A Method for Estimating Undiscovered Geothermal Resources in Nevada and the Great Basin

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ABSTRACT

A preliminary estimate of undiscovered geothermal resources in Nevada is made to illustrate the feasibility of making such an estimate and present one method of doing so using digital information in a geothermal geographic information system (GIS). Although the results are preliminary, they suggest that the total geothermal resources in Nevada capable of generating electricity may be four to five times the known reserves.

The method involves using geological, geophysical, and geochemical data to identify areas that are favorable and unfavorable for geothermal potential, and then assessing the degree of exploration in those areas based on the presence of drill-holes, wells, and depth to the water table. The "density of occurrence" (number of geothermal systems per km^2) is calculated, taking into account the favorability of the terrain, the degree of exploration, and the ability of geothermal systems to remain concealed. Favorable and unfavorable geothermal terrains in Nevada were defined using a logistic regression statistical model and five separate layers of evidence; young volcanic rocks, earthquakes, GPS measurements of strain, northeast-trending young faults, and regional gravity anomalies. The degree of geothermal exploration was estimated using digital maps of geothermal wells, temperature gradient holes, oil wells, water wells, and depth to the water table.

The resulting resource estimate does not include direct use of geothermal heat, nor does it consider potentially significant impacts from higher energy prices, technological improvements in plant design, successful development of enhanced geothermal systems (EGS), environmental issues, or the feasibility of locating these additional resources with known exploration technologies. This is only a preliminary estimate that illustrates a method; more formal estimates should be made that optimize the use of available digital information and incorporate advice from geothermal experts in the fields of economics, geology, and engineering.

Introduction

Twenty-six years have passed since the United States Geological Survey (USGS) made a comprehensive assessment of geothermal resources in the United States (Muffler, 1979). The need for a new estimate using modern techniques is clear (Long and Shevenell, 2001), and the USGS has, for some time, been pursuing congressional approval for a reassessment (Williams, 2004). Much has been learned about geothermal systems and many advances in geologic understanding, exploration geophysics, and geochemistry have been made since 1978. Further, the use of digital databases and GIS systems has also evolved dramatically, with the expectation that a new resource estimate could be compiled much more rapidly and efficiently. The objective of this paper is not to present a comprehensive new assessment of geothermal resources, but rather to introduce one way in which digital data in a GIS can be used to help generate such an estimate, using Nevada as an example.

For the purposes of this paper, resource assessment is divided into three categories. They involve the estimation of: 1) undeveloped resources in KGRAs or in known geothermal prospects, 2) undiscovered resources in poorly explored and unexplored regions, and, 3) the effect of radical changes in energy economics, new developments in energy conversion methods, or new techniques for energy extraction (such as EGS), which would broaden the definition of reserves capable of producing energy economically.

Category 1 is the most straightforward to estimate, but was not the focus of this paper. The best estimate is perhaps done with a team of geologists, engineers, and economists with detailed familiarity with the KGRAs and geothermal prospects in the areas being studied. Category 3 is the most difficult to estimate, and is beyond the scope of this paper. Category 2 resources are specifically addressed in this study. Their estimation involves the extrapolation of current reserves and category 1 resources from known areas into relatively poorly explored areas.

In building on the ranking philosophy outlined in Goudarzi (1984, p. 23-24), yet expanding the methodology to a digital GIS, the calculation of Category 2 resources, as defined above, was divided into three stages: 1) definition of favorable and unfavorable terrains for geothermal systems, 2) definition of well-explored versus poorly explored terrains, and, 3) spatial comparison of favorable (and unfavorable) geothermal areas with the degree of exploration to estimate undiscovered resources. The favorability model and degree of exploration are described first, followed by a discussion of the methodology.

