The study of geographical information systems (GIS) has moved from the domain of the computer specialist into the wider archaeological community, providing it with a powerful tool for research and data management. This clearly written but rigorous book provides a comprehensive guide to the archaeological uses of GIS. Topics covered include: the theoretical context and the basics of GIS; data acquisition including database design; creation of elevation models; exploratory data analysis including spatial queries; statistical spatial analysis; map algebra; spatial operations including the calculation of slope and aspect, filtering and erosion modelling; methods for analysing regions, visibility analysis; network analysis including hydrological modelling; the production of high-quality output for paper and electronic publication; and the use and production of metadata. Offering an extensive range of archaeological examples, it is an invaluable source of practical information about GIS for all archaeologists, whether engaged in cultural resource management or academic research. This is an essential handbook for both the novice and the advanced user.

James Conolly is former Lecturer in Archaeology at University College London and now Canada Research Chair in Archaeology at Trent University, Canada. Alongside the archaeological uses of GIS, his research interests include settlement and landscape archaeology, quantitative methods and population history, especially as applied to the origins and spread of agriculture and Aegean prehistory.

Mark Lake is a lecturer at the Institute of Archaeology, University College London, where he coordinates the M.Sc. GIS and Spatial Analysis in Archaeology. His research interests include early prehistory, spatial analysis and evolutionary archaeology. He is a contributor to *Handbook of Archaeological Sciences* and a member of the editorial board of *World Archaeology*. 
CAMBRIDGE MANUALS IN ARCHAEOLOGY

General editor
Graeme Barker, University of Cambridge

Advisory editors
Elizabeth Slater, University of Liverpool
Peter Bogucki, Princeton University

Books in the series
Pottery in Archaeology, Clive Orton, Paul Tyers and Alan Vince
Vertebrate Taphonomy, R. Lee Lyman
Photography in Archaeology and Conservation, 2nd edn., Peter G. Dorrell
Alluvial Geoarchaeology, A. G. Brown
Shells, Cheryl Claassen
Zooarchaeology, Elizabeth J. Reitz and Elizabeth S. Wing
Sampling in Archaeology, Clive Orton
Excavation, Steve Roskams
Teeth, 2nd edn., Simon Hillson
Geographical Information Systems in Archaeology, James Conolly and Mark Lake

Cambridge Manuals in Archaeology is a series of reference handbooks designed for an international audience of upper-level undergraduate and graduate students, and professional archaeologists and archaeological scientists in universities, museums, research laboratories and field units. Each book includes a survey of current archaeological practice alongside essential reference material on contemporary techniques and methodology.
GEOGRAPHICAL INFORMATION SYSTEMS IN ARCHAEOLOGY

James Conolly
Department of Anthropology, Trent University & Institute of Archaeology,
University College London

Mark Lake
Institute of Archaeology, University College London
To Lucy and Ella, Paddy and Katy
## CONTENTS

<table>
<thead>
<tr>
<th>List of figures</th>
<th>page xii</th>
</tr>
</thead>
<tbody>
<tr>
<td>List of tables</td>
<td>xvii</td>
</tr>
<tr>
<td>List of boxes</td>
<td>xix</td>
</tr>
<tr>
<td>Acknowledgements</td>
<td>xx</td>
</tr>
</tbody>
</table>

1 INTRODUCTION AND THEORETICAL ISSUES IN ARCHAEOLOGICAL GIS 1
   1.1 About this book         1
   1.2 Theoretical issues      3
   1.3 Conclusion             10

2 FIRST PRINCIPLES 11
   2.1 Introduction           11
   2.2 The basics             11
   2.3 Cartographic principles 16
   2.4 Data models and data structures: the digital representation of spatial phenomena 24
   2.5 Conclusion             31

3 PUTTING GIS TO WORK IN ARCHAEOLOGY 33
   3.1 Management of archaeological resources 33
   3.2 GIS and excavation       36
   3.3 Landscape archaeology    41
   3.4 Spatial and simulation modelling 45
   3.5 Conclusion              50

