others are site criteria. Actually all those criteria that fall under function and environmental could be considered as situation criteria. However, some of them are not modeled in this research, thus are considered as site criteria.
industrial plants. To take advantage of this service, industrial areas are usually located within two and one-half miles of a highway interchange. Highway locations also provide good visibility to industrial areas. Adjacency to the main line of a railroad is also desirable. Most industrial areas have rail on site, or have an available right-of-way for a spur to a main line within three miles (ULI, 1975). New industries will also benefit if located in close proximity to other industries closely related to, or relying upon their production process (ULI, 1975; Stafford, 1979). Thus, the close proximity to related industrial activities can reduce production costs by eliminating unnecessary movement of goods and personnel. Industries may also join together to develop collective facilities such as research institutions, or marketing organizations that individual manufacturers would be unable to provide for themselves.

Among the physical/costs factors, topography was judged to be the most important determinant of the suitability of a land area for industrial development (Keifer, 1965). The slopes must be flatter than those required for residential development. The requirements for other soil characteristics such as drainage class, depth to bedrock, depth to water, and flooding potential are less limiting because higher site development costs can generally be tolerated for industrial development, as long as the location is favorable. The costs of land and construction are usually only a small proportion of investment and operating costs, thus the "correctness" of the site is always much more important than its cost (Stafford, 1979). Most of the cost factors are related to soil characteristics, and their ratings were directly derived from the soil survey.

Fig 23 shows the industrial land use suitability model as implemented using the existing database and MAP II geographic information system. The figure shows the transformation of the base maps to derive several intermediate map layers to arrive at the final objective. These intermediate layers were then combined to create the final suitability map. Of the intermediate layers, the travel friction map layer needs further clarification. This map layer was used in all the proximity analysis. It represents the difficulty/cost of traveling across the land surface. Friction values have the effect of increasing distance values on the output map. A friction value of 0 means that no friction was used in the proximity analysis, thus the distance is calculated as direct Euclidean distance. A higher friction value means that travel through that zone is more difficult (or costly) than traveling through a zone without any friction. For the purpose of this study, highways were given
FIG. 23. SITE SUITABILITY MODEL FOR INDUSTRIAL LAND USE
FIG. 23 (continued)

SITE SUITABILITY MODEL FOR INDUSTRIAL LAND USE
FIG. 23 (continued)

SITE SUITABILITY MODEL FOR INDUSTRIAL LAND USE
no friction value as it is assumed that this provide the fastest access time. Primary and secondary roads were then weighted accordingly. It is assumed that traveling on the primary, and secondary roads is about 20% and 45% more difficult (slower) than traveling on a highway respectively. This calculation was based on the speed limit of 65, 55, and 45 miles per hour for highway, primary, and secondary roads respectively. Friction values were also assigned to land areas. In this case, the friction values were computed modified by an inverse distance function. This inverse distance function is intended to reduce the effect of transportation availability relative to distance from the cell. In other words, the difficulty/cost of development increases exponentially as one goes farther away from the road networks, thus giving greater advantages to sites with direct access to the network.

The suitability map for the industrial land use is shown in Fig. 24. The map shows that sites with the highest suitability scores are those located near major transportation network. Unlike commercial and residential land uses, the result of this suitability analysis constitute the final suitability for the land use. This is because industrial land use is the first one to be allocated in the allocation process, and will not be affected by other land uses to be allocated.

**Commercial land use suitability analysis**

Commercial services are major structuring elements as well as population-serving uses. They determine the shopping and work-trip patterns, thus are desirable for the distribution of residential uses (Chapin and Kaiser, 1979). On the other hand, they are also population-serving uses which are not as locationally independent of the local market as industrial or other similar employment generating activities. The location of commercial areas is most sensitive to the accessibility to, and the density and arrangement of residential areas (Keifer, 1965; Chapin, and Kaiser, 1979). In practice, the development of commercial areas goes hand-in-hand with the development of residential areas, and is usually located in or near the areas that are suited for residential areas.

Table 11 shows the ratings and weights of the factors used in determining the suitability of commercial land use. These factors are almost identical to those used for industrial land use, except that their ratings and relative importance are different. Commercial land use requires a much more competitive location. The suitability model for the commercial land use is shown in Figure 25. The input data to this model are similar to
FIG. 24 - SITE SUITABILITY FOR INDUSTRIAL LAND USE
Table 11: Siting Criteria for Commercial Land use

<table>
<thead>
<tr>
<th>FACTOR</th>
<th>Suitability points *</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td><strong>COSTS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil &amp; geologic suitability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth to bedrock **</td>
<td>&gt; 5 ft</td>
<td>2-5 ft</td>
</tr>
<tr>
<td>Flooding potential</td>
<td>Low</td>
<td>Low-Moderate</td>
</tr>
<tr>
<td>Drainage class</td>
<td>Well-drained</td>
<td>Moderately well-drained</td>
</tr>
<tr>
<td>Frost action potential</td>
<td>Low</td>
<td>Low-Moderate</td>
</tr>
<tr>
<td>Depth to water table **</td>
<td>&gt;5 ft</td>
<td>3.5 - 5 ft</td>
</tr>
<tr>
<td>Shrink-swell potential</td>
<td>Low</td>
<td>Low-Moderate</td>
</tr>
<tr>
<td>Corrosion potential - steel</td>
<td>Low</td>
<td>Low-Moderate</td>
</tr>
<tr>
<td>Corrosion potential - concrete</td>
<td>Low</td>
<td>Low-Moderate</td>
</tr>
<tr>
<td>Bearing capacity</td>
<td>Clean gravel &amp; sand</td>
<td>Silt &amp; clayey gravels</td>
</tr>
<tr>
<td>Soil erosion</td>
<td>&lt; 8 t/a</td>
<td>8 - 20 t/a</td>
</tr>
<tr>
<td><strong>Topographic limitation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Land slope</td>
<td>1 - 2 %</td>
<td>2 - 6 %</td>
</tr>
<tr>
<td>**Land availability *****</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Existing land uses</td>
<td>Forest, agriculture</td>
<td>Built-up areas &amp; water body</td>
</tr>
<tr>
<td><strong>FUNCTIONAL</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accessibility to transportation network</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proximity to highway / primary road</td>
<td>&lt; 1.5 mile</td>
<td>0.5 - 1 mile</td>
</tr>
<tr>
<td>Proximity to highway intersection</td>
<td>&lt; 1 mile</td>
<td>1 - 3 miles</td>
</tr>
<tr>
<td><strong>Proximity to supporting land uses</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proximity to other ***** commercial areas</td>
<td>&lt;3 mile</td>
<td>3 - 5 miles</td>
</tr>
<tr>
<td>Proximity to hospital</td>
<td>&lt; 3 miles</td>
<td>3 - 5 miles</td>
</tr>
</tbody>
</table>
Table 11 (continued)

<table>
<thead>
<tr>
<th>FACTOR</th>
<th>Suitability points *</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Proximity to city center</td>
<td>&lt; 3 mile</td>
<td>3 - 5 miles</td>
</tr>
<tr>
<td>Accessibility to center</td>
<td>&lt; 10 min</td>
<td>10 - 30 min</td>
</tr>
<tr>
<td>of population</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ENVIRONMENTAL</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water-related impacts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance to water body</td>
<td>&gt; 1000 ft</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Noise/air-related impacts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance to industrial areas</td>
<td>&gt; 2600 ft</td>
<td>1300 - 2600 ft</td>
</tr>
<tr>
<td>trial areas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance to residential areas</td>
<td>&gt; 3200 ft</td>
<td>1600 - 3200 ft</td>
</tr>
</tbody>
</table>

Note:--  
*  5 - "most suitable"  4 - "suitable"  3 - "moderately suitable"  
2 - "marginally suitable"  1 - "least suitable"  

**  Soil Conservation Service does not record soils information for depths below five feet.  
***  This factor is rated as 0 or 1, where 1 indicates the land is available, and 0 not available.  
**** These are the situation criteria used in this research. All others are site criteria. Actually all those criteria that fall under function and environmental could be considered as situation criteria. However, some of them are not modeled in this research, thus are considered as site criteria.
FIG. 25. SITE SUITABILITY MODEL FOR COMMERCIAL LAND USE
FIG. 25 (continued)

SITE SUITABILITY MODEL FOR COMMERCIAL LAND USE
SITE SUITABILITY MODEL FOR COMMERCIAL LAND USE
those used for the industrial so that the same description applies. Figure 26 shows the areas with high suitability for commercial land use. These are the areas that met the criteria set forth above, the areas located along the major roads network, and close proximity to residential areas. Unlike the industrial land use, the suitability map derived in this analysis does not constitute the final suitability. It only reflects the site characteristics. The final suitability will be derived once the industrial land use has been allocated, to be described in the prescriptive modeling section.

**Residential land use suitability analysis**

The third and last group of land uses to be considered in this study is residential. Residential land uses account for the greatest percentage of developed land in metropolitan fringe areas (Keifer, 1965). Besides providing shelter, residential areas are also the primary determinant of the general location of other related land uses such as commercial centers, and public facilities. Since the cost of housing is incurred by the resident, factors affecting the costs of land and construction are of primary importance to the location of residential areas. Thus, topographic characteristics, soil class, drainage class, depth to bedrock, and depth to water table are among the most important determinants of the suitability of the area for residential land use development (Keifer, 1965). At the same time, residential areas also need to be in close proximity to various public facilities and services. In addition, residential activities also require a pleasant environment, free of any environmental disturbance such as noise or air pollution from highways, railways, and industries.

Table 12 shows the criteria used in determining the suitability of the study area for residential development. These criteria were used as the basis for the development and implementation of the suitability model in the GIS environment, and is shown in Fig. 27. The final site suitability map (Fig. 28) shows the areas with high suitability for residential development. These areas met most of the siting criteria set forth, and are potential candidates for future development.
FIG. 26 - SITE SUITABILITY FOR COMMERCIAL LAND USE
Table 12: Siting Criteria for Residential Land Use

<table>
<thead>
<tr>
<th>FACTOR</th>
<th>Suitability points *</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td><strong>COST</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil &amp; geologic suitability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth to bedrock ** &gt; 5 ft</td>
<td>2-5 ft</td>
<td>&lt; 2 ft</td>
</tr>
<tr>
<td>Flooding potential Low</td>
<td>Low-Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Drainage class</td>
<td>Well-drained</td>
<td>Moderately well-drained</td>
</tr>
<tr>
<td>Frost action potential Low</td>
<td>Low-Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Depth to water table ** &gt; 5 ft</td>
<td>3.5 - 5 ft</td>
<td>2 - 3.5 ft</td>
</tr>
<tr>
<td>Shrink-swell potential Low</td>
<td>Low-Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Corrosion potential</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- steel Low</td>
<td>Low-Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>- concrete Low</td>
<td>Low-Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Bearing capacity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clean gravel &amp; sand</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silty &amp; clayey gravels</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silty &amp; clayey sands</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-plastic silts &amp; clays</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plastic &amp; organic silts &amp; clays; peats, muck</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Soil erosion  &lt; 8 t/a</td>
<td>8 - 20 t/a</td>
<td>&gt; 20 t/a</td>
</tr>
<tr>
<td>Limitation for septic tank</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>Moderate</td>
<td>Moderate-High</td>
</tr>
<tr>
<td>Topographic limitation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Land slope 1 - 2 %</td>
<td>2 - 6 %</td>
<td>6 - 12 %</td>
</tr>
<tr>
<td>Land availability ***</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Existing land uses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forest, agriculture</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Built-up areas &amp; water body</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Functional</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accessibility to transportation network</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Access to secondary/ local roads &lt; 0.5 mile</td>
<td>0.5 - 1 mile</td>
<td>&gt; 1 mile</td>
</tr>
<tr>
<td>Proximity to highway / primary road &lt; 1 mile</td>
<td>1 - 3 miles</td>
<td>&gt; 3 miles</td>
</tr>
<tr>
<td>Proximity to supporting land uses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proximity to other**** residential areas &lt; 2 mile</td>
<td>2 - 5 mile</td>
<td>&gt; 5 mile</td>
</tr>
</tbody>
</table>
Table 12 (continued)

<table>
<thead>
<tr>
<th>FACTOR</th>
<th>Suitability points *</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Proximity to elementary school</td>
<td>&lt; 1 mile</td>
<td>1 - 3 mile</td>
</tr>
<tr>
<td>Proximity to high school</td>
<td>&lt; 2.5 mile</td>
<td>2.5 - 5 miles</td>
</tr>
<tr>
<td>Proximity to local **** shopping center</td>
<td>&lt; 1.5 mile</td>
<td>1.5 - 4 mile</td>
</tr>
<tr>
<td>Proximity to urban center</td>
<td>&lt; 2 mile</td>
<td>2 - 5 miles</td>
</tr>
<tr>
<td>Proximity to hospital/ church</td>
<td>&lt; 2 miles</td>
<td>2 - 5 miles</td>
</tr>
<tr>
<td>Proximity to open spaces</td>
<td>&lt; 1 mile</td>
<td>1 - 3 miles</td>
</tr>
<tr>
<td>Accessibility to place of work</td>
<td>&lt; 30 min</td>
<td>30 - 45 min</td>
</tr>
</tbody>
</table>

**ENVIRONMENTAL**

*Water-related impacts*

- Distance to water body: > 1000 ft | < 1000 ft | 3

*Noise/air-related impacts*

- Distance to highway: > 2600 ft | 1300 - 2600 ft | < 1300 ft | 5
- Distance to rail road: > 2600 ft | 1300 - 2600 ft | < 1300 ft | 5
- Distance to industrial areas: > 3900 ft | 1600 - 3200 ft | < 1600 ft | 5
- Distance to commercial areas: > 2600 ft | 1300 - 2600 ft | < 1300 ft | 3

Note:-

* 5 - "most suitable" 4 - "suitable" 3 - "moderately suitable"
2 - "marginally suitable" 1 - "least suitable"

** Soil Conservation Service does not record soils information for depths below five feet.

*** This factor is rated as 0 or 1, where 1 indicates the land is available, and 0 not available.

**** These are the situation criteria used in this research. All others are site criteria. Actually all those criteria that fall under function and environmental could be considered as situation criteria. However, some of them are not modeled in this research, thus are considered as site criteria.
FIG. 27. SITE SUITABILITY MODEL FOR RESIDENTIAL LAND USE
FIG. 27 (continued)

SITE SUITABILITY MODEL FOR RESIDENTIAL LAND USE
FIG. 27 (continued)

SITE SUITABILITY MODEL FOR RESIDENTIAL LAND USE
FIG. 28 - SITE SUITABILITY FOR RESIDENTIAL LAND USE
4.5 Prescriptive Modeling

Land use demand

In the preceding section, the suitability of the study area for the 3 land uses was analyzed. This constitutes the land supply for the allocation process. Another critical data needed is the land use demand. The proposed methodology assumed that data on future land use demands for each land use is given, that is, determined exogenously. Unfortunately, these data were not available for the study area, thus were estimated for this research.

Specific techniques for estimating demand vary with the class of land use being analyzed. However, they do share a common four-step pattern (Chapin and Kaiser, 1979). The first step involves reviewing the existing density characteristics for each particular land use and the variation in these densities. The next step involves obtaining forecasts of or plans for future growth or decline of the land use category in question. For instance, projected population level and future employment estimates are usually used as growth indices for residential and industrial space needs respectively. The third step involves a derivation of future space standards or proposed densities. This may be based on a coordination of existing densities; on local, regional, and national trends; and on planning principles standards/demands from goals, objectives, and higher-level policies (Chapin and Kaiser, 1979). The last step is the application of these standards to the projected levels of growth or decline to determine the amount of future land demand.

The basic input data for this procedure is the forecast of future growth, and the standards. The standards were obtained from the literature. The forecasts of future growth, which are usually derived from projected population are lacking for the study area, thus were estimated as discussed below.

Population projection

The goal of these projections is not to arrive at an exact population figure, but just to give an estimate which can be employed to determine land demand and to simulate the water quality impacts of urban development in the Big Darby Creek. Several population projection techniques are presently available. These include historical trending,
mathematical trending, regression techniques, ratio and non-component techniques such as the step-down approach, and projections based on trends in the mortality, fertility, and migration components of population change (Cohort survival analysis) (Pittrenger, 1976). Each of these methods has its own strengths and limitations. The major flaw in each projection method lies in its assumption concerning the relationship between past and future demographic trends. However, the accuracy of the population forecast is not critically important in the present research, since it is only used to help drive the land use and environmental simulations.

Population growth in any local area is usually influenced to a great extent by regional trends at the national and states levels. Alternative projections at these regional levels are usually readily available from the Bureau of the Census or regional (state) planning agencies. These projections may then be stepped down to the county and townships (or minor civil division (MCD)) level using various algorithms which consider the county share of the state population and township (or MCD) share of the county. Some of these algorithms, together with a computer program which can be used to project MCD population based on a step down approach from the national to the state to the county, and finally the MCD level, are provided by Greenberg et al. (1973). The major objective of this approach is to ensure that the U.S Bureau of Census or regional projections are made consistent with projections at the other lower geographic levels. At each level, the projections are adjusted to insure that they add to the population projected for the next higher level.

The model assumes a set of national projections for the full projection period from 1930 to 2020 (or any other projection years) which may be selected from among the various projection series are available. These projections act as a growth ceiling for the state projection model. If the last decade of the available state projections (let's say 2000) is less than the national projections (e.g. 2020), then the state series must be extended to that year. This extension can be made as follows. Based on the historical and projected trend from 1930 to the end of the available projections, the growth rate for each decade is calculated for each state as follows (Greenberg et al., 1973):
\[ r_{t}^{ig} = \frac{S_{t}^{ig}}{S_{t-1}^{ig}} \]  \hfill (62)

where

\[ r_{t}^{ig} = \text{the growth rate for time } t \text{ for state } i \text{ for growth series } g. \]

\[ S_{t}^{ig} = \text{the population for time } t \text{ for state } i \text{ for growth series } g \]

\[ S_{t-1}^{ig} = \text{the population for time } t-1 \text{ for state } i \text{ for growth series } g \]

The next step then is to find the average of all rates for each state.

\[ \bar{r}^{ig} = \frac{\sum_{t=2}^{d} r_{t}^{ig}}{d - 1} \]  \hfill (63)

where

\[ \bar{r}^{ig} = \text{the growth rate for state } i \text{ for growth series } g \]

\[ d = \text{number of decades being averaged} \]

This rate is used to extend the population projection for the state to the last decade of the projections.

\[ S_{t}^{ig^*} = \bar{r}^{ig} (S_{t-1}^{ig}) \]  \hfill (64)

where the asterisk (*) implies an unadjusted projection.

Then all projections for each state are adjusted proportionally to the given national totals.

\[ N_{t}^{g^*} = \frac{\sum_{i=1}^{1+1} S_{t}^{ig^*}}{\sum_{i=1}^{1+1} S_{t}^{ig^*}} \]  \hfill (65)

\[ S_{t}^{ig} = \frac{S_{t}^{ig^*}}{N_{t}^{g^*}} \]  \hfill (66)

The county projection model has the same general structure as the state model. However, in this case the state projections are given and are those to which the various county projections must be adjusted (Greenberg et al., 1973). Thus, county projections are extended and adjusted to the state totals as follows:
\[ C_{tijg} = S_{tij} \cdot \frac{C_{ij}^*}{S_{tij}^*} \]  

(67)

where \( C_{tijg} \) - the population of county \( j \) at time \( t \) in state \( i \) for growth series \( g \).

Finally, the MCD projections are adjusted to the county projections as follow.

\[ M_{tijkg} = C_{tijg} \cdot \frac{M_{tijk}^*}{C_{tij}^*} \]  

(68)

where

\( M_{tijkg} \) - population of MCD \( k \) for county \( j \) state \( i \) and growth series \( g \) at time \( t \).

Using this methodology, population projections for all MCD's in the study area were derived through the year 2010. These projections were based upon the state and county population projections available from the Ohio Data Users Center (Ohio Data Users Center, 1985). All the algorithms were implemented by using SuperCalc 5 spreadsheet program.

For the purpose of this research, it is assumed that the fastest growing MCDs continue to grow at the present rate. Table 13 shows the results of the projections for each of the townships in the study area. The next step is to allocate the population to the townships which lie within the study area for each sub-basin. This is done based upon the proportion of the area of each MCD that lie within the study area. Using these areal proportions, the MCD's projection population are then distributed to the study area. The results of this calculation are shown in Table 14. This population constitutes the input data to the land demand estimation.

**Land use demand estimation**

Given the projected population, it was then possible to estimate the future land use demand for the study area. A simple ratioing approach was used for this purpose. The projected population was simply multiplied by the standard selected for each land use. The purpose is not to arrive at an exact figure, but just to get a rough estimate that can be used to demonstrate the proposed methodology. It is assumed that there is no existing shortage
<table>
<thead>
<tr>
<th>TOWNSHIP</th>
<th>1980</th>
<th>1990</th>
<th>2000</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Franklin County</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brown Twp</td>
<td>1,538</td>
<td>1,921</td>
<td>2,367</td>
<td>2,894</td>
</tr>
<tr>
<td>Norwich Twp</td>
<td>13,258</td>
<td>20,041</td>
<td>29,893</td>
<td>44,226</td>
</tr>
<tr>
<td>Pleasant Twp</td>
<td>6,068</td>
<td>7,741</td>
<td>9,745</td>
<td>12,168</td>
</tr>
<tr>
<td>Prairie Twp</td>
<td>16,340</td>
<td>21,845</td>
<td>28,816</td>
<td>37,704</td>
</tr>
<tr>
<td>Washington Twp</td>
<td>4,322</td>
<td>5,335</td>
<td>6,499</td>
<td>7,852</td>
</tr>
<tr>
<td>Others</td>
<td>827,606</td>
<td>867,709</td>
<td>897,692</td>
<td>921,165</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>869,132</td>
<td>924,592</td>
<td>975,013</td>
<td>1,026,008</td>
</tr>
</tbody>
</table>

| **Madison County**  |       |       |       |       |
| Canaan Twp          | 2,210 | 4,266 | 7,597 | 12,170|
| Darby Twp           | 2,015 | 2,034 | 1,894 | 1,586 |
| Deer Creek Twp      | 1,020 | 1,005 | 913   | 747   |
| Fairfield Twp       | 1,293 | 1,358 | 1,316 | 1,148 |
| Jefferson Twp       | 7,055 | 8,043 | 8,457 | 8,001 |
| Monroe Twp          | 1,066 | 1,667 | 2,406 | 3,123 |
| Pike Twp            | 438   | 386   | 313   | 229   |
| Other               | 17,907| 17,913| 16,529| 13,722|
| **Total**           | 33,004| 36,672| 39,425| 40,726|

| **Pickaway County** |       |       |       |       |
| Circleville Twp     | 15,039| 13,968| 12,724| 11,404|
| Darby Twp           | 1,268 | 3,689 | 4,960 | 6,510 |
| Jackson Twp         | 839   | 658   | 507   | 384   |
| Muhlenberg Twp      | 734   | 806   | 868   | 920   |
| Scioto Twp          | 4,458 | 4,786 | 5,040 | 5,221 |
| Others              | 21,324| 19,422| 17,349| 15,248|
| **Total**           | 43,662| 41,418| 38,931| 36,481|
or surplus in any of the land uses. Thus, all the future demand will come from the new population.

The standard selected for the industrial land use was 12 acres/1000 population (Nez, 1961). Several standards were available to estimate different types of commercial centers (ULI, 1985; Lynch, 1984). However these standards were not applicable to the present study for several reasons. In this study, commercial land use is broadly defined to include shopping centers, as well as other urban uses except residential and industrial uses. The study area is surrounded by several urban centers expanding towards the area, thus it is highly likely that the commercial land use will also be shared by residents outside the area. Therefore, it is reasonable to assume that the standard for this use will be higher than for a shopping center per se. A standard of 10 acres/1000 population was used in this study.

For the residential land use, it is assumed that all future demand will be in the form of suburban medium-density housing, with a minimum lot size of one-half acre. To estimate the amount of land required for this land use, the projected population was first converted into the number of families/households. This was done by dividing the population figure by the household size. The study area lie within three counties, thus the current average for these counties of 2.81 was used. Table 15 shows the number of expected households using this average household size.

Table 16 shows the future land demand for each use. By 2010, it is expected that an additional 9830 acres of land will be developed for urban uses. A large portion of this land will be for residential purposes (89%). Overall, this represents 8.0% of the study area. Table 17 to 19 show the distribution of these land demands by sub-basin.