Favorability Model

Favorable and unfavorable terrains for geothermal systems in Nevada were defined using maps of young volcanic rocks, earthquakes, GPS measurements of strain, northeast-trending young faults, and regional gravity anomalies. Analyses by Coolbaugh et al. (2002) helped quantify relationships between these maps that had been observed earlier by Sass et al. (1971), Rowen and Wetlaufer (1981), Blackwell (1983), Koenig and McNitt (1983), Wisian et al. (1999), and Blewitt et al. (2003). These 5 "evidence maps" were chosen because their mapped values are relatively uninfluenced by groundwater features or near-surface impermeable rocks that could conceal geothermal activity. Gravity measurements were used as a proxy for heat flow to minimize the possible influence of groundwater flow on temperature gradients.

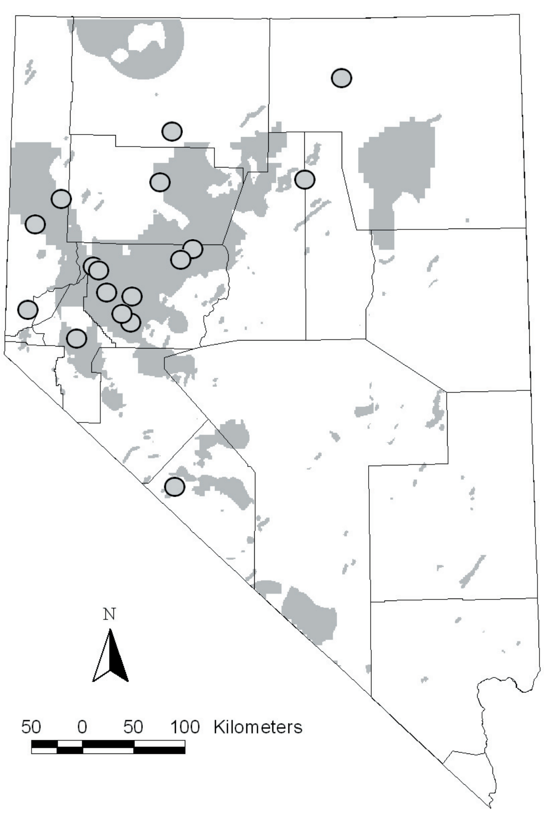

Figure 1. Distribution of favorable and unfavorable geothermal areas, based on a 5-layer logistic regression model. Economic and sub-economic geothermal systems (Table 1) are shown with circles.

Using logistic regression analysis similar to that employed by Coolbaugh et al. (2002), but with 5 evidence layers instead of 4 (a strain rate map from Blewitt (2003) was added), a binary map of favorable and unfavorable terrain for geothermal systems was produced (Figure 1), in which favorable terrain comprises 16% of Nevada. The threshold between favorable and unfavorable terrain was defined using the prior probability, the probability of occurrence of a geothermal system before any evidence is considered (Bonham-Carter, 1996).

Degree of Exploration

Implicit in the definition of well vs. poorly explored areas is that some geothermal systems remain concealed and have not yet been discovered. Although hot springs and/or fumaroles mark the locations of many geothermal systems, the presence of deep water tables, laterally flowing groundwaters, or near-surface impermeable "cap rocks" locally limits surface manifestations of geothermal activity. At least 6 of the 17 geothermal systems considered in this paper to be economic or sub-economic in Nevada (see following section) have little or no surface expression and were discovered by drilling water wells or heat flow holes (Table 1). Because only a fraction of Nevada has been drilled (about 18%, if a 2 km buffer on drill-holes is used), undiscovered geothermal resources are almost certainly present.

Table 1. Known economic/sub-economic geothermal systems used for modeling undiscovered resources in Nevada.

