

# Using Geographically Weighted Regression to Predict Site Representativity

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## Abstract

This paper presents an attempt to use GWR in the ArcGIS environment to explore representativity of sites (burial grounds) in the Mälardalen area in central Sweden. This area has a large number of burial grounds that survive in the landscape and form the base for a settlement analysis of the Iron Age landscape. Large-scale rescue excavations from the 1980s onwards have shown that although there are a large number of sites that are visible in the landscape, there are also a significant number that for different reasons have not been recorded. These are either sites that have been damaged by later agricultural activities, or that simply have been missed in the surveys. Building on the results of some of the major archaeological projects recently initiated as part of infrastructure developments in the region, the representativity of the known archaeological record is examined. This information is crucial for the further analysis of the region using the archaeological record of surveyed sites. The results of this analysis are presented in the paper, along with a discussion on the benefits of the GWR technique for raster-based landscape analysis in archaeology.

**Keywords:** GIS, GWR, statistical modeling, landscape archaeology

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## 1 INTRODUCTION

Geographically Weighted Regression (GWR) is a technique for modeling spatial relations developed by Stewart Fotheringham, Chris Brunsdon and Martin Charlton.<sup>1</sup> The benefit of using GWR is that it can allow variables to vary over space, and need not assume that the same relationships are valid for the whole area of study, as with a global statistical model (see fig. 6 below). Although GWR has been available for some time as a stand alone application, it is also included as a tool in version 9.3 of ArcGIS, which makes it more readily available for most archaeologists. As spatial modeling is at the core of archaeological applications of GIS, this technique seems to have great potential for archaeology. The purpose of this paper is thus two-fold; to predict how many burial grounds might be missing from the registry of monuments in the study area—the Mälardalen basin in central Sweden—and to test GWR on an archaeological material in order to evaluate its usefulness with that kind of data.

With a better understanding of how representative the record of burial grounds is, it would be possible to use this material for studies of the pre-historic landscape dynamics. These kinds of landscape studies received much attention in the 1960s and 1970s,<sup>2</sup> but with the

realization that many sites are missing in the record,<sup>3</sup> the burial grounds were seen as too problematic to use for large scale landscape studies. With a better understanding of the weaknesses of the data, and an estimation of how large a proportion of the information is missing, it would be possible to once again pick up this line of research in order to utilize the material to the best of its potential. GWR would seem as the ideal candidate for this task, since it is able to handle the spatially varying relations between variables, something that often leads to problems when traditional, non-spatial, statistics are applied to geographic information. The technique also holds promise for amending some of the problems concerning the modeling of relations where there is pronounced spatial autocorrelation, as well as the Modifiable Areal Unit Problem, i.e., that results are directly dependent on the scale of analysis.<sup>4</sup> These issues are often central to archaeological spatial analysis,<sup>5</sup> and an easily available tool for handling this technique thus holds great potential. To make the best use of regression analysis, however, one ideally needs a large set of quantitative data, and the burial grounds in

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<sup>1</sup>Stewart Fotheringham, Chris Brunsdon and Martin Charlton, *Geographically Weighted Regression, the Analysis of Spatially Varying Relationships* (Chichester: Wiley, 2002).

<sup>2</sup>Björn Ambrosiani, *Fornlämningar och bebyggelse: studier i Atundalands och Södertörns förhistoria* (Uppsala: Almqvist & Wiksells, 1964); Åke Hyenström, *Centralbygd-randbygd. Strukturella, ekonomiska och administrativa huvudlinjer i mellansvensk yngre järnålder* (Stockholm: Almqvist & Wiksell, 1974).

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<sup>3</sup>Agneta Bennet, "Mälardalens järnåldersgravfält," in *7000 år på 20 år. Arkeologiska undersökningar i Mellansverige*, ed. Tiiu Andræ, Margareta Hasselmo, and Kristina Lamm (Stockholm: Riksantikvarieämbetet, 1987) 146.

<sup>4</sup>Trevor M. Harris, "Scale as Artifact: GIS, Ecological Fallacy, and Archaeological Analysis," in *Confronting Scale in Archaeology. Issues of Theory and Practice*, ed. Gary Lock and Brian Leigh Molyneux (Boston: Springer, 2006) 48; Fotheringham, Brunsdon and Charlton, *Geographically Weighted Regression*, 144.

<sup>5</sup>James Conolly and Mark Lake. *Geographical Information Systems in Archaeology* (Cambridge: Cambridge University Press, 2006) 157.

Mälardalen could thus be a good case study to test GWR on an archaeological material.

In order to evaluate the result of the GWR analysis, it will be compared to the result of a standard linear regression, also available in ArcGIS 9.3; Ordinary Least Squares (OLS). Both tools provide a large set of outputs that can be used to evaluate and validate the results. One main issue that will be especially interesting from an archaeological perspective is how well the method handles small samples, as archaeologists often have a small number of known observations that are used for making more general claims about the material. Both tools have issues and benefits in regards to this, that we need to be aware of. Predictive modeling in archaeology is usually not based on regression techniques, and it is often very difficult to establish how effective a predictive model is.<sup>1</sup> One problem might be that archaeological data structure seldom matches the prerequisites of regression in terms of quantitative data at a ratio level. When properly defined, regression is a robust, well established method that has reliable methods of evaluating model performance that are firmly based in statistical research. For this study, a method of achieving the right data level required is accomplished through the use of sampling values from density interpolations (see below).

The Mälardalen area in central Sweden holds a large number of burial grounds that survive in the landscape (fig. 1). These have been registered by the Swedish National Heritage Board and made available for downloading for research from its Web site. In my current research project, I am looking into ways in which this set of data can be used for landscape analysis in a GIS environment in order to understand social change during the Late Iron Age period.<sup>2</sup> With over 1.7 million archaeological remains registered, this represents a rich data of heritage history, with pre-historic monuments virtually “everywhere” in the landscape. Recent large scale excavations in connection with infrastructural projects such as highways and railroads have uncovered parts of the unseen aspects of the landscape. By intensive archaeological surveys and excavations in the corridors that are affected by the projects it has been made clear that, although we have records for a vast number of sites, much is missing too.