Cluster analysis

Clustering is the grouping of units based on the similarity/dissimilarity over the characteristics which describe them. In this study, clustering is used to partition the study area into environmentally homogeneous groups. Clustering can be achieved in many ways. The common one is to use cluster analysis, a multivariate statistical technique. This section discusses the clustering methods, the clustering program, and the number of clusters used in this analysis.
### Table 14 - Projected Population of the Study Area (1990-2010)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub11</td>
<td>5,198</td>
<td>6,002</td>
<td>6,453</td>
<td>6,338</td>
</tr>
<tr>
<td>Sub12</td>
<td>2,620</td>
<td>3,707</td>
<td>5,202</td>
<td>7,053</td>
</tr>
<tr>
<td>Sub13</td>
<td>14,476</td>
<td>20,012</td>
<td>27,413</td>
<td>37,406</td>
</tr>
<tr>
<td>Sub14</td>
<td>3,702</td>
<td>4,715</td>
<td>5,862</td>
<td>7,165</td>
</tr>
<tr>
<td>Sub15</td>
<td>3,674</td>
<td>4,629</td>
<td>5,750</td>
<td>7,082</td>
</tr>
<tr>
<td>Sub16</td>
<td>1,033</td>
<td>1,454</td>
<td>1,839</td>
<td>2,304</td>
</tr>
<tr>
<td>Sub17</td>
<td>1,619</td>
<td>2,870</td>
<td>3,552</td>
<td>4,357</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>32,322</td>
<td>43,389</td>
<td>56,071</td>
<td>71,704</td>
</tr>
</tbody>
</table>

### Table 15 - Projected New Households in the Study Area (1990 - 2010)

<table>
<thead>
<tr>
<th>SUB-BASIN</th>
<th>1990</th>
<th>2000</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub11</td>
<td>286</td>
<td>446</td>
<td>405</td>
</tr>
<tr>
<td>Sub12</td>
<td>387</td>
<td>918</td>
<td>1,576</td>
</tr>
<tr>
<td>Sub13</td>
<td>1,968</td>
<td>4,599</td>
<td>8,150</td>
</tr>
<tr>
<td>Sub14</td>
<td>360</td>
<td>768</td>
<td>1,231</td>
</tr>
<tr>
<td>Sub15</td>
<td>340</td>
<td>738</td>
<td>1,212</td>
</tr>
<tr>
<td>Sub16</td>
<td>149</td>
<td>286</td>
<td>451</td>
</tr>
<tr>
<td>Sub17</td>
<td>445</td>
<td>687</td>
<td>973</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>3,934</td>
<td>8,442</td>
<td>13,998</td>
</tr>
</tbody>
</table>
Table 16 - Projected Total Land Demand (acres) in the Study Area (1990-2010)

<table>
<thead>
<tr>
<th>SECTOR</th>
<th>1990</th>
<th>2000</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>INDUSTRIAL</td>
<td>166.01</td>
<td>356.24</td>
<td>590.73</td>
</tr>
<tr>
<td>COMMERCIAL</td>
<td>138.34</td>
<td>296.87</td>
<td>492.28</td>
</tr>
<tr>
<td>RESIDENTIAL</td>
<td>2458.69</td>
<td>5276.09</td>
<td>8749.03</td>
</tr>
<tr>
<td>TOTAL</td>
<td>2763.04</td>
<td>5929.20</td>
<td>9832.04</td>
</tr>
</tbody>
</table>

Table 17 - Projected Industrial Land Demand (acres) in the Study Area (1990-2010)

<table>
<thead>
<tr>
<th>SUB-BASIN</th>
<th>1990</th>
<th>2000</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub11</td>
<td>12.06</td>
<td>18.82</td>
<td>17.09</td>
</tr>
<tr>
<td>Sub12</td>
<td>16.31</td>
<td>38.74</td>
<td>66.50</td>
</tr>
<tr>
<td>Sub13</td>
<td>83.04</td>
<td>194.06</td>
<td>343.95</td>
</tr>
<tr>
<td>Sub14</td>
<td>15.19</td>
<td>32.40</td>
<td>51.95</td>
</tr>
<tr>
<td>Sub15</td>
<td>14.34</td>
<td>31.14</td>
<td>51.13</td>
</tr>
<tr>
<td>Sub16</td>
<td>6.30</td>
<td>12.08</td>
<td>19.65</td>
</tr>
<tr>
<td>Sub17</td>
<td>18.76</td>
<td>29.00</td>
<td>41.07</td>
</tr>
<tr>
<td>Total</td>
<td>166.01</td>
<td>356.24</td>
<td>590.73</td>
</tr>
</tbody>
</table>
Table 18 - Projected Commercial Land Demand (acres) in the Test Area (1990-2010)

<table>
<thead>
<tr>
<th>SUB-BASIN</th>
<th>1990</th>
<th>2000</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub11</td>
<td>10.05</td>
<td>15.68</td>
<td>14.24</td>
</tr>
<tr>
<td>Sub12</td>
<td>13.59</td>
<td>32.28</td>
<td>55.41</td>
</tr>
<tr>
<td>Sub13</td>
<td>69.20</td>
<td>161.72</td>
<td>286.62</td>
</tr>
<tr>
<td>Sub14</td>
<td>12.66</td>
<td>27.00</td>
<td>43.29</td>
</tr>
<tr>
<td>Sub15</td>
<td>11.95</td>
<td>25.95</td>
<td>42.61</td>
</tr>
<tr>
<td>Sub16</td>
<td>5.25</td>
<td>10.06</td>
<td>15.88</td>
</tr>
<tr>
<td>Sub17</td>
<td>15.64</td>
<td>24.17</td>
<td>34.23</td>
</tr>
<tr>
<td>Total</td>
<td>138.34</td>
<td>296.87</td>
<td>492.28</td>
</tr>
</tbody>
</table>

Table 19 - Projected Residential Land Demand (acres) in the Test Area (1990-2010)

<table>
<thead>
<tr>
<th>SUB-BASIN</th>
<th>1990.00</th>
<th>2000.00</th>
<th>2010.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub11</td>
<td>178.62</td>
<td>278.75</td>
<td>253.13</td>
</tr>
<tr>
<td>Sub12</td>
<td>241.58</td>
<td>573.76</td>
<td>984.84</td>
</tr>
<tr>
<td>Sub13</td>
<td>1229.92</td>
<td>2874.10</td>
<td>5094.03</td>
</tr>
<tr>
<td>Sub14</td>
<td>225.02</td>
<td>479.87</td>
<td>769.35</td>
</tr>
<tr>
<td>Sub15</td>
<td>212.34</td>
<td>461.18</td>
<td>757.22</td>
</tr>
<tr>
<td>Sub16</td>
<td>93.31</td>
<td>178.87</td>
<td>282.14</td>
</tr>
<tr>
<td>Sub17</td>
<td>277.90</td>
<td>429.56</td>
<td>608.31</td>
</tr>
<tr>
<td>Total</td>
<td>2458.69</td>
<td>5276.09</td>
<td>8749.03</td>
</tr>
</tbody>
</table>
There are three basic clustering methods: simple linkage, average linkage, and complete linkage. Each of these methods affects the order of clustering and clusters differently, thus produces different outcomes. Of these methods, the average linkage method is the most commonly used clustering method because it avoids extreme clusters and the introduction of bias (Burneslon, 1988), and will be used in this research.

The clustering of the land units (cells) into environmentally homogeneous groups with the above method was achieved using the computerized statistical package SAS (Statistical Analysis System). SAS is readily available and relatively easy to use. The CLUSTER program in SAS offers 10 options of clustering procedures: the centroid method, Ward's method, average linkage, complete linkage, density linkage, EML, flexible-beta method, median method, simple linkage, and two-stage density linkage (SAS Institute Inc., 1987).

All of these procedures can be potentially used for this analysis. However, each of them is usually biased towards finding clusters possessing certain characteristics related to size, shape, or dispersion. To select which procedure to use for a particular study is a difficult task, usually influenced by the purpose of the study. Of the 10 procedures, the centroid method, Ward's minimum variance method, and average linkage are three variations of the average linkage technique.

The three average linkage procedures differ in terms of how the distance between clusters is computed. The centroid method uses the Euclidean distance between centroids or means as a measure of distance between 2 clusters (SAS Institute Inc., 1987). The average linkage method uses the average distance between pairs of observations in the clusters (SAS Institute Inc., 1987). Thus, it tends to join clusters with small variances and is slightly biased towards producing clusters with the same variance. The Ward's method uses the sum of squares between clusters added up over all the variables as the distance measure (SAS Institute Inc., 1987). Each cluster is produced by minimizing the within-cluster sum of squares over all partitions by averaging two clusters from the previous iteration. This method is very sensitive to outliers and tends to join clusters with a small number of observations. It is strongly biased towards producing clusters with roughly the same number of observations (SAS Institute Inc, 1987).
All the three clustering procedures could have been used in this analysis. However, many studies have found that the average linkage or Ward's minimum variance produce the best overall performance (SAS Institute Inc., 1987). They tend to produce more compact clusters than the centroid method. Ward's method is designed to optimize the minimum within-groups sum of squares or the error of squares (ESS), a characteristic which is desirable for determining environmentally homogeneous groups, and was used in this study.

Once the clustering method had been determined, it was then necessary to decide on the number of clusters, that is, the stage at which the clustering process stops. This is a difficult task as there are no satisfactory and objective methods yet existing for this purpose. The importance and difficulty of this problem has been noted by many authors including Sneath and Sokal (1973), Everitt (1980) and SAS Institute Inc. (1987). In any situation, the number of clusters can range from 1 to the total number of observations in the data set. In this study, the number of clusters can ranges from 1 to 3038.

Several attempts have been made to develop procedures for determining the number of clusters. Two basic approaches to determining the "optimal" number of clusters have evolved: heuristic procedures, and formal statistical tests (Aldenderfer and Blashfield, 1984). The heuristic procedures are the most commonly used methods. In one of these procedures, a hierarchical tree is "cut" by the subjective inspection of the different levels of the tree. This procedure is generally biased by the needs and opinions of the researcher, thus is hardly satisfactory. An alternative, more formal, but still heuristic approach to the problem is to graph the number of clusters implied by a hierarchical tree against the fusion or amalgamation coefficient, which is the numerical value at which various observations merge to form a cluster (Aldenderfer and Blashfield, 1984). A marked "flattening" in this graph suggests that no new information is generated by the following mergers of clusters. Another heuristic procedure, that has been made more formal but is still subjective, is one that also makes use of the values of the fusion coefficients to discover a significant "jump" in the value of the coefficients. This "jump" implies that two relatively dissimilar clusters have been merged; thus the number of clusters prior to the merger is the most probable solution.
The formal statistical tests involve the use of hypothesis testing. The development of this approach has been slow due to the formidable problems of complex multivariate sampling distributions. Milligan and Cooper (1983) and Cooper and Milligan (1984) in their study of 30 methods for estimating the number of clusters using four hierarchical clustering methods found that the three criteria that performed best are the pseudo F statistics, pseudo $t^2$, and the cubic clustering criterion (CCC). The number of clusters can be estimated by looking at the consensus among these three statistics, that is, where there are local peaks of the CCC and pseudo F statistics, combined with a small value of the pseudo $t^2$ statistic, and a larger pseudo $t^2$ for the next cluster fusion (SAS Institute Inc., 1987). All these three statistics can be requested from the SAS's CLUSTER procedure for the Ward's minimum variance method.

Figure 29 shows the result of the cluster analysis for the study area. The cluster analysis was based on the three major parameters of the environmental model used in this research. These parameters are the hydrologic soil groups, slope, and flow length. The figure shows that significant "jump" occur at several locations. However, thirty clusters were used as the starting point for this research. Figure 30 shows the spatial distribution of the thirty clusters in the study area.

**Implementation and Evaluation of the Proposed Methodology on a Test Sub-basin**

The issues involved in allocating urban land uses for sub-basin 13 (Fig. 9) were used to guide and test the development of the proposed methodology. This sub-basin has the largest population and highest potential to further urbanize, thus to impact the water quality of the Big Darby Creek. This test also provided the opportunity to compare and evaluate the performance of the methodology with an array of other methods that included: 1) land use allocation using the traditional land capability/suitability analysis methods, 2) land use allocation using random generation methods, and 3) land use allocation using the convex combination method of nonlinear programming.

The methodology called for the determination of sample size based on the population characteristics of the environmental impact to be simulated (i.e. biochemical oxygen demand). However, these data do not presently exist for the study area. Thus, it
FIG. 29 - RESULTS OF THE CLUSTER ANALYSIS USING WARD'S METHOD
FIG. 30 - DISTRIBUTION OF THE ENVIRONMENTAL CLUSTERS IN THE BIG DARBY CREEK STUDY AREA.
was not possible to strictly determine the sample size according to the environmental impact to be simulated. An alternative strategy was used instead. It was decided that at least one sample should be selected from each group. The samples should be selected among the land available for development. The reason for this latter criteria is obvious. It is assumed that existing built-up areas will maintain their present uses, and will not be converted to any other urban uses in the future.

Based upon the cluster analysis described earlier, there are 17 types of environmental groups in sub-basin 13. Thus, at least 17 samples need to be selected. However, a total of 30 samples were selected for this demonstration. These samples were distributed in proportion to the number of land units (cells) in each group, and is shown in Table 20. Once the sample size has been determined, the next step is to randomly select the initial sample locations for each group. Figure 31 shows the initial locations of these samples.

By the year 2010, it was projected that sub-basin 13 will require an additional 344, 287, and 5094 acres of industrial, commercial, and residential land respectively. The next step was to allocate these land uses in the sub-basin, starting with the industrial land use. For this research, it was assumed that the size requirements for industrial, commercial, and residential were 40, 40, and 0.5 acres respectively. These requirements were selected based on literature (e.g. Lynch, 1984) as well as on the need to suit the cell size of the data base. Thus the number of sites (cells) allocated for each land use was determined by dividing the land use demand by the cell size (40 acres), rounded to an integer. For residential, although the size requirement is less than the cell size, it was assumed that each cell will be totally occupied by such use. Thus each cell will accommodate about 80 housing units.

Figure 32 shows the GIS procedure for allocating the industrial land use. The first step was to simulate the water quality impacts of locating industrial land use on each of the sample sites selected earlier. These impacts were then used to classify all sites in the study area into different impact categories to produce an environmental impact suitability map for industrial land use. Next, using the results of the site suitability analysis, several sites were
Table 20. The Distribution of Samples in Sub-basin 13 by Environmental Groups

<table>
<thead>
<tr>
<th>Environmental groups</th>
<th>No. of Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>2</td>
</tr>
<tr>
<td>10</td>
<td>0 *</td>
</tr>
<tr>
<td>11</td>
<td>3</td>
</tr>
<tr>
<td>12</td>
<td>3</td>
</tr>
<tr>
<td>13</td>
<td>3</td>
</tr>
<tr>
<td>14</td>
<td>3</td>
</tr>
<tr>
<td>15</td>
<td>1</td>
</tr>
<tr>
<td>16</td>
<td>1</td>
</tr>
<tr>
<td>17</td>
<td>1</td>
</tr>
</tbody>
</table>

* - No land available for development in this group.
FIG. 31 - INITIAL SAMPLE LOCATIONS FOR TEST SUB-BASIN 13
FIG. 32 - CARTOGRAPHIC MODEL FOR ALLOCATING INDUSTRIAL LAND USE
chosen as the candidate for future locations of industrial land use. This task was accomplished by normalizing the suitability score of each site onto a 0 to 100 scale. The original suitability score was divided by the maximum score on the map, and then multiplied by a constant value of 100. Sites with 75 points or above were then chosen as the candidate sites. Figure 33 shows the distribution of these sites. This map together with the impact suitability map created earlier were then used to select the locations of future industrial use such that those with the lowest impact will be allocated first, and adding others in the order of increasing impacts.

Once the industrial land use has been allocated, the land availability and sample locations for the commercial land use were updated. Then, using the new land use information, the water quality impacts of locating commercial land use on each of the sample sites were simulated, and used to create the environmental impact suitability map for this land use. Figure 34 shows the GIS procedure to allocate this land use. For this land use, unlike the industrial land use, it was first necessary to generate the situation suitability map to make use of the new information generated during the industrial land use allocation process. To this end, a map of distance zones was created, and then rated and scored according to the criteria set earlier (Table 11). This map was then added to the site suitability map to generate the overall suitability map for commercial land use. Next, the suitability score of each site (cell) was normalized onto a 0 to 100 scale, as described earlier. Sites with 75 points or above were then chosen as the candidate sites (Fig. 35). This map together with the impact suitability map were then used to select the future locations of commercial land use such that those with the lowest impact will be allocated first, and adding others in the order of increasing impacts.

The residential land use was allocated in a similar manner as described for the industrial and commercial land uses. Figures 36 and 37 show the GIS allocation procedure and the candidate sites for this land use.

Figure 38 shows the distribution of the newly allocated land uses for the first iteration, i.e. for year 2010. This allocation was expected to produce a peak runoff of 2415.5 cfs, and biochemical oxygen demand (BOD) concentration of about 6.9 mg/l. As a result the dissolved oxygen concentration at the sub-basin outlet was reduced to 5.8 mg/l.
FIG. 33 SPATIAL DISTRIBUTION OF CANDIDATE SITES FOR INDUSTRIAL LAND USE AT ITERATION 1.
FIG. 34 - CARTOGRAPHIC MODEL FOR ALLOCATING COMMERCIAL LAND USE
FIG. 35 SPATIAL DISTRIBUTION OF CANDIDATE SITES FOR COMMERCIAL LAND USE AT ITERATION 1.
FIG. 36 - CARTOGRAPHIC MODEL FOR ALLOCATING RESIDENTIAL LAND USE
Although this concentration is above the national minimum standard of 4 mg/l, it is slightly below the minimum standard of 6 mg/l, the standard required to maintain the status of that portion of the Big Darby Creek as exceptional warm water habitat. The changes in the BOD concentrations in the sub-basin were also statistically significant at the 0.05 level as tested using Equation 46 as given in Chapter 3. The methodology calls for the reduction in the amounts of land to be allocated, and then proceed to the next iteration. Table 21 shows the distribution of the amounts of land uses to be allocated in each subsequent iteration (year). These amounts of land uses were determined by subtracting the annual decrement from the amount of land uses of the previous iteration. The annual decrement was derived by dividing the land demand for year 2010 by the number of years (that is, 30 years). Each iteration corresponds to a separate application of the proposed procedure, that is, there is no linkage between the iterations. The complete results of the allocation are shown in Table 22 and Figure 39. The figure shows that the minimum D.O. standard of 6 mg/l will be met at iteration 19, when 160, 120, and 2040 acres of industrial, commercial, and residential land uses are allocated respectively.

Comparison of the proposed methodology with the traditional land capability/suitability analysis

The premise of land use allocation is that certain geographic areas are physically, environmentally, socially, as well as economically more suited for certain use than other areas (Diamond, 1988). Land capability/suitability analysis has been a standard part of this land use allocation process for many years (see Chapin & Kaiser, 1979; and Hopkins, 1977). Perhaps a large number of existing predictive land use models as reviewed in Chapter 2 work within the framework of this approach. Land capability/suitability analysis is usually used to assess the relative suitability of each location in a geographic area for various land uses or facilities, and help planners cope with the "supply side" of the land use plan design problem.
Table 21: The Amount of Land Uses Allocated at Each Iteration/Year for Sub-basin 13

<table>
<thead>
<tr>
<th>Iteration</th>
<th>ACRES</th>
<th># OF CELLS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Industrial</td>
<td>Commercial</td>
</tr>
<tr>
<td>1</td>
<td>343.95</td>
<td>286.62</td>
</tr>
<tr>
<td>2</td>
<td>332.48</td>
<td>277.07</td>
</tr>
<tr>
<td>3</td>
<td>321.02</td>
<td>267.52</td>
</tr>
<tr>
<td>4</td>
<td>309.55</td>
<td>257.96</td>
</tr>
<tr>
<td>5</td>
<td>298.09</td>
<td>248.41</td>
</tr>
<tr>
<td>6</td>
<td>286.62</td>
<td>238.85</td>
</tr>
<tr>
<td>7</td>
<td>275.16</td>
<td>229.30</td>
</tr>
<tr>
<td>8</td>
<td>263.69</td>
<td>219.75</td>
</tr>
<tr>
<td>9</td>
<td>252.23</td>
<td>210.19</td>
</tr>
<tr>
<td>10</td>
<td>240.76</td>
<td>200.64</td>
</tr>
<tr>
<td>11</td>
<td>229.30</td>
<td>191.08</td>
</tr>
<tr>
<td>12</td>
<td>217.83</td>
<td>181.53</td>
</tr>
<tr>
<td>13</td>
<td>206.37</td>
<td>171.97</td>
</tr>
<tr>
<td>14</td>
<td>194.90</td>
<td>162.42</td>
</tr>
<tr>
<td>15</td>
<td>183.44</td>
<td>152.87</td>
</tr>
<tr>
<td>16</td>
<td>171.97</td>
<td>143.31</td>
</tr>
<tr>
<td>17</td>
<td>160.51</td>
<td>133.76</td>
</tr>
<tr>
<td>18</td>
<td>149.04</td>
<td>124.20</td>
</tr>
<tr>
<td>19</td>
<td>137.58</td>
<td>114.65</td>
</tr>
<tr>
<td>20</td>
<td>126.11</td>
<td>105.10</td>
</tr>
<tr>
<td>21</td>
<td>114.65</td>
<td>95.54</td>
</tr>
<tr>
<td>22</td>
<td>103.18</td>
<td>85.99</td>
</tr>
<tr>
<td>23</td>
<td>91.72</td>
<td>76.43</td>
</tr>
<tr>
<td>24</td>
<td>80.25</td>
<td>66.88</td>
</tr>
<tr>
<td>25</td>
<td>68.79</td>
<td>57.32</td>
</tr>
<tr>
<td>26</td>
<td>57.32</td>
<td>47.77</td>
</tr>
<tr>
<td>27</td>
<td>45.86</td>
<td>38.22</td>
</tr>
<tr>
<td>28</td>
<td>34.39</td>
<td>28.66</td>
</tr>
<tr>
<td>29</td>
<td>22.93</td>
<td>19.11</td>
</tr>
<tr>
<td>30</td>
<td>11.46</td>
<td>9.55</td>
</tr>
</tbody>
</table>

Note: The actual amounts of land allocated were adjusted to fit the cell size. The cell size is 40 acres.
Table 22: The Environmental Impacts of Land Uses Allocated using the Proposed Methodology

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Peak Discharge (cfs)</th>
<th>BOD Conc. (mg/l)</th>
<th>D.O. Conc (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>2415.39</td>
<td>6.89</td>
<td>5.83</td>
</tr>
<tr>
<td>2.00</td>
<td>2378.21</td>
<td>6.85</td>
<td>5.84</td>
</tr>
<tr>
<td>3.00</td>
<td>2373.80</td>
<td>6.82</td>
<td>5.85</td>
</tr>
<tr>
<td>4.00</td>
<td>2365.41</td>
<td>6.78</td>
<td>5.87</td>
</tr>
<tr>
<td>5.00</td>
<td>2367.64</td>
<td>6.76</td>
<td>5.88</td>
</tr>
<tr>
<td>6.00</td>
<td>2359.96</td>
<td>6.73</td>
<td>5.89</td>
</tr>
<tr>
<td>7.00</td>
<td>2358.59</td>
<td>6.69</td>
<td>5.90</td>
</tr>
<tr>
<td>8.00</td>
<td>2357.32</td>
<td>6.66</td>
<td>5.91</td>
</tr>
<tr>
<td>9.00</td>
<td>2359.47</td>
<td>6.64</td>
<td>5.92</td>
</tr>
<tr>
<td>10.00</td>
<td>2360.99</td>
<td>6.62</td>
<td>5.92</td>
</tr>
<tr>
<td>11.00</td>
<td>2364.33</td>
<td>6.58</td>
<td>5.94</td>
</tr>
<tr>
<td>12.00</td>
<td>2366.03</td>
<td>6.57</td>
<td>5.95</td>
</tr>
<tr>
<td>13.00</td>
<td>2368.51</td>
<td>6.55</td>
<td>5.95</td>
</tr>
<tr>
<td>14.00</td>
<td>2366.32</td>
<td>6.53</td>
<td>5.96</td>
</tr>
<tr>
<td>15.00</td>
<td>2362.35</td>
<td>6.51</td>
<td>5.97</td>
</tr>
<tr>
<td>16.00</td>
<td>2361.57</td>
<td>6.50</td>
<td>5.97</td>
</tr>
<tr>
<td>17.00</td>
<td>2357.12</td>
<td>6.49</td>
<td>5.97</td>
</tr>
<tr>
<td>18.00</td>
<td>2354.77</td>
<td>6.46</td>
<td>5.98</td>
</tr>
<tr>
<td>19.00</td>
<td>2360.08</td>
<td>6.42</td>
<td>6.00</td>
</tr>
<tr>
<td>20.00</td>
<td>2360.25</td>
<td>6.42</td>
<td>6.00</td>
</tr>
<tr>
<td>21.00</td>
<td>2357.07</td>
<td>6.39</td>
<td>6.01</td>
</tr>
<tr>
<td>22.00</td>
<td>2355.64</td>
<td>6.38</td>
<td>6.01</td>
</tr>
<tr>
<td>23.00</td>
<td>2352.09</td>
<td>6.36</td>
<td>6.02</td>
</tr>
<tr>
<td>24.00</td>
<td>2352.36</td>
<td>6.35</td>
<td>6.02</td>
</tr>
<tr>
<td>25.00</td>
<td>2350.57</td>
<td>6.33</td>
<td>6.03</td>
</tr>
<tr>
<td>26.00</td>
<td>2351.15</td>
<td>6.32</td>
<td>6.03</td>
</tr>
<tr>
<td>27.00</td>
<td>2347.73</td>
<td>6.30</td>
<td>6.04</td>
</tr>
<tr>
<td>28.00</td>
<td>2348.49</td>
<td>6.28</td>
<td>6.05</td>
</tr>
<tr>
<td>29.00</td>
<td>2349.59</td>
<td>6.28</td>
<td>6.05</td>
</tr>
<tr>
<td>30.00</td>
<td>2350.71</td>
<td>6.27</td>
<td>6.05</td>
</tr>
<tr>
<td>Existing</td>
<td>2346.16</td>
<td>6.24</td>
<td>6.06</td>
</tr>
</tbody>
</table>

Note: Refer to Table 21 for the amount of land uses allocated at each iteration.
FIG. 37 SPATIAL DISTRIBUTION OF CANDIDATE SITES FOR RESIDENTIAL LAND USE AT ITERATION 1.
FIG. 38 DISTRIBUTION OF NEW LAND USES AT ITERATION 1 ALLOCATED USING THE PROPOSED METHODOLOGY (30 CLUSTERS)
FIG. 39 - THE IMPACTS OF THE LAND USES ALLOCATED USING THE PROPOSED METHODOLOGY ON DISSOLVED OXYGEN CONCENTRATIONS.
Land use is allocated to sites which it is most suited, adding others in the order of decreasing suitability until the total amount of space required is met. In this research, the land uses were also allocated sequentially, started with the industrial land use. Once all the industrial land use has been allocated, the land availability and suitability for commercial were updated. Sites were allocated to commercial use in a similar fashion as the industrial land use, started with sites having the highest suitability, and adding others until the land requirement for this use was met. This process was then repeated for the residential land use.

