ENVIRONMENTAL MEASURES

Another important consideration in assessing the value of energy resources is the potential environmental risk associated with gas and oil development activities. In this chapter, we describe a method for characterizing energy resources according to selected environmental measures of the lands they occupy. Such a characterization provides an important starting point for assessing potential environmental risks. Different lands may be more or less susceptible to environmental impacts, and evaluating the risk of such impacts requires an understanding of the proposed activities and a characterization of the environmental attributes of those lands. Our approach links this environmental characterization to the energy resources in an effort to include it as a component of the resource assessment. We apply this method to the natural gas resources in the Greater Green River Basin.

As outlined in a previous report (LaTourrette et al., 2002), a useful way to consider the potential environmental risks of gas and oil development is in terms of characteristics of the lands in which they are located. Our environmental analysis therefore focuses on identifying relevant environmental measures of the lands in which natural gas may be present and calculating the locations and amounts of potential gas resources within areas having differing values of these measures. Different values of environmental measures reflect different levels of potential environmental risk, which may, in turn, translate to a need for further environmental analysis, greater mitigation requirements, or actual environmental impacts. For example, producing gas in certain areas indicated as having higher species density may pose greater risk to biodiversity or require greater mitigation efforts.

This analysis is intended to be part of a broader set of information sources to be used by decisionmakers in assessing gas and oil resources. We do not intend to define particular areas where drilling may be inappropriate, nor do we suggest that gas or oil project–related impacts in these areas would definitely occur. Rather, our intent is to provide a framework for treating environmental characteristics as an attribute of energy resources and to provide decisionmakers with a way to evaluate these attributes when assessing energy resources for strategic planning purposes.

METHODOLOGY

Issues and Measures

Consideration of environmental issues and selection of environmental measures were based on their relevance to the potential impacts of natural gas and oil exploration and development in general. In defining general categories of issues to address, we consulted three general sources: scoping reports of environmental impact statements in which various stakeholder groups identified a number of potentially relevant issues for gas and oil extraction projects in Wyoming (e.g., U.S. Bureau of Land Management and U.S. Department of Agriculture, 2000), U.S. Bureau of Land Management and Forest Service access restrictions (e.g., Potential Gas Committee, 2001, Table 16), and experts with knowledge of environmental issues in the study area. Further discussion and review of the literature regarding potential measures of environmental impacts from gas and oil development are given in LaTourrette et al. (2002). From these sources, three general categories of environmental issues emerged:

- Ecosystem quality,

- Human environmental considerations, and

- Water quality.

Our selection of measures was guided not only by their relevance to potential impacts but also by our desire to minimize the use of complex or controversial model-dependent measures (e.g., hydrologic transport rates). Our selection was further constrained by the availability of data. The suite of environmental measures we present is not an exhaustive list of relevant environmental indicators but is intended to provide meaningful insight into some potential environmental risks across the majority of the study area. Conversely, some of the measures (aquifer recharge rate and depth to groundwater) are less relevant to the Greater Green River Basin than other areas, as production methods in the Greater Green River Basin thus far have had relatively low impacts on groundwater quality. We selected seven environmental measures for this analysis:

- Terrestrial vertebrate species richness,

- Proximity to sensitive species observed locations,

- Surface water and riparian habitat zones,

- Proximity to human settlements,

- Surface slope,

- Aquifer recharge rate, and

- Depth to groundwater.

In addition to these measures, we also examined the distribution of different categories of lease restrictions for natural gas development on federal land.

Overlay Analysis

To evaluate the amount of resource having different values of the environmental measures, the measure values were grouped or "binned" at various cutoff points. Ideally, bins would be chosen on the basis of empirical relationships between gas and oil development activities and potential environmental impacts. However, this requires knowledge of a causal relationship between measures and impacts which we do not possess. Therefore, in this initial analysis, we define the bins primarily from statistical criteria. In some cases scientific or regulatory criteria were also used. Using statistically derived bins does provide a relative sense of environmental concern for this specific area and in so doing provides useful guidance. However, they say little about actual environmental risk and in that sense the environmental measures need to be developed further.

