SEMANTIC NET OF UNIVERSAL ELEMENTARY GIS FUNCTIONS

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ABSTRACT

Current use of GIS is data-driven, prohibiting the application of model-based procedures The analysis of user surveys and functional taxonomies leads to a classification of data model-independent elementary GIS functions whose relations were examined employing a semantic net An important finding is the notion that there is no universal set of application-independent elementary GIS functions Each application has its own view onto the semantics, expressed as a web of relations, that is determined by domain context and can be made explicit in simple knowledge bases The Virtual GIS shell presented here, supports the knowledge building as well and offers an easy-to-use task-oriented Graphical User Interface (GUI) that allows the domain scientists to concentrate on their tasks rather than on their data.

INTRODUCTION

Currently available GIS technology, while impressive, is isolated from both the actual problem context and the users' conceptualization of the problem It provides 'powerful toolboxes in which many of the tools. are as strange to the user as a robot-driven assembly plant for cars is to the average home handyman' (Burrough, 1992, page 9) The Virtual GIS (VGIS) project currently pursued at the Institute for Spatial Analysis and Planning in Areas of Intense Agriculture (ISPA) is geared to overcome this problem Its goals — the theoretical foundation of which is presented in this paper — are

(1) to develop a taxonomy of fundamental GIS operations with conditions for their application
(2) to help the user to develop a plan for an analysis using available data and operational capabilities of the GIS, as well as mapping a general operation description into a specific set of commands or actions appropriate for the current GIS
(3) to define a model for relating and retrieving information based on the users' description of context This model consists of
    - data or objects broad categories that generalize both the information the user is trying to retrieve and the information already available
    - relations general categories that describe how objects are connected or related, such as sequence, instance, or composition
    - context schemes patterns of knowledge categories that are composed of particular objects and relations

    The model representation will be based on semantic nets or frames that have been employed in artificial intelligence work.
(4) Semantically-assisted information retrieval as described in previous works by Bennett and Armstrong (1993) and Walker *et al.* (1992) where a user's description of a desired (geographic) dataset is matched with metadata stored with that dataset

The VGIS project emphasizes a user-oriented visualization of tasks instead of the commonly used (technically oriented) functions (Albrecht, 1994b) These tasks can be dissected into universal, elementary GIS functions that are independent of any data structures and thereby of any underlying GIS No matter whether data is collected, manipulated or analyzed, all we do with data can be reduced to a small number of functional groups (see Table 1) that are subordinate to goals (see Figure 1). The author examined a suite of taxonomies as they can be found in the relevant literature of the past few years (Burrough, 1992, Goodchild, 1992; de Man, 1988, Rhind and Green, 1988, Unwin, 1990). To be included into the resulting list, each function needs to be system (or vendor) -independent.

In the following, *task* shall be used for all combined actions that requires some (human or machine-based) knowledge about semantic and spatial relations such as 'map updating', 'routing' or 'siting' whereas the term *function* shall be used for singular actions that can be performed automatically, i.e. 'multivariate analysis' While tasks, as used here, are always application-oriented, *functional groups* are the attempt to aggregate functions and tasks on an abstract technical level Following Monckton (1994) one can differentiate between overall goals (i e inventory, reference, prediction), the tasks used to accomplish them and inferior functions which are called while performing a task

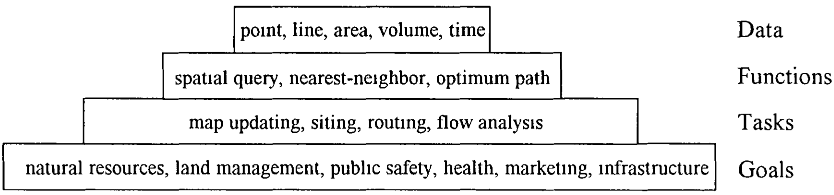


Figure 1 The information pyramid consisting of data, functions, tasks and goals *(after Huxhold, 1989, adapted)*