Fig. 40 shows the spatial distribution of the new land uses in the test sub-basin for the year 2010 as allocated using the traditional land capability/suitability analysis. This allocation was expected to produce a stormwater BOD concentration of 7.48 mg/l, and reducing the stream dissolved oxygen to 5.65 mg/l (Table 23). This dissolved oxygen level is considerably lower than those produced by the proposed methodology. Figure 41 shows the comparison of the dissolved oxygen levels of these two approaches. The figure shows that the differences between the two approaches get larger as the amount of land uses to be allocated become larger. These differences were statistically significant at 0.05 level as calculated using the formula mentioned earlier (Eq. 46). This test indicates that the land use allocation from the proposed methodology does produce a lower overall environmental impact than those produced by the traditional land capability/suitability analysis. This was not surprising because, as argued earlier, land capability/suitability analysis, although it has traditionally been used as an approach to integrate various environmental factors, does not have the means to quantify environmental impacts. With this approach, environmental impacts are usually implied by scientific data such as slope, and proximity to water. It operates mainly on a location-by-location (atomistic) basis, and is unable to capture the cumulative and combinatorial nature of environmental impact.

Comparison of the proposed methodology with land use allocation using random generation method

Several attempts have been made in the past to apply random generation methods to urban land use plan design problems (e.g. Sinhs, Adamski, and Schlager, 1973; and Chang, Brill, and Hopkins, 1982 - see review in Chapter 2). The major motivation for using this approach was that land use planning problems are usually too complex to be
FIG. 40 - DISTRIBUTION OF NEW LAND USES AT ITERATION 1
ALLOCATED USING THE TRADITIONAL LAND CAPABILITY/SUITABILITY ANALYSIS METHOD.
Table 23: The Environmental Impacts of Land Uses
Allocated using the Traditional Land Capability/Suitability Analysis

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Peak Discharge (cfs)</th>
<th>BOD Conc. (mg/l)</th>
<th>D.O. Conc. (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2573.65</td>
<td>7.60</td>
<td>5.57</td>
</tr>
<tr>
<td>2</td>
<td>2568.52</td>
<td>7.58</td>
<td>5.58</td>
</tr>
<tr>
<td>3</td>
<td>2562.15</td>
<td>7.56</td>
<td>5.58</td>
</tr>
<tr>
<td>4</td>
<td>2541.43</td>
<td>7.47</td>
<td>5.62</td>
</tr>
<tr>
<td>5</td>
<td>2540.88</td>
<td>7.45</td>
<td>5.62</td>
</tr>
<tr>
<td>6</td>
<td>2531.43</td>
<td>7.40</td>
<td>5.64</td>
</tr>
<tr>
<td>7</td>
<td>2516.43</td>
<td>7.30</td>
<td>5.68</td>
</tr>
<tr>
<td>8</td>
<td>2519.19</td>
<td>7.29</td>
<td>5.68</td>
</tr>
<tr>
<td>9</td>
<td>2516.35</td>
<td>7.28</td>
<td>5.69</td>
</tr>
<tr>
<td>10</td>
<td>2514.77</td>
<td>7.26</td>
<td>5.69</td>
</tr>
<tr>
<td>11</td>
<td>2499.79</td>
<td>7.16</td>
<td>5.73</td>
</tr>
<tr>
<td>12</td>
<td>2497.69</td>
<td>7.15</td>
<td>5.73</td>
</tr>
<tr>
<td>13</td>
<td>2499.32</td>
<td>7.14</td>
<td>5.74</td>
</tr>
<tr>
<td>14</td>
<td>2493.19</td>
<td>7.05</td>
<td>5.77</td>
</tr>
<tr>
<td>15</td>
<td>2468.32</td>
<td>7.03</td>
<td>5.78</td>
</tr>
<tr>
<td>16</td>
<td>2463.68</td>
<td>7.00</td>
<td>5.79</td>
</tr>
<tr>
<td>17</td>
<td>2460.09</td>
<td>6.98</td>
<td>5.79</td>
</tr>
<tr>
<td>18</td>
<td>2455.36</td>
<td>6.90</td>
<td>5.82</td>
</tr>
<tr>
<td>19</td>
<td>2453.57</td>
<td>6.88</td>
<td>5.83</td>
</tr>
<tr>
<td>20</td>
<td>2456.83</td>
<td>6.86</td>
<td>5.83</td>
</tr>
<tr>
<td>21</td>
<td>2418.72</td>
<td>6.73</td>
<td>5.88</td>
</tr>
<tr>
<td>22</td>
<td>2418.64</td>
<td>6.72</td>
<td>5.89</td>
</tr>
<tr>
<td>23</td>
<td>2421.52</td>
<td>6.70</td>
<td>5.90</td>
</tr>
<tr>
<td>24</td>
<td>2421.97</td>
<td>6.69</td>
<td>5.90</td>
</tr>
<tr>
<td>25</td>
<td>2409.75</td>
<td>6.60</td>
<td>5.93</td>
</tr>
<tr>
<td>26</td>
<td>2409.59</td>
<td>6.57</td>
<td>5.94</td>
</tr>
<tr>
<td>27</td>
<td>2401.69</td>
<td>6.53</td>
<td>5.96</td>
</tr>
<tr>
<td>28</td>
<td>2398.17</td>
<td>6.47</td>
<td>5.98</td>
</tr>
<tr>
<td>29</td>
<td>2398.21</td>
<td>6.46</td>
<td>5.98</td>
</tr>
<tr>
<td>30</td>
<td>2386.99</td>
<td>6.43</td>
<td>5.99</td>
</tr>
</tbody>
</table>

Existing 2346.16 6.24 6.06

Note: Refer to Table 21 for the amount of land uses allocated at each iteration.
FIG. 41 COMPARISON OF THE IMPACTS OF THE LAND USE ALLOCATION USING THE TRADITIONAL LAND CAPABILITY ANALYSIS (LCA) AND THE PROPOSED METHODOLOGY ON THE DISSOLVED OXYGEN LEVELS.
fully represented by a mathematical model (Chang, Brill, and Hopkins, 1982). Many planning issues are ill-defined and cannot be explicitly modeled (Hopkins, 1984); objectives are qualitative and conflicting; and many constraints may not be clearly defined.

In this research, land uses were randomly allocated using a random number generator. Unlike the previous studies, which generated the solutions within the framework of an optimization model, the random solutions for this research were generated within the framework of the land capability/suitability analysis. The land areas were selected among those considered as suitable and available for each particular land use. Thus, the solutions obtained were not really random in the strictest sense. The land areas considered suitable for each land use (i.e. the candidate sites) were defined and derived in the same manner as the proposed methodology, except that only the site suitability was considered. The site suitability scores were normalized into a 0 to 100 scale, by dividing the score of each cell with the maximum score in the map. Those cells with 75 points or above were then selected as the candidate sites. The land uses were also allocated sequentially, in the same order as used in the proposed methodology. The procedure begins by allocating all the land areas required for industrial land uses. Once the land areas for this land use have been selected, the land availability for the commercial use is then updated, and the random solutions are generated for this use. Taking into account the locations of the newly allocated industrial and commercial uses, the solutions for the residential use are then randomly generated.

To discount for any experimental error, three random solutions were derived for each land use. Figures 42 to 44 show the spatial distribution of the three land use plans for the first iteration generated by the random generation method. These solutions were expected to produce a stormwater BOD concentration of 7.43, 7.39, and 7.19 mg/l respectively, and consequently will reduce the stream dissolved oxygen levels to 5.63, 5.65, and 5.72 mg/l. These dissolved oxygen levels were relatively lower than those produced by the proposed methodology. The detail results of the experiment using this method are shown in Table 24 to 26. Figure 45 shows the comparison of the dissolved oxygen levels affected by these two approaches. The figure shows that the differences between the two approaches vary from one iteration to another, reflecting the randomness of the solutions derived by the random generation method. All these land use allocations are statistically different at the 0.05 level, indicating that the result from the proposed
FIG. 42 DISTRIBUTION OF NEW LAND USES AT ITERATION 1 ALLOCATED USING THE RANDOM GENERATION METHOD (SOLUTION #1)
FIG. 43 DISTRIBUTION OF NEW LAND USES AT ITERATION 1 ALLOCATED USING THE RANDOM GENERATION METHOD (SOLUTION #2)
FIG. 44 DISTRIBUTION OF NEW LAND USES AT ITERATION 1 ALLOCATED USING THE RANDOM GENERATION METHOD (SOLUTION #3)
Table 24: The Environmental Impacts of Land Uses
Allocated using the Random Generation Method - Run # 1

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Peak Discharge (cfs)</th>
<th>BOD Conc. (mg/l)</th>
<th>D.O. Conc (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2540.09</td>
<td>7.43</td>
<td>5.63</td>
</tr>
<tr>
<td>2</td>
<td>2574.16</td>
<td>7.50</td>
<td>5.60</td>
</tr>
<tr>
<td>3</td>
<td>2589.35</td>
<td>7.47</td>
<td>5.61</td>
</tr>
<tr>
<td>4</td>
<td>2531.80</td>
<td>7.24</td>
<td>5.70</td>
</tr>
<tr>
<td>5</td>
<td>2495.01</td>
<td>7.26</td>
<td>5.69</td>
</tr>
<tr>
<td>6</td>
<td>2489.77</td>
<td>7.24</td>
<td>5.70</td>
</tr>
<tr>
<td>7</td>
<td>2511.97</td>
<td>7.21</td>
<td>5.71</td>
</tr>
<tr>
<td>8</td>
<td>2494.65</td>
<td>7.20</td>
<td>5.71</td>
</tr>
<tr>
<td>9</td>
<td>2488.77</td>
<td>7.09</td>
<td>5.75</td>
</tr>
<tr>
<td>10</td>
<td>2436.36</td>
<td>6.97</td>
<td>5.80</td>
</tr>
<tr>
<td>11</td>
<td>2511.09</td>
<td>7.05</td>
<td>5.77</td>
</tr>
<tr>
<td>12</td>
<td>2465.40</td>
<td>6.96</td>
<td>5.80</td>
</tr>
<tr>
<td>13</td>
<td>2519.25</td>
<td>7.11</td>
<td>5.75</td>
</tr>
<tr>
<td>14</td>
<td>2467.44</td>
<td>6.86</td>
<td>5.84</td>
</tr>
<tr>
<td>15</td>
<td>2487.17</td>
<td>6.99</td>
<td>5.79</td>
</tr>
<tr>
<td>16</td>
<td>2463.00</td>
<td>6.83</td>
<td>5.85</td>
</tr>
<tr>
<td>17</td>
<td>2436.64</td>
<td>6.83</td>
<td>5.85</td>
</tr>
<tr>
<td>18</td>
<td>2459.27</td>
<td>6.82</td>
<td>5.85</td>
</tr>
<tr>
<td>19</td>
<td>2463.83</td>
<td>6.85</td>
<td>5.84</td>
</tr>
<tr>
<td>20</td>
<td>2446.11</td>
<td>6.70</td>
<td>5.89</td>
</tr>
<tr>
<td>21</td>
<td>2419.25</td>
<td>6.69</td>
<td>5.90</td>
</tr>
<tr>
<td>22</td>
<td>2372.11</td>
<td>6.52</td>
<td>5.96</td>
</tr>
<tr>
<td>23</td>
<td>2377.84</td>
<td>6.61</td>
<td>5.93</td>
</tr>
<tr>
<td>24</td>
<td>2372.60</td>
<td>6.62</td>
<td>5.92</td>
</tr>
<tr>
<td>25</td>
<td>2407.48</td>
<td>6.56</td>
<td>5.95</td>
</tr>
<tr>
<td>26</td>
<td>2401.35</td>
<td>6.49</td>
<td>5.97</td>
</tr>
<tr>
<td>27</td>
<td>2365.47</td>
<td>6.38</td>
<td>6.01</td>
</tr>
<tr>
<td>28</td>
<td>2383.20</td>
<td>6.37</td>
<td>6.02</td>
</tr>
<tr>
<td>29</td>
<td>2373.47</td>
<td>6.35</td>
<td>6.03</td>
</tr>
<tr>
<td>30</td>
<td>2386.33</td>
<td>6.42</td>
<td>6.00</td>
</tr>
<tr>
<td>Existing</td>
<td>2346.16</td>
<td>6.24</td>
<td>6.06</td>
</tr>
</tbody>
</table>

Note: Refer to Table 21 for amount of land uses allocated at each iteration.
Table 25: The Environmental Impacts of Land Uses Allocated using the Random Generation Method - Run # 2

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Peak Discharge (cfs)</th>
<th>BOD Conc. (mg/l)</th>
<th>D.O. Conc (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2549.69</td>
<td>7.39</td>
<td>5.65</td>
</tr>
<tr>
<td>2</td>
<td>2546.93</td>
<td>7.40</td>
<td>5.64</td>
</tr>
<tr>
<td>3</td>
<td>2505.01</td>
<td>7.27</td>
<td>5.69</td>
</tr>
<tr>
<td>4</td>
<td>2572.60</td>
<td>7.46</td>
<td>5.62</td>
</tr>
<tr>
<td>5</td>
<td>2502.16</td>
<td>7.22</td>
<td>5.71</td>
</tr>
<tr>
<td>6</td>
<td>2418.09</td>
<td>7.03</td>
<td>5.78</td>
</tr>
<tr>
<td>7</td>
<td>2493.72</td>
<td>7.22</td>
<td>5.71</td>
</tr>
<tr>
<td>8</td>
<td>2499.69</td>
<td>7.07</td>
<td>5.76</td>
</tr>
<tr>
<td>9</td>
<td>2447.64</td>
<td>7.07</td>
<td>5.76</td>
</tr>
<tr>
<td>10</td>
<td>2518.63</td>
<td>7.01</td>
<td>5.78</td>
</tr>
<tr>
<td>11</td>
<td>2543.96</td>
<td>7.16</td>
<td>5.73</td>
</tr>
<tr>
<td>12</td>
<td>2467.93</td>
<td>7.01</td>
<td>5.78</td>
</tr>
<tr>
<td>13</td>
<td>2534.01</td>
<td>7.12</td>
<td>5.74</td>
</tr>
<tr>
<td>14</td>
<td>2435.85</td>
<td>6.86</td>
<td>5.84</td>
</tr>
<tr>
<td>15</td>
<td>2424.16</td>
<td>6.79</td>
<td>5.86</td>
</tr>
<tr>
<td>16</td>
<td>2450.29</td>
<td>6.89</td>
<td>5.83</td>
</tr>
<tr>
<td>17</td>
<td>2433.43</td>
<td>6.75</td>
<td>5.88</td>
</tr>
<tr>
<td>18</td>
<td>2459.52</td>
<td>6.88</td>
<td>5.83</td>
</tr>
<tr>
<td>19</td>
<td>2440.83</td>
<td>6.69</td>
<td>5.90</td>
</tr>
<tr>
<td>20</td>
<td>2410.83</td>
<td>6.55</td>
<td>5.95</td>
</tr>
<tr>
<td>21</td>
<td>2406.52</td>
<td>6.53</td>
<td>5.96</td>
</tr>
<tr>
<td>22</td>
<td>2464.55</td>
<td>6.70</td>
<td>5.90</td>
</tr>
<tr>
<td>23</td>
<td>2403.44</td>
<td>6.55</td>
<td>5.95</td>
</tr>
<tr>
<td>24</td>
<td>2429.17</td>
<td>6.66</td>
<td>5.91</td>
</tr>
<tr>
<td>25</td>
<td>2351.96</td>
<td>6.41</td>
<td>6.00</td>
</tr>
<tr>
<td>26</td>
<td>2372.16</td>
<td>6.44</td>
<td>5.99</td>
</tr>
<tr>
<td>27</td>
<td>2402.63</td>
<td>6.47</td>
<td>5.98</td>
</tr>
<tr>
<td>28</td>
<td>2357.01</td>
<td>6.38</td>
<td>6.01</td>
</tr>
<tr>
<td>29</td>
<td>2390.91</td>
<td>6.45</td>
<td>5.99</td>
</tr>
<tr>
<td>30</td>
<td>2367.95</td>
<td>6.35</td>
<td>6.02</td>
</tr>
<tr>
<td>Existing</td>
<td>2346.16</td>
<td>6.24</td>
<td>6.06</td>
</tr>
</tbody>
</table>

Note: Refer to Table 21 for amount of land uses allocated at each iteration.
Table 26: The Environmental Impacts of Land Uses Allocated using the Random Generation Method - Solution 3

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Peak Discharge (cfs)</th>
<th>BOD Conc. (mg/l)</th>
<th>D.O. Conc (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2536.89</td>
<td>7.19</td>
<td>5.72</td>
</tr>
<tr>
<td>2</td>
<td>2519.89</td>
<td>7.30</td>
<td>5.68</td>
</tr>
<tr>
<td>3</td>
<td>2511.01</td>
<td>7.22</td>
<td>5.71</td>
</tr>
<tr>
<td>4</td>
<td>2474.75</td>
<td>7.04</td>
<td>5.77</td>
</tr>
<tr>
<td>5</td>
<td>2507.45</td>
<td>7.16</td>
<td>5.73</td>
</tr>
<tr>
<td>6</td>
<td>2472.11</td>
<td>6.99</td>
<td>5.79</td>
</tr>
<tr>
<td>7</td>
<td>2500.04</td>
<td>7.07</td>
<td>5.76</td>
</tr>
<tr>
<td>8</td>
<td>2491.35</td>
<td>7.06</td>
<td>5.76</td>
</tr>
<tr>
<td>9</td>
<td>2455.20</td>
<td>6.91</td>
<td>5.82</td>
</tr>
<tr>
<td>10</td>
<td>2463.04</td>
<td>6.93</td>
<td>5.81</td>
</tr>
<tr>
<td>11</td>
<td>2480.77</td>
<td>6.92</td>
<td>5.81</td>
</tr>
<tr>
<td>12</td>
<td>2446.76</td>
<td>6.78</td>
<td>5.87</td>
</tr>
<tr>
<td>13</td>
<td>2437.00</td>
<td>6.94</td>
<td>5.81</td>
</tr>
<tr>
<td>14</td>
<td>2439.27</td>
<td>6.83</td>
<td>5.85</td>
</tr>
<tr>
<td>15</td>
<td>2422.56</td>
<td>6.84</td>
<td>5.84</td>
</tr>
<tr>
<td>16</td>
<td>2421.01</td>
<td>6.76</td>
<td>5.87</td>
</tr>
<tr>
<td>17</td>
<td>2417.45</td>
<td>6.73</td>
<td>5.89</td>
</tr>
<tr>
<td>18</td>
<td>2417.83</td>
<td>6.68</td>
<td>5.90</td>
</tr>
<tr>
<td>19</td>
<td>2392.16</td>
<td>6.58</td>
<td>5.94</td>
</tr>
<tr>
<td>20</td>
<td>2399.15</td>
<td>6.66</td>
<td>5.91</td>
</tr>
<tr>
<td>21</td>
<td>2439.85</td>
<td>6.71</td>
<td>5.89</td>
</tr>
<tr>
<td>22</td>
<td>2371.49</td>
<td>6.49</td>
<td>5.90</td>
</tr>
<tr>
<td>23</td>
<td>2411.73</td>
<td>6.55</td>
<td>5.95</td>
</tr>
<tr>
<td>24</td>
<td>2376.15</td>
<td>6.52</td>
<td>5.96</td>
</tr>
<tr>
<td>25</td>
<td>2391.85</td>
<td>5.56</td>
<td>5.95</td>
</tr>
<tr>
<td>26</td>
<td>2392.40</td>
<td>6.48</td>
<td>5.98</td>
</tr>
<tr>
<td>27</td>
<td>2351.52</td>
<td>6.36</td>
<td>6.02</td>
</tr>
<tr>
<td>28</td>
<td>2354.39</td>
<td>6.32</td>
<td>6.03</td>
</tr>
<tr>
<td>29</td>
<td>2365.40</td>
<td>6.33</td>
<td>6.03</td>
</tr>
<tr>
<td>30</td>
<td>2345.92</td>
<td>6.30</td>
<td>6.04</td>
</tr>
</tbody>
</table>

Note: Refer to Table 21 for the amount of land uses allocated at each iteration.
FIG. 45 - COMPARISON OF THE IMPACTS OF LAND USES ALLOCATED USING A RANDOM GENERATION METHOD AND THE PROPOSED METHODOLOGY ON DISSOLVED OXYGEN CONCENTRATIONS.
methodology could produce a lower overall environmental impact than those generated randomly.

Comparison of the Land use Allocation from the Proposed Methodology with the Optimal Solutions

In any land use allocation problem, the ideal solutions are those that are optimal. Thus, the performance of any new approach would be best evaluated against the optimal solutions, especially if the approach is heuristic in nature. These optimal solutions can be generated using the appropriate mathematical optimization techniques. Although numerous land use optimization models have been developed to date, probably the only one that has attempted to explicitly model combinatorial environmental impacts was the one developed by Guldmann (1979a). This model was adapted from the convex combinations method of nonlinear programming, and was used to generate the optimal solutions for this research. This model has been briefly reviewed in Chapter 2 and 3, and the details of the computational approach are given below.

In this research, the optimal solutions are generated by solving the optimization problem with the objective function Eq. (27) subject to the constraints in Eqs. (25), (26), and (33) - refer to Chapter 3. Constraint Eq. (33) is used instead of Eq. (35) due to the assumptions of the convex combinations method of nonlinear programming approach that the function be continuous and the constraints be linear. For this reason, the land suitability index $s_{kj}$ in Eq. (33) will be calculated only based upon the site characteristics (criteria), which is static, and determined exogenously to the model. The computational approach of the convex combinations consists of the following steps (Guldmann, 1979a, p. 56):

**Step 1:** Select an arbitrary initial feasible solution $X^0$.

**Step 2:**

1. Evaluate all the partial derivatives $\frac{\partial E(X^m)}{\partial x_{kj}}$ at the trial point $X^m$. Since the partial derivatives $\frac{\partial E(X^m)}{\partial x_{kj}}$ cannot be expressed analytically, they are approximated by using ratios of finite differences as follow:

\[
\frac{\partial E(X^m)}{\partial x_{kj}} \approx \frac{\Delta E(X^m)}{\Delta x_{kj}} = \frac{E(X^m + \Delta X^m) - E(X^m)}{\Delta x_{kj}}
\]  

(69)

For every possible increment $\Delta x_{kj}$ ($k=1,...,K$, $j=1,...,C$), the environmental simulation model is implemented to compute the impact $E(X^m + \Delta X^m)$. 

(2). Solve the linear programming problem consisting of the objective function

\[ E_m(Z) = \sum_{k=1}^{K} \sum_{j=1}^{C} \frac{\partial E(X^m)}{\partial x_{kj}} \cdot Z_{kj}^m \]  

(70)

and the constraints of the general problem as described in Section 3.4. (The \(Z_{kj}^m\) are now the variables, and are substituted to the \(x_{kj}\) in the constraints.)

(3). Define the directions \(d_{kj}^m = Z_{kj}^m - x_{kj}\), where \(Z_{kj}^m\) is the optimal value of \(Z_{kj}^m\) in the previous linear program.

(4). Terminate the calculations when no further improvements of the objective function are possible, i.e. if:

\[ \sum_{k,j} \frac{\partial E(X^m)}{\partial x_{kj}} \cdot Z_{kj}^m \geq \sum_{k,j} \frac{\partial E(X^m)}{\partial x_{kj}} \cdot x_{kj} \]  

(71)

(5). Otherwise, find a step size \(t\) such that \(F(X^m + t \cdot d^m)\) is minimized, with \(t \in [0, 1]\).

**Step 3:** Compute \(X^{m+1} = X^m + t \cdot d^m\). Go back to Step 2 to start iteration \(m+1\).

The above algorithm is an approximation technique generally leading to local optima. In order to find the global optimal solution, this algorithm requires that several runs with different initial solutions be made, and the best result be selected.