Many sites have been damaged by later agriculture so that they can no longer be observed before excavation. And some sites were simply overlooked during the two rounds of surveying that was carried out throughout Sweden during the twentieth century. It is possible to trace “lost” burial grounds through the study of historical maps from the seventeenth and eighteenth century, something that has been done by geographers. Often there are indications of burials on early maps that are missing on later maps and have not been recorded during the surveys.<sup>3</sup> Sometimes it has been possible to confirm the existence of archaeological sites at the location through excavations. It would, however, be difficult to try to quantify how many sites are missing using the maps, since there are so many other difficulties with the material, in terms of how the maps have been created, what was included in the maps and what was not, as well as which areas were mapped in times before the agricultural revolution, when, presumably, sites would start disappearing at higher rates. It would thus be connected with great uncertainties to make any estimates of the “original” number of burial grounds in the landscape as a whole using historical maps.<sup>4</sup> There have also been a few attempts to estimate how much agriculture has affected the archaeological record,<sup>5</sup> but only at a much generalized level and with great uncertainty. Studies focused on the intensity of agriculture also have problems in accounting for the effect of difficulties in surveying, and the fact that different parts of the landscape were surveyed with different levels of ambition and intensity.

## 2 VARIABLES

In order to achieve a reliable estimate of how many burial grounds are missing from the record, the results of large infrastructural projects were collected and evaluated. Criteria were set up for selecting which projects to include. From the 1980s onwards, the excavation method of large scale removal of the topsoil was adopted in Sweden. This resulted primarily in a larger number of settlements being uncovered, but also the discovery of previously unknown burial grounds. Thus only excavations from after 1980 were included in

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<sup>1</sup>Kenneth Kvamme, “The Fundamental Principles and Practice of Predictive Archaeological Modeling,” in *Mathematics and Information Science in Archaeology: A Flexible Framework*, ed. Albertus Voorrips (Bonn: Holo-Verlag, 1990); Philip Verhagen, “Testing Archaeological Predictive Models: A Rough Guide,” in *Layers of Perception. Proceedings of the 35th International Conference on Computer Applications and Quantitative Methods in Archaeology (CAA) Berlin, Germany, April 2–6, 2007*, ed. Axel Posluschny, Karsten Lambers, and Irmela Herzog (Bonn: Dr. Rudolf Habelt GmbH, 2008).

<sup>2</sup>Daniel Löwenborg, “Landscapes of Death: GIS Modeling of a Dated Sequence of Prehistoric Cemeteries in Västmanland, Sweden,” *Antiquity* 83 (2009) 1134–1143.

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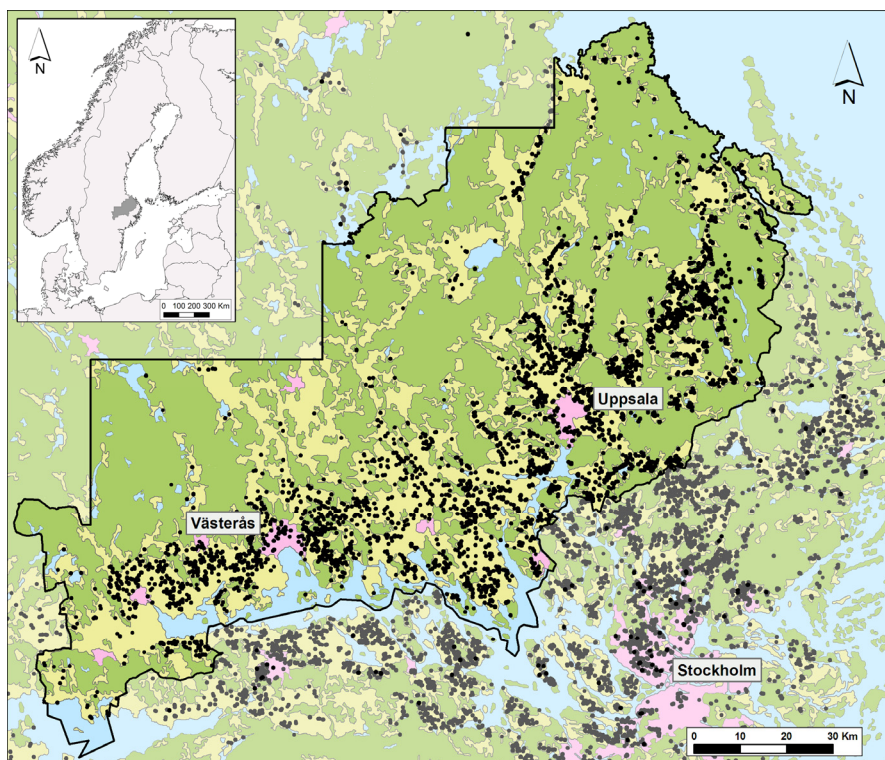
<sup>3</sup>Therese Fast, Ulf Jansson, and Anne Philipson, *Landskapet kring väg 250* (Stockholm: Kultur-geografiska Institutionen, 2002) 15.

<sup>4</sup>Ulf Sporrang, *Mälabygd : agrar bebyggelse och odling ur ett historisk-geografiskt perspektiv* (Stockholm: Stockholm University, 1985).

<sup>5</sup>Dan Carlsson and Bengt Windelhed, *Kvantitativ Bortodlingsanalys. Diskussion av jordbrukets inverkan på fornlämningsbeståndet, förd på material från Skaraborgs län* (Stockholm: Riksantikvarieämbetet rapport, 1973); Ola Kyhlberg, *Uppodling, överodling och bortodling. En metodstudie* (Stockholm: Stockholm University, 1983).

the analysis. A further criterion for the projects selected was that only those parts that were new to exploitation were used for the analysis. This means that a few projects where a road was expanded with a new lane or a railroad was expanded from single rail to parallel rails were excluded, since the results of these projects deviated from the rest. It was assumed that archaeological remains had been damaged in the first instance of exploitation, and renewed investigations

would thus not give representative results. A third criterion for the projects was that the results must be published or reported in a form that made it possible to have an overview of all the results, both from survey and from excavation. Six projects, or parts of projects, met all criteria demanded and were included in the analysis.



**Figure 1.** Burial grounds registered in the study area, parts of the provinces of Västmanland and Uppsala, and the surroundings. The location of the study area in Sweden, northern Europe is inlayed. Data from the National Heritage Agency. Background map published with permission: © Lantmäteriet Gävle 2009. Medgivande MEDGIV-2009-20920.