Name	Current MWe	Concealed	Geo/Oil Database 1=yes, 2=no	NDWR Database 1=yes, 2=no	Geothermal Favorability 1=yes, 2=no	Water Table 1 < 60 feet 2 > 60 feet
Tuscarora	0.0	No	1	2	2	2
Beowawe	16.6	No	1	1	2	1
Dixie Valley	62.0	No	1	1	1	2
Empire	4.8	No	1	1	1	1
Bradys	21.1	No	1	1	1	1
Stillwater	21.0	Yes	1	1	1	1
Wabuska	2.2	No	2	1	1	1
Humboldt House	0.0	No	1	2	1	1
Dixie Comstock	0.0	No	1	1	1	1
Soda Lake	26.1	Yes	1	1	1	1
Fish Lake Valley	0.0	Yes	1	1	2	2
Eight Mile Flat	0.0	No	1	2	1	1
Desert Peak	12.5	Yes	1	1	1	2
Steamboat	73.0	No	1	1	2	1
Needle Rock Hot Sprs	0.0	No	2	2	1	1
Blue Mountain	0.0	Yes	1	2	2	2
Fallon Naval Air Station	0.0	Yes	1	1	1	1

Nevada was subdivided into 4 classes of "degree of exploration", based on the type of drill-holes present and the depth to the water table. The first ranking is based on the presence of geothermal wells, temperature gradient wells, and oil wells (Figure 2), which are typically drilled to test geothermal potential or are drilled to sufficient depths to detect sub-surface geothermal activity or the temperature aureoles associated with them. All land within a 2 km radius of these drill-holes was classified into this first category as being the most explored. Databases of geothermal wells and temperature gradient wells were provided by David Blackwell of the Southern Methodist University Geothermal Laboratory (http://www.smu.edu/geothermal/) and by John Sass of the USGS (http://wrgis.wr.usgs.gov/open-file/of99-425/webmaps/home.html). A Nevada oil well database was provided by Hess (2001).

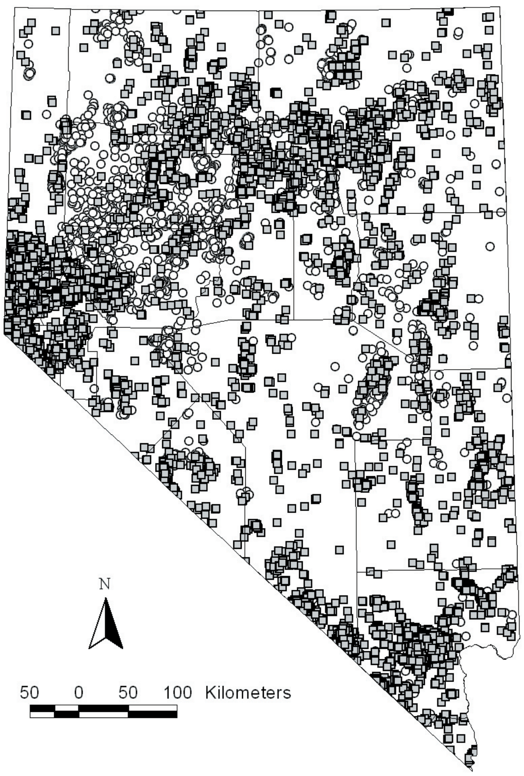

Figure 2. Distribution of geothermal and oil wells (circles) and wells from the NDWR database (squares). Geothermal wells and temperature gradient wells were provided by David Blackwell of the Southern Methodist University Geothermal Laboratory and by John Sass of the USGS (see text). A Nevada oil well database was provided by Hess (2001).