The algorithm was used to solve the land use allocation problem for each iteration (year) separately and was programmed in FORTRAN 77. The original listing of the program code was obtained from Professor Guldmann, and then modified for this research as seen appropriate (Appendix C). The size requirements of industrial, commercial, and residential land uses were assumed to be 10, 10 and 0.5 acres respectively. For each iteration, four different initial solutions were used in an attempt to find the local optimum. The first initial solution was derived by solving the conventional linear programming model with the objective function Eq. (24) subject to the constraints in Eqs. (25), (26), and (33) - refer to Chapter 3. The other three initial solutions were generated randomly. Since the solution set generated by the above algorithm was different from those generated by the
Table 27: The Environmental Impacts of Land Uses
Allocated using the Convex Combinations
Method of Nonlinear Programming

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Peak Discharge (cfs)</th>
<th>BOD Conc. (mg/l)</th>
<th>D.O. Conc. (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2384.19</td>
<td>6.71</td>
<td>5.89</td>
</tr>
<tr>
<td>2</td>
<td>2384.63</td>
<td>6.69</td>
<td>5.96</td>
</tr>
<tr>
<td>3</td>
<td>2381.92</td>
<td>6.73</td>
<td>5.88</td>
</tr>
<tr>
<td>4</td>
<td>2364.25</td>
<td>6.57</td>
<td>5.97</td>
</tr>
<tr>
<td>5</td>
<td>2371.45</td>
<td>6.71</td>
<td>5.89</td>
</tr>
<tr>
<td>6</td>
<td>2380.79</td>
<td>6.57</td>
<td>5.94</td>
</tr>
<tr>
<td>7</td>
<td>2380.84</td>
<td>6.58</td>
<td>5.94</td>
</tr>
<tr>
<td>8</td>
<td>2381.29</td>
<td>6.55</td>
<td>5.95</td>
</tr>
<tr>
<td>9</td>
<td>2372.12</td>
<td>6.61</td>
<td>5.93</td>
</tr>
<tr>
<td>10</td>
<td>2376.45</td>
<td>6.60</td>
<td>5.93</td>
</tr>
<tr>
<td>11</td>
<td>2372.57</td>
<td>6.53</td>
<td>5.98</td>
</tr>
<tr>
<td>12</td>
<td>2372.44</td>
<td>6.54</td>
<td>5.95</td>
</tr>
<tr>
<td>13</td>
<td>2371.92</td>
<td>6.43</td>
<td>6.00</td>
</tr>
<tr>
<td>14</td>
<td>2370.84</td>
<td>6.39</td>
<td>5.99</td>
</tr>
<tr>
<td>15</td>
<td>2376.07</td>
<td>6.39</td>
<td>6.01</td>
</tr>
<tr>
<td>16</td>
<td>2373.16</td>
<td>6.38</td>
<td>6.01</td>
</tr>
<tr>
<td>17</td>
<td>2371.44</td>
<td>6.40</td>
<td>6.01</td>
</tr>
<tr>
<td>18</td>
<td>2368.57</td>
<td>6.40</td>
<td>6.01</td>
</tr>
<tr>
<td>19</td>
<td>2370.84</td>
<td>6.39</td>
<td>6.01</td>
</tr>
<tr>
<td>20</td>
<td>2373.23</td>
<td>6.39</td>
<td>6.01</td>
</tr>
<tr>
<td>21</td>
<td>2361.68</td>
<td>6.32</td>
<td>6.04</td>
</tr>
<tr>
<td>22</td>
<td>2369.79</td>
<td>6.28</td>
<td>6.05</td>
</tr>
<tr>
<td>23</td>
<td>2364.41</td>
<td>6.34</td>
<td>6.03</td>
</tr>
<tr>
<td>24</td>
<td>2367.19</td>
<td>6.31</td>
<td>6.04</td>
</tr>
<tr>
<td>25</td>
<td>2357.24</td>
<td>6.29</td>
<td>6.05</td>
</tr>
<tr>
<td>26</td>
<td>2360.69</td>
<td>6.29</td>
<td>6.05</td>
</tr>
<tr>
<td>27</td>
<td>2354.33</td>
<td>6.27</td>
<td>6.05</td>
</tr>
<tr>
<td>28</td>
<td>2354.23</td>
<td>6.25</td>
<td>6.06</td>
</tr>
<tr>
<td>29</td>
<td>2353.09</td>
<td>6.26</td>
<td>6.06</td>
</tr>
<tr>
<td>30</td>
<td>2353.27</td>
<td>6.25</td>
<td>6.06</td>
</tr>
</tbody>
</table>

Note: Refer to Table 21 for the amount of land uses allocated at each iteration. Using the optimization model, it is possible for cells to have mix of land uses.
FIG. 46 - COMPARISON OF THE ENVIRONMENTAL IMPACTS OF THE PROPOSED METHODOLOGY AND THE OPTIMAL SOLUTIONS.
proposed approach due the differences in the characteristics of both approaches, the evaluation was made only on the basis of the overall dissolved oxygen concentration that each approach produces. Table 27 and Figure 46 show the comparison of the optimal solutions with those generated by the proposed methodology. The figure shows that the environmental impacts of the land use plans from the proposed methodology are slightly worse than, but relatively close to the environmental impacts of the optimal solutions. However, the optimal solutions meet the 6 mg/l water quality standard at iteration 14, much more quickly than the proposed methodology (at iteration 19). In other words, the exact optimization model is able to allocate more intense land uses before violating the standard. At iteration 15, 200, 200, and 2920 acres of industrial, commercial, and residential uses are allocated as compared to about 160,120, and 2040 acres at iteration 19.

The results of the proposed methodology and the exact (optimal) solutions were also statistically analyzed using linear regression method in order to determine the technical (not causal) relationship between the two approaches. The regression analysis was carried out using the REG procedure of the SAS statistical package (SAS Institute Inc., 1987). To provide a meaningful interpretation of the result, the regression model was forced to have a zero intercept (using the RESTRICT INTERCEPT=0 option). Figure 47 shows the relationship between the two approaches. The dependent variable was the dissolved oxygen levels of the optimal solutions, with dissolved oxygen levels of the proposed approach as the independent variable. Table 28 shows the result of the linear regression analysis. The regression coefficient (b) of 1.005 correctly indicates that the optimal solutions will always be better than the results of the proposed methodology. One of major reason for the superior performance of the optimization method is that it allows each cell to have mix land uses, which is not possible with the proposed methodology. This may lead to overachievement with the optimization method due to less constraints on allocation. However, the coefficient and the root mean square error (RMSE) are relatively close to 1.0 and 0.0 respectively, suggesting that the proposed model produces land use plans that are environmentally acceptable as compared to the optimal solutions. The regression equation may be expressed as:

\[ X_o = 1.005X_p \]
### TABLE 28:
REGRESSION ANALYSIS OF THE PROPOSED METHODOLOGY AND THE OPTIMAL SOLUTION

**DEP VARIABLE: OPTIMAL**

#### ANALYSIS OF VARIANCE

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>DF</th>
<th>SUM OF SQUARES</th>
<th>MEAN SQUARE</th>
<th>F VALUE</th>
<th>PROB&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODEL</td>
<td>0</td>
<td>0.07312248</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ERROR</td>
<td>29</td>
<td>0.01610782</td>
<td>0.000555442</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C TOTAL</td>
<td>29</td>
<td>0.08923030</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROOT MSE</td>
<td></td>
<td>0.02356782</td>
<td>R-SQUARE</td>
<td>0.8195</td>
<td></td>
</tr>
<tr>
<td>DEP MEAN</td>
<td></td>
<td>5.9907</td>
<td>ADJ R-SQ</td>
<td>0.8195</td>
<td></td>
</tr>
<tr>
<td>C.V.</td>
<td></td>
<td>0.3934067</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### PARAMETER ESTIMATES

| VARIABLE     | DF | PARAMETER ESTIMATE | STANDARD ERROR | T FOR H0: PARAMETER=0 | PROB > |T! |
|--------------|----|-------------------|----------------|------------------------|--------|
| INTERCEP     | 1  | 2.22045E-16       | 5.61901E-09    | 0.000                  | 1.000  |
| PROP         | 1  | 1.00505534        | 0.000721866    | 1392.302               | 0.0015 |
| RESTRICT     | -1 | 0.005045311       | 0.001437752    | 3.509                  | 0.0015 |

Source: SAS Output.
FIG. 47 - SCATTER DISTRIBUTION OF THE DISSOLVED OXYGEN CONCENTRATION OF THE OPTIMAL SOLUTIONS AND THE PROPOSED METHODOLOGY.
where $X_o$ is the optimal dissolved oxygen concentration (mg/l), and $X_p$ is the dissolved oxygen concentration from the proposed methodology.

Discussion of computational results

The results of the experiments on the test sub-basin are quite encouraging. Overall, the methodology has generated land use plans that are environmentally better than the traditional land capability/suitability analysis, and the random generation method, and slightly worse than the optimal solutions (Fig. 48). It was observed that the performance of the methodology was getting better as the amount of land uses to be allocated become larger. This is encouraging because the methodology could offer serious advantages over the traditional land capability/suitability analysis if applied to land use allocation problems involving more intense and polluting urban development. Contrary to expectations, it was also observed that the random generation method, as a whole, produced land use plans that are environmentally better than the traditional methods. These results also seem to support the argument made earlier (in Chapter 2) that the land capability/suitability analysis, although has traditionally been used as an approach to integrate various environmental factors, does not have the means to explicitly quantify environmental impacts. In this approach, environmental impacts are usually implied from various physical characteristics such as slope, and soils, and more commonly proximity to certain land uses/features. While analytically simple, this implicit consideration of impacts is not sufficient to capture the cumulative and combinatorial nature of many environmental impacts (either over space or time) such as nonpoint source water or air pollution.

The regression of the optimal solutions onto the results of the proposed methodology suggests that the land use plans formulated by the methodology produce environmental impacts that are quite acceptable as compared to the optimal solutions. However, these results should be interpreted with care for several reasons. First, the algorithm used to find the optimal solutions is only an approximation technique generally leading to local optima. In order to find the global optimal solution, this algorithm requires that several runs with different initial solutions be made, and the best result be selected. It is possible that the optimal solutions obtained for this study were only local optima since the number of initial solutions and runs for each iteration (case) were relatively small (only four). This suggests that the results of the optimization methodology may underestimate the
FIG. 48 - OVERALL COMPARISON OF THE PROPOSED METHODOLOGY AND OTHER METHODS.
true optimum. Another possibility is that the optimization problem might have been overconstrained considering that the amounts of lands (cells) that need to be allocated are relatively high as compared to the available lands. For instance, at the first iteration about 145 (or 70%) of the 200 available cells need to be allocated to any of the 3 land uses. As a whole, the analysis presented above did provide some valuable evaluation of the proposed methodology.

Implementation of the Methodology on Big Darby Creek Study Area

The purpose of this section is to demonstrate the use of the proposed methodology to the whole, much larger, Big Darby Creek study area. As described earlier, the study area is comprised of 7 sub-basins, and a total of 30 types of environmental groups. For this demonstration, a total of 50 samples were selected to be used in simulating the environmental impacts of a small changes in the land use pattern. By the year 2010, it was projected that the study area will need an additional 591, 492, and 8,749 acres of industrial, commercial, and residential respectively (Refer Table 16). The GIS procedures for allocating the industrial, commercial, and residential land uses are similar to those described earlier, and shown in Figures 32, 34, and 36 respectively.

Table 29 shows the environmental impacts of allocating the new land uses for the first iteration (i.e. year 2010). The impacts of this allocation upon the stream reaches vary. Overall, the dissolved oxygen concentration at the watershed outlet is still relatively high, well above the 6 mg/l standard. The only exception is for sub-basin 13, where the critical dissolved oxygen (D.O) concentration of 5.9 is slightly below the minimum standard. For this reason, the methodology proceeds to the next iteration, and the amounts of land uses to be allocated are reduced proportionately. This iterative process was continued until the D.O. concentration levels at all reaches meet the standard. For this study area, the allocation process stops after 5 iterations. Table 30 and Figure 49 show the final results of this demonstration.
Table 29. The Environmental Impacts of the New land Uses in the Study Area for Iteration 1

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2158.53</td>
<td>6.65</td>
<td>6.77</td>
<td>6.41</td>
</tr>
<tr>
<td>2</td>
<td>2703.04</td>
<td>4.97</td>
<td>6.99</td>
<td>6.41</td>
</tr>
<tr>
<td>3</td>
<td>2382.00</td>
<td>6.48</td>
<td>5.97</td>
<td>5.97</td>
</tr>
<tr>
<td>4</td>
<td>2067.45</td>
<td>5.96</td>
<td>6.94</td>
<td>6.41</td>
</tr>
<tr>
<td>5</td>
<td>1727.05</td>
<td>4.40</td>
<td>6.64</td>
<td>6.41</td>
</tr>
<tr>
<td>6</td>
<td>1708.12</td>
<td>6.30</td>
<td>6.45</td>
<td>6.41</td>
</tr>
<tr>
<td>7</td>
<td>1692.08</td>
<td>4.72</td>
<td>6.41</td>
<td>6.41</td>
</tr>
</tbody>
</table>

Table 30. The Environmental Impacts of the New land Uses in the Study Area for Iteration 5

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2159.74</td>
<td>6.63</td>
<td>6.78</td>
<td>6.44</td>
</tr>
<tr>
<td>2</td>
<td>2598.46</td>
<td>4.89</td>
<td>7.01</td>
<td>6.44</td>
</tr>
<tr>
<td>3</td>
<td>2359.87</td>
<td>6.39</td>
<td>6.01</td>
<td>6.01</td>
</tr>
<tr>
<td>4</td>
<td>2068.84</td>
<td>5.82</td>
<td>6.96</td>
<td>6.44</td>
</tr>
<tr>
<td>5</td>
<td>1671.55</td>
<td>4.54</td>
<td>6.67</td>
<td>6.44</td>
</tr>
<tr>
<td>6</td>
<td>1670.79</td>
<td>6.94</td>
<td>6.48</td>
<td>6.44</td>
</tr>
<tr>
<td>7</td>
<td>1794.98</td>
<td>5.29</td>
<td>6.44</td>
<td>6.44</td>
</tr>
</tbody>
</table>
FIG. 49 DISTRIBUTION OF NEW LAND USES AT ITERATION 5 ALLOCATED USING THE PROPOSED METHODOLOGY FOR THE BIG DARBY CREEK STUDY AREA.
CHAPTER V
CONCLUSIONS AND RECOMMENDATION

5.1 Summary

Land capability/suitability analysis has become a standard part of land use planning especially with the recent advances in computer tools such as geographic information systems. While these tools have been able to remove some of the limitations of this planning technique, many of its fundamental limitations still remain. It is static and deterministic in an environment which is dynamic and probabilistic. It is subjective. It fails to adequately quantify environmental impacts, making environmental impact assessments difficult. Finally, it does not produce an implementable land use plan as output. With the recent increases in environmental concerns, the inability to adequately quantify environmental impacts and the missing linkage with environmental models are of particular importance to the future role of this technique in urban and environmental planning. Although environmental impacts have been included in most previous land capability/suitability studies, they were mainly implied by scientific data on land characteristics such as slope, erosion, runoff, proximity to water body, etc. With this approach, impacts are considered on a location-by-location (atomistic) basis, thus are usually insufficient to capture the combinatorial and cumulative nature (either in space and/or time) of many environmental impacts such as air pollution dispersion, and nonpoint source water pollution.

This study has developed a modeling approach that links land capability/suitability analysis with environmental models using geographic information systems. Its utility has been demonstrated in allocating hypothetical urban land uses involving nonpoint source water pollution. The basis of the proposed methodology was derived from the land use suitability/allocation model of Tomlin and Johnston (1988), and the convex combinations method of non-linear programming adapted by Guldmann (1979a). The methodology proposed is mainly implemented as a cartographic model. It extends Tomlin and Johnston's model in that it attempts to explicitly quantify and use the magnitude of environmental
impacts in allocating land uses to different sites. This is accomplished by using an environmental simulation technique. The proposed methodology is different from Guldmann's model in that land uses are allocated sequentially rather than simultaneously. This is important to suit the existing geographic information system (GIS) modeling environment where the capability to solve mathematically rigorous optimization models is not yet available. To further suit the GIS environment, the methodology proposed also makes use of classification (clustering) and spatial sampling techniques. This was intended to reduce the computational requirement in implementing the methodology. In order to formulate an environmentally acceptable land use plan, the methodology proposed also works in an iterative manner. It starts by allocating land uses for the end of a planning horizon. If the land uses allocated for this year (period) are not acceptable, the methodology then proceeds to the next iteration by adjusting (reducing) the land uses to be allocated. This iterative process continues until an environmentally acceptable land use plan is found.

The implementation of the proposed methodology on a test sub-basin leads to two major implications: technical and planning/management. Technically, the methodology had generated land use plans that are environmentally better than the traditional land capability/suitability analysis, and the random generation method. It is observed that the performance of the methodology improves as the amount of land uses to be allocated become larger. This is encouraging because the methodology offers serious advantages over the traditional land capability/suitability analysis if applied to land use allocation problems involving more intense and polluting urban development. Surprisingly, it is also observed that the random generation method, as a whole, produced land use plans that are environmentally better than the traditional methods. These results also seem to support the argument made earlier (in Chapter 2) that the land capability/suitability analysis, although it has traditionally been used as an approach to integrate various environmental factors, does not have the means to explicitly quantify environmental impacts. Furthermore, since it operates mainly on a location-by-location (atomistic) basis, it is unable to capture the cumulative and combinatorial nature of environmental impacts (either over space or time).

The regression of the results of the proposed methodology onto the optimal solutions suggests that the methodology produces acceptable results as compared to the optimal solutions. However, these results should be treated as preliminary for several reasons. The optimal solutions were derived using an approximation technique. There is a
possibility that the solutions obtained were only local optima. The second reason, related to the first one, is the possibility that the optimization problem might have been overconstrained considering that the amounts of land uses needing to be allocated are relatively high as compared to the available lands.

In terms of planning/management, this study has also found that land use planning (non-structural controls) can, up to a certain period, be used as a measure to minimize the environmental impacts of urban nonpoint source pollution on the water quality. However, as an area becomes more developed, land use planning alone is not sufficient to maintain the environmental quality above the minimum standard. In this latter case, the use of other non-structural measures (such as street sweeping), or structural measures (such as sedimentation basin) may then become necessary.

In conclusion, this study has demonstrated the usefulness of geographic information systems for linking land capability/suitability analysis with environmental models in allocating urban land uses. It has also demonstrated the potential of using classification and sampling procedures in simulating the possible impacts of land use changes. The methodology proposed can be used to formulate a preliminary land use plan that protects the valuable resources of environmental quality. It offers several advantages over the traditional land capability/suitability analysis, and provides an alternative approach to an optimization model. Its potential can be further enhanced if the proper tools (mechanisms) for its implementation become widely available.

5.2 Toward Implementation

The methodology proposed in this study requires at least four basic tools: environmental simulation models, clustering procedures, spatial sampling procedure, and geographic information systems. The methodology makes use of the clustering technique, a classification technique that has been commonly used for various spatial analyses in the past. Unfortunately this capability is not yet widely available in existing geographic information systems. Exceptions to this are those systems initially developed for image processing purposes. The methodology is also based on spatial sampling, another important technique in spatial analysis as well as in environmental simulation modeling. It is also surprising that no existing geographic information systems (at least to the
knowledge of this author) provide the user with this capability. Thus, it is recommended that these procedures be included as standard capabilities of future geographic information systems.

The methodology proposed also works in an iterative manner. The amounts of land uses to be allocated at each iteration are adjusted until an acceptable plan is derived. This process was mainly implemented as cartographic models. Thus, to accommodate this task efficiently, it is essential to have a GIS that has a macro language or batch processing capability. For more efficient implementation, all these tools should be integrated within a single geographic information system. However, this is not yet possible given the present state-of-the-art. Each of these tools must be run independently outside the GIS environment. At the present time, it is not yet feasible to run any environmental simulation models directly from within a GIS for several reasons. Most environmental simulation models require extensive computational requirements. Furthermore, most of these models have been developed before the recent advance in GIS technology, thus their data structures are incompatible with those commonly used for the GIS. For these reasons, environmental simulation models have been and continue to be run outside the GIS. In this case, it is essential to have a GIS that is open-ended, and capable of supporting multiple file formats (especially ASCII) so that it can be linked to any environmental model through a "bridging" program.

Finally, given the fact that environmental simulation models (as well as most other spatial models) will continue to be run outside the GIS (thus land capability/suitability analysis), it may be more efficient to implement the proposed methodology within the framework of a spatial decision support system (SDSS). A SDSS is basically a GIS based decision support system (DSS). A DSS is "an interactive computer based system that help decision makers utilize data and models to solve unstructured problems" (Sprague and Carlson, 1982). It typically "consists of a database, a group of models, and a control program shielded from the user through an extremely user friendly interface" (Van der Vlugt, 1988, p. 462). Thus, a DSS provides a "framework for integrating analytical

---

11 An exception to this is the latest version (Version 3.2) of IDRISI, another low-cost GIS package available from Clark University (Eastman, 1990). This new version has a RANDOM operation, which may be used for selecting random samples. This version was released in October/November 1990, thus was not available for this study.
modeling capabilities, database management systems and graphics display capability to improve decision-making processes" (Densham and Goodchild, 1988, pp. 710). While the concept of DSS has been existed for many years (especially in operations research and management science to address business problems), its applications in the spatial problem domain has just begun to get some attention in recent years. The development of a DSS based on GIS is perhaps one of the major research agenda to be (presently) addressed by the National Center for Geographic Information and Analysis (NCGIA) recently established by the National Science Foundation (NCGIA, 1989).

5.3 Possible Extensions.

There are several aspects of the land use capability/suitability analysis and allocation model proposed in this research that are recommended for further study. First, the formulation and performance of the methodology could be tested on other land capability/suitability analysis methods. This study has used the linear combination method for determining the suitability of each land unit for each use. It would be interesting to see if similar results can be obtained using other capability/suitability methods reviewed in Chapter 2. Second, the formulation of the model can be expanded to include other objectives (environmental impacts) or constraints. In this study, the main objective was to minimize environmental impacts given certain level of land suitability and land use requirements. It is also possible to formulate the problem as the maximization of land suitability subject to certain levels of environmental impacts. Within this framework, it is also possible to use the simulated impact as another factor in determining the overall suitability of each site for certain use. This factor can be rated and then given the appropriate weight. Land uses can then be allocated to sites with the highest suitability, adding others with decreasing suitability.

The methodology proposed can also be extended to solve land use allocation problems involving other spatial constraints such as size, shape, compactness, and adjacency. Adding these constraints is not expected to pose any problem to the proposed methodology (at least in terms of implementation) since it works on an geographic information system environment, which is very efficient in handling and manipulating geographic and spatial data. While the size constraint was initially proposed in the methodology, it was not implemented for several reasons. The cell size of the spatial
database is quite large (40 acres), thus was assumed to be sufficient to accommodate most land uses allocated in this study.

In this study, the land uses for each iteration were allocated sequentially in a single pass. This could be extended such that for each iteration, the land use allocation process is repeated for several passes until a stable solution for that iteration is achieved. However, for this approach to be practical, it is essential to have a GIS with a macro or batch processing capability. As this capability become a standard feature of future GIS, an analysis of the effect of this technique on the performance of the methodology is thus suggested as a topic for future research.
BIBLIOGRAPHY


Gordon, Steven I. and John Simpson (1990). The Big Darby Creek Watershed Project. Final Report. Department of City and Regional Planning and Department of Landscape Architecture. The Ohio State University, Columbus, Ohio.


Gross, Meir; Daniel J. Bucko; Julius G. Fabos; & John H. Foster (1984), Landscape Planning & Evaluation: A Combined Goal-Oriented and Benefit/Loss Approach, Research Bulletin No.692, Massachusetts Agricultural Experiment Station, University of Massachusetts, Amherst, MA.


Milligan, G.W. and Cooper, M.C. (1985). "An Examination of Procedures for Determining the Number of Clusters in a Data Sets", Psychometrika,


Smullen, J.T., J.P. Hartigan, and T.J. Grizzand (no date). Assessment of Runoff Pollution in Coastal Watersheds (cited by Lynard et al., 1980)


Tomlin, C.D. (1989). Course Lectures on Cartographic Modeling. School of Natural Resources, Ohio State University, Columbus, Ohio.