The above mentioned examination of functional taxonomies is condensed in the tables at the end of this paper. Each of the 144 functions screened is related to its neighbors by answering the following two questions (i) how does a function fit into a thematic context, i e is a operation similar to another one, and (ii) how does a function fit into the work flow, i e. what needs to be done before that function can be called and what other function does it lay ground for? The result is a very complex net of relations that is comprehensible only if transformed to a net of more general *tasks* (Figure 2)

One interesting insight gained here though, is that different users or applications call for different connections (the edges of this semantic net). Figure 3 gives one possible view onto this net of universal GIS functions The most surprising result, however, was that there doesn't seem to be a set of universal, elementary GIS functions that is application-independent

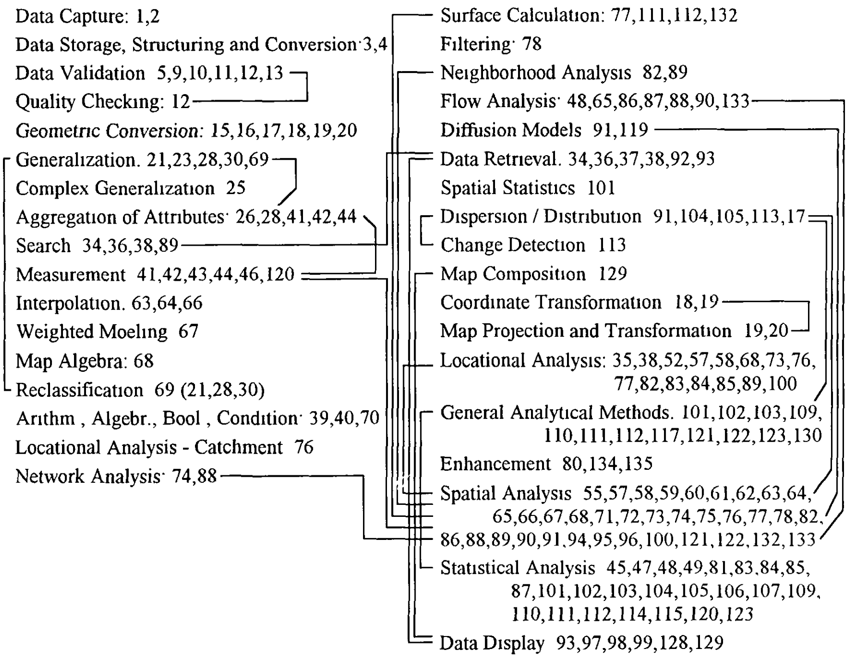


Figure 2. Semantic net of GIS tasks. Displayed are only the relations given in the cited references; obviously there are more such as *Map Algebra* and *Spatial Analysis*