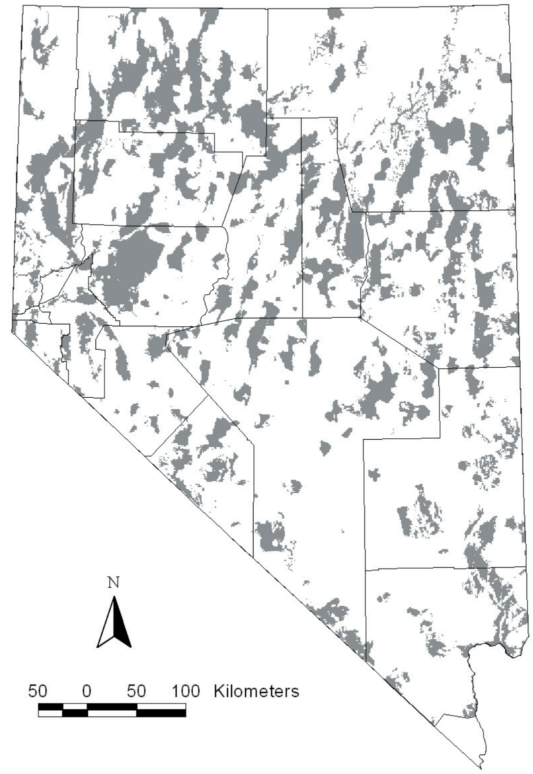

Figure 3. Modeled areas of shallow groundwater ≤ 60 ft (gray areas), generated by Tim Minor of the Desert Research Institute, University of Nevada.

A 2nd ranking of explored ground, exclusive of ranking 1 above, consists of land lying within 2 km of wells registered in the Nevada Division of Water Resources (NDWR) well drillers database (http://water.nv.gov/IS/wlog/wlog.htm), which includes water wells, metals exploration drill-holes, and any other wells permitted with the state (Figure 2). This database is considered less reliable for the detection of geothermal systems, because some wells were drilled only to reach groundwater, which is shallow in many cases, and because it is possible that thermal waters were encountered in some wells, but not reported.

For areas without drill-holes or wells, two additional "degree of exploration" rankings were created based on depth to the water table. Areas with a water table depth ≤ 60 ft were ranked as shallow groundwater and areas where the depth was > 60 ft were ranked as deep groundwater. Based on observations of Koenig and McNitt (1983) and statistics of Coolbaugh et al. (2002), areas with relatively deep groundwater tables were considered more likely to conceal geothermal activity than areas with shallow water tables (in the absence of drilling). The observation of surface hot springs can be considered one method of "exploration". If a deep water table impedes the formation of hot springs, areas with deep water tables can be considered less well explored than areas with shallow water tables. The boundary between "shallow" and "deep" water tables (60 ft) equals the depth of maximum statistical contrast between a positive association with geothermal systems (shallow groundwater) and a negative association with geothermal systems (deep groundwater), using a weights-of-evidence statistical process (Coolbaugh et al., 2002). Tim Minor of the Desert Research Institute provided a digital map of depth to groundwater (Figure 3).

Methodology

Undiscovered geothermal resources were estimated by extrapolating known resources into unexplored areas. Because of this, the number of undiscovered systems that are predicted is dependent on how many known systems there are in explored areas. But the number of known economic systems in explored areas will increase with time, as more reserves are developed in existing KGRAs and exploration prospects. Consequently, for this study, it was necessary to estimate the amount of resource growth in known geothermal areas, prior to calculating the magnitude of the undiscovered resource.

Specifically, it was assumed that 17 geothermal systems from current KGRAs and exploration prospects in Nevada would ultimately produce electrical power. Of these, 9 already are producing power (Table 1) and the remaining 8 are either under active exploration and development, or have produced at least some quantity of high temperature fluid according to the criteria of Edmiston and Benoit (1984). It is assumed that some combination of these sub-economic systems and other geothermal prospects in Nevada will eventually produce power, for a total of 17 power producing systems from currently known areas. In the future, a more rigorous estimate of these category 1 resources (see introduction) would provide a better constraint on undiscovered resources. The criteria used in selecting the 8 sub-economic systems were only partly rigorous here, as they depended in part on published press releases or statements of intent to produce electricity.

The two rankings of geothermal favorability (favorable and unfavorable) and 4 rankings of "degree of exploration" were combined together to form 12 unique conditions or rankings, each with their own unique area in the state of Nevada (Table 2a). The density of occurrence of known geothermal systems (number of geothermal systems per km^2) was calculated for each of the 12 rankings (Table 2b), in a manner analogous to the "constant of proportionality" developed by McCammon and Kork (1992) in their "one-level prediction" method.