For each environmental measure, we evaluated the amount of potential natural gas resource underlying lands having different bin values. This was accomplished using GIS overlay analysis—a process by which separate spatial distributions are combined to generate a new distribution representing their intersection. Note that in most cases environmental data were available for Wyoming only. Maps of environmental measures and overlay analyses are therefore confined to the portion of the study area in Wyoming. Overlay results presented in this chapter are normalized to totals for Wyoming only. Separate overlays were calculated for the technically recoverable gas and the economically recoverable gas at several costs. In each case, the overlay resulted in an amount of gas underlying land possessing a particular value of an environmental measure. The environmental measures were defined such that every point in the study area is assigned one value for a given measure. Thus, there is no overlap between areas having different values and there is no area where no value is assigned. As a result, the sum of gas from each overlay is the same and equal to the total gas with no overlay. Overlays were calculated for gas distributions from the USGS-based scenario only.

ECOSYSTEM QUALITY

The development of gas and oil resources has the potential to disrupt complex associations of vegetation and wildlife in the study area, potentially warranting greater care or mitigation in certain areas to maintain an acceptable level of ecological function.

Ecological Setting

The Wyoming Basin (Omernik, 1987) defines the largest ecoregion within our study area. This semiarid region is characterized by relatively low rainfall (less than 16 inches annually throughout the entire basin, and less than seven inches annually in some areas in Wyoming) and irregular basin terrain that includes isolated mountains and plateaus with local relief generally greater than 30 meters. Vegetation includes widely scattered shrubs and grasses dominated by sagebrush, saltbush, and various short-stem grasses. Some uplands include juniper and pine. A number of wet val-

leys, riparian areas, and wetlands also occur across the Wyoming Basin, each containing more water-dependent plant species. At higher elevations, the study area includes open woodland, coniferous forest, and alpine meadows. This variety of landform and vegetation across the study area defines a number of interrelated habitats for a variety of species, including fish, fowl, and big game species, as well as important macroinvertebrates and microbes found in soil and streams.[1]

Measures of Ecological Function

According to the National Research Council (2000) the level of ecological functioning can be indicated by a number of measures including species diversity, soil condition, and nutrient runoff. In a subsequent section (Water Quality), we will consider the potential for increased nutrient runoff and disruption of soils as they may relate to gas and oil development. In this section, we present three ecological measures that correlate with species diversity and species density:

- Terrestrial vertebrate species richness,

- Proximity to sensitive species observed locations, and

- Surface water and riparian habitat zones.

These measures are intended to indicate areas of different levels of general ecological function and do not differentiate between the particular characteristics or needs of individual species.

Terrestrial Vertebrate Species Richness. Species richness is an important indicator of available ecological resources of an area. We consider richness of higher trophic-level species (i.e., vertebrates), which may correspond with areas of greater ecological complexity. Degradation of an area may have an adverse effect on species richness, indicating a loss of ecological resources or a decrease in ecological function in that area.

In our analysis, we use data compiled by the Wyoming Gap Analysis Program (WYGAP; Wyoming Gap Analysis, 1996a), which is part of the larger National Gap Analysis Program under the Biological Resources Division of the U.S. Geological Survey. These data describe predicted distributions of 445 terrestrial vertebrate species, represented by 116 species of mammals, 291 birds, 26 reptiles, and 12 amphibians in Wyoming. These data reflect overall species richness in that they comprise numbers of species, not individuals. All species are treated equally, regardless of numbers of individuals within each species. Note also that richness describes the number of species groups within a given modeled habitat area; these functional areas may vary in size. Areas of higher richness values correlate with higher species diversity in those areas.

WYGAP generates species richness data in a GIS modeling process using more than 700,000 point observations, species-habitat association rules, and habitat condi-

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[1]See Mac et al. (1998) for an overview of ecosystems and species within the Rocky Mountain area.

tions.[2] The median value of the species richness distribution is 119 species per area, with areas of highest species richness nearer water and at higher elevations. To characterize the variability in species richness across the basin, we selected bins separated at the first quartile and median richness values as follows:

- Less than 98 species per area,

- 98 to 119 species per area, and

- Greater than 119 species per area.

The spatial distribution of species richness according to these bins is shown in Map 4.1 in the maps section.