## 2.1 The Dependent Variable—Sites Gained

For this study, I use the results of the large excavating projects as a sample of a cut through the landscape, and as a glimpse of what results a full examination would give. The results are summarized in table 1 and figure 2. As can be seen from table 1, there are considerable differences in the outcome of the archaeological investigations for the various projects. This could be a reflection of different preconditions in terms of how many sites were present from the start, how well they have been preserved in the landscape, and to what extent the factors that would be damaging to burial grounds varied. Ideally, these processes could be estimated and accounted for in a GIS analysis. There might, however, be times when other factors influence the results, such as the development of new methods for archaeological fieldwork. One such example could be that new categories of burials have been increasingly observed during the last years, not least for the

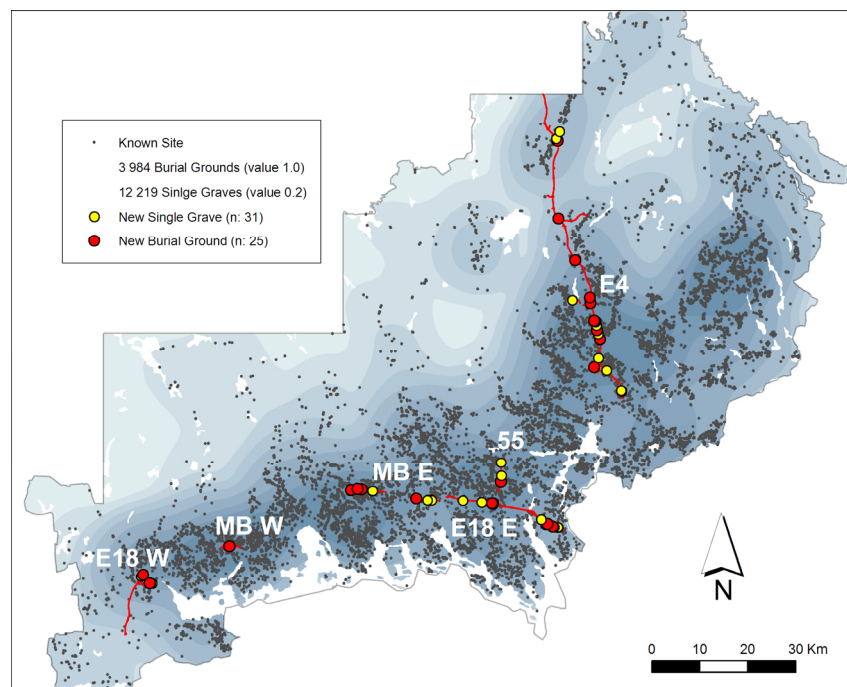
excavations for the E4 project. What appears to be regular graves, but contains no traces of burials, has been observed, and sometimes dominates whole burial grounds. At the same time, there can be fragments of burnt human bones scattered over a large area without any kind of external marker.<sup>1</sup> Hence, the concept of ‘grave’ is highly problematic in itself, and something that is being discussed and debated.<sup>2</sup> These burials could not be observed before, and have thus not been

<sup>1</sup>Tony Engström, “De dolda döda—och deras betydelse för gravbegreppet,” in *Att nå den andra sidan. Om begravning och ritual i Uppland*, ed. Michel Notelid (Uppsala: Riksantikvarieämbetet, 2007) 77.

<sup>2</sup>Anders Kaliff, *Fire, Water, Heaven and Earth : Ritual Practice and Cosmology in Ancient Scandinavia : An Indo-European Perspective* (Stockholm: Riksantikvarie-ämbetet 2007) 26; Anna Gatti, *The Archaeological Discourse on Sex and Graves* (forthcoming).

Project	Area, km <sup>2</sup>	Known sites	After proj	Gain	%	New sites / km <sup>2</sup>	Clay %
E18 W	2	2.8	4.4	1.6	57.14%	0.80	59.90%
MB W	0.47	2	2.2	0.2	10.00%	0.43	71.15%
MB E	0.87	3.8	5.6	1.8	47.37%	2.07	75.57%
E18 E	3.43	6.4	13.2	6.8	106.25%	1.98	51.50%
55	0.75	3.6	5	1.4	38.89%	1.87	78.10%
E4	9.74	4.6	17.2	12.6	273.91%	1.29	44.98%

**Table 1.** The results of the six projects used in the study. The table shows how large an area was examined for each project, how many sites (see below) that were known before investigations in connection to the road projects and how many were known after the project. Figures are given both in real number, ratio and number of sites per square kilometer. Finally, a figure is given of how long a stretch of each project that ran over clay, since this might be seen as relevant for the survival of burial grounds in the landscape.



**Figure 2.** The archaeological data used for the analysis. Sites recorded in the registry are displayed both as individual sites, either burial grounds or single graves, and as a density interpolation. The extent and name of the projects included in the study are shown, along with the new sites observed during fieldwork. Data from the National Heritage Agency.

included in the survey; to some extent this has probably contributed to the high ratio of new sites for the E4 project. At the same time, the E4 excavations form the most recent project, and much effort was involved in avoiding known sites at the planning stage. This could also have contributed to the low number of known sites that were affected by the project, in relation to the large area that was utilized.

Both sites registered as single graves and burial grounds were included in the analysis. Since five or more graves within close range of each other are defined as a burial ground in the registry, burial ground were given a value of 1 and the single graves a value of 0.2. It has been observed that single graves might often be an indication

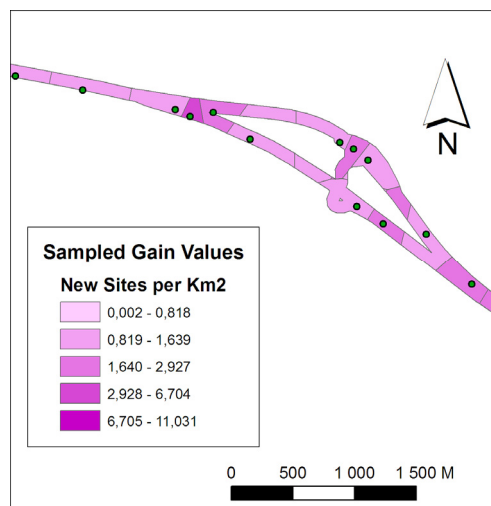
of a burial ground at that location, even though only a few graves are visible in the landscape.<sup>1</sup> It was thus seen as important to include the single graves in the analysis in order to account for as much of the record as possible. However, the fact that the number of graves at a burial ground often increases drastically between survey and excavation results was not considered here.