The *total* geothermal resource (discovered plus undiscovered) was estimated by calculating a total "crustal" density of occurrence for each of the 12 unique conditions or rankings, taking into account the degree of exploration. This is a challenging step, because it involves estimating densities for undiscovered systems. The density of geothermal systems in well-explored areas might be used as an approximation for un-drilled areas, but since geothermal wells are concentrated in areas with high geothermal potential, the density of occurrence is not likely to be representative. Conversely, oil wells in Nevada are concentrated in areas of relatively low geothermal potential.

The crustal densities of geothermal systems were approximated with the help of exploration "efficiency factors", which represent the percentage of geothermal systems in each ranking that have been discovered (based on expert judgment). Areas with geothermal or oil wells should have an efficiency factor close to 100%, whereas areas without drilling should have lower factors (Table 2c). The crustal density of geothermal systems (discovered and undiscovered) for each ranking can be obtained by dividing the observed densities by the efficiency factors (Table 2d). The total number of geothermal systems in Nevada can be estimated by multiplying the crustal density for each ranking by its respective area, and summing the results.

The assignment of exploration efficiency factors is a subjective process best done by experts familiar with geothermal systems and the challenges of finding them. Expert input was not obtained for this preliminary paper, but plausible examples of efficiency factors are given in Table 2c. The efficiency of geothermal or oil well drilling was considered 90%, high, but not perfect. The efficiency of wells in the NDWR database was considered to be slightly lower, because they consist largely of water wells that were not drilled to the same depths as the geothermal or oil wells. For NDWR wells, an efficiency of 85% was adopted for shallow water tables and 80% for deep water tables.

Where no drilling data exists, lower exploration efficiencies were assigned, and the level of efficiency was constrained by the depth to the water table. For shallow water tables (< 60 ft), the estimate was guided by the fact that 25% of known geothermal systems (3 out of 12) in shallow water table areas did not have known surface expressions and were discovered by drilling (Table 1); therefore it was concluded that the exploration efficiency (in the absence of drilling) must be lower than 75% (9 out of 12), and a 50% efficiency was chosen. For deep water tables, 60% (3 out of 5) were blind and discovered by drilling. The efficiency factor was assumed to be less than 40%, and a value of 25% was adopted.

The estimation of the density of known geothermal systems in un-drilled areas with shallow water tables is challenging because almost all known geothermal systems fall within areas drilled by geothermal and oil exploration wells. The density would be underestimated if geothermal systems in drilled areas were excluded from the calculation. Conversely, the density would be overestimated if it were assumed to be equal to the density in drilled areas, because geothermal wells often occur in areas with high geothermal potential. The solution used here was to include all geothermal systems (within shallow water tables), regardless of whether they were drilled or not. But when calculating the *number* of *undiscovered* geothermal systems in un-drilled areas with shallow water tables, only the un-drilled areas were multiplied by the densities.

Table 2a. Areas in Nevada associated with each of the 12 unique conditions or rankings of geothermal favorability and degree of exploration.

	Area (sq. km)				
Favorability	Favorable		Unfavorable		
Water Table	Shallow	Deep	Shallow	Deep	Total
SMU/Oil	4,182	4,418	4,491	7,443	20,534
Well Drillers	3,107	3,511	8,091	15,998	30,707
No Drilling	10,366	20,390	41,388	158,802	230,946

Table 2b. Density of occurrence for known economic/sub-economic geothermal systems according to favorability and exploration ranking.

	Known Densities (systems/km2)			
Favorability	Favorable		Unfavorable	
Water Table	Shallow	Deep	Shallow	Deep
SMU/Oil	0.001913	0.000453	0.000445	0.000403
Well Drillers	0.001546	0.000474	0.000216	0.000056
No Drilling	0.000566	0.000071	0.000037	0.000016

Table 2c. Exploration efficiency factors for predicting crustal densities of undiscovered geothermal systems (expressed as a fraction).