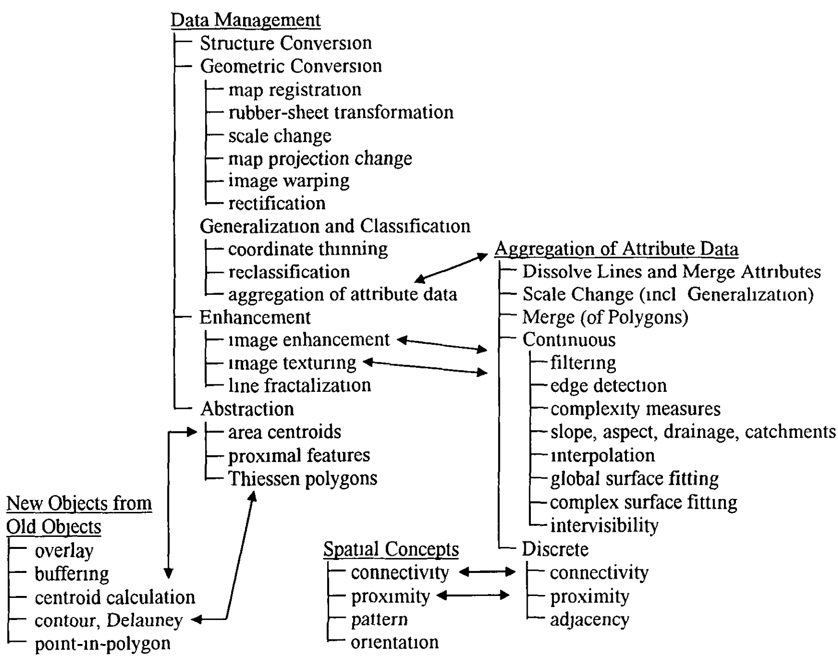


Figure 3. One of many possible views onto the semantic net of GIS functions

GIS TASKS

In addition to this literature-based work the author conducted informal surveys conveying that practitioners of GIS tend to categorize their tasks into the following 15 functional groups:

• Visualize / Show	• Aggregate / Summarize
• Encode	• Compare
• Find	• (partial) Select
• Monitor	• Substitute
• Create	• Derive
• Combine / Relate	• Correct
• Allocate	• Evaluate
• Determine	

Table 1 Functional groups of GIS tasks.

Special emphasis was given to the spatial, logical, procedural, and cognitive relations among each of these functionalities. The results compare favorably with the findings in cognitive science where image schemata are used to describe spatial categorizations Of all the schemata summarized by Mark (1989) only *'direction'* and *'center-periphery'* were missing These seem to be more of scientific interest and the findings of this survey suggest that spatially-aware professionals outside geography do not use these relations

TASK-ORIENTED PROCESSING TEMPLATES

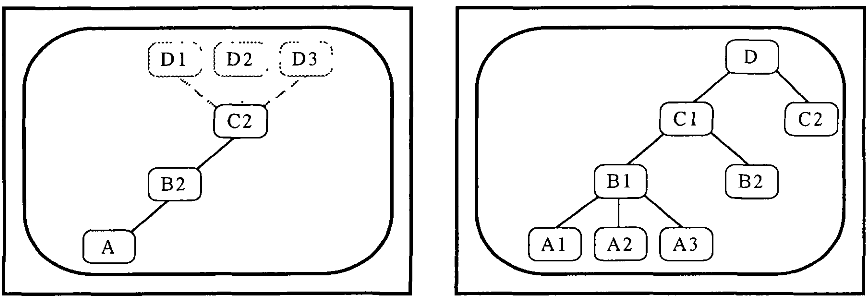
In general there are two possible ways to ascertain the independence from the multitude of data models. The OGIS project (Gardels, 1994) and the 'Virtual Data Set' (Stephan *et al.*, 1993) approach suggest that data objects rather than operations are the primary focus of attention This conforms with the view held by many users of GIS who (driven by the demands of the system they use) tend to think in terms of building data layers or making maps rather than in terms of applying particular GIS operations to manipulate data Especially analytic functionality is distinctively underrepresented in the listing given above This is reflected (or determined?) by the offerings on the vendor's side. less than 10% of the functions listed in ESRI's ARC command reference are analysis-related (ESRI, 1991) But there is also evidence that experienced users (those that have used a couple of different systems and learned to think in tasks rather than in the manipulation of data layers) as well as those who have never encountered a GIS do not think about these layers as isolated, individual entities

A table of elementary methods such as those from the previous section can be regarded as a periodic chart of universal GIS functionalities which allows the building of typical applications much like molecules are made up of atoms (Albrecht, 1994b) Their difference to the generally available GIS functions is in their top-down approach to user needs (as they are derived from general tasks instead of technical conceptions of the manufacturer) and their independence from the underlying system