An important aspect of the results of the excavation projects is that information about the areas where no

<sup>1</sup>Katarina Appelgren and Maria Renck, "Vad är en grav?" in *Att nå den andra sedan. Om begravning och ritual i Uppland*, ed. Michel Notelid (Uppsala: Riksantikvarieämbetet, 2007) 43–45.

new sites have been found is as important as information on where and how many sites have been encountered. Since the method assumes a “full” investigation, areas with no sites are used as evidence for absence of sites at those locations. This is not entirely unproblematic since it is possible that even the close investigation of modern rescue archaeology occasionally misses something, and it would also make the results vulnerable to differences in implementation between projects. Despite this, it is necessary to account for the absence of sites in the analysis, since it is such an important part of the available data.

Computationally, information for the areas with no sites was included in the following manner: the extent of each project was buffered with the width that was investigated, generally 50 meters on both sides of the center of the new road. Within those areas, random points (N=316) were generated with the constraint of leaving at least 100 meters between points. Thiessen polygons were then created for each point and cut for the road buffer, so that each point would be represented by an area. The “gain” values were sampled from the interpolation of values at each point and then multiplied with a factor in order to have the average of the points of each project correspond to the average of each project (from table 1), in relation to the size of each thiessen polygon. This would average out the values gained for each project, but still maintain a substantial part of the spatial component of the data. The mean gain of all the points in the sample thus matches the value of “sites gained per square kilometer” (see table 1) for each project as a whole (see fig. 3).



**Figure 3.** An example of the unit of analysis for the dependent variable; generated random points transformed into thiessen polygons.

Further, since it would be an open question at what scale the analysis would be best, the density interpolations were performed with several different search radii, at 4000, 6000, 8000, 10000, and 12000 meters respectively. Since a larger search radius would even out the values over a large area, they would miss

some of the local differences of where in the landscape new sites have been observed. However, since there are a few instances of long parts of the new roads that have been investigated without any new finds of new burials (see fig. 2), only the search radius of 12000 meters would give values for all samples in the study area. In order to test which combination of variables would give the best results, all analyses were calculated with measures from all different interpolations.

## 1.2 The Independent Variables—The Landscape

What aspects of the landscape would be relevant for predicting where large numbers of sites are missing? These independent, or explanatory, variables would need to be identified and sampled in order to have a model that gave the most reliable results that the material could provide. This is a question both on testing which aspects of the landscape that would be relevant for the analysis, and at what scale they would give the best results. In order to test this, the values were computed at different scales and tested for correlation strength and relevance (p-values). Several different variables were tested, and five variables were considered to be relevant for the analysis. These were calculated at different scales and compared to the different versions of the dependent variable. First a visual estimation was made of the maps of the variables. Then scatter plots and correlations were calculated, as summarized in table 2.

All the independent variables were rasters that had been modified by different means in order to acknowledge the fact that often the value present at the exact location of the sample is not as important as the dominating value in the vicinity. The problem is to define how much to include in the definition of “vicinity”. Each variable was thus interpolated as a density (d) with a different length of search radius; alternatively, a focal statistics function (fs) was run that counts the values within a specified distance.

*Clay/Soil* is the most used variable for modeling conditions for pre-historic settlements in the area,<sup>1</sup> and shows good correspondence with burial grounds on a map (see fig. 4). This variable was calculated from the soil map using both the value clay by itself and together with other types of soil that would indicate good soils for agriculture.

The variable *Fragmentation* represents an attempt to account for the problem of determining where sites would have better or worse possibilities of surviving agriculture. Line elements delimiting cultivated land were used to calculate a density raster where high density would indicate a “fragmented” interface between land types. Where there are numerous islands

<sup>1</sup>Sporrong, *Målarbygd*, 38 (above, p. 204n4).

	GAIN 4000	GAIN 6000	GAIN 8000	GAIN 10000	GAIN 12000
Soil—1000 fs	-0.096	-0.099	-0.065	-0.118	-0.134
Soil—2000 fs	-0.115	-0.069	-0.034	-0.081	-0.102
Soil—4000 fs*	-0.134	-0.026	0.017	0.004	-0.007
Clay—1000 fs	-0.063	0.021	0.065	0.032	0.026
Clay—10000 fs	-0.034	0.107	<b>0.167</b>	<b>0.198</b>	<b>0.217</b>
Fragmentation—500 d	-0.037	0.027	-0.046	0.001	0.028
Fragmentation—1000 d	0.021	0.065	-0.003	0.032	0.046
Fragmentation—1500 d	0.03	0.038	-0.034	-0.008	-0.006
Fragmentation—3000 d	0.108	0.09	0.037	0.05	0.042
Fragmentation—5000 d	-0.052	0.018	-0.054	-0.005	0.022
Fragmentation—2000 fs*	-0.028	-0.073	-0.109	-0.09	-0.081
Fragmentation—4000 fs	0.055	0.001	-0.082	-0.078	-0.078
Built up—1500 fs	-0.155	-0.085	-0.06	-0.037	-0.033
Built up—3000 fs	-0.172	-0.089	-0.066	-0.046	-0.039
Built up—5000 fs	-0.183	-0.121	-0.104	-0.086	-0.092
Built up—7500 fs*	-0.185	-0.135	-0.120	-0.110	-0.116
Survey—1000 d	0.142	0.145	0.137	0.120	0.110
Survey—1500 d	0.158	<b>0.187</b>	<b>0.186</b>	<b>0.176</b>	<b>0.173</b>
Survey—2000 d	0.155	<b>0.208</b>	<b>0.217</b>	<b>0.215</b>	<b>0.218</b>
Survey—3000 d	0.106	<b>0.208</b>	<b>0.237</b>	<b>0.252</b>	<b>0.263</b>
Survey—5000 d*	0.088	<b>0.242</b>	<b>0.286</b>	<b>0.306</b>	<b>0.316</b>
Water—distance	<b>0.070</b>	<b>0.071</b>	-0.075	<b>0.077</b>	-0.106
Water—density	<b>0.082</b>	<b>0.083</b>	-0.087	<b>0.090</b>	-0.103
Water—distance + density*	0.072	<b>0.216</b>	<b>0.264</b>	<b>0.278</b>	<b>0.287</b>
<i>Correlation is significant at the 0.05 level.</i>		*-the variable used in the final analysis			
<b>Correlation is significant at the 0.01 level.</b>					