Results of the overlay analysis are shown in Table 4.1 and Figure 4.1. The tables in this chapter list the results in terms of both the percentage of economically recoverable resource and the percentage of technically recoverable resource at each cost. The percentage of economically recoverable resource reflects the distribution of the economically recoverable resource among the different measure values; these values sum to 100 for each measure. This is illustrated by the relative proportion of the different shadings within each column in Figure 4.1. The percentage of technically recoverable resource gives the percentage of technically recoverable gas that is both recoverable at the listed cost and has the specified value of the environmental measure. This is illustrated by the absolute amount of each shading within each column in Figure 4.1. The sums in these columns give the economically recoverable fraction of the technically recoverable gas and are consistent with the values in Table 3.2 (slight differences occur because the results in Table 4.1 are for the Wyoming portion of the study area only).

These results indicate that areas containing more than 119 species groups, or greater than the median value for the study area, contain approximately 18 percent of the total technically recoverable resource. Areas potentially supporting 98–119 species and less than 98 species account for 46 and 36 percent of the technically recoverable resource, respectively (right-most column in Table 4.1). When considering the economically recoverable resource, these percentages decrease as the modeled cost decreases. For example, 7 percent of the technically recoverable resource is both economical to produce at or below $3/MMBtu *and* is on lands with >119 species/area.

When cast in terms of the percentage of economically recoverable resource, the percentages of gas having different values of vertebrate species richness are nearly independent of cost. For example, regardless of the cost considered, the fraction of economically recoverable gas on land with >119 species per area ranges only from 17 to 18 percent (Table 4.1). The similarity of the relative distributions at different costs is apparent from the similar proportions of different shadings in each column in

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[2]Range limits of each species were delineated within a grid of 436 hexagons (635 square kilometers each) and refined by consideration of additional information describing land cover, elevation, riparian model, and review by more than 60 local experts. Comparisons of species predicted to occur in eight field sites to species lists maintained for the sites indicated an overall accuracy of 79.5 percent. These data are meant to be used at 1:100,000 scale or smaller (Wyoming Gap Analysis, 1996b).

Table 4.1

Natural Gas at Different Costs from USGS-Based Scenario Having Different Values of Ecosystem Quality Measures

Environmental Measure	Cost ($/MMBtu)						
	≤3		≤5		≤10		
	% of ERR	% of TRR	% of ERR	% of TRR	% of ERR	% of TRR	% of TRR
Terrestrial vertebrate species richness							
>119 species/area	17	7	17	10	18	16	18
98–119 species/area	43	18	43	25	46	40	46
<98 species/area	41	18	40	23	36	32	36
Sum	100	43	100	57	100	87	100
Proximity to sensitive species observed locations							
<2,000 meters	14	6	14	8	14	12	14
≥2,000 meters	85	37	86	49	86	75	86
Sum	100	43	100	57	100	87	100
<6,500 meters	65	28	65	37	65	57	64
≥6,500 meters	35	15	35	20	35	31	36
Sum	100	43	100	57	100	87	100
Surface water and riparian habitat zones							
Open water, wetland, riparian	9	4	10	6	11	10	11
Upland	91	39	90	51	89	77	89
Sum	100	43	100	57	100	87	100

NOTES: % of ERR = [economically recoverable gas at listed price with specified value of environmental measure]/[economically recoverable gas at listed price]. % of TRR = [economically recoverable gas at listed price with specified value of environmental measure]/[technically recoverable gas]. Sums may differ slightly from totals because of rounding .

Figure 4.1. This finding holds true for all of the environmental measures considered in this study. Note that this results from the particular distributions of resources and environmental measures in this basin and cannot necessarily be generalized to other areas.

Proximity to Sensitive Species Observed Locations. Rarer species often have greater conservation interest than more common species. Their loss is associated with reduced biodiversity in local areas as well as increased risk for regional or global endangerment. These species often have very particular habitat requirements and are very sensitive to their loss. Thus, degradation of areas potentially constituting critical habitat for sensitive species may have implications for biological diversity and ecosystem health.