4 THE GEODATABASE 51
   4.1 Introduction            51
   4.2 Designing a relational database for attribute data 55
   4.3 Spatial data storage and management 57

5 SPATIAL DATA ACQUISITION 61
   5.1 Introduction            61
   5.2 Primary geospatial data 61
   5.3 Secondary data          77
Contents

5.4 Map rectification and georeferencing 86
5.5 A note on spatial error and map generalisation 88

6 BUILDING SURFACE MODELS 90
6.1 Introduction 90
6.2 Interpolation 90
6.3 Global methods 91
6.4 Local methods 94
6.5 Interpolation with geostatistics: kriging 97
6.6 Creating digital elevation models 100
6.7 Conclusion 111

7 EXPLORATORY DATA ANALYSIS 112
7.1 Introduction 112
7.2 The query 112
7.3 Statistical methods 122
7.4 Data classification 135
7.5 Conclusion 148

8 SPATIAL ANALYSIS 149
8.1 Introduction 149
8.2 Linear regression 149
8.3 Spatial autocorrelation 158
8.4 Cluster analysis 162
8.5 Identifying cluster membership 168
8.6 Density analysis 173
8.7 Local functions 177
8.8 Predictive modelling 179
8.9 Conclusion 186

9 MAP ALGEBRA, SURFACE DERIVATIVES AND SPATIAL PROCESSES 187
9.1 Introduction: point and spatial operations 187
9.2 Map algebra 188
9.3 Derivatives: terrain form 189
9.4 Continuity and discontinuity 197
9.5 Surface processes: erosion 202
9.6 Conclusion 206

10 REGIONS: TERRITORY, CATCHMENTS AND VIEWSHEDS 208
10.1 Introduction: thinking about regions 208
10.2 Geometrical regions 209
## Contents

10.3 Topographical regions 213
10.4 Conclusion 233

11 ROUTES: NETWORKS, COST PATHS AND HYDROLOGY 234
11.1 Introduction 234
11.2 Representing networks 234
11.3 Analysing networks 238
11.4 Networks on continuous surfaces 252
11.5 Conclusion 262

12 MAPS AND DIGITAL CARTOGRAPHY 263
12.1 Introduction 263
12.2 Designing an effective map 263
12.3 Map design 264
12.4 Thematic mapping techniques 265
12.5 Internet mapping 276
12.6 Conclusion 278

13 MAINTAINING SPATIAL DATA 280
13.1 Introduction 280
13.2 Metadata standards 281
13.3 Creating metadata 283
13.4 Conclusion 287