**Table 2.** The correlation between independent and dependent variables at different scales of analysis. The scale of analysis of each variable is given in meters. Most variables give stronger correlations when calculated at a wide scale for both independent and dependent variables. For a discussion of the variables used, see the text.

in the field, impediments, or an irregular borderline, there might be less risk that burial grounds have been destroyed by agricultural impact. The density raster was combined with a straight line distance raster, calculated from open field areas, giving high values to locations far from an open field. Otherwise, there would be similar low values of the variable for both highly cultivated areas and for fully forested areas. The usefulness of similar variables in this context has been discussed by Sigurd Ramqvist.<sup>1</sup>

*Built up* is a variable calculated with focal statistics with different search radii from built up areas. This variable could be seen as reflecting high population density and thus a probable higher strain on archaeological remains. Where many modern constructions exist, there would be greater risk of sites being damaged or removed, perhaps permanently. At the same time, the locations in the landscape that are used today often date back at least to medieval times, and might reflect positive attractors in the landscape, such as good communications and fertile land, which might have also attracted population in pre-historic times. The negative correlation of the variable might indicate that the latter was less influential in the present analysis.

<sup>1</sup>Sigurd Ramqvist, "Om försvinna graver," in *Inventori in Honorem. En vänbok till Folke Hallberg*, ed. Åke Hyenstrand (Stockholm: Riksantikvarieämbetet, 1980) 84.

Water was calculated both as straight line distance, as a density of line elements of rivers and coast line, and as a combination of both, weighted in different ways. The reason for using density in the analysis is to give the coastline (where there usually are several line segments together) greater weight than rivers (usually one or two lines per river). The combination of density and distance rasters gave the best results (see fig. 4).

A density of all the sites registered before excavation is given at different scales by the variable *Survey*. It was not clear if this variable should be included, since it is so closely related to the variable that is being predicted. If it had been possible to give a highly accurate model of where in the landscape burial grounds occur, it might have been possible to exclude the survey variable, but this was not the case here. It would seem likely that

there are more sites missing in areas that have many remaining ones, if this is a reflection of the original situation, i.e., there were more sites to lose. This was also the variable that gave the strongest correlation, and thus seemed important to include (compare fig. 2).

A few variables were tested but not included in the analysis, such as two variables from elevation. Raw height values were tested in order to account for the land rise and shore displacement in the area. Another use of topography that is often used in similar studies is “relative relief”, or how much difference in elevation there is within a specific distance. Neither of these variables gave statistically valid results, but it should be noted that the study area is generally very flat, with a maximum elevation of 216 meters above sea level.

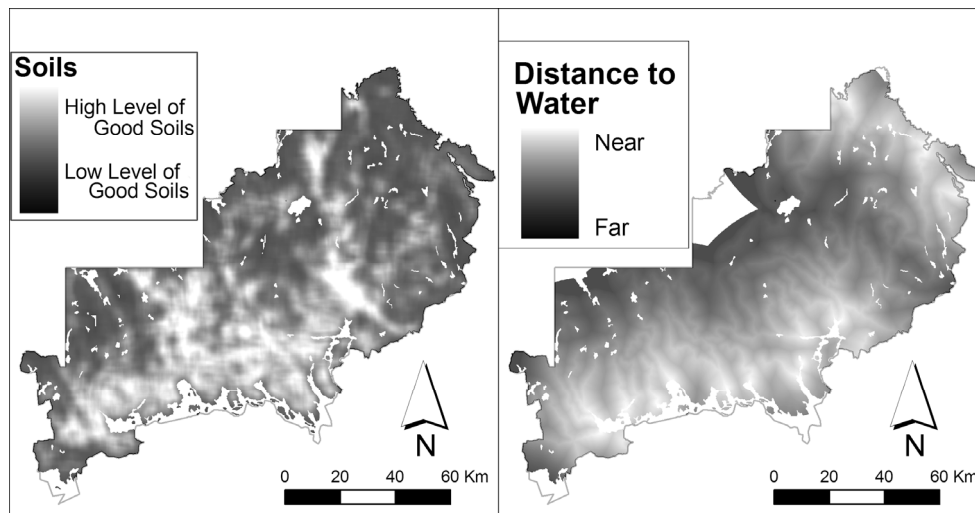


Figure 4. Two of the landscape variables used in the analysis; concentrations of good soils and distance to water.

### 3 METHOD-ANALYSIS

2037 random points were generated within the study area, and all the independent variables were sampled for each point. In order to calculate a regression of the relationship between the gain values and the variables from the landscape, the intention was initially to use the OLS script, available in the Spatial Statistics Toolset in ArcGIS. However, there seems to be a problem with the functionality of the regression features that are new in ArcGIS version 9.3. It was not possible to include the cases where there were unknown values for the dependent values, since those cases were disregarded if they were given a <Null> value, and would disrupt the regression if they were given a value of “0.” Thus, the analysis was computed in SPSS 15, and then transferred back to ArcGIS. The analysis was tested with a range of

different combinations of variables, and the results of the analysis with best fit (R-squared) are summarized in table 3a-b and figure 6.

An alternative method that could be used is GWR, where each coefficient is allowed to vary over space, so that the method can account for, and benefit from, the fact that there might be differences in the strength of correlations between variables in different parts of the study area. Spatial dependency is often seen as a problem in traditional statistical analysis and something that needs to be reduced through different sampling methods. In spatial statistics, on the other hand, the spatial component is seen as meaningful and something that should be considered an asset, when it can be properly included in the analysis. The theory behind

**Table 3a: Coefficients<sup>(a)</sup>**

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	2.862	.684		4.182	.000
	Fragmentation	.000	.000	-.206	-3.454	.001
	Water	3.051	1.010	.165	3.020	.003
	Survey	.814	.099	.479	8.231	.000
	Built_up	.000	.000	-.203	-3.542	.000
	Soil	-.001	.000	-.281	-4.430	.000

a Dependent Variable: Gain\_12

**Table 3b: Model Summary<sup>(b)</sup>**

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.518(a)	.268	.256	1.17325980725324

b Predictors: (Constant), Fragmentation, Water, Survey, Built Up, Soil

**Table 3a and 3b.** As can be seen from table 3a, all the variables were statistically significant, with a p-value (called Sig. in SPSS) of 0.003 or lower. The coefficients are rather low, which to some extent can be explained by high variable values, but the model as a whole only explains around 26% of the variance in the material (R Square and Adjusted R Square), with a rather high standard error value of 1.17.