The locations of species or associations that scientists have identified as sensitive or are protected by conservation laws[3] are recorded in the Wyoming Natural Diversity Database (WYNDD). The WYNDD includes observations of terrestrial and aquatic

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[3]Sensitive species can be defined under a number of federal, state, and local regulations. Two measures of sensitivity we consider are threatened or endangered listing under the federal Endangered Species Act (ESA) and imperiled or critically imperiled status under the Natural Heritage ranking system. The Heritage ranking system was developed, and rankings are continually updated as biological information is acquired, by NatureServe and its Natural Heritage Program members. In this system, element occurrences (field observations of species, subspecies, or ecological communities) are assigned ranks on global (G), national (N), and subnational (S) scales. These ranks range from critically imperiled (1) to widespread, abundant, and secure (5). In accordance with the protocol used by Florida Natural Areas Inventory (FNAI) (2001), we consider sensitive species with Heritage ranks 1 or 2 on G, N, or S scales in our analysis.
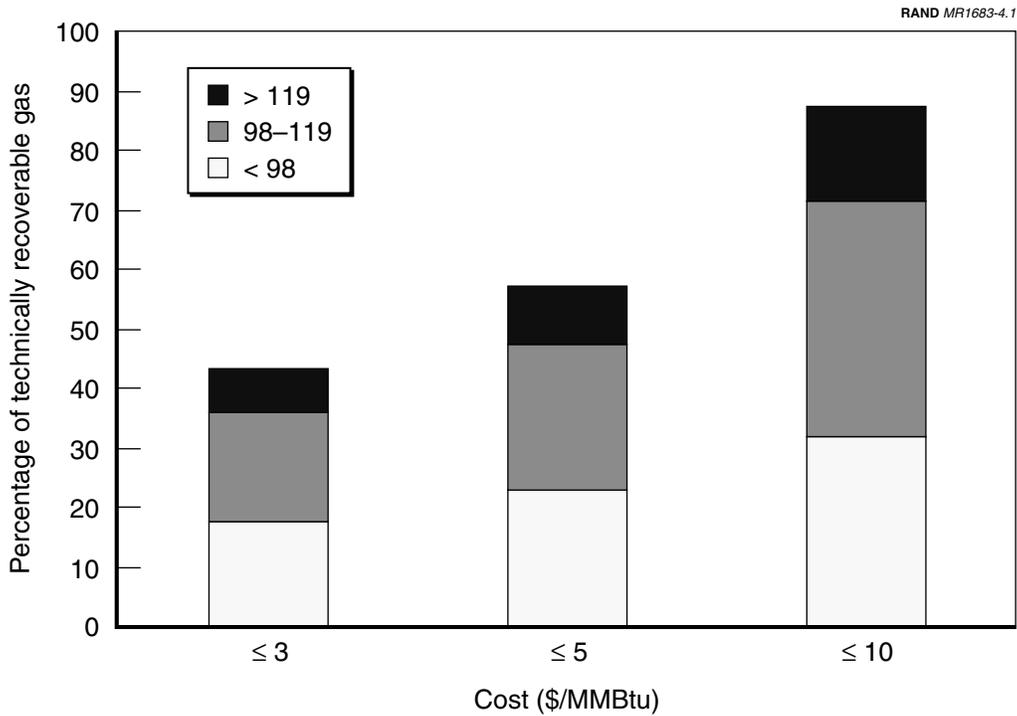
Figure 4.1—Terrestrial Vertebrate Species Richness Overlay Results

vertebrates (i.e., mammals, birds, reptiles, amphibians, and fish), invertebrates, plant species, as well as vegetation associations. A spatial precision attribute is also included with each observation in the WYNDD.[4] Note that the WYNDD includes point observations of species over a 50 year time frame and that the vast majority of WYNDD data represent results of spring and summer field surveys. The WYNDD point data by themselves do not define habitat ranges and in particular may not capture winter species patterns.

Our overlay analysis requires environmental measures with spatial dimensions of area; to derive spatial areas from sensitive species observation points, it was necessary to define areas that correlate reasonably to species ranges. We used a buffering approach based in part on a method defined in the Florida Natural Areas Inventory (2001). FNAI defines buffers around observation points based on the biology of the individual species. These buffers generally range from approximately 2,000 to 6,500 meters at minutes precision. According to the FNAI protocol, buffers are subsequently refined by expert review of suitability of habitat enclosed by the buffer. Unsuitable habitat is discounted from the modeled areas.

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[4]For this measure, we consider only points with minutes precision (approximately one mile) or seconds precision (a few hundred meters), consistent with the protocol used in Florida Natural Areas Inventory (2001).