Glossary 289
References 307
Index 327
FIGURES

2.1 The main tasks performed by GIS. page 12
2.2 Spatial and aspatial characteristics of archaeological data. 14
2.3 Polar coordinates. 18
2.4 A conical projection with two lines of secancy and one line of tangency. 19
2.5 Albers equal-area conical projection with one line of tangency and a meridian. 20
2.6 An azimuthal projection. 20
2.7 A cylindrical projection. 21
2.8 Cartesian coordinate system. 23
2.9 Pythagoras' theorem. 23
2.10 Vector ‘geographic primitives’. 25
2.11 Vector objects linked to attribute data. 26
2.12 Topologically related polygons. 27
2.13 Raster representations of point, line and polygon. 28
2.14 Problems with raster representation of complex curves. 31
3.1 A simple data model for excavation records. 38
3.2 West Heslerton Web-CD. 40
3.3 KIP GIS. 44
3.4 KIP survey tract attribute database. 44
3.5 A computer-simulated artefact distribution. 49
4.1 An entity-relationship (E-R) diagram. 56
4.2 A simple arc-node storage structure. 58
4.3 A raster grid with cell values overlay. 59
4.4 A typical raster storage file. 60
4.5 Raster file compression using RLC. 60
5.1 A ‘total station’. 62
5.2 A differential GPS. 65
5.3 The electromagnetic spectrum. 66
5.4 Pixel values recorded by a digital sensor. 67
5.5 Dot-density overlay on an aerial photograph. 75
5.6 Steps in digitising map data. 81
5.7 A polygon before and after the removal of redundant vertices. 84
5.8 Two common topological errors in digitised lines. 84
5.9 Three common topological errors in digitised polygons. 85
### List of figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.10</td>
<td>Survey tract polygon topology in the KIP GIS.</td>
<td>86</td>
</tr>
<tr>
<td>5.11</td>
<td>Translation, scaling and rotation.</td>
<td>87</td>
</tr>
<tr>
<td>6.1</td>
<td>Trend surface analysis.</td>
<td>92</td>
</tr>
<tr>
<td>6.2</td>
<td>Linear interpolation.</td>
<td>94</td>
</tr>
<tr>
<td>6.3</td>
<td>Interpolation using inverse distance weighting.</td>
<td>95</td>
</tr>
<tr>
<td>6.4</td>
<td>A variogram.</td>
<td>99</td>
</tr>
<tr>
<td>6.5</td>
<td>Isometric view of a hillshaded DEM draped with an artefact distribution.</td>
<td>102</td>
</tr>
<tr>
<td>6.6</td>
<td>Problems associated with the simple interpolation of contour data.</td>
<td>104</td>
</tr>
<tr>
<td>6.7</td>
<td>Typical problems of using contour data for interpolation.</td>
<td>105</td>
</tr>
<tr>
<td>6.8</td>
<td>Comparison of interpolations produced using IDW and a TIN.</td>
<td>106</td>
</tr>
<tr>
<td>6.9</td>
<td>A Delaunay triangulation.</td>
<td>107</td>
</tr>
<tr>
<td>6.10</td>
<td>Use of contour data for TIN building.</td>
<td>108</td>
</tr>
<tr>
<td>6.11</td>
<td>Isometric view of a hillshaded DEM generated using TOPOGRID in ArcInfo 7.2.</td>
<td>110</td>
</tr>
<tr>
<td>7.1</td>
<td>The Boolean operators.</td>
<td>114</td>
</tr>
<tr>
<td>7.2</td>
<td>The point-in-polygon problem.</td>
<td>116</td>
</tr>
<tr>
<td>7.3</td>
<td>The line-in-polygon problem.</td>
<td>117</td>
</tr>
<tr>
<td>7.4</td>
<td>Polygon overlay.</td>
<td>118</td>
</tr>
<tr>
<td>7.5</td>
<td>Buffering of a point, line and polygon feature.</td>
<td>119</td>
</tr>
<tr>
<td>7.6</td>
<td>Elevation, land-use capability and distribution of cairns in west Shetland.</td>
<td>120</td>
</tr>
<tr>
<td>7.7</td>
<td>Boxplot of artefacts recovered from transects.</td>
<td>129</td>
</tr>
<tr>
<td>7.8</td>
<td>Boxplot of repotaro sizes for the Takuvaine and Tupapa Tapere.</td>
<td>131</td>
</tr>
<tr>
<td>7.9</td>
<td>Frequency distributions of repotaro sizes for the Takuvaine and Tupapa Tapere.</td>
<td>131</td>
</tr>
<tr>
<td>7.10</td>
<td>Cumulative proportion distribution of repotaro sizes for Takuvaine and Tupapa Tapere.</td>
<td>131</td>
</tr>
<tr>
<td>7.11</td>
<td>Boxplot of artefact densities for coastal and inland survey areas.</td>
<td>132</td>
</tr>
<tr>
<td>7.12</td>
<td>Boxplot of logged artefact densities for coastal and inland survey areas.</td>
<td>134</td>
</tr>
<tr>
<td>7.13</td>
<td>Different qualitative classifications on the same stone-tool dataset.</td>
<td>135</td>
</tr>
<tr>
<td>7.14</td>
<td>Hypothetical reclassification of qualitative variables to rank-order variables.</td>
<td>138</td>
</tr>
<tr>
<td>7.15</td>
<td>Normal, rectangular, bimodal and skewed distributions.</td>
<td>141</td>
</tr>
<tr>
<td>7.16</td>
<td>Classification of normally distributed data.</td>
<td>142</td>
</tr>
<tr>
<td>7.17</td>
<td>Distribution of sherd density.</td>
<td>143</td>
</tr>
<tr>
<td>7.18</td>
<td>Six possible numerical classifications of the same dataset.</td>
<td>144</td>
</tr>
<tr>
<td>7.19</td>
<td>Classification of pixel values recorded by a digital sensor.</td>
<td>147</td>
</tr>
<tr>
<td>8.1</td>
<td>Idealised correlation patterns.</td>
<td>150</td>
</tr>
<tr>
<td>8.2</td>
<td>‘Line of regression’.</td>
<td>153</td>
</tr>
</tbody>
</table>
List of figures