GWR is discussed by Fotheringham, Brunsdon and Charlton.<sup>1</sup> The basic principle is that coefficients are described graphically as a continuous gradient, and not as a single value. The examples provided are generally derived from large statistical datasets such as, for instance, house prices in the London area, where the different variables influence the house prices to a different extent for different parts of greater London.<sup>2</sup> Although this would represent a case where there are many sources of information available—the prices of houses sold previously—GWR includes functions for handling irregularities in the samples. The kernel used for determining how many of the surrounding samples to include in the analysis can be fixed or adaptive. With an adaptive kernel, samples are included from a larger area where feature distribution is sparse, and from a smaller area where feature distribution is dense. The extent can be determined through a statistical method that finds the bandwidth that gives the optimal results, either Akiake Information Criterion (AICc) or Cross Validation (CV). AICc testing is a method for

comparison between statistical models to find which gives the best result,<sup>3</sup> and it is also provided as part of the output for results of the OLS and GWR analysis. By using AICc testing to establish how many samples to include in the analysis, GWR has built in functions to provide information on the appropriate scale of analysis and meet some of the issues in the Modifiable Areal Unit Problem.<sup>4</sup>

The workflow suggested by ESRI in the documentation of the tool is to first test which variables that are best for the analysis in OLS, and then use those variables in a GWR if the results of the OLS analysis suggest that there is a significant spatial element to the dataset. Figure 5 illustrates how the coefficients of the same variables used in table 3a look in a GWR analysis.

Statistically, the GWR gave a somewhat better result, with an R Square value of 0.295 and Adjusted R Square value of 0.280, thus an improvement of about 0.025

<sup>1</sup>Fotheringham, Brunsdon, and Charlton, *Geographically Weighted Regression* (above, p. 203n1).

<sup>2</sup>Ibid., 27.

<sup>3</sup>Kenneth P. Burnham and David R. Anderson, *Model Selection and Multimodel Inference: A Practical Information-theoretic Approach* (New York: Springer, 2002).

<sup>4</sup>Fotheringham, Brunsdon, and Charlton, *Geographically Weighted Regression*, 127.



points compared to the results of the OLS analysis. To facilitate comparing model fit of different regressions models, we were provided with an AICc value. For OLS this was 1003.7 and for GWR 995.9, thus a slight improvement, since low values indicate good overall model performance.

Another important indicator of how reliable the results are is the distribution of the values of the residuals. These should ideally be in a random distribution, with over- and underestimates mixed, if there is no bias for certain parts of the model. In this case, there seems to be a good distribution of values for the larger projects in the eastern part of the study area, where there is also more information on which to build the analysis. In the western part there seem to be some issues that probably also reflect the rather low sampling density in this area as well as the low outcome of the excavations (compare with table 1, where MB W have the lowest gain per square kilometer).

## 1 RESULTS

The dependent variable in the analysis is thus an estimated value of how many sites would be gained if the whole of the landscape was fully excavated, expressed as new sites per square kilometer. As can be seen from figure 6a and 6b, there are limited differences between the results of analysis in OLS and GWR. The values of sites gained in figure 6 should be compared to the column of “sites gained per square kilometer” in table 1. Some parts of the landscape display a higher result than any of the projects, since the projects are only accounted for as a mean. There are, of course, parts of each project that have considerably higher values. The negative predicted values in the north and north-west should probably only be understood as difficulties in giving an estimate in those areas, where conditions differ too much from those where the samples are located. This is also reflected in high standard error values (see fig. 8).

In order to facilitate interpretation and enable further analysis, the results of the prediction were aggregated as a mean for each parish in the study area as polygon features (see fig. 7a). This can be compared to how many sites are known from survey and are registered in the record (see fig. 7b). With this information, it would be possible to give a rough estimate of how much information is missing from the registry, i.e., how representative of the original material the database of burial grounds is. It would be difficult to give an accurate estimate in the parts of the study area that are too different from the central parts, where the majority of the archaeological investigations have been carried out. This is reflected in a high standard error, and the same is true of the parts of the landscape where an important variable is missing. In the location of the major towns there are few sites registered, and thus too low values for the variable “survey”. Since many of the