For our analysis, we calculated overlays for buffers of 2,000 meters and 6,500 meters. Buffering aggregated sensitive species data occurrences by these values gives us a range of values that likely encloses actual sensitive habitat areas for many species occurring within our study area.[5] The smaller buffer may underestimate the range of some vertebrates, whereas the larger buffer may overestimate the range of certain plants, vegetation associations, and invertebrates. In our screening-level analysis, we do not qualify buffered areas on the basis of habitat conditions, which may contribute to an overestimate of the range of species in some buffered areas.

Note that the environmental study area includes a small number of species of large mammals, raptors, and migratory birds, with ranges on the order of ten to 1,000 kilometers. We do not consider wide-ranging mammals and birds in our analysis, in part because buffering points with appropriate radii would cover the entire environmental study area (thus not introduce variability useful for decisionmakers) and also because most of these points are reported with general precision, which, according to FNAI protocol, are not included. We note that the most frequented habitats by wide-ranging species within the environmental study area occur at higher elevations beyond the Wyoming Basin. For our analysis, we consider areas within and beyond 2,000 and 6,500 meter buffers, according to the following bins:

- Within 2,000 meters of sensitive species observed locations,
- Beyond 2,000 meters of sensitive species observed locations,
- Within 6,500 meters of sensitive species observed locations, and
- Beyond 6,500 meters of sensitive species observed locations.

The spatial distribution of sensitive vertebrate species distribution according to these bins is shown in Map 4.2 in the maps section.

As shown in Table 4.1, our results indicate that potential habitat for sensitive species may account for between approximately 14 and 65 percent of the total technically recoverable resource or the economically recoverable resource at any cost. Results of overlays for different gas costs are shown in Figure 4.2.

Surface Water and Riparian Habitat Zones. Water is an important factor for the survival of many plant and animal species in the study area. Development in close proximity to areas that are hydraulically connected may have relatively greater chance of affecting surface water quality. Species diversity and density are strongly associated with surface water habitats. According to the Wyoming Gap Analysis (1996b), 83 percent of terrestrial vertebrate species have an association with aquatic

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[5]No single buffer is appropriate for all species considered. Certain species, e.g., plants and invertebrates, may occur over distances of approximately 200–500 meters from their observed point. Adding error at minutes precision (approximately 1,600 meters), an appropriate buffer radius for these species is approximately 2,000 meters. Similarly, many vertebrates occur over a range of up to 5,000 meters, suggesting an appropriate buffer radius of approximately 6,500 meters.
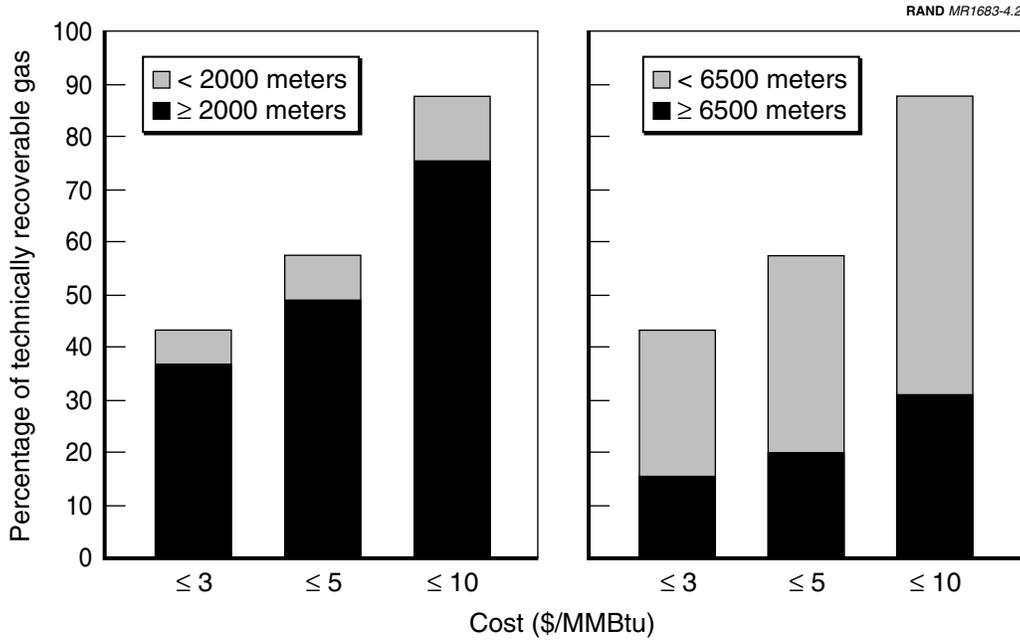
Figure 4.2—Proximity to Sensitive Species Observed Locations Overlay Results

and riparian habitats. In our own separate analysis, we found a strong association of WYNDD sensitive species observed locations with these areas.[6]

To capture this important ecological zone, we have defined a measure that distinguishes surface water and riparian habitat zones from uplands:

- Surface water, wetlands, and riparian areas,[7] and

- Uplands.