APPENDIX A
GEOMETRIC CHARACTERISTICS AND PARAMETER OF
THE SEVEN REACHES IN THE STUDY AREA
Data set for the Streeter-Phelps D.O. Modeling

<table>
<thead>
<tr>
<th>TITLE1 - RIVER TYPE/FROM-TO REACHES</th>
</tr>
</thead>
<tbody>
<tr>
<td>REACH NO : 1</td>
</tr>
<tr>
<td>REACH NO : 2</td>
</tr>
<tr>
<td>REACH NO : 3</td>
</tr>
<tr>
<td>REACH NO : 4</td>
</tr>
<tr>
<td>REACH NO : 5</td>
</tr>
<tr>
<td>REACH NO : 6</td>
</tr>
<tr>
<td>REACH NO : 7</td>
</tr>
</tbody>
</table>

| ENDATA |

<table>
<thead>
<tr>
<th>TITLE2 - BEGINNING/ENDING DISTANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>REACH NO : 1</td>
</tr>
<tr>
<td>REACH NO : 2</td>
</tr>
<tr>
<td>REACH NO : 3</td>
</tr>
<tr>
<td>REACH NO : 4</td>
</tr>
<tr>
<td>REACH NO : 5</td>
</tr>
<tr>
<td>REACH NO : 6</td>
</tr>
<tr>
<td>REACH NO : 7</td>
</tr>
</tbody>
</table>

| ENDATA |

<table>
<thead>
<tr>
<th>TITLE3A - INITIAL(AMBIENT) DISSOLVED OXYGEN</th>
</tr>
</thead>
<tbody>
<tr>
<td>REACH NO : 1</td>
</tr>
<tr>
<td>REACH NO : 2</td>
</tr>
<tr>
<td>REACH NO : 3</td>
</tr>
<tr>
<td>REACH NO : 4</td>
</tr>
<tr>
<td>REACH NO : 5</td>
</tr>
<tr>
<td>REACH NO : 6</td>
</tr>
<tr>
<td>REACH NO : 7</td>
</tr>
</tbody>
</table>

| ENDATA |

<table>
<thead>
<tr>
<th>TITLE3B - INITIAL(AMBIENT) BIOCHEMICAL OXYGEN</th>
</tr>
</thead>
<tbody>
<tr>
<td>REACH NO : 1</td>
</tr>
<tr>
<td>REACH NO : 2</td>
</tr>
<tr>
<td>REACH NO : 3</td>
</tr>
<tr>
<td>REACH NO : 4</td>
</tr>
<tr>
<td>REACH NO : 5</td>
</tr>
<tr>
<td>REACH NO : 6</td>
</tr>
<tr>
<td>REACH NO : 7</td>
</tr>
</tbody>
</table>

| ENDATA |

<table>
<thead>
<tr>
<th>TITLE3C - INITIAL(AMBIENT) FLOW RATES</th>
</tr>
</thead>
<tbody>
<tr>
<td>REACH NO : 1</td>
</tr>
<tr>
<td>REACH NO : 2</td>
</tr>
<tr>
<td>REACH NO : 3</td>
</tr>
<tr>
<td>REACH NO : 4</td>
</tr>
<tr>
<td>REACH NO : 5</td>
</tr>
<tr>
<td>REACH NO : 6</td>
</tr>
<tr>
<td>REACH NO : 7</td>
</tr>
</tbody>
</table>

| ENDATA |

<table>
<thead>
<tr>
<th>TITLE4 - FLOW RATE ADDED FROM POINT SOURCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>REACH NO : 1</td>
</tr>
<tr>
<td>REACH NO : 2</td>
</tr>
<tr>
<td>REACH NO : 3</td>
</tr>
<tr>
<td>REACH NO : 4</td>
</tr>
<tr>
<td>REACH NO : 5</td>
</tr>
<tr>
<td>REACH NO : 6</td>
</tr>
<tr>
<td>REACH NO : 7</td>
</tr>
</tbody>
</table>

| ENDATA |

<table>
<thead>
<tr>
<th>TITLE5 - VELOCITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>REACH NO : 1</td>
</tr>
<tr>
<td>REACH NO : 2</td>
</tr>
<tr>
<td>REACH NO : 3</td>
</tr>
<tr>
<td>REACH NO : 4</td>
</tr>
</tbody>
</table>

<p>| ENDATA |</p>
<table>
<thead>
<tr>
<th>REACH NO</th>
<th>CBOD (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1.112</td>
</tr>
<tr>
<td>6</td>
<td>1.129</td>
</tr>
<tr>
<td>7</td>
<td>1.261</td>
</tr>
</tbody>
</table>

**Title 6: Point Source CBOD**

<table>
<thead>
<tr>
<th>REACH NO</th>
<th>CBOD (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>0.0</td>
</tr>
<tr>
<td>3</td>
<td>0.0</td>
</tr>
<tr>
<td>4</td>
<td>0.0</td>
</tr>
<tr>
<td>5</td>
<td>0.0</td>
</tr>
<tr>
<td>6</td>
<td>0.0</td>
</tr>
<tr>
<td>7</td>
<td>0.0</td>
</tr>
</tbody>
</table>

**Title 7: Point Source Dissolved Oxygen**

<table>
<thead>
<tr>
<th>REACH NO</th>
<th>DO (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>0.0</td>
</tr>
<tr>
<td>3</td>
<td>0.0</td>
</tr>
<tr>
<td>4</td>
<td>0.0</td>
</tr>
<tr>
<td>5</td>
<td>0.0</td>
</tr>
<tr>
<td>6</td>
<td>0.0</td>
</tr>
<tr>
<td>7</td>
<td>0.0</td>
</tr>
</tbody>
</table>

**Title 8: Nonpoint Source CBOD (Without Increased in Flow)**

<table>
<thead>
<tr>
<th>REACH NO</th>
<th>CBOD (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>0.0</td>
</tr>
<tr>
<td>3</td>
<td>0.0</td>
</tr>
<tr>
<td>4</td>
<td>0.0</td>
</tr>
<tr>
<td>5</td>
<td>0.0</td>
</tr>
<tr>
<td>6</td>
<td>0.0</td>
</tr>
<tr>
<td>7</td>
<td>0.0</td>
</tr>
</tbody>
</table>

**Title 9: Temperature**

<table>
<thead>
<tr>
<th>REACH NO</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21.0</td>
</tr>
<tr>
<td>2</td>
<td>22.0</td>
</tr>
<tr>
<td>3</td>
<td>22.0</td>
</tr>
<tr>
<td>4</td>
<td>20.5</td>
</tr>
<tr>
<td>5</td>
<td>23.5</td>
</tr>
<tr>
<td>6</td>
<td>22.0</td>
</tr>
<tr>
<td>7</td>
<td>25.3</td>
</tr>
</tbody>
</table>

**Title 9: CBOD Removal (Deoxygenation) Rate**

<table>
<thead>
<tr>
<th>REACH NO</th>
<th>Rate (mg/L/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.898</td>
</tr>
<tr>
<td>2</td>
<td>0.890</td>
</tr>
<tr>
<td>3</td>
<td>2.049</td>
</tr>
<tr>
<td>4</td>
<td>0.619</td>
</tr>
<tr>
<td>5</td>
<td>0.806</td>
</tr>
<tr>
<td>6</td>
<td>0.757</td>
</tr>
<tr>
<td>7</td>
<td>0.745</td>
</tr>
</tbody>
</table>

**Title 10: Reaeration Rate**

<table>
<thead>
<tr>
<th>REACH NO</th>
<th>Rate (m3/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.052</td>
</tr>
<tr>
<td>2</td>
<td>1.338</td>
</tr>
<tr>
<td>3</td>
<td>2.126</td>
</tr>
<tr>
<td>4</td>
<td>1.369</td>
</tr>
<tr>
<td>5</td>
<td>1.186</td>
</tr>
<tr>
<td>6</td>
<td>0.914</td>
</tr>
<tr>
<td>7</td>
<td>1.163</td>
</tr>
</tbody>
</table>
APPENDIX B
COMPUTER PROGRAM OF THE ENVIRONMENTAL MODEL
NOTE: THIS PROGRAM IS USED IN CONJUNCTION WITH THE PROGRAM LISTED IN
APPENDIX C.

DIMENSION X0(NLT,NCT,MLU)
DIMENSION RIMP(MLU),S(MLU),XT(MLU)
INTEGER CN(NCT,NLT),SLOPE(NCT,NLT),LENGTH(NCT,NLT),
1 ASPEK(NCT,NLT),LUT(NCT,NLT),HYDRO(NCT,NLT),
1 SUIT(NCT,NLT,MLU),ICN(NHGR,MLU)
CHARACTER TITLE*80, FMT*80

C.....READ CONSTANT VARIABLES
IOU = 5
NL = MLU
ILT = NLT
ICT = NCT

C.....GET POLLUTANT CONSTANT FOR EACH LAND USE
READ(*,310) (RIMP(IK),IK=1,NK)
310 FORMAT(5F7.2)
WRITE(*,310) (RIMP(IK),IK=1,NK)

C.....GET CURVE NUMBER ASSIGNMENT MATRIX FOR EACH LAND USE AND
C HYDROLOGIC SOIL GROUP.

DO 350 IK=1,NK
READ(*,360) (ICN(IH,IK),IH=1,NHGR)
360 FORMAT(5I5)
350 CONTINUE

C.....LAND REQUIREMENT DATA
READ(*,400) (S(IK),IK=1,NK)
400 FORMAT(5F5.0)
WRITE(6,400) (S(IK),IK=1,NK)

C.....LAND DEMAND
READ(*,450) (XT(IK),IK=1,5)
WRITE(6,450) (XT(IK),IK=1,5)
450 FORMAT(5F5.0)

C.....READ ALL NECESSARY INPUT OF SITE CHARACTERISTICS
10 FORMAT (A)
11 FORMAT (A)
C
C.....SLOPE
C
  READ(*,10) TITLE
  READ(*,11) FMT
  WRITE(6,10) TITLE
  WRITE(6,10) FMT
C
  DO 110 IR=1,ILT
    READ(*,FMT) (SLOPE(IC,IR),IC=1,ICT)
110  WRITE(6,FMT) (SLOPE(IC,IR),IC=1,ICT)
C
C.....FLOW LENGTH
C
  READ(*,12) TITLE
  FORMAT (A)
  READ(*,11) FMT
  WRITE(6,10) TITLE
  WRITE(6,10) FMT
C
  DO 120 IR=1,ILT
    READ(*,FMT) (LENGTH(IC,IR),IC=1,ICT)
120  WRITE(6,FMT) (LENGTH(IC,IR),IC=1,ICT)
C
C.....ASPECT
C
  READ(*,12) TITLE
  READ(*,11) FMT
  WRITE(6,10) TITLE
  WRITE(6,10) FMT
C
  DO 130 IR=1,ILT
    READ(*,FMT) (ASPEK(IC,IR),IC=1,ICT)
130  WRITE(6,FMT) (ASPEK(IC,IR),IC=1,ICT)
C
C.....LAND USE TYPE
C
  READ(*,12) TITLE
  READ(*,11) FMT
  WRITE(6,10) TITLE
  WRITE(6,10) FMT
C
  DO 140 IR=1,ILT
    READ(*,FMT) (LUT(IC,IR),IC=1,ICT)
140  WRITE(6,FMT) (LUT(IC,IR),IC=1,ICT)
C
C.....HYDROLOGIC SOIL GROUP
C
  READ(*,12) TITLE
  READ(*,11) FMT
  WRITE(6,10) TITLE
WRITE(6,10) FMT
C
DO 150 IR=1,ILT
   READ(*,FMT) (HYDRO(IR,IC),IC=1,ICT)
150   WRITE(6,FMT) (HYDRO(IR,IC),IC=1,ICT)
C
C.....SUITABILITY OF EACH LAND USE........................
C
DO 160 IK=1,NK
   READ(*,12) TITLE
   READ(*,11) FMT
   WRITE(6,10) TITLE
   WRITE(6,10) FMT
C
DO 160 IR=1,ILT
   READ(*,FMT) (SUIT(IC,IR,IK),IC=1,ICT)
   WRITE(6,FMT) (SUIT(IC,IR,IK),IC=1,ICT)
160 CONTINUE
C
RETURN
END
C
C===SUBROUTINE GETLUT(ICT,ILT,NK,ST,S,LUT,XO)===
C
C
INTEGER LUT(ICT,ILT)
DIMENSION S(NK), XO(ILT,ICT,NK)
CHARACTER TITLE*80, FMT*80
C
C
C.....LAND USE TYPE
C
READ(*,11) TITLE
READ(*,11) FMT
WRITE(6,11) TITLE
WRITE(6,11) FMT
11 FORMAT (A)
   DO 140 IR=1,ILT
      READ(*,FMT) (LUT(IC,IR),IC=1,ICT)
140   WRITE(6,FMT) (LUT(IC,IR),IC=1,ICT)
C
C
DO 145 IR=1,ILT
   DO 145 IC=1,ICT
   DO 146 IK=1,NK
      XO(IR,IC,IK) = 0.0
      IF (LUT(IC,IR),EQ,IK) THEN
         XO(IR,IC,IK) = ST/S(IK)
      END IF
CONTINUE

RETURN
END

SUBROUTINE IMPACT(IR,IC,IK,IMODE,NCT,NLT,MLU,NHGR,MRCH,NRCH,
  ST,JOR,IOC,ISEG,ALPHA,RAIN,NK,NKS,NC,DELTA,
  XO,ATTIMP,R0,RV,RT,RF,RP,RC,RIMP,S,XT,IA,IB,RA,RB,
  CN,SLP,LNGTH,ASPEK,LUT,HYDRO,SUIT,ICN,
  QO,V,D1,D2,CBP,CBD,DOI,RK,TMP,RK2,P,RKS,R,DO,
  IRTYPE,JFRTO,QW,CI,CBDS,DI,BODI,QOI,DOP,EIMP)

C

C.....THIS ROUTINE SIMULATE THE ENVIRONMENTAL IMPACT (BOD) OF A GIVEN
C LAND USE.
C
DIMENSION XO(NL,NTC,MLU), ATTIMP(NLT,NCT,MLU)
DIMENSION RO(NCT,NLT), RV(NCT,NLT), RTY(NCT,NLT), RF(NCT,NLT),
   RC(NCT,NLT)
DIMENSION RIMP(MLU), S(MLU), XT(MLU)

INTEGER CN(NCT,NLT), SLOP(NCT,NLT), LNGTH(NCT,NLT),
   ASPEK(NCT,NLT), LUT(NCT,NLT), HYDRO(NCT,NLT),
   SUIT(NCT,NLT,MLU), ICN(NHGR,MLU)
INTEGER IA(NCT,NLT), IB(NCT,NLT)
REAL RA(NCT,NLT), RB(NCT,NLT)
REAL TXO(MLU)
DIMENSION QO(MRCH), V(MRCH), D1(MRCH), D2(MRCH),
   CBP(MRCH), CBD(MRCH), DOI(MRCH), RK(MRCH), TMP(MRCH),
   RK2(MRCH), P(MRCH), RKS(MRCH), R(MRCH), DO(MRCH),
   IRTYPE(MRCH), JFRTO(MRCH), QW(MRCH), CI(MRCH),
   CBDI(MRCH), DI(MRCH), BODI(MRCH), QOI(MRCH), DOP(MRCH)

ST = 40.0
JCL = NC
JR = NLT
JC = NCT
NLU = MLU
IOUT = I0*NCT + I0C

C
C.....IMODE=1 MEANS IN SIMULATION MODE. IMODE=0 TO CALCULATE
C OVERALL IMPACT
C
IF (IMODE .EQ. 1) THEN
C
C.....THIS PORTION OF THE ROUTINE WILL BE USED FOR RUNNING SIMULATION.
C THE RESULT OF EACH SIMULATION WILL BE STORED AT THAT PARTICULAR
C CELL. IT REQUIRES LAND USE DATA TOGETHER WITH THE HYDROLOGIC
C SOIL GROUP DATA - TO BE USED TO REDEFINE THE NEW CN DATA FOR THE
C SIMULATION
C
C ATTIMP(IR,JC,IK) = 0.
C
C
C..............DEFINE NEW CN AND INTERCHANGE WITH INITIAL CN VALUE. OLD
C CN VALUE IS SAVED IN TEMPORARY VARIABLE - ITCN
C
C ITCN = CN(IC,IR)
C
C..............INTERCHANGE NEW LAND USE TYPE WITH INITIAL ONE. OLD LAND
C USE DATA IS SAVED IN TEMPORARY VARIABLE - TXO
DO 200 K=1,5
    TXO(K) = XO(IR,IC,K)
200 CONTINUE
C
C DO 201 KK=1,NK
    AMTXO= XO(IR,IC,IK)*S(KK)
    IF (INT(AMTXO).EQ. INT(ST), AND. KK.EQ.IK) GOTO 202
    IF (AMTXO.GE. (ST/2.) ) THEN
        XO(IR,IC,IK) = XO(IR,IC,IK)+DELTA
        XO(IR,IC,KK) = (AMTXO-XO(IR,IC,IK)*S(IK))/S(KK)
    GOTO 202
    ENDIF
201 CONTINUE
C
C..............DEFINE NEW COMPOSITE CURVE NUMBER
C
C 202 WCN = 0.
    SAREA = 40.0
    DO 100 J=1,5
        WCN = WCN+XO(IR,IC,J)*ICN(HYDRO(IC,IR),J)*S(J)
    IF (SAREA .EQ. 0.0) THEN
        CN(IC,IR) = 0
        ELSE
            CN(IC,IR) = INT(0.5 + WCN/SAREA)
    ENDIF
C
C........SAVE OLD RUNOFF, VELOCITY, AND TRAVEL TIME OF
C CELL (I,J) BEFORE CALCULATING NEW VALUES. THESE
C VALUES WILL RESTORED AFTER THE SIMULATION FOR
C THAT CELL.
C
C TRO = RO(IC,IR)
    TRV = RV(IC,IR)
    TRT = RT(IC,IR)
C
C CALL INTIMP(IR,IC,NCT,NLT,MLU,NHGR,RAIN,ST,
              1    CN,LENGTH,SLOPE,RO,RV,RT,XO,S)
C
C ELSE
C
C.....CALCULATE INITIAL RUNOFF, VELOCITY, AND TRAVEL
C
T racks. These values change individually, thus
C NEED NOT BE RECALCULATED ENTIRELY FOR EACH IMPACT
C
COMPUTATION.
C
DO 102 I=1,NLT
DO 102 J=1,NCT
RO(I,J) = 0.0
102 CONTINUE
DO 101 IR=1,NLT
DO 101 IC=1,NCT
CALL INTMP(RC,IC,NCT,NLT,MLU,NHGR,RAIN,ST,
1 CN,LENGTH,SLOPE,RO,RV,RT,XO,5)
101 CONTINUE
C
END IF
C
C
C
C********************************************************************
C * RUN MODEL WITH NEW DATA *
C
C********************************************************************
C
C
C
C****CALCULATE TIME OF CONCENTRATION
C INPUT : ASPECT DATA (INTEGER #)
C TRAVEL TIME (REAL #)
C OUTPUT : TIME OF CONC. (REAL #)  STORE IN RT)
C THIS REQUIRE THE USE OF SUBROUTINE TRAVEL
C
CALL SWAP(JC,IR,ASPEK,IA)
CALL TRAVEL(JC,IC,IR,IA,IB,RT,1R,2)
C
C
C
C****CALCULATE PEAK FLOW
C INPUT : AREA (REAL #)
C RUNOFF (REAL #)  STORE IN RO) \RUNOFF!
C TIME OF CONC. (REAL #)  STORE IN RT()\TIME!
C OUTPUT : PEAK FLOW RATE (REAL #)  STORE IN RFO
C
AREA = ST/640.
C
DO 400 I=1,JR
DO 410 J=1,JC
IF (RB(J,J) .EQ. 0.) THEN
RF(J,J) = 0.0
ELSE
RF(J,J) = 726.* AREA * RO(J,J)/RB(J,J)
ENDIF
410 CONTINUE
400 CONTINUE
C
C*****DETERMINE THE POLLUTION LEVEL AT CELL
C THE POLLUTION LEVEL AT EACH CELL IS ASSUMED TO BE THE
C AVERAGE OF ALL LANDUSES IN THE CELL.
C
C INPUT : PEAK FLOW (REAL #) STORE IN RF(0) PKFLOW!
C LAND USE TYPE (INT #) STORE IN IA() SOURCE!
C POLL. MULTIPLIER (REAL #) STORE IN RIMP() SOURCE!
C OUTPUT : POLLUTANT CONC. (REAL #) STORE IN RP()
C
C.....CALCULATE POLLUTION CONC.
C
DO 500 J=1,JC
DO 500 I=1,IR
   RP(1,I) = 0.0
   CMAX = 0.000
   TEMP = 0.0
   DO 501 K=1,KC
      IF (XO(I,J,K) LE. 0.0) GOTO 501
      CMAX = CMAX + 0.0
      TEMP = TEMP + RF(J,K)*RIMP(K)
   501 CONTINUE
      IF (CMAX EQ. 0.0 OR. RF(J,J) LE. 0.) GOTO 500
C
   RP(J,J) = TEMP/CMAX
C
500 CONTINUE
C
C
C*****ACCUMULATE (USING DRAIN SUBROUTINE) PEAK FLOW AND POLLUTION CONC.
C INPUT : PEAK FLOW (REAL #) STORE IN RA() PKFLOW!
C POLLUTION CONC. (REAL #) STORE IN RB() POLLEV!
C DRAIN REQUIRES ASPECT DATA & DATA TO BE DRAINED
C OUTPUT : ACCUMULATED PEAK FLOW STORE IN RA()
C ACCUMULATED POLLUTION CONC. STORE IN RB()
C
C.....DRAIN PEAK FLOW & SAVE ACCUMULATED PEAK FLOW
C
   NC = JC
   NR = JR
C
   CALL SWAP(JC,JR,RA,1A)
   CALL RSWAP(JC,JR,RF,RA)
   CALL DRAIN(1C,JC,JR,1A,1B,RF)
C
C.....NOW ACCUMULATE POLLUTION, DATA PASSED FROM MAIN PROGRAM
C
   CALL SWAP(1C,JR,RA,1A)
CALL DRAIN(JCL,K,JR,IA,IB,RP)

C

C *****CALCULATE WEIGHTED CONCENTRATION
C

C INPUT : ACC. PEAK FLOW (REAL #) - STORE IN RA() 
C COMPUTE!
C ACC. POLLUTION CONC. (REAL #) - STORE IN RB() 
C COMPUTE!
C OUTPUT : WEIGHTED CONCENTRATION (REAL #) - STORE IN RA()
C

DO 600 I=1, JR
   DO 600 J=1, JC
      IF (RF(J,J) .EQ. 0.) THEN
         RC(J,J) = 0.
      ELSE
         RC(J,J) = RP(J,J)/RF(J,J)
      ENDIF
600 CONTINUE

C

CBD(ISEG) = RC(IOC,IOR)
Q(ISEG) = RF(IOC,IOR)

C....FIND THE IMPACT OF THE NEW B.O.D LEVEL ON THE DISSOLVED OXYGEN.
C CALL D.O. MODEL
C
C CALL DOMEDEL(MRCH,NRCH,QO,V,D1,D2,CBP,CBD,DOI,RK,TMP,
   1 RK2,P,RKS,R,DO,IRTYPE,IKFRK,OW,C1,CBDI,QI,BODI,
   1 QO1,DOP)
C....FIND THE MINIMUM D.O. AT DOWNSTREAM REACHES.
C
C CALL MINDO (MRCH,NRCH,QO,V,D1,D2,CBP,CBD,DOI,RK,TMP,
   1 RK2,P,RKS,R,DO,IRTYPE,IKFRK,OW,C1,CBDI,QI,BODI,
   1 QO1,DOP,ISEG,CEMAR)
C
C....MODEL COMPUTATION END HERE

C

IF (IMODE .EQ. 1) THEN
C
C........ASSIGN THE IMPACT COEFFICIENT TO CELL (IC,IR) OF LAND USE IK.
C ATTMPR IR,IC,IK) = (EIMP - CEMAR)
C
C........RESTORE THE INITIAL VALUES OF CN AND LAND USE TO BE USED
C FOR NEXT SIMULATION
C
C
CN(IC,IR) = ITCN
RO(IC,IR) = TRO
RV(IC,IR) = TRV
RT(IC,IR) = TRT