Each task is associated with a task description file that can recursively call another task This file lists the required input parameters, a pointer to a visualizing icon, meta information and, most important of all, a macro consisting of elementary GIS functions and possibly other tasks. Similarly, there is a file for each class or data type (e g DEM, vector file, point source) describing the methods that are used to create an object instance These files can be seen as a crude form of external knowledge base

The results of both the literature review and the survey were analyzed with a methodology borrowed from speech analysis to construct semantic nets (Birnthaler *et al.*, 1994) For the purposes of the VGIS project, the edges of the semantic net are weighted by the relative importance with which they contribute to a typical GIS procedure These weights are encoded in the task description file Since there are no application-independent paths through the semantic net, each application will require a task tree such as the ones depicted in Figure 4

Almost any situation that requires the presentation of a series of processing steps, especially in its planning stage is best visualized by flow charts. VGIS utilizes flow charts as a graphical means to guide the user through the steps necessary to accomplish a given task By selecting a task from the main menu the first questions for input parameters are triggered If the input data exists in the correct format then the macro of elementary GIS function, stored in the base file, is executed Otherwise the system tries to generate the necessary data based on the knowledge stored in the base files. This might require further input by the user. Data and all operations on them are displayed by icons and connecting edges In the ideal case that all necessary data already exists, the user will get to see the bottom leaf of the task tree only. Otherwise the tree will unfold as in Figure 4a



a) unfolding task tree from user perspective

b) bottom-up creation of a task tree from developer perspective

Figure 4 Task trees

VGIS addresses two classes of users One is the spatially-aware professional who does not want to have to know about GIS internals This kind of user is interested in accomplishing a task and VGIS supports this approach as depicted in Figure 4a The other kind of users that VGIS tries to support are conceptual models Scientists who want to "play" with a variety of models. This latter group utilizes elementary GIS functions to build new task trees. They need to actively rearrange the connections of the semantic net, testing the results and thereby creating new knowledge bases that then can be used by members of the first group Figure 4b describes this bottom-up approach

The base files that store the knowledge about processing procedures can be thought of as preprogrammed model templates (Kirby *et al.*, 1990) that are independent of any data Previous runs are stored in metadata files and can be triggered at any time again, either with links to the old data files or crunching new files after the metadata file has been edited accordingly Lineage information and other metadata are of special importance The methodoloy used for VGIS follows the ideas presented in (Lanter and Veregin, 1992, Lanter, 1994) This usage of metadata information applies to both user classes Model builders may include conditional operators as they are used in formal programming languages The effect is a prototyping and development platform similar to the famous STELLA® (HPS, 1994) but working with real GIS data

CONCLUSION

What is the practical value of yet another taxonomy? The trivial answer to this is that the VGIS project is based upon these universal elementary GIS functions and would have to fail without them. However, there are a number of more universal applications. At larger sites that used numerous GIS in parallel for different applications, a user interface such as VGIS could be used to pick the highlights of whatever functionality a particular system is especially good at One might have an especially intuitive digitizing module while another one shows its strengths in spatial statistics or produces exceptionally good cartographic output. Within a single project it is not advisable to switch from one system to another VGIS enables the GIS manager to build a user interface made of the elementary GIS functions which then invisibly call the functions of the underlying system (see Albrecht, 1994a and Ehlers *et al.*, 1994 for a detailed description of the technical issues).

An additional advantage of such a systemization of GIS functions is the opportunity to use them for software benchmarks Up to now all attempts to objectively compare geographic information systems had to fail because a comparison beyond the boundaries of certain data models is like comparing apples with oranges Since VGIS is based on task-oriented elementary GIS functions that represent the desired functionality without being restrained by the usually historically evolved oddities of a particular vendor system, it is possible to use these as evaluation criteria. New built applications are then the basis for studies as to how much a given system diverges from the desired functionality and thereby how difficult it is to handle this system. VGIS strengthens the toolbox character of GIS by·

- identifying elementary GIS tools (functions),
- providing users a framework (semantic nets) to integrate functions and present different views on task-oriented GIS application design,
- encouraging users to switch from currently dominant data-centered perspectives to procedure-based (task-oriented) GIS project design

This then allows to comply with the demand by cognitive scientist Dan Norman (1991) who wrote 'Good tools do not just extend or amplify existing skills, they change the nature of the task itself, and with it the understanding of what it is we are doing.'