These bins are differentiated by distance from surface water and are distinguished by differences in species density. Riparian areas generally correlate with higher species density relative to uplands. In addressing habitat zones, this measure complements the species diversity and sensitive species observations measures as an indicator of

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[6]Sensitive species observed locations from WYNDD (critically imperiled, endangered, or threatened vertebrates) were associated with the nearest stream, lake, or reservoir, taken from digital line graph data from the U.S. Geological Survey (Wyoming Gap Analysis, 1996c) and a distance was measured. A histogram of these distances shows a clear maximum at zero distance and a smooth decrease in number of species with distance from water. Mean distance from water increased in order for fish, amphibians, mammals, birds, and reptiles as one might expect. The median distance for all species was less than 300 meters, and the third quartile score was approximately 850 meters. Mean distance for fish observations was approximately 150 meters, which provides an estimate of the positional uncertainty in the data.

[7]Surface waters and wetlands data were taken from U.S. Fish and Wildlife Service (1997). Riparian areas were defined by a buffer around streams. We model riparian areas using stream buffer distances specified by WYGAP, which range from 40 to 210 meters, depending on the stream order.

ecological function.[8] Note that the quality of riparian habitat can vary considerably, and differentiating areas of higher and lower quality would improve this measure. However, collecting data in riparian habitat quality requires detailed field surveys and such data are not available for much of our study area. We therefore include all riparian areas in our measure. The spatial distribution of these zones is shown in Map 4.3 in the maps section.

Results in Table 4.1 show that surface water, wetland, and riparian areas account for approximately 10 percent of the resource recoverable at any cost, and upland areas account for approximately 90 percent of the economically recoverable resource. Overlay results for gas distributions at different economic costs are shown in Figure 4.3.
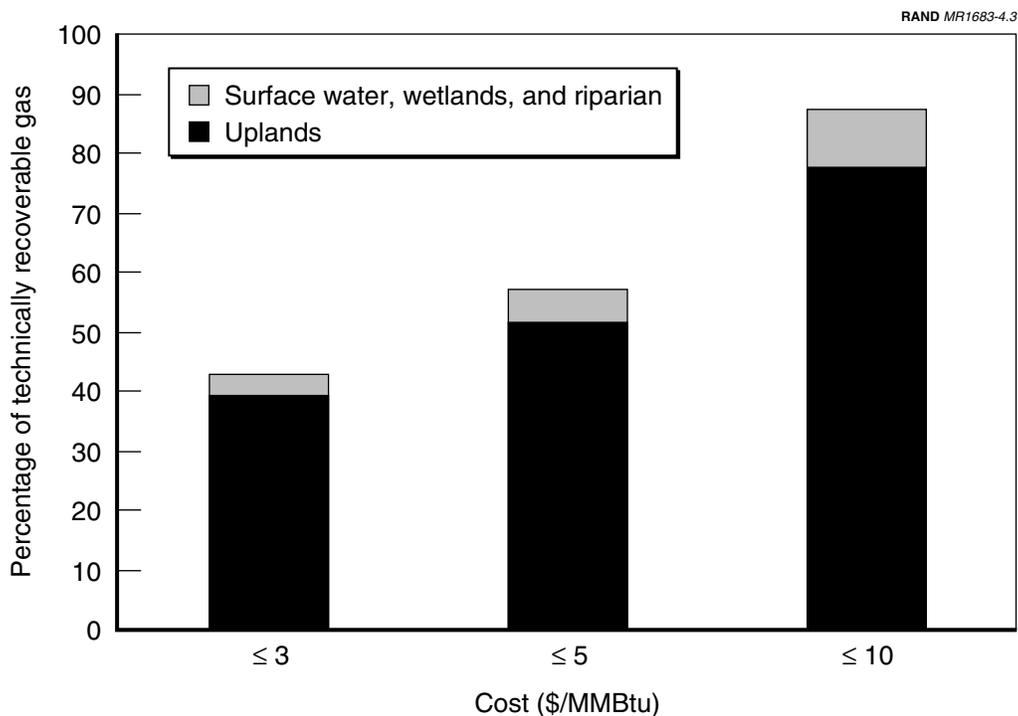