	Efficiency Factors (expressed as fraction)			
Favorability	Favorable		Unfavorable	
Water Table	Shallow	Deep	Shallow	Deep
SMU/Oil	0.90	0.90	0.90	0.90
Well Drillers	0.85	0.80	0.85	0.80
No Drilling	0.50	0.25	0.50	0.25

Table 2d. Modeled crustal densities for undiscovered economic/sub-economic geothermal systems in Nevada.

Density of Undiscovered Systems (systems/km2)				
Favorability	Favorable		Unfavorable	
Water Table	Shallow	Deep	Shallow	Deep
SMU/Oil	0.000213	0.000050	0.000049	0.000045
Well Drillers	0.000273	0.000118	0.000038	0.000014
No Drilling	0.000566	0.000212	0.000037	0.000049

Results

Using the exploration efficiency factors of Table 2c, a total of 23 undiscovered geothermal systems capable of producing electric power are predicted (Table 3). Assuming the same average power capacity/geothermal system seen today, this suggests a total potential power capacity of 1,060 MWe (for all known plus unknown systems), which is about 4 ½ times the current power capacity of Nevada. As mentioned previously, this prediction is based on the premise that 17 geothermal systems from known KGRAs and exploration prospects will ultimately produce electrical power. The 1,060 MWe consists of 239 MWe of existing production capacity, 213 MWe that would be produced from 8 new geothermal systems in known areas, and 612 MWe from 23 undiscovered systems.

Table 3. Number of undiscovered geothermal systems predicted for each favorability and exploration ranking. The relatively large number of undiscovered systems in unfavorable areas with deep water tables is due to the large percentage of the state (Table 2a) falling into this category, and not due to a high crustal density.

	Undiscovered Resources (Number of Systems)				
Favorability	Favorable		Unfavorable		
Water Table	Shallow	Deep	Shallow	Deep	Total
SMU/Oil	0.9	0.2	0.2	0.3	1.7
Well Drillers	0.8	0.4	0.3	0.2	1.8
No Drilling	5.9	4.3	1.5	7.8	19.6
Total	7.6	5.0	2.1	8.4	23.0

As expected, un-drilled areas are predicted to contain the greatest numbers of undiscovered geothermal systems (Table 3). More surprising is that 40% of undiscovered systems are predicted to occur in areas of shallow groundwater. This is caused partly by the relatively low exploration efficiency factor for un-drilled shallow water tables (Table 2c), and partly by the fact that known geothermal systems occur more frequently in shallow groundwater areas than deep groundwater areas. This may reflect a more fundamental relationship between geothermal favorability and shallow groundwater, such as, for example, a tendency of active Quaternary faults to occur at low elevations.

The highest densities of undiscovered geothermal systems are predicted where a shallow water table, geothermal favorability, and lack of drilling, coincide (Figure 4). One of the largest such areas occurs in the northern Carson Desert, which has fewer drill-holes compared to the southern Carson Desert. Another area occurs around Pyramid Lake – where "off-shore drilling" is non-existent, and the number of wells elsewhere in the Pyramid Lake Indian Reservation may be minimal. Two other areas, Buffalo Valley and south of Fairview Peak, have recently been independently identified as good geothermal exploration targets (Shevenell et al., 2003), based on geodetic measurements of crustal strain (Blewitt et al., 2003), regional GIS modeling (Coolbaugh, 2003), and seismic measurements of crustal thickness (Louie, 2002).