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#	name	reference	requires	necessary for	task or function	raster vector TIN all	related to
1	Data Capture / Import	R&G	0	2,3	T	A	2,3,5,6,7,8,9,17
2	Digitizing, Scanning	R&G	(17)		F	A	1,3,5,6,7,8,9,17
3	Data Storage	R&G	1	4	T	A	1,2,4
4	Data Structuring	R&G	3	5,6,7	T	A	3,5,6,7,8,9
5	Planar Enforcement		1,3	12	F	V	3,4
6	Structure Conversion	R&G	3	7,8	T	A	7,8
7	Raster/Vector	G, R&G	3,6	11	F	R	6,8
8	Quadtree/Vector	R&G	3		F	R	6,7
9	Data Validation	R&G	3	all	T	A	1,2,5,9,10,11,12,13
10	Distortion Elimination	G	15,(16),17		F	A	9,12,15,16,17
11	Sliver Polygon Removal	G	1,2,3,4,5,9,10		F	V	12,13
12	Quality Checking	A, U	3,4,9		T	A	
13	Data Editing	R&G	3	14	T	A	10,11,14,22
14	Generate Graphical Feature	G	0		F	A	
15	Geometric Conversion	R&G	3	10,18	T	A	15,16,17,18,19,20
16	Georeferencing	A, B, R&G, U	0		T	A	19,20,27,28,29,56,124, 125,126,127
17	Map Registration	A, R&G	0	2	F	A	1,2,3,4,5,6,7,8,9,10,11,12 13,14,15,16
18	Rubber-Sheet Transformation	G, R&G, U			F	A	15
19	Scale Change (simple)	B, R&G, U			F	A	16,20,27,28,29,56, 124,125,126,127
20	Projection Change	B, R&G, U			F	A	16,19,27,28,29,56, 124,125,126,127
21	Generalization	R&G			T	A	23,25,26,28,30, 69
22	Line Thinning / Smoothing	G, U			F	A	21,22,25,26,27,29,30
23	Line Generalization	A			F	A	
24	Area Centroid Calculation	G, R&G			F	A	24,31,32,33,42,52, 55,58,59,60,61,66, 114,119
25	Complex Generalization	G			T	A	
26	Aggregation	M			F	A	21, 30,69
27	Dissolve Lines and Merge Attributes	B, G			F	A	16,19,20,28,29,56,124, 125,126,127
28	Aggregation of Attributes	B, M, R&G			T	A	16,19,20,27,29,56,124, 125,126,127
29	Scale Change (incl Generalizat)	B, G			T	A	16,19,20,26,27,2829,41. 42,44,56,124,125,126, 127
30	Coordinate Thinning	R&G			F	A	21,26,69
31	Proximal Feature (Abstraction)	R&G			F	A	24,32
32	Thiessen Polygons	R&G			F	A	24,31,32,33,52,55,58,59, 60,61,66,114,119
33	Line Smoothing with Splines	B			F	V	24,32,33,52,55,58,59,60. 61,66,114, 119
34	Search	A, M			T	A	36,38,39
35	Point-in Polygon	G, M			F	A	
36	Search Attribute	G, M	39		F	A	
37	Select	R&G	39		F	A	
38	Search by Region	G, M	39		F	A	
39	Logical Condition	M			F	A	
40	Suppress (Converse of Select)	G, M	39		F	A	
41	Measurements	R&G			T	A	42,43,44,46,120
42	Number of Items	G, U, M			F	A	24,32,33,52,55,58,59,60, 61,66,114, 119
43	Distance	A, G, R&G, U			F	A	41,42,44,46,83,87,102, 107
44	Perimeter, Acreage, Volume	A, G, R&G, M			F	A	41,42,43,46
45	Calculate Bearing (to the north)	G			F	A	