8.3 A line of regression fitted to a heteroscedastic point distribution. 155
8.4 Transforming a variable to improve the correlation coefficient. 156
8.5 Plot of the residuals of predicted versus actual medieval pottery. 157
8.6 Nearly random, nearly clustered and nearly regular point distributions. 163
8.7 Smaller-scale point patterns with a near-random distribution. 164
8.8 Multiscale point patterning. 166
8.9 Identification of multiscale clustering in the Kytheran Early Bronze Age using Ripley's K. 167
8.10 A simple point distribution. 169
8.11 A single-link cluster analysis of the point distribution in Fig. 8.10. 170
8.12 A cluster analysis using Ward's method. 171
8.13 A k-means cluster analysis of medieval castles on Okinawa Island, Japan. 172
8.14 Distribution of stone artefacts from trench 4b at Boxgrove, England. 173
8.15 Rate of change of sum of squares for 1–20 cluster solutions. 174
8.16 The two-cluster solution of a k-means cluster analysis. 175
8.17 Three intensity surfaces of the stone artefact distribution at Boxgrove 4b. 176
8.18 Kernel density estimates of the stone artefact distribution at Boxgrove 4b. 178
8.19 Distribution of artefact densities in five fields. 179
8.20 Generalised flowchart of stages in the generation of a predictive model. 182
8.21 Cumulative per cent correct predictions for model sites and non-sites. 185
9.1 Calculation of a mean value as a spatial operation. 188
9.2 ESRI's ArcGIS 'raster calculator'. 190
9.3 The slope experienced while traversing terrain depends on the direction of travel. 191
9.4 A GRASS GIS rule file to reclassify aspect values to compass directions. 193
9.5 A histogram of slope values in Dentdale and Garsdale, UK. 193
9.6 A histogram of aspect values in Dentdale and Garsdale, UK. 194
9.7 Equal-interval and equal-area classifications of slope. 195
9.8 A shaded relief model. 196
9.9 Two points with the same slope and aspect but different plan and profile complexity. 196
9.10 A simple low-pass filter. 199
9.11 Mode, range and diversity calculated using filters. 200
List of figures

9.12 High-pass filters applied to a synthetic DEM containing traces of a field system. 202
10.1 Multiple buffer zones around a point. 210
10.2 Multiple merged buffers. 211
10.3 Thiessen tessellations. 212
10.4 Linear barrier breached by diagonal moves. 216
10.5 Least-cost paths derived using relative and fixed costs. 217
10.6 Calculation of effective slope. 218
10.7 Sign of effective slope. 219
10.8 Energetic cost of traversing slopes according to Llobera (2000). 219
10.9 Energetic cost of traversing slopes according to Bell and Lock (2000). 220
10.10 Energetic cost of traversing slopes according to van Leusen (2002). 221
10.11 Iteration of a basic spreading function. 222
10.12 Algorithm artefacts in an accumulated cost-surface. 223
10.13 Cross-tabulation of land-use potential. 226
10.14 Multiple viewshed. 227
10.15 Cumulative viewshed. 227
10.16 Edge effect in visibility analysis. 229
10.17 Non-reciprocity of intervisibility. 230
10.18 Probabilistic viewshed. 231
11.1 Connected and disconnected simple graphs. 235
11.2 Paths and cycles in a simple graph. 235
11.3 Weighted digraph of a road network. 236
11.4 Transport network. 238
11.5 Planar graphs. 239
11.6 Turn table for a node in a transport network. 239
11.7 Sparsely and well-connected networks. 242
11.8 Serbian trade routes in the thirteenth and fourteenth centuries. 244
11.9 The C_ij matrix for a trade network. 245
11.10 Distribution of accessibility in the medieval Serbian oecumene. 246
11.11 Justified graph. 247
11.12 Visibility graph. 248
11.13 Mackie’s (2001) shell midden network. 250
11.14 Results of Mackie’s (2001) location–allocation analysis. 250
11.15 The travelling salesman problem. 251
11.16 Errors in least-cost paths. 253
11.17 Collischonn and Pilar’s (2000) least-cost path. 253
11.18 A globally suboptimal least-cost path. 254
11.19 LDD map and derivatives. 256
11.20 Stream order indices. 259
11.21 Watersheds and ridges. 259
List of figures