C

DO 210 K=1,5
210 XO(IR,IC,K) = TXO(K)
C
ELSE
EIMP = CEMAR
WRITE(6,'(A)') '************** NEW **************'
WRITE(6,*)(IOC,IOR,RF(IOC,IOR),RC(IOC,IOR),EIMP)
ENDIF
C
9999 RETURN
END
C
SUBROUTINE SWAP(NCT,NLT,IA,IB)
C
C....THIS PROGRAM SWAP VALUES OF TWO ARRAYS FOR INTEGER #
C
INTEGER IA(NCT,NLT),IB(NCT,NLT)
C
DO 10 I=1,NLT
   DO 20 J=1,NCT
      IB(J,I) = IA(J,I)
   CONTINUE
10 CONTINUE
20 CONTINUE
C
RETURN
END
C
SUBROUTINE RSWP(NCT,NLT,RA,RB)
C
C....THIS PROGRAM SWAP VALUES OF TWO ARRAYS FOR REAL #
C
REAL RA(NCT,NLT),RB(NCT,NLT)
C
DO 10 I=1,NLT
   DO 20 J=1,NCT
      RB(J,I) = RA(J,I)
   CONTINUE
10 CONTINUE
20 CONTINUE
C
RETURN
END
C
CREATE MAP OF NEW LAND USE
SUBROUTINE NWMAPIPH(NLT,NCT,NK,ST,XO,IYR)
C
C....THIS ROUTINE CREATE A MAP USING CHARACTER PRINT
C
REAL XO(NLT,NCT,NK),S(NK)
CHARACTER*1 DOT(5),MAP(20)
DATA DOT/1,2,3,4,5/
C
WRITE(6,70) IYR
70 FORMAT('1.', NEW LAND USE MAP :2X,I5//)
DO 10 I=1,NLT
DO 15 J=1,NCT
C    II = NCT-J+1
      MAP(J) = 0
DO 20 K=1,NK
      AMXTXO = XO(I,J,K)*S(K)
      IF (AMXTXO.GT. (ST/2.) ) THEN
      MAP(J) = DOT(K)
      ENDF
20 CONTINUE
15 CONTINUE
      WRITE(*,6,100) (MAP(J),J=1,NCT)
100 FORMAT(4X,20(1X,1A))
10 CONTINUE
C
      WRITE(6,*) ' '  
C
RETURN
END  
C
C----------------------------------------------------------------------------------
C
      SUBROUTINE RVT(NCT,NLT,MLU,NHGR,RAIN,XO,RO,RV,RT,S,ST,
1      CN,SLOPE,LENGTH)
C----------------------------------------------------------------------------------
C.....THIS ROUTINE CALCULATE THE INITIAL VALUES OF RUNOFF, VELOCITY, AND TRAVEL TIME FOR ALL CELLS.
C
C
      DIMENSION XO(NLT,NCT,MLU)
      DIMENSION RO(NCT,NLT),RV(NCT,NLT),RT(NCT,NLT)
      DIMENSION S(MLU),XT(MLU)
      INTEGER CN(NCT,NLT),SLOPE(NCT,NLT),LENGTH(NCT,NLT)
C
      JCL = NC
      JR = NLT
      JC = NCT
      NLU = NK
C
      DO 250 I=1,JR
      DO 250 J=1,JC
      CALL INTIMP(I,J,NCT,NLT,MLU,NHGR,RAIN,ST,
1      CN,LENGTH,SLOPE,RO,RV,RT,XO,5)
250 CONTINUE
C
RETURN
END
C
C----------------------------------------------------------------------------------
C
      SUBROUTINE INTIMP(I,J,NCT,NLT,MLU,NHGR,RAIN,ST,
*THIS ROUTINE CALCULATE THE INITIAL VALUES OF RUNOFF,
VELOCITY, AND TRAVEL TIME FOR ONE CELL A TIME.*

```
DIMENSION XQ(NLT,NCT,MLU)
DIMENSION RO(NCT,NLT),RV(NCT,NLT),RT(NCT,NLT)
DIMENSION S(MLU),XT(MLU)
INTEGER CN(NCT,NLT),SLOPE(NCT,NLT),LENGTH(NCT,NLT)
REAL TXQ(MLU)

JCL = NC
JR = NLT
JC = NCT
NLU = MLU
NK = MLU
RAIN = 2.5
ST = 40.0

C*****CALCULATE RUNOFF
C INPUT : CURVE NUMBER (CN)
C       RAINFALL (RAIN)
C OUTPUT: RUNOFF (REAL #) - STORE IN RO)
C
C VARIABLES:
C JCL  - TOTAL # CELLS
C CN()  - CONTAINS INPUT LE CURVE NUMBER
C RAIN() - CONTAINS INPUT LE RAINFALL DATA
C RO()  - CONTAINS OUTPUT LE RUNOFF
C
IF (CN(J,J) .EQ. 0) THEN
  RO(J,J) = 0.0
ELSE
  SR = (1000./CN(J,J)) .- 10.
  RG(J,J) = ((RAIN - 0.2*SR)**2)/(RAIN + 0.8*SR)
ENDIF

C*****CALCULATE VELOCITY FOR EACH CELL
C INPUT : SLOPE (INTEGER #) - SLOPE()
C       LAND USE DATA (REAL #) - XQ)
C OUTPUT : VELOCITY (REAL #) - STORE IN RV()
C
RV(J,J) = 0.0
IF (SLOPE(J,J) .GT. 0) THEN
  DO 260 K=1,5
  IF (XQ(J,K,J).GT.0.) THEN
    IF (K .EQ. 5) THEN
      RV(J,J) = RV(J,J) + (10.**((0.5*ALOG10(1.*SLOPE(J,J)))- 0.29)
      *XQ(J,K,J)*S(K)/ST)
    ELSEIF (K .EQ. 4) THEN
```
RV(J,I) = RV(J,I) + (10.**((0.5*ALOG10(1.*SLOPE(J,I)))- 0.17))
          *XO(J,K)*S(K)/ST)
ELSEIF (K .GE. 1 .AND. K .LE. 3 ) THEN
   RV(J,I) = RV(J,I) + (10.**((0.5*ALOG10(1.*SLOPE(J,I)))- 0.01))
          *XO(J,K)*S(K)/ST)
ENDIF
ENDIF
260  CONTINUE
ENDIF

C
C*****CALCULATE TRAVEL TIME
C INPUT : FLOW LENGTH (INTEGER #)*LENGTH
C VELOCITY (REAL #) - RV
C OUTPUT : TRAVEL TIME IN SEC (REAL #) - STORE IN RT()
C
C IF (RV(J,I) .EQ. 0.) THEN
   RT(J,I) = 0.0
ELSE
   RT(J,I) = LENGTH(J,I)/(3600.*RV(J,I))
ENDIF

C RETURN
END

C
C--------------------------------------------------------------------------------
C SUBROUTINE CURNUM (NCT,NLT,MLU,NHGR,XO,S,ICN,HYDRO,CN)
C--------------------------------------------------------------------------------
C.....THIS ROUTINE CALCULATE THE WEIGHTED CURVE NUMBER FOR EACH CELL.
C
C DIMENSION XO(NLT,NCT,MLU),S(MLU)
   INTEGER CN(NCT,NLT),ICN(NHGR,MLU),HYDRO(NCT,NLT)
C
C.....DEFINE NEW COMPOSITE CURVE NUMBER
C DO 100 IR=1,NLT
   DO 110 IC=1,NCT
      WCN = 0.
      AREA = 40.0
      DO 120 IK=1,MLU
      120  WCN = WCN + XO(IR,IC,IK)*ICN(HYDRO(IC,IR),IK)*S(IK)
      IF (AREA .GT. 0.0) THEN
         CN(IC,IR) = INT(0.5 + WCN/AREA)
      END IF
110  CONTINUE
100  CONTINUE
RETURN
END
C
C
C*******************************************************************************
SUBROUTINE DRAIN (JCL, JC, JR, IA, IB, RA)

C******************************************************************************
C
C THIS ROUTINE ACCUMULATES WATER (OR ANY OTHER DATA) DOWNHILL
C AT THE STEEPEST SLOPE USING THE GIVEN ASPECT DATA, IT
C REQUIRES ASPECT DATA INSTEAD OF ALTITUDE DATA, AS IN THE
C ORIGINAL. ALSO DATA TO BE DRAINED IS PASSED FROM THE
C CALLING ROUTINE, NOT BY READING FROM FILE, THIS DATA
C IS IN REAL # FORMAT.
C THIS ROUTINE WAS ORIGINALLY WRITTEN BY DR. DANA TOMLIN
C
C INPUT : ASPECT DATA (INTEGER #) - STORE IN IA()
C DATA TO BE DRAINED (REAL #) - STORE 'N RA();
C OUTPUT : ACCUMULATED DATA (REAL #) - STORE 'N RA();
C
C INTEGER INDEK, SPOUTS, DI TEST, FRONT, REAR,
1    NEXTL(1000), NEXTK(1000), IA(JC, JR), IB(JC, JR),
1    DICODE(3,3), KSHIFT(8), LSHIFT(8),
1    KMOVE(8), LMOVE(8)
INTEGER ECHOED
REAL SHARE, MAX, RA(JC, JR)
DATA DICODE/1,2,4,8,0,16,32,64,128/;
1    KSHIFT/1,0,-1,1,-1,0,-1/;
1    LSHIFT/1,1,1,0,0,-1,-1/;
1    KMOVE/0,1,1,0,-1,-1,-1/;
1    LMOVE/-1,-1,0,1,1,0,-1/;
C.....IA = ASPECT THEN ACCUMULATION; IB = DRAINAGE INDICATOR
C.....IN IB, RECORD DRAINAGE INFO DERIVED FROM ALTITUDE VALUES IN IA
C ECHOED = 1
C
C
DO 100 L = 1, JR
DO 100 K = 1, JC
100    IB(K, L) = 0
C
C.....DETERMINE DIRECTION(S) OF EACH CELL'S DOWNSTREAM NEIGHBOR(S)
C
C  8  1  2      NW  N  NE
C  7  0  3      W   O  E
C  6  5  4      SW  S  SE
C
C
DO 300 L = 1, JR
DO 300 K = 1, JC
    LL = L
    KK = K
C
C.....CHECK FOR BLANK CELL
    IF (IA(K, L) .GT. 0 .AND. IA(K, L) .LE. 8) THEN
        LL = L + LMOVE(IA(K, L))
        KK = K + KMOVE(IA(K, L))
    ENDIF
C
    IF (LL .LT. 0) THEN
LL = 1
ELSE
  IF (KK .LT. 0) THEN
    KK = 1
  ENDIF
ENDIF

C
  IF (LL .GT. JR) THEN
    LL = JR
  ELSE
    IF (KK .GT. JC) THEN
      KK = JC
    ENDIF
  ENDIF
C
C......ENCODE DRAINAGE INFO FOR EACH CELL AS AN IB VALUE COMPUTED AS:
C......# OF UPSTREAM NEIGHBORS * 2048 + DOWNSTREAM NEIGHBORS * 256
C......+ 128, 64, 32, 16, 8, 4, 2, AND/OR 1, RESPECTIVELY, FOR
C......SE, S, SW, E, W, NE, N, AND NW DOWNSTREAM NEIGHBORS
C
  IB(KK,LL) = IB(KK,LL) + 2048
  IB(K,L) = IB(K,L) + 256 + DICODE(2+KK,K,2+LL-L)
300  CONTINUE
C
C
C......BEGIN THE DRAINAGE PROCESS
C
C
C......LOAD QUEUE WITH HEADWATER CELLS (IE HAVING NO UPSTREAM NEIGHBORS)
  INDEK = 0
500  REAR = 0
  DO 600 L = 1,JR
    DO 600 K = 1,JC
      IF (IB(K,L).GE.2048) GO TO 600
        REAR = REAR + 1
        NEXTK(REAR) = K
        NEXTL(REAR) = L
      IF (REAR.EQ.500) GO TO 601
600      CONTINUE
C
C......WHEN NO MORE HEADWATER CELLS, STOP EVERYTHING
C
  IF (REAR.EQ.0) RETURN
C
C
C......CYCLE THRU QUEUE, DELETING OLD HEADWATER CELLS FROM THE FRONT
C......AS THEY ARE POURED DOWNSTREAM AND ADDING NEW ONES TO THE REAR
C
601  FRONT = 1
C
C......GET THE COORDINATES OF THE NEXT HEADWATER CELL
C
  700  K = NEXTK(FRONT)
L = NEXTL(FRONT)
INDEK = INDEK + 1

C
C......DETERMINE HOW MUCH GETS POURRED TO EACH DOWNSTREAM NEIGHBOR
C
SPOUTS = IB(K,L) / 256
IF (SPOUTS.EQ.0) GO TO 810
SHARE = RA(K,L) / SPOUTS
C
IF (SHARE.EQ.0.0 .AND. RA(K,L).GT. 0.0) SHARE = 1.0
C
C......ITERATIVELY DECODE DRAINAGE INFO TO LOCATE DOWNSTREAM NEIGHBORS
C
IB(K,L) = IB(K,L) - (256 * SPOUTS)
DITEST = 128
DO 800 N = 1,8
IF (IB(K,L),LT,DITEST) GO TO 800
C
C............DOWNSTREAM NEIGHBOR FOUND; GET ITS COORDINATES
C
IB(K,L) = IB(K,L) - DITEST
KK = K + KSHIFT(N)
LL = L + LSHIFT(N)
C
C............ADD TO NEIGHBOR'S ACCUMULATION WITHOUT EXCEEDING 32000
C
MAX = RA(KK,LL) + SHARE
RA(KK,LL) = MAX
C
C............DECREMENT THIS NEIGHBOR'S UPSTREAM NEIGHBOR-COUNT
C
IB(KK,LL) = IB(KK,LL) - 2048
IF (IB(KK,LL),GE,2048) GO TO 790
C
C.......................AND IF NEIGHBOR BECOMES A HEADWATER CELL,
C.......................ADD IT TO REAR OF QUEUE UNLESS FULL
C
REAR = REAR + 1
IF (REAR.EQ.100) REAR = 1
IF (REAR.EQ.FRONT) GO TO 790
NEXTK(REAR) = KK
NEXTL(REAR) = LL
C
C..............IF ALL DOWNSTREAMS ALREADY FOUND, DON'T LOOK FOR MORE
C
790 IF (SPOUTS.EQ.1) GO TO 810
SPOUTS = SPOUTS - 1
C
C......IF MORE DOWNSTREAMS TO FIND, KEEP DECODING
800 DITEST = DITEST / 2
C
C......MARK THIS HEADWATER CELL EMPTY
C 810 IB(K,L) = 32767
C C.....WHENEVER QUEUE BECOMES EMPTY, TRY TO RELOAD IT
C IF (FRONT.EQ.REAR) GO TO 500
C C.....OTHERWISE, INCREMENT FRONT OF QUEUE AND DO NEXT HEADWATER CELL
C FRONT = FRONT + 1
IF (FRONT.EQ.1001) FRONT = 1
GO TO 700
C C RETURN
END
C
C*******************************************************************************
SUBROUTINE TRAVEL(JCL, JC, JR, IA, IB, RB, RA)
*******************************************************************************
C THIS ROUTINE INCREASES LENGTH (OR ANY OTHER DATA) DOWNHILL
C AT THE STEEPEST SLOPE (USING THE GIVEN ASPECT DATA). IT
C REQUIRES ASPECT DATA INSTEAD OF ALTITUDE DATA, AS IN THE
C ORIGINAL. ALSO DATA TO BE INCREMENTED IS PASSED FROM THE
C CALLING ROUTINE, NOT BY READING FROM FILE. THIS DATA
C IS IN REAL # FORMAT. THE INCREMENTED DATA IS ASSIGNED TO
C THE SOURCE CELL RATHER THE DESTINATION CELL AS IN DRAIN.
C THIS ROUTINE WAS ORIGINALLY WRITTEN BY DR. DANA TOMLIN.
C AND MODIFIED FOR THIS PURPOSE WITH THE HELP OF DR. TOMLIN.
C MODIFICATIONS INCLUDE INDICATING CELLS FLOWING INTO A CELL
C AS THE UPSTREAM, AND REPLACING SHARE = IA() SPOUTS WITH
C SHARE = IA() .
C C INPUT : ASPECT DATA (INTEGER #) STORE IN IA()
C DATA TO BE INCREMENTED (REAL #) STORE IN RB()
C OUTPUT : INCREMENTED DATA (REAL #) STORE IN RA()
C
INTEGER INDEK, SPOTS, DITEST, FRONT, REAR,
1 NEXTL(1000), NEXTK(1000), IA(1C, JR), IB(1C, JR),
1 DICODE(3,3), KSHIFT(8), LSHIFT(8), MAXK(8), MAXL(8),
1 KDIR(9), LDIR(9)
INTEGER ECHOED
REAL SHARE, MAX, RA(JC, JR), RB(JC, JR)
DATA DICODE/1,2,4,8,0,16,32,64,128/,
1 KSHIFT/1,0.-1.1.-1.1,0.-1,1,0.-1,1,0,-1,1,0/-,
1 KDIR/0,1,1,1,0.,-1,-1,0,0,0,0,0,0,0,0,0/,
C.....IA = ASPECT THEN ACCUMULATION; IB = DRAINAGE INDICATOR
C.....IN IB, RECORD DRAINAGE INFO DERIVED FROM ALTITUDE VALUES IN IA
ECHOED = 1
C
C
DO 100 L = 1, JR
DO 100 K = 1, JC
RA(K,L) = RB(K,L)
100 IB(K,L) = 0
C
C.....DETERMINE DIRECTION(S) OF EACH CELL'S DOWNSTREAM NEIGHBOR(S)
C
C 8 1 2  NW  N  NE
C 7 0 3  W  0  E
C 6 5 4  SW  S  SE
C
C
C
DO 300 L = 1, JR
DO 300 K = 1, JC
LTOP = L - 1
IF (LTOP.LT.1) LTOP = 1
LBOT = L + 1
IF (LBOT.GT.JR) LBOT = JR
KLEFT = K - 1
IF (KLEFT.LT.1) KLEFT = 1
KRIGHT = K + 1
IF (KRIGHT.GT.JC) KRIGHT = JC
MAX = 0.0
INDEK = 0
DO 200 LL = LTOP, LBOT
DO 200 KK = KLEFT, KRIGHT
   IF (IA(KK,LL).LE.0.OR. IA(KK,LL).GT.8) GO TO 200
   KKK = KK + KDIR(IA(KK,LL))
   LLL = LL + LDIR(IA(KK,LL))
   IF (KKK.EQ. K AND. LLL.EQ. L) THEN
       INDEK = INDEK + 1
       MAXK(INDEK) = KK
       MAXL(INDEK) = LL
   END IF
200  CONTINUE
C.....ENCODE DRAINAGE INFO FOR EACH CELL AS AN IB VALUE COMPUTED AS:
C.....# OF UPSTREAM NEIGHBORS * 2048 + DOWNSTREAM NEIGHBORS * 256
C.....+ 128, 64, 32, 16, 8, 4, 2, AND/OR 1, RESPECTIVELY, FOR
C.....SE, S, SW, E, W, NE, N, AND NW DOWNSTREAM NEIGHBORS
   IF (INDEK.LE.0) GO TO 300
   DO 250 N = 1, INDEK
      KK = MAXK(N)
      LL = MAXL(N)
      IB(KK,LL) = IB(KK,LL) + 2048
   250    IB(K,L) = IB(K,L) + 256 + DICODE(2+KK.K,2+LL.L)
250  CONTINUE
C
C.....BEGIN THE DRAINAGE PROCESS
C
C.....LOAD QUEUE WITH HEADWATER CELLS (IE HAVING NO UPSTREAM NEIGHBORS)
INDEK = 0
500 REAR = 0
DO 600 L = 1, JR
DO 600 K = 1, JC
   IF (IB(K,L).GE.2048) GO TO 600
      REAR = REAR + 1
      NEXTK(REAR) = K
      NexTL(REAR) = L
   IF (REAR.EQ.500) GO TO 601
   CONTINUE
C
C....WHEN NO MORE HEADWATER CELLS, STOP EVERYTHING
C
   IF (REAR.EQ.0) RETURN
C
C....CYCLE THRU QUEUE, DELETING OLD HEADWATER CELLS FROM THE FRONT
C....AS THEY ARE POURED DOWNSTREAM AND ADDING NEW ONES TO THE REAR
C
601 FRONT = 1
C
C....GET THE COORDINATES OF THE NEXT HEADWATER CELL
C
700 K = NEXTK(FRONT)
   L = NEXTL(FRONT)
   INDEK = INDEK + 1
C
C....Determine how much gets poured to each downstream neighbor
C
   SPOUTS = IB(K,L)/256
   IF (SPOUTS.EQ.0) GO TO 810
   SHARE = RA(K,L)
C
   IF (SHARE.EQ.0.0 .AND. RA(K,L).GT. 0.0) SHARE = 1.0
C
C....Iteratively decode drainage info to locate downstream neighbors
C
   IB(K,L) = IB(K,L) - (256 * SPOUTS)
   DITEST = 128
   DO 800 N = 1, 8
      IF (IB(K,L).LT.DITEST) GO TO 800
C
800 C.................DOWNSTREAM NEIGHBOR FOUND; GET ITS COORDINATES
C
   IB(K,L) = IB(K,L) - DITEST
   KK = K + KSHIFT(N)
   LL = L + LSHIFT(N)
C
C.................ADD TO NEIGHBOR'S ACCUMULATION WITHOUT EXCEEDING 32000
C
   MAX = RA(KK,LL) + SHARE
   RA(KK,LL) = MAX
C
C..............DECREMENT THIS NEIGHBOR'S UPSTREAM NEIGHBOR-COUNT
C
   IB(KK,LL) = IB(KK,LL) - 2048
   IF (IB(KK,LL).GE.2048) GO TO 790
C
C..............AND IF NEIGHBOR BECOMES A HEADWATER CELL,
C..............ADD IT TO REAR OF QUEUE UNLESS FULL
C
   REAR = REAR + 1
   IF (REAR.EQ.1001) REAR = 1
   IF (REAR.EQ.FRONT) GO TO 790
      NEXTK(REAR) = KK
      NEXTL(REAR) = LL
C
C..............IF ALL DOWNSTREAMS ALREADY FOUND, DON'T LOOK FOR MORE
C
   790  IF (SPOUTS.EQ.1) GO TO 810
      SPOUTS = SPOUTS - 1
C
C..............IF MORE DOWNSTREAMS TO FIND, KEEP DECODING
C
   800  DITEST = DITEST / 2
C
C............MARK THIS HEADWATER CELL EMPTY
C
   810  IB(K,L) = 32767
C
C..............WHENEVER QUEUE BECOMES EMPTY, TRY TO RELOAD IT
C
   IF (FRONT.EQ.REAR) GO TO 500
C
C............OTHERWISE, INCREMENT FRONT OF QUEUE AND DO NEXT HEADWATER CELL
C
   FRONT = FRONT + 1
   IF (FRONT.EQ.1001) FRONT = 1
   GO TO 700
C
C
C  RETURN
END

C================================= DODATA  =======================
SUBROUTINE DODATA (MRCH,NRCH,QO,V,D1,D2,CBP,CBD,DOI,RK,TMP,
                   RK2,P,PKS,R,DO,IRTYPE,IFRO,QQW,CL,CBDI,CLQ,BODI,
                   QOL,DOP)
C
C THIS ROUTINE READ A FILE THAT CONTAINS ALL THE DATA FOR THE
C D.O MODEL. THE FILE IS ASSUMED FORMATTED. THE FILE STRUCTURE
C IS COLUMN-WISE, AND EACH SECTION ENDS WITH -9 (OR OTHER NEGATIVE
C NUMBER). DATA SHOULD BE ORDERED AS FOLLOWS:
C
NRCH - # OF REACHES
QO() - FLOW RATE (CFS)
V0 - REACH VELOCITY (M/S)
D10 - BEGINNING DISTANCE (MILE)
D20 - END DISTANCE (MILE)
DOI() - DO LEVEL AT BEGINNING OF REACH
CBP() - POINT SOURCE CBOD (MG/L)
CBDO() - DISTRIBUTED/NONPOINT SOURCE CBOD (MG/L)
RK() - CBOD REMOVAL (DEOXYGENATION) RATE (PER DAY)
TMP() - REACH TEMPERATURE (C)
RK2() - RATE OF ATMOSPHERIC REAERATION (MG/L/DAY)
P0 - REACH PHOTOSYNTHESIS RATE (MG/L/DAY)
R() - REACH RESPIRATION RATE (MG/L/DAY)
RKS() - REACH SEDIMENT OXYGEN DEMAND RATE (MG/L/DAY)

FILE STRUCTURE:

# OF REACHES
1ST TITLE CARD - FLOW RATES
REACH # DATA-VALUE
1 30
.
.9 .9
2ND TITLE CARD - REACH VELOCITY
REACH # DATA-VALUE
1 5
.
.9 .9
.
.
.