#	name	reference	requires	necessary for	task or function	raster vector TIN all	related to
46	Direction Measurement	B			F	A	41,42,43,44
47	Calculate Height	G			F	A	
48	Calculate Angles and Distances along Linear Features	G		65	F	A	
49	Calculate Endpoint of Traverse	G			F	A	
50	Windowing, Clipping	A			F	A	
51	Overlay	A			F	A	
52	Line-on-Polygon	G, M			F	A	24,32,33,42,55,58,59,60, 61,66,114, 119
53	Graphic Overlay	G			F	A	
54	Line Intersection	A, U			F	A	
55	Polygon Overlay	G, R&G			F	A	24,32,33,42,52,57, 58,59,60,61,73,66, 95,114,119
56	Merge	A, B			F	A	16,19,20,27,28,29, 124,125,126,127
57	Route Allocation	R&G, M			G	A	55,73,95
58	Buffering	A, G, M, U			F	A	24,32,33,42,52,55,59,60, 61,66,114, 119
59	Buffer Zones	B			F	A	24,32,33,42,52,55,58,60, 61,66,114, 119
60	Simple Buffer	B			F	A	24,32,33,42,52,55,58,59, 61,66,114, 119
61	(An-)Isotropic Buffer	B			F	A	24,32,33,42,52,55,58,59, 60,66,114, 119
62	Corridors	A, U			F	A	
63	Interpolation	B			T	A	64,66,73,74,76,83,84,87, 95, 111,112,118
64	Interpolation of Heights	G			F	A	
65	Height Along Streams	G	48		F	A	
66	Interpolate Contour from Points	G, U			F	A	24,32,33,42,52,55, 58,59,60,61,114, 119
67	Weighted Modeling	G			T	A	
68	Map Algebra	A,M			T	R	
69	Reclassification	A, B, R&G			T	A	21,26,28,30
70	Arithm Algebraic, Bool Cond	B, G, M			T	A	39,40,70,71,72,109,110
71	Weighted Boolean Operations	B			F	A	70,72,109,110
72	Bayesian prior Probabilities	B			F	A	70,71,109,110
73	Slope and Aspect	B, G, R&G			F	T,R	55,57,63,74,76,83,84,87, 95, 111,112,118
74	Drainage Network	B			F	T,R	63,73,76,83,84,87,88,95, 111,112,118
75	Watershed Boundaries	G			F	A	
76	Locational Analysis -Catchment	B, M			T	A	63,73,74,83,84,87, 95, 111,112,118
77	Surface Calculation	M			T	A	71,111,112,132
78	Filtering	M			T	A	
79	Geometric Filtering	B			F	A	22,80,103
80	Image Edge Detection/Enhance	B, R&G			F	R	
81	Discrimination	B			F	A	
82	Neighborhood Analysis	M			T	A	89
83	Proximity	A			F	A	43,84,87,102,109
84	Adjacency	B			F	A	83,87
85	Contiguity Analysis	G			F	A	
86	Flow Analysis	M			T	A	48,65,87,88,90,133
87	Connectivity Analysis	B, G, M, U			F	A	43,63,73,74,76,83,84,95, 102,107,111,112,118
88	Network Analysis	A,G, M, U			T	A	74
89	Nearest Neighbor Search	G			F	A	82
90	Shortest Path	G			F	A	
91	Diffusion Models	M			T	A	119
92	Data Retrieval, incl Selection	R&G			T	A	34,36,37,38,93
93	Create Lists and Reports	B, G			F	A	99,113,115,117,123
94	Generate Viewshed Maps	G			F	A	
95	Intervisibility	R&G			F	A	55,57,63,73,74,76,83,84, 87,111,112, 118
96	Line-of -Sight	G			F	A	
97	Generate Block Diagram	G			F	A	
98	Scene generation	G			F	A	
99	Generate Cross-Section	B, G			F	A	93,113,115,117,123