12.1 Effect of polygon shading. 266
12.2 Choropleth mapping. 267
12.3 Mapping enumeration unit variability. 269
12.4 Continuous distribution mapping. 270
12.5 Use of proportional symbols. 271
12.6 A dot-density map. 273
12.7 Isochronic map. 274
12.8 Isoplethic map. 275
12.9 Interactive SVG map. 278
13.1 XMLInput editor. 286
13.2 ESRI’s ArcCatalogue Metadata editor. 286
13.3 ESRI’s ArcCatalogue Metadata search tool. 287
### TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>The main types of question that can be answered using GIS</td>
</tr>
<tr>
<td>3.1</td>
<td>KIP geospatial datasets</td>
</tr>
<tr>
<td>3.2</td>
<td>The four scales of measurement</td>
</tr>
<tr>
<td>3.3</td>
<td>Variables used in Woodman’s (2000b) predictive model</td>
</tr>
<tr>
<td>4.1</td>
<td>A flat-file database</td>
</tr>
<tr>
<td>4.2</td>
<td>Three normalised database tables</td>
</tr>
<tr>
<td>5.1</td>
<td>Sources of digital satellite imagery</td>
</tr>
<tr>
<td>5.2</td>
<td>NASA Landsat-7 ETM+ bands</td>
</tr>
<tr>
<td>5.3</td>
<td>Principal applications of Landsat TM spectral bands</td>
</tr>
<tr>
<td>5.4</td>
<td>Common satellite and raster image file formats</td>
</tr>
<tr>
<td>5.5</td>
<td>Common vector file formats</td>
</tr>
<tr>
<td>5.6</td>
<td>A correspondence table</td>
</tr>
<tr>
<td>5.7</td>
<td>RMSE and error values</td>
</tr>
<tr>
<td>6.1</td>
<td>Attribute, distance values and weighted attributes</td>
</tr>
<tr>
<td>6.2</td>
<td>Surface models that can be computed from a DEM</td>
</tr>
<tr>
<td>7.1</td>
<td>SQL logical operators</td>
</tr>
<tr>
<td>7.2</td>
<td>Results of a grouping and aggregate SQL statement</td>
</tr>
<tr>
<td>7.3</td>
<td>Observed number of cairns and houses on each land class</td>
</tr>
<tr>
<td>7.4</td>
<td>Contribution of each land class to the study area</td>
</tr>
<tr>
<td>7.5</td>
<td>Summary statistics of elevation values for cairns and houses</td>
</tr>
<tr>
<td>7.6</td>
<td>Basic statistical terms and concepts</td>
</tr>
<tr>
<td>7.7</td>
<td>Observed number of cairns and houses on each land class</td>
</tr>
<tr>
<td>7.8</td>
<td>Expected number of cairns and houses on each land class</td>
</tr>
<tr>
<td>7.9</td>
<td>( \frac{(O_i - E_i)^2}{E_i} ) values</td>
</tr>
<tr>
<td>7.10</td>
<td>Critical values for the chi-squared test</td>
</tr>
<tr>
<td>7.11</td>
<td>Expected numbers of monuments based on land-class areas</td>
</tr>
<tr>
<td>7.12</td>
<td>( \frac{(O_i - E_i)^2}{E_i} ) values adjusted for area</td>
</tr>
<tr>
<td>7.13</td>
<td>Artefacts recovered from ten transects</td>
</tr>
<tr>
<td>7.14</td>
<td>Ranked transect values</td>
</tr>
<tr>
<td>7.15</td>
<td>Ranked measures</td>
</tr>
<tr>
<td>7.16</td>
<td>Critical values of ( D ) for the Kolmogorov–Smirnov test</td>
</tr>
<tr>
<td>7.17</td>
<td>Mesolithic artefact densities from coastal and inland survey areas on Islay</td>
</tr>
</tbody>
</table>
**List of tables**