DIMENSION QO(MRCH),V(MRCH),D1(MRCH),D2(MRCH),
CBP(MRCH),CBDO(MRCH),DOI(MRCH),RK(MRCH),TMP(MRCH),
RK2(MRCH),P(MRCH),RKS(MRCH),R(MRCH),DO(MRCH),
IRTYPE(MRCH),IFRTO(2,MRCH),QW(MRCH),CI(MRCH),
CBDI(MRCH),Q1(MRCH),BODI(MRCH),QO1(MRCH),DOP(MRCH)

CHARACTER TITLE*72, ENDC*3
CHARACTER*10 LABEL
DATA ENDC/END/

READ(*,10) TITLE
READ(*,5) NRCH, NJCT
WRITE(6,10) TITLE
WRITE(6,5) NRCH, NJCT
5 FORMAT(215)

REACH TYPE & FROM/TO REACHES
READ(*,10) TITLE
WRITE(6,10) TITLE
DO 560 I=1,NRCH+1
READ(*,561) LABEL, IRCH, ITYPE, IFROM, ITO
WRITE(6,561) LABEL, IRCH, ITYPE, IFROM, ITO
561  FORMAT(A10,415)
    IF (LABEL(1:3) .EQ. ENDC) GOTO 570
    IRTYPE(IRCH) = ITYPE
    IFRTO(I1) = ITO
    IFRTO(1,1) = IFROM
560  CONTINUE
C
C.....READ PARAMETER #2 - BEGINNING/ENDING DISTANCE
570  READ(*.10) TITLE
    WRITE(6,10) TITLE
    DO 170 I=1,NRCH+1
    READ(*,155) LABEL, IRCH, RTEMP,RTEMP2
    WRITE(6,155) LABEL, IRCH, RTEMP,RTEMP2
155  FORMAT(A10,I5,2F10.3)
    IF (LABEL(1:3) .EQ. ENDC) GOTO 190
    D1(IRCH) = RTEMP
    D2(IRCH) = RTEMP2
170  CONTINUE
C
C.....READ PARAMETER #3A - INITIAL DO LEVEL
190  READ(*.10) TITLE
    WRITE(6,10) TITLE
    DO 200 I=1,NRCH+1
    READ(*,15) LABEL, IRCH, RTEMP
    WRITE(6,15) LABEL, IRCH, RTEMP
    IF (LABEL(1:3) .EQ. ENDC) GOTO 205
    DOI(IRCH) = RTEMP
200  CONTINUE
C
C.....READ PARAMETER #3B - INITIAL BOD LEVEL
205  READ(*.10) TITLE
    WRITE(6,10) TITLE
    DO 211 I=1,NRCH+1
    READ(*,15) LABEL, IRCH, RTEMP
    WRITE(6,15) LABEL, IRCH, RTEMP
    IF (LABEL(1:3) .EQ. ENDC) GOTO 215
    BODI(IRCH) = RTEMP
211  CONTINUE
C.....READ PARAMETER #3C - INITIAL FLOW RATES
215  READ(*.10) TITLE
    WRITE(6,10) TITLE
    DO 221 I=1,NRCH+1
    READ(*,15) LABEL, IRCH, RTEMP
    WRITE(6,15) LABEL, IRCH, RTEMP
    IF (LABEL(1:3) .EQ. ENDC) GOTO 230
    QO(I(IRCH)) = RTEMP
221  CONTINUE
C.....READ PARAMETER #4 - FLOW RATES OF ADDED FLOW
230  READ(*.10) TITLE
    WRITE(6,10) TITLE
10  FORMAT(A)
DO 100 I=1,NRCH+1
READ(*,15) LABEL, IRCH, RTEMP
WRITE(6,15) LABEL, IRCH, RTEMP
15 FORMAT(A,15,F10.3)
IF (LABEL(1:3) .EQ. ENDC) GOTO 110
QO(IRCH) = RTEMP
QI(IRCH) = 0.0
100 CONTINUE
C
C.....READ PARAMETER #5 - REACH VELOCITY
110 READ(*,10) TITLE
WRITE(6,10) TITLE
DO 130 I=1,NRCH+1
READ(*,15) LABEL, IRCH, RTEMP
WRITE(6,15) LABEL, IRCH, RTEMP
IF (LABEL(1:3) .EQ. ENDC) GOTO 150
V(IRCH) = RTEMP
130 CONTINUE
C
C.....READ PARAMETER #6 - POINT SOURCE CBOD (MG/L)
150 READ(*,10) TITLE
WRITE(6,10) TITLE
DO 157 I=1,NRCH+1
READ(*,15) LABEL, IRCH, RTEMP
WRITE(6,15) LABEL, IRCH, RTEMP
IF (LABEL(1:3) .EQ. ENDC) GOTO 210
CBP(IRCH) = RTEMP
CBDI(IRCH) = 0.0
157 CONTINUE
C.....READ PARAMETER #6B - POINT SOURCE DISSOLVED O (MG/L)
210 READ(*,10) TITLE
C WRITE(6,10) TITLE
DO 220 I=1,NRCH+1
READ(*,15) LABEL, IRCH, RTEMP
C WRITE(6,15) LABEL, IRCH, RTEMP
IF (LABEL(1:3) .EQ. ENDC) GOTO 270
DOP(IRCH) = RTEMP
220 CONTINUE
C.....READ PARAMETER #7 - DISTRIBUTED/NONPOINT SOURCE CBOD (MG/L)
270 READ(*,10) TITLE
WRITE(6,10) TITLE
DO 290 I=1,NRCH+1
READ(*,15) LABEL, IRCH, RTEMP
WRITE(6,15) LABEL, IRCH, RTEMP
IF (LABEL(1:3) .EQ. ENDC) GOTO 310
CBDI(IRCH) = RTEMP
290 CONTINUE
C.....READ PARAMETER #8 - TEMPERATURE (C)
310 READ(*,10) TITLE
WRITE(6,10) TITLE
DO 330 I=1,NRCH+1
READ(*,15) LABEL, IRCH, RTEMP
WRITE(6,15) LABEL, IRCH, RTEMP
IF (LABEL(1:3) .EQ. ENDC) GOTO 350
   TMP(IRCH) = RTEMP
330 CONTINUE
C......READ PARAMETER #9 - CBOD REMOVAL RATE
350 READ(*,10) TITLE
   WRITE(6,10) TITLE
   DO 370 I=1,NRCH+1
      READ(*,15) LABEL, IRCH, RTEMP
      WRITE(6,15) LABEL, IRCH, RTEMP
      IF (LABEL(1:3) .EQ. ENDC) GOTO 390
      RK(IRCH) = RTEMP
370 CONTINUE
C......READ PARAMETER #10 - REACH REAERATION RATE
390 READ(*,10) TITLE
   WRITE(6,10) TITLE
   DO 410 I=1,NRCH+1
      READ(*,15) LABEL, IRCH, RTEMP
      WRITE(6,15) LABEL, IRCH, RTEMP
      IF (LABEL(1:3) .EQ. ENDC) GOTO 430
      RK2(IRCH) = RTEMP
410 CONTINUE
C......READ PARAMETER #11 - REACH RATE OF PHOTOSYNTHESIS
430 READ(*,10) TITLE
   DO 450 I=1,NRCH+1
      READ(*,15) LABEL, IRCH, RTEMP
      IF (LABEL(1:3) .EQ. ENDC) GOTO 470
      P(IRCH) = RTEMP
450 CONTINUE
C
C......READ PARAMETER #12 - RATE OF SEDIMENT OXYGEN DEMAND
470 READ(*,10) TITLE
   DO 490 I=1,NRCH+1
      READ(*,15) LABEL, IRCH, RTEMP
      IF (LABEL(1:3) .EQ. ENDC) GOTO 510
      RKS(IRCH) = RTEMP
490 CONTINUE
C
C......READ PARAMETER #13 - RESPIRATION RATE
510 READ(*,10) TITLE
   DO 530 I=1,NRCH+1
      READ(*,15) LABEL, IRCH, RTEMP
      IF (LABEL(1:3) .EQ. ENDC) GOTO 550
      R(IRCH) = RTEMP
530 CONTINUE
C
C
C......CHECK IF THERE IS ANY JUNCTION. IF YES, READ PARAMETER #14
C
550 IF (NJCT .LE. 0) GOTO 590
C
C
WRITE(6,580),
580 FORMAT(1H 'DATA SUCCESSFULLY READ.')
C
C......CONVERT RATES TO STREAM TEMPERATURE
   ALPHA = 1.024
   BETA = 1.047
DO 700 I=1,NRCH
   TEMP1 = RK2(I)*(ALPHA**2(TMP(I) - 20.0))
   TEMP2 = RK(I) * (BETA**2(TMP(I)-20.0))
   RK2(I) = TEMP1
   RK(I) = TEMP2
700 CONTINUE
RETURN
END

C............................................................................DISOLVED OXYGEN MODEL.................................................................
SUBROUTINE DOMODEL(MRCH,NRCH,Q0,V,D1,D2,CP,B,D,O,I,RK,TMP,
1 R2,P,RKS,R,DO,IRTYPE,IFRTO,QW,CI,CBD,QI,BODI,
1 Q0L,DOP)
C.............................................................................
C .... THIS ROUTINE CALCULATES DO LEVEL AFFECTED BY CBOD.
C    THE FORMULAE AND PROGRAMMING OF THIS MODEL ARE BASED ON
C    THE FOLLOWING REFERENCES RESPECTIVELY.
C
C 1. CLARK C.K. LIU (1986). SURFACE WATER QUALITY ANALYSIS. IN
C    LAWRENCE K. WANG & NORMAN C. PEREIRA (EDS.). HANDBOOK OF
C    ENVIRONMENTAL ENGINEERING. (CLIFTON, NEW JERSEY. THE HUMAN
C    PRESS.
C 2. RICHARD J. HUGHTO & ROBERT P. SCHREIBER (1982). "MICRO-
C    COMPUTER WATER QUALITY SIMULATION MODEL", CIVIL ENGINEERING
C    (MARCH), PP.58-59.
C
C INPUT REQUIREMENT:
C NRCH - # OF REACHES
C Q0() - FLOW RATE (CFE)
C V() - REACH VELOCITY (MS)
C D1() - BEGINNING DISTANCE (MILE)
C D2() - ENDING DISTANCE (MILE)
C DO() - INITIAL DO LEVEL (MG/L)
C CP() - POINT SOURCE CBOD (MG/L)
C CBD() - DISTRIBUTED(NONPOINT SOURCE CBOD (MG/L)
C TMP() - REACH TEMPERATURE (C)
C RK() - CBOD REMOVAL(DEOXYGENATION) RATE (PER DAY)
C RK2() - RATE OF ATMOSPHERIC REAERATION (MG/L/DAY)
C P() - REACH PHOTOSYNTHESIS RATE (MG/L/DAY)
C RKS() - REACH SEDIMENT OXYGEN DEMAND RATE (MG/L/DAY)
C R() - REACH RESPIRATION RATE (MG/L/DAY)
C
C DIMENSION Q0(MRCH),V(MRCH),D1(MRCH),D2(MRCH),
1  CBP(MRCH),CBD(MRCH),DOI(MRCH),RK(MRCH),TMP(MRCH),
1  RK2(MRCH),P(MRCH),RKS(MRCH),R(MRCH),DO(MRCH),
1  TRTYPE(MRCH),IFRTO(2,MRCH),QW(MRCH),CI(MRCH),
1  CBDI(MRCH),QI(MRCH),BODI(MRCH),QOI(MRCH),DOP(MRCH)
C
C
DO 10 I=1,NRCH
QW(I) = 0.0
DO(I) = 0.0
10  CI(I) = 0.0
C
C2=0.0
N2=0.0
W2=0.0
DO 100 IO=1,NRCH
C
IFR = IFRTO(1,IO)
ITO = IFRTO(2,IO)
C........CONVERT VELOCITY
U = V(IO)*86400./5280.
C........FIND WEIGHTED CBOD
CW = (QOI(IO)*BODI(IO)+QO(IO)*CBP(IO)+QI(IO)*CBDI(IO)+
1  QW(IO)*CI(IO))/((QOI(IO)+QO(IO)+QI(IO)+QW(IO))
CO = CW
C........CALCULATE DO SATURATION
C........THE FOLLOWING D.O. SATURATION FORMULA IS FROM HUGHTO.
C
T5 = 14.652-41022*TMP(IO)
C
T6 = .00799*(TMP(IO)**2)+7.77E-.05*(TMP(IO)**3)
C
DOS=T5+T6
C
C........THE FOLLOWING D.O. SATURATION EQUATION IS FROM EPA QUAL II
C
MODEL
TK = 273.15 + TMP(IO)
DSM = -139.34410+(1.575701E+.05/TK)
1  (-6.642308E+07/(TK*TK))
2  +(1.243800E+10/(TK*TK*TK))
3  -8.621949E+11/(TK*TK*TK*TK))
DOS = EXP(DSM)
C........CALCULATE WEIGHTED DO LEVEL
C
DOW = (QOI(IO)*DOI(IO)+QW(IO)*DO(IO))/
1  (QOI(IO)+QW(IO))
C........CALCULATE DO DEFICIT AT BEGINNING POINT OF STREAM REACH
DOB = DOS-DOW
C........CALCULATE TRAVEL TIME - DISTANCE/VELOCITY
C
TT = ABS(D2(IO)-D1(IO))/U
C
NOTE: ALTERNATIVE WAY TO COMPUTE TRAVEL (CRITICAL) TIME
TT1 = 1/(RK2(IO)-RK(IO))
TT2 = RK2(IO)/RK(IO)
TT3 = (RK2(IO)-RK(IO))*DOB/(RK(IO)*CO)
TT = TT1*LOG(TT2*(1-TT3))
DOD = (CO*RK(IO)/RK2(IO))*EXP(-TT*RK(IO))
DO(IO) = DOC
500 FORMAT(10F7.4)
IF (TTO .LE. 0) GOTO 999
C........REPEAT CALCULATION FOR NEXT REACH. FIRST REINITIALIZE
C            APPROPRIATE VARIABLES.
C
C........CALCULATE IN-STREAM CBOD LEVEL
C
Cl(IO) = CO*EXP(-RK(IO)*TT)
C.........ACCUMULATE FLOW RATES-AMBIENT FLOW RATES+POINT SOURCE
C
QW(IO) = QW(IO) + QO(I) + QQ(IO) + QI(IO)
DOT = (QW(IO)*DO(IO)+QW(TTO)*DO(TTO))/(QW(IO)+QW(TTO))
DO(TTO) = DOT
DO(I) = DO(TTO)
C2 = (Cl(IO)*QW(IO)+Cl(TTO)*QW(TTO))/(QW(IO)+QW(TTO))
Cl(TTO) = C2
QWT = QW(TTO) + QW(IO)
QW(TTO) = QWT
100 CONTINUE
C
999 RETURN
C
END
C
SUBROUTINE MINDO (MRCH,NRCH,QO,Y,D1,D2,CBP,CBD,DOI,RK,TMP,
1         RK2,P,RKS,R,DO,IRTYPE,IFRTO,QW,CI,CBDI,QI,BODI,
1         QOLDOP,ISUB,DOMIN)
C
C........THIS ROUTINE FIND THE MINIMUM D.O. LEVEL.
C
DIMENSION QO(MRCH),Y(MRCH),D1(MRCH),D2(MRCH),
1         CBP(MRCH),CBD(MRCH),DOI(MRCH),RK(MRCH),TMP(MRCH),
1         RK2(MRCH),P(MRCH),RKS(MRCH),R(MRCH),DO(MRCH),
1         IRTYPE(MRCH),IFRTO(2,MRCH),QW(MRCH),Cl(MRCH),
1         CBD(MRCH),QI(MRCH),BOD(MRCH),QOI(MRCH),DOP(MRCH)

REAL TEMP(MRCH)
C
IO = ISUB
INX = ISUB
KK = 1
200 TEMP(KK) = DO(INX)
C
IO = INX
INX = IFRTO(2,IO)
IF (INX .LE. 0) GOTO 99
KK = KK + 1
GOTO 200
99  DOMIN = 99999.
   DO 100 I=1,KK
      IF (TEMP(I) .LT. DOMIN) DOMIN = TEMP(I)
100  CONTINUE
C
   RETURN
   END
APPENDIX C
COMPUTER PROGRAM FOR THE CONVEX
COMBINATIONS OF NONLINEAR
PROGRAMMING MODEL
NOTE: THIS PROGRAM IS USED IN CONJUNCTION WITH THE PROGRAM LISTED IN APPENDIX B.

C
C.....PROGNAME : NEWMAP  - 10/20/90
C
C THIS PROGRAM SOLVE AN OPTIMIZATION ALLOCATION PROBLEM
C INVOLVING COMBINATORIC ENVIRONMENTAL IMPACT. THE ALGORITHM
C IS ADAPTED FROM THE CONVEX COMBINATIONS OF NONLINEAR PROGRAM
C DEVELOPED BY PROF. GULDAMN.
C IN THIS RESEARCH THE IMPACT IS THE WATER QUALITY FROM SURFACE
C RUNOFF. THE ORIGINAL COPY OF THIS PROGRAM WAS OBTAINED FROM
C PROF. GULDAMN
C
C CREATED : 1/24/90.
C
C
C.....VARIABLE NAMES:
C GENERAL
C .......
C NCELL, NC  - # VACANT CELLS
C NCT,NC,ICT  - # COLUMNS
C NLT,NRJLT  - # ROWS
C MLU,NK  - # LAND USES
C NKS  - # LAND USES IN OPTIMIZATION MODEL
C NHGR  - # SOIL HYDROLOGIC GROUPS
C MC  - # CONSTRAINTS
C MV  - # VARIABLES
C MIT,ITMAX  - MAX. # ITERATION
C XO  - AMOUNT OF LAND USE (IN UNIT)
C ATTIMP  - CHANGE IN OVERALL IMPACT
C EIMP  - OVERALL IMPACT OF INITIAL (EXISTING) LAND USES.
C RIMP()  - ENVIRONMENT QUALITY OF EACH LAND USE
C S()  - LAND USE REQUIREMENT
C XTX()  - LAND USE DEMAND
C RHS()  - RIGHT-HAND VALUES OF CONSTRAINT IN L.P MODEL
C A()  - COEFFICIENT MATRIX FOR L.P MODEL
C B()  - CONSTRAINTS IN L.P MODEL
C C()  - COEFFICIENT OF OBJECTIVE FUNCTION IN L.P MODEL
C PSOL()  - OPTIMAL SOLUTION FROM L.P ROUTINE
C DSOL()  - DUAL SOLUTION OF L.P MODEL
C XLB(),XUB()  - LOWER AND UPPER BOUND VALUES OF VARIABLES
C ICTYPE()  - TYPE OF CONSTRAINTS =, <=, OR >=
C XOT()  - TEMPORARY ARRAY TO STORE AMOUNT OF LAND USES
C XOM()  - TEMPORARY ARRAY TO STORE AMOUNT OF LAND USES
C VOPV()  - OVERALL IMPACT OF EACH INCREMENT
C DELV()  - CHANGES IN ENVIRONMENTAL IMPACT FOR EACH ITERATION
C DX()  - CHANGES IN LAND USES FOR EACH ITERATION
C
C ALL OTHER VARIABLES ARE FOR ENVIRONMENTAL MODEL.
C
C
C PARAMETER (NCELL = 199)
PARAMETER (NCT=19, NLT=64, MLU=5, NHGR=5, MC=NCELL+MLU+2, 
1  MV=NCELL*MLU, MIT=10, MIS=10, MST=MIT*MIS)
PARAMETER (MRCH = 10, MCT=1)
DIMENSION XO(NLT, NCT, MLU), ATT(IPT, NLT, NCT, MLU)
DIMENSION RO(NLT, NCT, MLU), RT(NCT, NLT), RF(NCT, NLT), 
1  RP(NLT, NCT, MLU), RC(NCT, NLT)
DIMENSION RIMP(MLU), S(MLU), XT(MLU)
INTEGER CN(NCT, NLT), SLOPE(NCT, NLT), LENGTH(NCT, NLT), 
1  ASPEK(NCT, NLT), LUT(NCT, NLT), HYDRO(NCT, NLT), 
1  SUIT(NCT, NLT, MLU), ICN(NHGR, MLU)
INTEGER IA(NCT, NLT), IB(NCT, NLT), ICNT(NHGR, MLU)
REAL RA(NCT, NLT), RB(NCT, NLT)
DIMENSION QO(MRCH), V(MRCH), D1(MRCH), D2(MRCH), 
1  CBP(MRCH), CBM(MRCH), DO(MRCH), RK(MRCH), TMP(MRCH), 
1  RK2(MRCH), P(MRCH), KS(MRCH), R(MRCH), DO(MRCH), 
1  IRCTYPE(MRCH), IFRTO(2, MRCH), QW(MRCH), Ci(MRCH), 
1  CB1(MRCH), QI(MRCH), BODI(MRCH), QO(MRCH), DOP(MRCH)
DIMENSION VOPT(MLU), RHS(MC)
DIMENSION A(MC, MV), B(MC), C(MV), PSOL(MV), DSOL(MC)
DIMENSION XLB(MV), XUB(MV), ICTYPE(MC), XOT(NLT, NCT, MLU)
DIMENSION XOM(NLT, NCT, MLU, MIT), VOPV(MIT), DELV(NLT, NCT, MLU, MIT), 
1  DX(NLT, NCT, MLU, MIT), XOS(NLT, NCT, MLU), VOP2(MIT)
INTEGER SUBIDX(NCT, NLT)
COMMON /WORKSP/RWKS
REAL RWKSP(650000)
C
EXTERNAL DLPR5
SAVE CN
C
CALL JWKN (650000)
C
PMAX = 9.9
ITMAX=10
DELTA=1.
ISMAX=10
IOS=0
ICT=NCT
ILT=NLT
NK=5
NKS=3
ST=40.
ALPHA=1.
IHX=10
NC=NCELL
N=NC*NKS
M1=MC
M2=NKS
IAC=M1+M2+2
NEQ=M1+M2
LDA = MC
SMALL = 1.0
NOUT = 6
RAIN = 2.5
IOR = 64
IOC = 10
ISEG = 3
IYR = 2009

C
C.....GET THE INPUT DATA FOR IMPACT MODEL
C
CALL GETDAT(NCT,NLT,MLU,NHGR,ST,RIMP,S,XT,CN,SLOPE,LENGTH,
    1 ASPEK,LUT HYDRO,SUIT,ICN,XO)
C.....READ DATA FOR D.O MODELING
CALL DODATA (MRCH,NRCH,QO,V,D1,D2,CBP,CBD,DOI,RK,TMP,
    1 RK2,P,RK5,R,DO,IRTYP,IFRTO,QW,C1,CBD1,Q1,BOD1,
    1 QO,DOP)
C
C ASSUMED INITIAL LAND-USE AS EXISTING, AND WHOLE CELL CONTAINS
C ONLY ONE LANDUSE
C
WRITE(6,*) 'INITIAL LAND USE'
DO 145 IR=1,ILT
DO 145 IC=1,ICT
DO 146 IK=1,NK
  XO(IR,IC,IK) = 0.0
  IF (LUT(IC,IR),EQ, IK) THEN
    XO(IR,IC,IK) = ST/S(K)
  END IF
146 CONTINUE
WRITE(6,29) IR,IC,(XO(IR,IC,IK),IK=1,NK)
C
145 CONTINUE

C
C.....BUILD AREA INDEX. THIS IS TO BE USED IN TRANSFERING
C SITE AREA INTO LINEAR PROGRAMMING FORMULATION. ONLY
C EFFECTIVE CELLS WILL BE USED IN THE OPTIMIZATION.
C THIS WILL CONSIDERABLY REDUCED SPACE & TIME REQUIRE-
C MENTS.
C
IDX = 0
DO 1500 I=1,ILT
DO 1500 J=1,ICT
  SUBIDX(I,J) = 0
  IF (SUIT(J,I,5),LE, 0) GOTO 1500
C
  IDX = IDX + 1
  SUBIDX(I,J) = IDX
1500 CONTINUE
C
C
C.....CALCULATE INITIAL CURVE NUMBER (USING CURNUM ROUTINE), AND
C THEN OVERALL ENVIRONMENTAL IMPACT (DO LEVELS) OF EXISTING
C LAND USES.
C.....NOTE: SUBROUTINE IMPACT () HAS 2 PURPOSES:
C 1. SIMULATE OVERALL ENVIRONMENTAL IMPACT(MODE 0)
C 2. SIMULATE CHANGE IN ENVIRONMENTAL IMPACT DUE
C TO ADDING "DELTA" UNIT OF LAND USE K.
C
CALL CURNUM (NCT,NL,T, NK,NHGR, XG,S, ICN, HYDRO, CN)
CALL IMPACT(1,1,0,NCT, NL, MLU, NHGR, MRCH, NRCH,
1   ST, JOR, IOC, JSEG, ALPH, RAIN, NK, NKS, NC, DELTA,
1   XO, ATTIMP, RO, RV, RT, RF, RP, RC, RIMP, S, XT, IA, IB, RA, RB,
1   CN, SLOPE, LENGTH, ASPEK, LUT, HYDRO, SUIT, ICN,
1   QO, V, D1, D2, CBP, CBD, DOI, RK, TMP, RK2, P, RKS, R, DO,
1   IRTYPE, IFRTO, QW, CI, CBDI, QI, BODI, QOI, DOP, EIMP)
WRITE(6,1) EIMP
1 FORMAT(' INITIAL IMPACT IS ',F10.4/
C
WRITE(6,('A')) ' INITIAL D.O LEVEL'.
DO 128 JL=1,NRCH
C......FIND MINIMUM D.O. FOR EACH REACH
   CALL MINDO (MRCH, NRCH, QO, V, D1, D2, CBP, CBD, DOI, RK, TMP,
   1   RK2, P, RKS, R, DO, IRTYPE, IFRTO, QW, CI, CBDI, QI, BODI,
   1   QO, DOP, JL, CEMAR)
   WRITE(6,1281) JL, DO(JL), CEMAR
1281   FORMAT('REACH #: ',I5, 'X', 2F10.4)
   128 CONTINUE
C
C......IF NOT USING LP RESULT AS INITIAL LAND USE
C THEN GET NEW LAND USE PATTERN
C
C
IF(IOS.EQ.1) THEN
   CALL GETLUI(ICT, ILT, NK, ST, S, IA, XO)
   GOTO 100
END IF
C
C......COMPUTE CHANGE IN OVERALL IMPACT FOR EACH CELL FOR
C EACH LAND USE.
C
DO 3 JL=1, ILT
   DO 3 JC=1, ICT
   C
C......CASE OF ALREADY BUILT-UP AREA
   IF (SUBIDX(JC, JL) .LE. 0) THEN
      DO 4 IK=1, NKS
         4   ATTIMP(JL, JC, IK) = 0.0
      C
C......CASE OF VACANT LAND
C
   ELSE
      DO 6 IK=1, NKS
C
C......CASE OF NOT SUITABLE FOR LAND USE IK. ASSIGN PMAX
C AS IMPACT COEFFICIENT I.E DUMMY NUMBER.
C
   IF (SUJT(JC, JL, IK) .EQ. 0 ) THEN
ATTIMP(JL,JC,IK) = PMAX