#	name	reference	requires	necessary for	task or function	raster vector TIN all	related to
100	Optimal Location	M			G	A	
101	Spatial Statistics	M			T	A	130
102	Pattern	A, M, U			F	A	43,83,107
103	Complexity/Variation Measure	B, M			F	A	
104	Measures of Dispersion	M, R&G, U	42		F	A	105,109,113,115,117
105	Point Dispersion / Distribution	A, U	42		F	A	104,106,131
106	Point Centrality	A, U	42		T	A	
107	Orientation	A, U			F	A	43, 83,102
108	Multi-Criteria Decision Making	A			G	A	
109	Multivariate Analysis	B, R&G			F	A	70,71,72,104,110,115, 117
110	Regression Models	B			F	A	70,71,72,109
111	Global Surface Fitting (Trend)	B			F	A	63,73,74,76,83,84,87,95, 112,118
112	Complex Surface Fit (Fourier)	B			F	A	63,73,74,76,83,84,87,95, 111,118
113	Change Detection	B, G, M			T	A	93,99,115,117,123
114	Statistical Functions	G			F	A	24,32,33,42,52,55,58,59, 60,61,66,119
115	Histograms	B, R&G			F	A	93,99,104,109,113,117, 123
116	Discrimination	B			F	A	
117	Frequency Analysis	B, M			F	A	93,99,104,109,113,115, 123
118	Kriging	B			F	A	63,73,74,76,83,84,87,95, 111,112
119	Spread over Friction Surface	B, M			F	A	24,32,33,42,52,55, 58,59,60,61,66,119
120	Measurement of Shapes	B			F	A	41,85,87,88,121, 122
121	Topology, Description of Holes	B			F	A	41,85,87,88,120, 122
122	Topology; Upstream Elements	B			F	A	41,85,87,88,120, 122
123	Indices of Similarity	B			F	A	93,99,113,115,117
124	Map Join	B			F	A	16,19,20,27,28,29, 56, 125,126,127
125	Object Join	B			F	A	16,19,20,27,28,29, 56, 124,126,127
126	Snap	B			F	A	16,19,20,27,28,29, 56, 124,125,127
127	Scissors and Cookie Operations	B			F	A	16,19,20,27,28,29, 56, 124,125,126
128	Plotting	A			F	A	
129	Map Composition	A			T	A	
130	Spatial Autocorrelation	M			F	A	101
131	Tessellation from Point Data	U			F	R, T	42,104,105,106
132	Delineation of Homogenous Areas	M			F	A	
133	Flow Between Regions	M			F	A	
134	Image Texturing	R&G			F	R	
135	Line Fractalization	R&G			F	R	
136	Coordinate Transformation	U		18,19	T	A	18,19
137	Map Projection and Transformation	U		20	T	A	19,20
138	Location Analysis	M			T	A	35,38,52,57,58,68,73,76, 77,82,83,84,85,89,100
139	General Analytical Methods	M			T	A	101,102,103,109,110, 111,112,117,121,122, 123,130
140	Enhancement	R&G			T	A	80,134,135
141	Abstraction	R&G			T	A	
142	Spatial analysis	R&G			T	A	55,57,58,59,60,61,62,63, 64,65,66,67,68,71,72,73, 74,75,76,77,78,82,86,88, 89,90,91,94,95,96,100, 121,122,132,133
143	Statistical Analysis	R&G			T	A	45,47,48,49,81,83,84,85, 87,101,102,103,104,105, 106,107,109,110,111, 112,114,115,120,123
144	Data Display	R&G			T	A	93,97,98,99,128,129

Table 2. List of universal GIS functions drawn from cited references (some columns are yet incomplete!).