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.1</td>
<td>Example values used for calculating the correlation coefficient, $r$</td>
<td>152</td>
</tr>
<tr>
<td>8.2</td>
<td>Example data used for calculating the standard error in a linear regression analysis</td>
<td>154</td>
</tr>
<tr>
<td>8.3</td>
<td>Counts of prehistoric and medieval pottery recovered from ten surface collection areas</td>
<td>157</td>
</tr>
<tr>
<td>8.4</td>
<td>Some common problems, consequences and solutions with regression analysis</td>
<td>159</td>
</tr>
<tr>
<td>8.5</td>
<td>A distance matrix for hierarchical cluster analysis</td>
<td>169</td>
</tr>
<tr>
<td>8.6</td>
<td>A distance matrix for Getis’s $G_i^*$ statistic</td>
<td>180</td>
</tr>
<tr>
<td>9.1</td>
<td>The universal soil loss equation</td>
<td>203</td>
</tr>
<tr>
<td>11.1</td>
<td>Basic measures of network structure</td>
<td>240</td>
</tr>
<tr>
<td>11.2</td>
<td>Local measures of network structure</td>
<td>240</td>
</tr>
<tr>
<td>11.3</td>
<td>Global measures of network structure</td>
<td>242</td>
</tr>
<tr>
<td>12.1</td>
<td>Essential map items</td>
<td>264</td>
</tr>
<tr>
<td>13.1</td>
<td>ISO 19115 core elements</td>
<td>282</td>
</tr>
<tr>
<td>13.2</td>
<td>Standard UK metadata elements</td>
<td>284</td>
</tr>
</tbody>
</table>
BOXES

2.1 GIS tasks and descriptions  
5.1 Root-mean-square error  
6.1 Interpolation using kriging in ArcGIS  
7.1 Using R  
7.2 Univariate statistics in R  
8.1 Monte-Carlo simulation  
8.2 Clark and Evans’ nearest neighbour statistic  
9.1 How to calculate slope and aspect  
9.2 Parameters for the ANSWERS erosion model  
10.1 Weighting Thiessen polygons  
11.1 A method for locating confluences
ACKNOWLEDGEMENTS

Many people facilitated the writing of this book and we would like to take the opportunity to thank: Professors Peter Ucko and Stephen Shennan for their encouragement and advice; Dr Andrew Bevan for many discussions on landscape archaeology and GIS; Dr Cyprian Brookbank for his ‘early-adopter’ enthusiasm for spatial technologies; Dr Sue College for her keen eye; Drs Andre Costopolous and Andrew Gardner for their opinions on Chapter 1; Professor Yvonne Edwards for her helpful comments on a draft version of the manuscript; Sach Killam for his new user’s perspective; Professor Clive Orton for guidance on all matters statistical; Dr Paddy Woodman for sharing her expertise; all of our students from the MSc programme in GIS and Spatial Analysis at the Institute of Archaeology (UCL) whose feedback on drafts of this book has been invaluable; Simon Whitmore at CUP for his patience; and the two anonymous reviewers whose constructive criticism greatly improved the text. Mark Lake’s use of GIS has at various times been generously supported by the Natural Environment Research Council and the Leverhulme Trust. James Conolly would like to acknowledge the Department of Anthropology of the University of Auckland for welcoming him as a Visiting Research Fellow and, during the latter phases of writing, the support of the Social Science and Humanities Research Council of Canada (Canada Research Chairs Program).