C
C......CASE OF SUITABLE, THEN COMPUTE CHANGE IN IMPACT
C
ELSE
  DELTA = 1.0
  CALL IMPACT(JL,JC,IK,1,NCT,NLT,MLU,NHGR,MRCH,NRCH,
1     ST,1,OR,JOC,ISEG,ALPHA,RAIN,NK,NKS,NC,DELTA,
1     XO,ATTIMP,RO,RV,RT,RF,RP,RC,RIMP,S,XT,JA,IB,RA,RB,
1     CN,SLOPE,LENGTH,ASPEX,LOT,HYDRO,SUIT,ICN,
1     DO,V,D1,D2,CPB,CBD,DO1,RK,TMP,RK2,P,RKS,R,DO,
1     IRTYPE,FRTO,QW,CI,CBD1,QI,BOD1,QO1,DOP,EIMP)
ENDIF
6 CONTINUE
ENDIF
3 CONTINUE
DO 39 JL = 1,ILT
   DO 39 JC = 1,ICT
   DO 39 IK = 1,NKS
   IF (SUBIDX(JC,JL) .EQ. 0) GOTO 39
   WRITE(6,101) JL,JC,IK,ATTIMP(JL,JC,IK)
101  FORMAT(2X,'JL=',I3,'JC=',I3,'IK=',I3,'IMPACT=.',F20.10)
39 CONTINUE

C
C......START LP FORMULATION
C
C
C......INITIALIZE COEFFICIENT MATRIX, CONSTRAINTS,
C CONSTRAINT TYPE (ICTYPE), AND OBJECTIVE COEFFICIENTS.
C
DO 9 I = 1,IAC
   DO 9 J = 1,N
5   A(I,J) = 0.
   DO 10 I = 1,IAC
5   ICTYPE(I) = 0
10   B(I) = 0.
   DO 11 J = 1,N
5   CJ(J) = 0.
11
C
C......ASSIGN OBJECTIVE FUNCTION COEFFICIENT (C)
   DO 12 JL = 1,ILT
   DO 12 JC = 1,ICT
   DO 12 IK = 1,NKS
       I = IK + (SUBIDX(JC,JL)-1)*NKS
5   C(I) = ATTIMP(JL,JC,IK)
12 CONTINUE
C
C......CASE OF NOT VACANT LAND - SKIP
   IF (J .LE. 0) GOTO 12
   CJ(J) = ATTIMP(JL,JC,IK)
C
12 CONTINUE
C
C......ASSIGN CONSTRAINT VALUES
DO 13 JL=1,ILT
DO 13 JC=1,ICT
C
   IL=SUBIDX(JC,JL)
C.......CASE OF NOT VACANT LAND - SKIP
   IF (IL.LT. 0) GOTO 13
      B(IL) = ST
C
C.......INSERT TYPE OF CONSTRAINT AS REQUIRED BY NEW IMSL ROUTINE
C   0 - = , 1 - <=, 2 - =>, 3 - BOUNDED RANGE
C   INITIALIZE ONLY ONCE, HERE IS CELL CONSTRAINT.
C   CELLS CONSTRAINTS ARE: <= ST, 1,E 1. (ADDED 1/24/90)
C
   ICTYPE(IL) = 1
   DO 14 IK=1,NKS
      IC=IK+(SUBIDX(JC,JL)-1)*NKS
      IF (IC .LE. 0) GOTO 14
   C.............ASSIGN LAND REQUIREMENT.
   C      ASSIGN LOWER AND UPPER BOUND (XLB & XUB).
   C      XLB = 0 IF LAND NOT SUITABLE.
   C      XUB = ST IF LAND IS SUITABLE.
     A(IL,IC)=S(IK)
     XLB(IC)=0.
     XUB(IC)=ST* SUIT(IC,JL,IK)/S(IK)
  14 CONTINUE
  13 CONTINUE
C
C.......SET CONSTRAINT OF EACH LAND USE
C
   DO 8 IK=1,NKS
      IL=M1+IK
      B(IL)=XT(IK)/S(IK)
C
C.......INSERT TYPE OF CONSTRAINT AS REQUIRED BY NEW IMSL ROUTINE
C   0 - = , 1 - <=, 2 - =>, 3 - BOUNDED RANGE
C   INITIALIZE ONLY ONCE, HERE IS LAND DEMAND CONSTRAINT. THEY
C   ARE IN THE FORM OF EQUALITY, I.E TYPE 0. (ADDED 1/24/90)
C
   ICTYPE(IL) = 0
   DO 7 JL=1,ILT
      DO 7 JC=1,ICT
         IC=IK+(SUBIDX(JC,JL)-1)*NKS
         IF (IC .LE. 0) GOTO 7
         A(IL,IC)=1.
    7 CONTINUE
    6 CONTINUE
C
C.......CALL LP ROUTINE
C.......CALL DLPRLS(M,NVAR,A(M,NVAR),LDA,BL(M),BU(M),C(NVAR),ICTYPE(M),
C       XLB(NVAR),XUB(NVAR),OBJ,XSOL(NVAR),DSOL(M))
C
   CALL DLPRLS(NEQ,N,A,LDA,R,B,C,ICTYPE,XLB,XUB,OBJ,PSOL,DSOL)
C
C.....SAVE CURVE NUMBER COMBINATION INTO TEMPORARY ARRAY
C BEFORE CALL LP ROUTINE. THERE IS PROBLEM OF LOSING
C VALUES. REASON STILL UNKNOWN.
DO 1109 K=1,NK
   DO 1109 I=1,NHGR
      ICNT(LK) = ICN(LK)
   1109 CONTINUE
C
C....WRITE OUTPUT OF OPTIMAL LAND USE
   WRITE(6,20) IYR
   20 FORMAT(1H1,15X,'OUTPUT OF LINEAR PROGRAM',1X,I5/15X,24(1H*//'
   WRITE(6,21) OBJ
   21 FORMAT(5X,'VALUE OF OBJECTIVE FUNCTION FROM L.P. ',F15.4//'')
   DO 72 I=1,NEQ
      RHS(I) = 0.
      DO 73 J=1,N
         RHS(I) = RHS(I) + A(I,J)*PSOL(J)
      73 CONTINUE
   72 CONTINUE
   WRITE(6,27)
   DO 16 JL=1,ILT
      DO 16 JC=1,ICT
         AMTXO = 0.0
      16 CONTINUE
   DO 26 IK=1,NKS
      J=IK+(SUBIDX(JC,JL)-1)*NKS
C.......CASE OF NOT VACANT LAND, ASSIGN NEW LAND USE AS
C EXISTING LAND USE.
C
      IF (J .LE. 0) THEN
         IKT = LUT(JC,JL)
         IF (IKT .EQ. 0) THEN
            XO(JL,JC,IKT) = 0.0
         ELSE
            XO(JL,JC,IKT) = ST/S(IKT)
         END IF
      GOTO 26
      END IF
C.......ASSIGN RESULTS OF LP AS NEW LAND USE
C
      XO(JL,JC,IK) = PSOL(J)
C
C.......ACCUMULATE LAND AREAS OF EACH CELL.
C
      AMTXO = AMTXO + XO(JL,JC,IK)*S(IK)
   26 CONTINUE
C
C.......CHECK TO MAKE SURE TOTAL LAND USE IN EACH CELL
C
      EQUAL CELL SIZE. IF NOT ASSIGN UNUSED LAND TO ITS ORIGINAL
      IKT = LUT(JC,JL)
      IF (IKT .LE. 0) THEN
         GOTO 16
      END IF
      IF (INT(AMTXO) .GT. INT(ST)) THEN
WRITE(6,139) JL,JC
139 FORMAT(' ERROR!!!! TOTAL LAND USE > CELL SIZE AT ',I2)
STOP
ELSE
C............ASSIGN UNUSED LAND TO ITS ORIGINAL USE.
   XO(JL,JC,IKT) = (ST - AMTXO)/S(IKT)
END IF
C
WRITE(6,29) ILT,ICT,IL,J,C,(XO(JL,JC,IK),IK=1,NK)
DO 140 IK=1,NK
140 XOT(JL,JC,IK) = XO(JL,JC,IK)
C
16 CONTINUE
C........REASSIGN CURVE NUMBER COMBINATION TO ITS ORIGINAL ARRAY.
DO 1207 K=1,NK
DO 1208 I=1,NHGR
   ICN(I,K) = ICNT(I,K)
1208 CONTINUE
1207 CONTINUE
27 FORMAT(1H1,5X,'LAND USES OPTIMAL LOCATIONS//')
WRITE(6,114) ILT,ICT,NK
114 FORMAT(1X,'ILT = ',I5,1X,'ICT = ',I5,1X,'NK = ',I5)
   ICT=NCT
   ILT=NLT
   NK=5
DO 28 JL=1,ILT
   DO 28 JC=1,ICT
      WRITE(6,29) JL,JC,(XO(JL,JC,IK),IK=1,NK)
   29 FORMAT(1X,'JL= ',I4,1X,'JC= ',J4,3X,F10.4)
C
28 CONTINUE
WRITE(6,30)
30 FORMAT(1H1,5X,'VALUES OF THE CONSTRAINTS//')
DO 32 I=1,NEQ
      WRITE(6,31) I,B(I),RHS(I),DSOL(I)
31 FORMAT(1X,'I= ',I,1X,'B= ',F10.4,2X,'RHS= ',F10.4,2X,'DSOL= ',F20.7)
32 CONTINUE
C
C........COMPUTE NEW WEIGHTED CURVE NUMBER AND OVERALL ENVIRONMENTAL
CIMPACT.
   CALL CURNUM (NCT,NLT,MLU,NHGR,XO,S,ICN,HYDRO,CN)
C
   CALL IMPACT(1,1,1,0,NCT,NLT,MLU,NHGR,MRCH,NRCH,
      1 ST,JOR,J0C,ISEG,ALPHA,RANK,NK,NKS,NC,DELTA,
      1 XO,ATTMP,RO,RT,RF,RP,RC,rimp,S,XT,JA,JB,RA,RB,
      1 CN,SLOPE,LENGTH,ASPEK,LUT,HYDRO,SUTT,ICN,
      1 QO,D1,D2,CBP,CBD,DO1,RR,TMP,RK2,P,RK3,DO,
      1 IR,TYPE,IFRTO,QW,CI,CBDI,QL,BODI,QO1,DOP,TEIMP)
   WRITE(6,111) TEMPP
111 FORMAT(' NEW NPS IMPACT AFTER 1ST L.P. ',F10.4/)
C
C
104 WRITE(6,37)
37 FORMAT(1H1,5X,NPS ANALYSIS OF THE OPTIMAL LOCATIONS ACCOUNTING
1 FOR INTERRELATIONSHIP///)
C
C IF (IOS .EQ. 0) THEN
   DO 1103 I=1,NLT
   DO 1103 J=1,NCT
   DO 1103 K=1,NK
      XO(J,K) = XOT(L,J,K)
1103 CONTINUE
ENDIF
C.....COMPUTE NEW WEIGHTED CURVE NUMBER AND NPS IMPACTS.
   CALL CURNUM (NCT,NLT,MLU,NHGR,XO,S,ICN,HYDRO,CN)
C
   TEIMP = EIMP
   CALL IMPACT(1,1,1,0,NCT,NLT,MLU,NHGR,MRCH,NRCH,ST,IR,IOC,ISEG,ALPHA,RAIN,NK,NKS,NC,DELTA,
1      XO,ATTIMP,RO,RV,RT,RF,RP,RC,IMP,I,S,I,A,RA,RA,RA,
1      CN,SLOPE,LENGTH,ASPEK,LUT,HYDRO,SUIT,ICN,
1      JO,V1,D1,D2,CBP,CBD,D0I,RA,RA,RA,RA,RA,RA,RA,RK1,D1,RK2,D1,RK3,RA,RA,RA,
1      IRTYPE,IRFRT,QW,CL,CBQ,QR,BDI,QO1,DO1,VOP)
   WRITE(6,109) VOP
109 FORMAT ('NEW ADJUSTED OVERAL NPS IMPACT - ',F15.4)
   EIMP = TEIMP
   GO TO 103
100 GO TO 104
C
C.....START THE CONVEX COMBINATION OPTIMIZATION PROCEDURE
C
103 WRITE(6,18)
18 FORMAT(1H1,10X,START OF THE CONVEX COMBINATION OPTIMIZATION PROCE
1DURE///)
   KOUNT = 0
   DO 50 II=1,ITMAX
      WRITE(6,62) II
50 FORMAT(1H1,10X,ITERATION=',I4,'///)
   IF(IT.GT.1) GO TO 98
   VOPV(II)=VOP
   DO 51 JL=1,ILT
      DO 51 JC=1,ICT
      DO 51 IK=1,NK
         XOM(JL,JC,IK,IT)=XO(JL,JC,IK)
      51 CONTINUE
C
C.....NOTE: NWMAPH() IS A ROUTINE USED TO DRAW CHARACTER MAP
C     JUST FOR DISPLAY PURPOSES.
C
98 CALL NWMAPH(NLT,NCT,NK,ST,XO,IYR)
C
   DO 52 JLO=1,ILT
      DO 52 JCO=1,ICT
      DO 52 IKO=1,NKS
DO 53 IL=1,ILT
DO 53 IC=1,ICT
DO 53 IK=1,NK
   XO(IL,IC,IK)=XOM(IL,IC,IK,IT)
53  CONTINUE

C
C C X0(JLO,JCO,IKO)=XOM(JLO,JCO,IKO,IT)+DELTA
C
C ......CASE OF ALREADY BUILT-UP AREA, I.E. NOT VACANT
C IF (SUBIDX(JCO,JLO),EQ. 0) THEN
C     DELV(JLO,JCO,IKO,IT) = 0.0
C     ATTIMP(JLO,JCO,IKO) = 0.0
C
C ......CASE OF VACANT
C
C       ELSE
C
C ......CASE OF NOT SUITABLE
C IF (SUIT(JCO,JLO,IKO),EQ. 0) THEN
C     DELV(JLO,JCO,IKO,IT) = PMAX
C     ATTIMP(JLO,JCO,IKO) = PMAX
C
C     ELSE
C
C ......CASE OF VACANT AND SUITABLE, CALCULATE NEW CHANGE IN
C DELTA=1.0
C CALL IMPACT(JLO,JCO,IKO,1,NCT,NLT,MLU,NHGR,MRCH,NRCH!,
C ST,10R,JOC,1SEG,ALPHA,RAIN,NK,NKS,NC,DELTA,
1  XO,ATTIMP,RO,RV,RT,RF,RP,RC,RIMP,S,XT,IA,IB,RA,RB,
1  CN,SLOPE,LENGTH,ASPEK,LUT,HYDRO,SUIT,ICN,
1  QO,V,D1,D2,CBP,CBD,DOI,RK,TKP,RK2,P,RKS,R,DO,
1  IRTYPE,IFRTO,QW,CI,CBDI,QI,BD1,QOI,DOP,VOP)
C       ENDF
C       ENDIF
C
52 CONTINUE
C
C ......TRANSFER CHANGES IN IMPACTS TO NEW ARRAY DELV()
C
DO 106 IL=1,ILT
DO 106 IC=1,ICT
DO 106 IK=1,NKS
C
   DELV(IL,IC,IK,IT) = ATTIMP(IL,IC,IK)
C ......WRITE NEW CHANGE IN IMPACTS. SKIP IF NOT VACANT
C
   IF (SUBIDX(JC,JL) .EQ. 0) GOTO 106
      WRITE(6,101)JL,JC,IK,ATTIMP(JL,JC,IK)
   C
106  CONTINUE
C
C.....SET THE LP FORMULATION
C
   DO 65 I=1,IAC
   DO 65 J=1,N
      65   A(I,J)=0.
   DO 66 I=1,IAC
      66   B(I)=0.
   DO 67 J=1,N
      67   C(J)=0.
   DO 68 JL=1,ILT
      68   C(J)= DELV(JL,JC,IK,IT)
   C
   CONTINUE
C
   DO 69 JL=1,ILT
      69   JL=SUBIDX(JC,JL)
      IF (JL.LE. 0) GOTO 69
         B(JL) = ST
C
C.....INSERT TYPE OF CONSTRAINT AS REQUIRED BY NEW IMSL ROUTINE
C   0 - = , 1 - <= , 2 - =>, 3 - BOUNDED RANGE
C   INITIALIZE ONLY ONCE. HERE IS CELL CONSTRAINT.
C   CELLS CONSTRAINTS ARE: <= ST, I.E 1
C
   ICTYPE(JL) = 1
   DO 70 IK=1,NKS
      IC=IK+(SUBIDX(JC,JL)-1)*NKS
      IF (IC.GT. 0) THEN
         A(IL,IC)=S(IK)
         XLB(IC)=0.
         XUB(IC)=ST* SUIT(JC,JL,IK)/S(IK)
      ENDIF
   70  CONTINUE
   69  CONTINUE
C
C   B(1)=0.000001
   DO 71 IK=1,NKS
      71   IL=M1+IK
B(IL)=XT(IK)/S(IK)
ICTYPE(IL)=0
DO 74 JL=1,ILT
DO 74 JC=1,ICT
C
    IC=IK+(SUBIDX(JC,JL)-1)*NKS
    IF (IC.LE.0) GO TO 74
    A(IL,IC)=1.
74 CONTINUE
71 CONTINUE
C
C....SAVE CURVE NUMBER COMBINATION INTO TEMPORARY ARRAY
C BEFORE CALL LP ROUTINE. THERE IS PROBLEM OF LOSING C
VALUES AFTER CALLING LP ROUTINE.
    DO 1509 K=1,NK
    DO 1509 I=1,NHGR
       ICNT(I,K)=ICN(I,K)
1509 CONTINUE
C
C....CALL LP ROUTINE
C WRITE(6,'(A)') ' BEFORE CALLING TO LP'
C
CALL DLPRS(NEQ,N,LA,B,B,C,ICTYPE,XLB,XUB,OBJ,PSOL,DSOL)
C
C
C WRITE(6,20) IYR
WRITE(6,21) OBJ
DO 75 I=1,NEQ
   RHS(I)=0.
DO 76 J=1,N
76   RHS(I)=RHS(I)+A(IJ)*PSOL(J)
75 CONTINUE
DO 77 JL=1,ILT
DO 77 JC=1,ICT
AMTXO = 0.0
77 CONTINUE
C
C.....CASE OF BUILT-UP AREAS, ASSIGN EXISTING LAND USE TO C
XO().
C
IF (SUBIDX(JC,JL).LE.0) THEN
   IKT = LUT(JC,JL)
   IF (IKT.EQ.0) THEN
      XO(JL,JC,IKT) = 0.0
   ELSE
      XO(JL,JC,IKT) = ST/S(IKT)
   ENDIF
ELSE
END
ELSE
C
C.....CASE OF VACANT LAND, ASSIGN RESULT OF LP TO XO()
C
DO 277 IK=1,NKS
C
J=IK+(SUBIDX(JC,JL)-1)*NKS
XO(JL,JC,IK)=PSOL(I)
AMTXO = AMTXO + XO(JL,JC,IK)*S(IK)

CONTINUE

IKT = LUT(JC,JL)
IF (INT(AMTXO).GT. INT(ST)) THEN
WRITE(6,149) JL,JC
149  FORMAT( ERROR!!!! TOTAL LAND USE > CELL SIZE IN '215
STOP
ELSE
C......ASSIGN LAND AREA NOT USED BY LP MODEL TO ITS ORIGINAL
C  LAND USE TYPE.
C
XO(JL,JC,IKT) = (ST - AMTXO)/S(IK)
END IF
ENDIF

CONTINUE

WRITE(6,27)
DO 78 JL=1,ILT
DO 78 JC=1,ICT
IF (SUBIDX(JC,JL).LE. 0) GOTO 78
WRITE(6,29) JL,JC,(XO(JL,JC,IK),IK=1,NK)
78 CONTINUE

IL=1
IC=1

C.....REASSIGN CURVE NUMBER COMBINATION TO ITS ORIGINAL ARRAY.

DO 1507 K=1,NK
DO 1508 I=1,NHGR
  ICN(I,K) = ICNT(I,K)
1508 CONTINUE
1507 CONTINUE

C.....COMPUTE NEW WEIGHTED CURVE NUMBER AND NPS IMPACTS.
C
CALL CURNUM (NCT,NLT,MLU,NHGR,XO,S,ICN,HYDRO,CN)
C
TEIMP = EIMP
C
CALL IMPACT(1,1,1,0,NCT,NLT,MLU,NHGR,MRCH,NRCH,
  1 ST,IOJ,IOC,ISEG,ALPHA,RAI,NK,NKS,NC,DELTA,
  1 XO,ATTIMP,RO,RV,RT,RF,RP,RC,IMP,S,XT,IA,IB,RA,RB,
  1 CN,SLOPE,LENGTH,ASPEK,LUT,HYDRO,SWIT,ICN,
  1 QO,V,D1,D2,CBP,CDL,DLT,TK,IMP,RK2,P,RKS,R,DO.
  1 JRTYPE,EJRT,OQW,CI,CDI,QI,QDI,OQD,DOP,VOP)
WRITE(6,119) VOP
119 FORMAT (' NEW OVERALL NPS IMPACT - ',F10.4,')
C  EIMP = TEIMP
CALL NWMAPH(NLT,NCT,NK,S,ST,XO,IT)

C
WRITE(6,81) IT,VOP
81 FORMAT(/10X,TT=':3,2X,VOP=':F15.4)
IF(VOP.LE.VOPV(TT)) GO TO 200
DO 82 JL=1,ILT
DO 82 JC=1,ICT
DO 182 IK=1,NK
   DX(JL,JC,IK,IT)=0.0
   XOS(JL,JC,IK)=0.0
   DX(JL,JC,IK,IT)=XO(JL,JC,IK)-XOM(JL,JC,IK,IT)
   XOS(JL,JC,IK)=XO(JL,JC,IK)
IF(SUBIDX(JC,JK).LE.0) GO TO 182
WRITE(6,83) JL,JC,IK,DX(JL,JC,IK,IT),XO(JL,JC,IK)
83 FORMAT(2X,3(I3,2X),F10.4,2X,F15.4)
182 CONTINUE
82 CONTINUE
DO 84 IS=1,ISMAX
   DT=FLOAT(IS)/FLOAT(ISMAX)
DO 85 JL=1,ILT
DO 85 JC=1,ICT
   C IF(SUBIDX(JC,JK).GT.0) THEN
      DO 851 IK=1,NK
         XO(JL,JC,IK)=XOM(JL,JC,IK,IT)+DT*DX(JL,JC,IK,IT)
851 CONTINUE
   C ENDIF
85 CONTINUE
C.....COMPUTE NEW WEIGHTED CURVE NUMBER AND NPS IMPACTS.
C
C CALL CURNUN(NCT,NLT,MLU,NHGR,XO,S,ICN,HYDRO,CN)
C
C TEIMP = EIMP
C
C CALL IMPACT(1,1,1,0,NCT,NLT,MLU,NHGR,MRCH,NRCH,
1      ST,IOR,IOC,ISEG,ALPHA,RAIN,NK,NKS,NC,DELTA,
1      XO,ATTIMP,RO,RV,RT,RF,RP,RC,RIMP,S,XT,IA,IB,RA,RB,
1      CN,SLOPE,LENGTH,ASPEK,LUT,HYDRO,SUIT,ICN,
1      QO,V,D1,D2,CBP,CBD,DOI,RK,TEM,RK2,P,RKS,R,DO,
1      IR_TYPE,IFRTO,QW,CI,CBDI,QI,BODI,QO,DOP,TEIMP)
WRITE(6,129) TEIMP
129 FORMAT( 'NEW NPS IMPACT' , 'F10.4,/')
VOP2(IS)=TEIMP
C
C WRITE (6,202) IS,VOP2(IS)
202 FORMAT(20X,'IS=',I4,2X,'VOP2(IS)=',F15.4/)
84 CONTINUE
C
C.....FIND THE INCREMENT THAT PRODUCE LEAST IMPACT
C
VOPM=-.1E5
DO 93 IS=1,ISMAX
   IF(VOP2(IS).LT.VOPM) GO TO 93
   VOPM=VOP2(IS)
IDM=IS
93 CONTINUE
  WRITE(6,94) IDM,VOPM
94  FORMAT(/5X,'IDM=',I4,5X,'VOPM=',F15.4)
  IT1=IT+1
  VOPV(IT1)=VOPM
  WRITE(6,95)
95  FORMAT(/10X,'NEW OPTIMAL SOLUTION'/)
  DO 96 JL=1,ILT
  DO 96 JC=1,ICT
  DO 961 IK=1,NK
    DT=FLOAT(IDM)/FLOAT(ISMAX)
    XM(JL,JC,IK,IT1)=XM(JL,JC,IK,IT)+DT*DX(JL,JC,IK,IT)
    IF (SUBIDX(JC,JL).EQ.0) COTO 961
    WRITE(6,97) JL,JC,IK,XM(JL,JC,IK,IT1)
  961 CONTINUE
  96 CONTINUE
  95 CONTINUE
  94 CONTINUE
  200 WRITE(6,201)
201  FORMAT(/20X,'IMPOSSIBLE TO GET BETTER SOLUTION'/)
   STOP
999  END