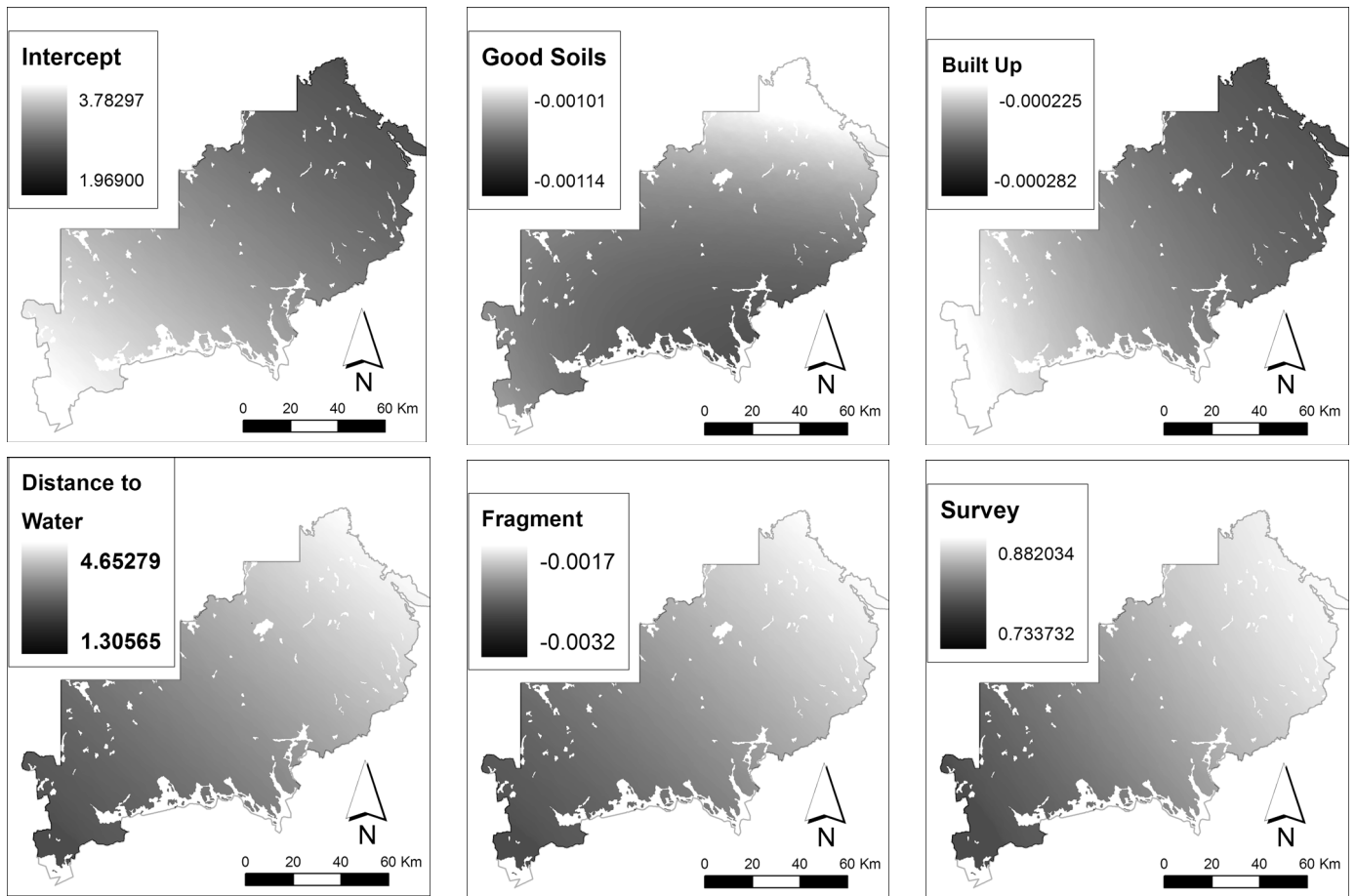
towns date back to medieval times, many burial grounds are long lost, and the archaeological record is thus not accurate, which upsets the analysis for those areas and results in high standard errors. We are also missing the impact of the eustatic uplift in this analysis, since no variable for elevation was included. The parishes that have a mean elevation below 11 meters are thus also grayed out in figure 9, indicating that results for them would be difficult to estimate this way. Caution is advised, however, for the interpretation of all locations near the coast or the shore of Lake Mälaren.

The high ratio results in the northern part should be seen in relation to the low number of sites that are registered there (see figs. 1 and 7b), since a small increase in the number of predicted sites would alter the situation considerably. The result indicates that there is a substantial number of burial grounds missing from the registry in these parts. This is not surprising, and might well reflect reality, since these parts of the landscape are peripheral today, with low impact of exploitation and few excavations. It is quite possible that surveys have been less intensive in those parts and missed a greater number of sites. This is indicated by an intensive survey of parts of northern Uppland that revealed a considerable number of previously unknown sites.<sup>1</sup> The small number of sites known for the northern part of the study area might thus be somewhat misleading. However, even in the central parts of the landscape, where we have information about a large number of sites, the archaeological record is probably far from complete. In a much generalized statement, it seems as though around half or more of the sites are missing for much of the region.

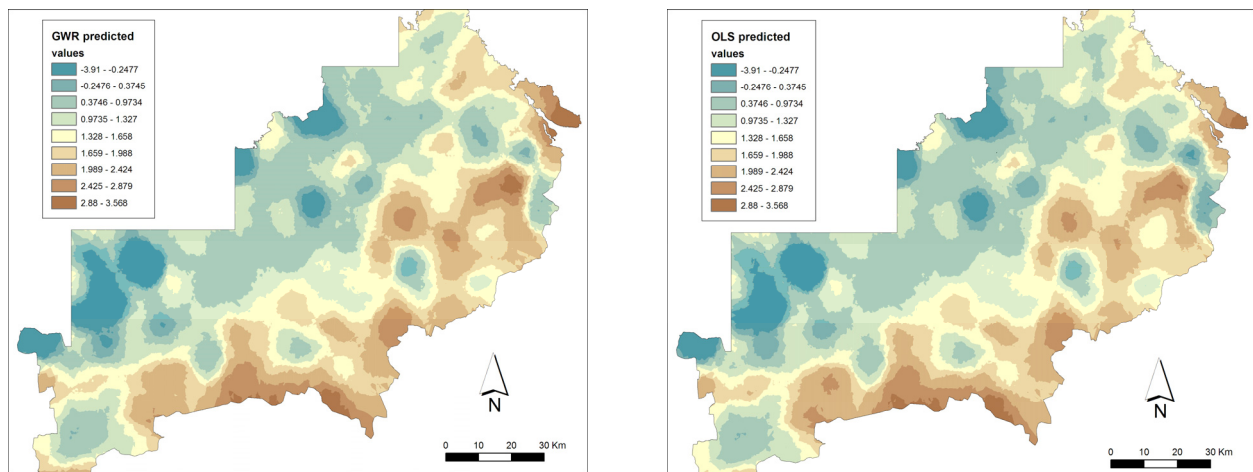
The fact that there is a large number of burial grounds that are no longer visible in the landscape but only observable through excavation is well established in Swedish archaeology, and is confirmed by new large-scale excavations. How much is missing and how large a part of the whole material this represents is so far not very well understood. It is difficult to estimate what the situation would be outside the excavated areas. The present study suggests that a substantial proportion of the burial grounds is missing throughout the study area. This information is important for further research on the social development of the prehistoric society based on landscape analysis, including the burial grounds. It is also important for cultural resource management to be able to have some idea of how representative the archaeological record is. Not least, this could be of relevance for archaeologists who are planning new extensive excavations and need to be able to make budgets that would have to include a large entry for unknown sites that are likely to exist under the topsoil.

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<sup>1</sup>Örjan Hermodsson, *1999–2001 års fornminnes-inventering i Uppsala län Tierps, Östhammars och Uppsala kommuner* (Stockholm: Riksantikvarieämbetet 2002).



**Figure 5a-f.** The coefficients for all the variables in the GWR analysis. Owing to the distribution of the sample data used, the coefficients only have a general North-South and East-West tendency.