The methodology described here is sensitive to the choice of exploration "efficiency factors", but by changing these factors to unreasonably high or low values, the resource estimate can be bracketed. This was done for un-drilled areas, which contain most of the undiscovered resources. Efficiency factors of 75% and 40% respectively for high and low water table areas are considered high because they equal the percent of known economic systems not concealed prior to drilling (the presence of undiscovered geothermal systems would lower these numbers). To obtain unreasonably low efficiency factors, the factors were decreased until the calculated crustal density of geothermal systems (discovered plus undiscovered) in un-drilled areas equaled that of drilled areas (this required factors ranging from 4 to 27 %). These efficiency factors are considered low because the density of geothermal systems in drilled areas should be higher than that of un-drilled areas, since geothermal wells usually target areas with high geothermal potential. With these modified factors, the estimated total geothermal resource ranges from 770 MWe to 3,500 MWe. Although this suggests that the total resource is likely to be at least 3 times the current known reserves, the range of the estimates is large. This highlights the need to quantify "efficiency factors" as much as possible.

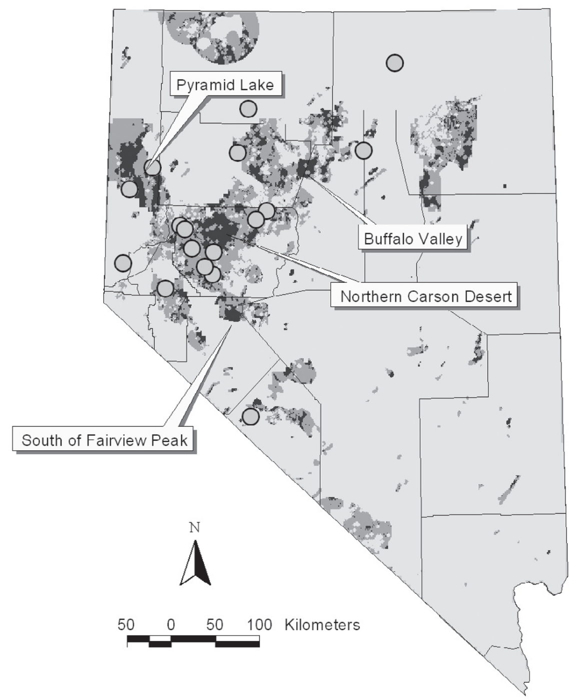

Figure 4. Predicted crustal density of undiscovered geothermal resources. Dark areas have high predicted densities, medium-grey areas have moderately high predicted densities, light gray densities are relatively low. Circles are known economic and sub-economic geothermal systems.

Conclusions and Recommendations for Future Work

This methodology demonstrates the ease with which resource calculations can be made in a geothermal GIS. Digital map layers are used to predict geothermal favorability, and digital drilling data and water table features are used to identify areas most likely to conceal geothermal systems. The model presented here is preliminary; alternative models can be built that employ multi-class favorability rankings and additional measures of the degree of exploration, such as the presence of laterally-flowing aquifers that could limit surface expressions of geothermal activity. Expert advice from geologists and engineers should be used to optimize the exploration efficiency factors and quantify other variables, such as the distance from the nearest drill-hole used to define "explored ground". The drill-hole databases used in this study do not include all wells and holes drilled in the state, and efforts to compile additional drill-hole data should be made. This would be especially important before investigating any of the areas in Figure 4.

Two of the more significant sources of error in the estimate are related to the low number of geothermal systems present in some favorability and exploration rankings (Table 1), and the subjective nature with which exploration efficiencies are assigned. Nevertheless, the method provides a useful constraint on the magnitude of the undiscovered resource. The division of Nevada into favorable and unfavorable zones, and the calculation of exploration efficiencies based on drill-hole and water data, helps constrain the estimate.

Finally, the estimate only considers the conversion of geothermal energy to electricity, and does not consider direct use of geothermal heat, or potentially significant impacts from energy prices, technological improvements in plant design, successful development of EGS, environmental issues, or the feasibility of locating these additional resources with known exploration technologies. This paper is designed primarily to illustrate a method of using digital data in a GIS to assess geothermal resources. It is recommended that more comprehensive resource assessments be undertaken using some of these same methods.

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