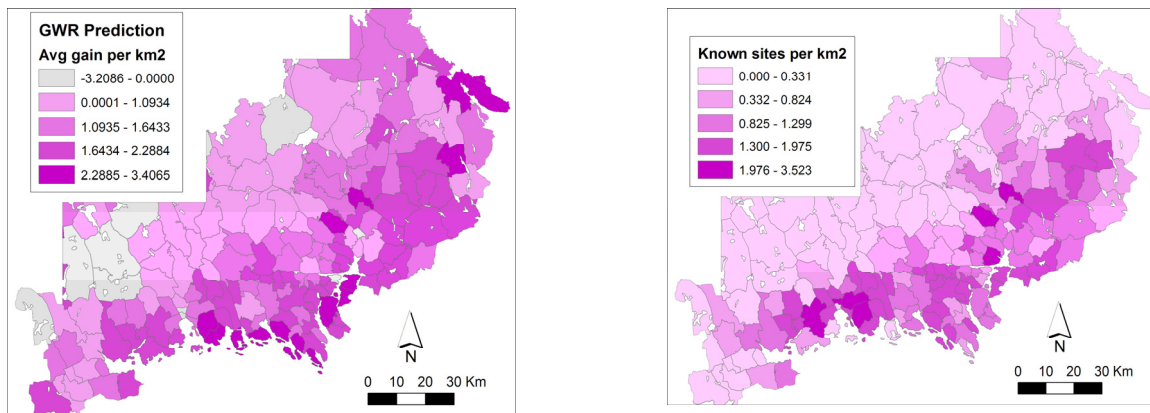
**Figure 6a and 6b.** Interpolations of the results of the GWR and the OLS analysis displayed with a common key for comparison. The two models gave very similar results.

## 5 CONCLUSIONS

On a methodological note, it seems that GWR has great potential for archaeological modeling of the landscape. Since archaeological samples are usually fairly small—we often do not have much information in relation to that which we are trying to say something about—it makes much sense to make the best use of the information available. One way to do that would be to include the spatial component and information on how relations might differ throughout space. There might also be a danger in this, since GWR primarily seems to be tested on materials with large samples, where there are known values for many locations. It might be the case that a small sample would introduce a spatial bias that might not always be positive on the outcome. This could potentially be a problem with small samples, where poorly representative measurements could be amplified if they are on the edge of the sampled area. The OLS technique would perhaps be preferable in that case, since OLS would use the same coefficients for the whole area. In GWR this would be dealt with through the possibility of defining bandwidth—the number of surrounding samples to be used for the prediction at each point—so that results are evened out. The question is how well that works with small samples, such as the excavated areas in this example, something which is

common in archaeology, and which underlines the need for source criticism.

Another problem might be how to include negative results of investigations, where a location was investigated but nothing of interest was found. This is important information in its own right, and thus needs to be considered, even though it might not be obvious how to include that kind of data in a regression. For this study, the problem with “absence of values” was dealt with through the use of a large search radius for creating a density raster of the sample, in order to cover the whole area that was investigated. The result was sampled to random points and transferred to polygons so that meaningful values in relation to area could be produced. It would perhaps not always be straightforward to represent the archaeological information at a true ratio scale, which is necessary for regression analysis. It would thus often be necessary to modify the data in some way, depending on the nature of the data and the questions at hand. When there is a well defined area of investigation, the method presented here might prove useful, but there might also be a danger of making the results too level to provide useful information.

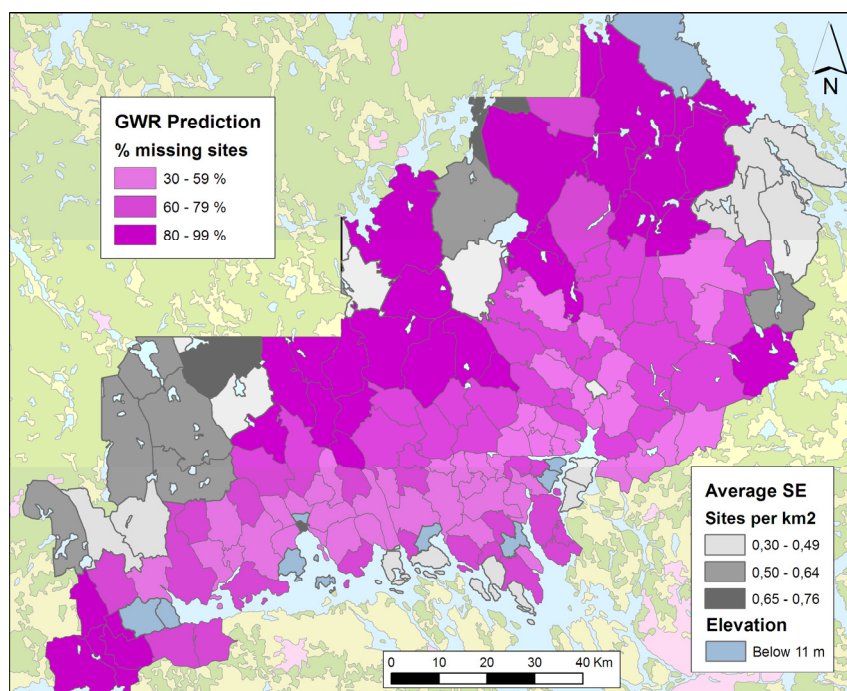


**Figure 7a and 7b.** The results of the GWR analysis on a parish basis, and the number of sites per km<sup>2</sup> by parish, as recorded in the registry.

A benefit of using regression methods is the rich information of standard error and measurements of model fit and performance that comes with the results. ESRI also provides extensive documentation and guidelines for interpreting the outputs, which is highly valuable both for improving the analysis and for making the best use of the results. Since both the GWR and the OLS functions are new in ArcGIS 9.3, they still seem to suffer from some issues.

One problem is that the units that should have the dependent variable predicted need to be defined as “null,” and can thus not be a normal Shapefile but have

to be a feature in a Personal Geodatabase. This caused me considerable difficulty, since it was not specified in the documentation. More problematic was the fact that both OLS and GWR seem to have issues in handling those “null” values in the regression, and fail to give output for the values that should be predicted in the regression. This explains the poor results of the regressions that were presented at the conference in Williamsburg. The calculations presented here have been done in SPSS and Excel, using sampled values of the GWR coefficients. ESRI has been notified about these issues and they will hopefully be amended in a future version of ArcGIS.



**Figure 8.** The result of the analysis; gain prediction by parish. Areas with high standard error or low mean elevation are grayed out since predictions would be unreliable. Background map published with permission: © Lantmäteriet Gävle 2009. Medgivande MEDGIV-2009-20920.

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