Figure 4.3—Surface Water, Wetlands, and Riparian Habitat Zone Overlay Results

HUMAN ENVIRONMENTAL CONSIDERATIONS

Along with various ecological issues, we consider environmental issues typically associated with the "human environment." From a human environmental perspective, concerns often center around maintaining the function of an area for some designated human use. In many instances, human environmental issues are closely tied

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[8]Note that certain sensitive species occur in upland areas and are protected by many of the same conservation laws found in riparian areas.

to such ecological issues as air quality and water quality. Although much of our study area is sparsely populated, it includes a number of human settlements[9] with adjacent lands potentially affected by gas and oil development.

Gas and oil production can contribute to a risk of increased atmospheric haze, acid deposition on streams and vegetation, and various issues of human health that are correlated with degraded air quality. Many of these issues operate at larger regional areas that include sources and receptors well outside our study area and would require complex modeling that extends beyond the scope of this analysis.[10] Instead, we focus on local human environmental issues that can be related to lands within our study area. We present a simple measure that considers proximity to human settlements within the study area.

Proximity to Human Settlements. Air quality effects of some pollutants, such as carbon monoxide, fugitive dust, and less reactive toxics (e.g., benzene) occur at local levels, local being defined here as within approximately 20 kilometers. Ignoring specific factors affecting dispersion of emitted chemicals (e.g., source characteristics, climate, weather, and topography), we assume that development within areas uniformly enclosed by a 20 kilometer buffer around human settlements poses a potentially greater human health risk associated with degraded air quality. Thus, we consider two areas of relatively greater and relatively less concern for local air quality:

• Less than 20 kilometers from human settlements, and

• Greater than 20 kilometers from human settlements.

This same buffer may also enclose an area potentially susceptible to relatively higher impacts associated with noise, vibration, and local water supply and quality. Thus, this measure may also capture broader risks of potential land use incompatibility of gas and oil development nearer human settlements.

The spatial distribution of our proximity to human settlements measure according to these bins is shown in Map 4.4 in the maps section.

As shown in Table 4.2, areas within 20 kilometers of human settlements account for 5–8 percent of the resource at any cost, with the remaining 95–92 percent located beyond 20 kilometers of human settlements. Results for different economic costs are shown in Figure 4.4.

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[9]In 1990, Green River, Rock Springs, and Laramie had populations of 12,711, 19,050, and 26,287, respectively. The populations of most cities within the study area are less than 10,000 and over half of them are less than 2,000 (Wyoming Department of Administration and Information, 2002).

[10]Regional and global air quality issues associated with oil and gas extraction, or the cumulative effects of increased production in the study area, may be very important. Analysis of cumulative effects are often insufficiently treated by individual project-level analyses conducted as part of an environmental impact statement, required by the National Environmental Policy Act (NEPA). An appropriate quantitative analysis of cumulative, regional air quality issues associated with oil and gas extraction would require extensive air quality modeling similar to the ongoing work of the Western Regional Air Partnership.

Table 4.2

Natural Gas at Different Costs from USGS-Based Scenario Having Different Values of Proximity to Human Settlements

| | Cost ($/MMBtu) | | | | | | |
| | ≤3 | | ≤5 | | ≤10 | | |
Environmental Measure	% of ERR	% of TRR	% of ERR	% of TRR	% of ERR	% of TRR	% of TRR
Proximity to human settlements							
< 20 kilometers	5	2	6	3	8	7	8
≥ 20 kilometers	95	41	94	54	92	81	92
Sum	100	43	100	57	100	87	100

NOTES: % of ERR = [economically recoverable gas at listed price with specified value of environmental measure]/[economically recoverable gas at listed price]. % of TRR = [economically recoverable gas at listed price with specified value of environmental measure]/[technically recoverable gas]. Sums may differ slightly from totals because of rounding.
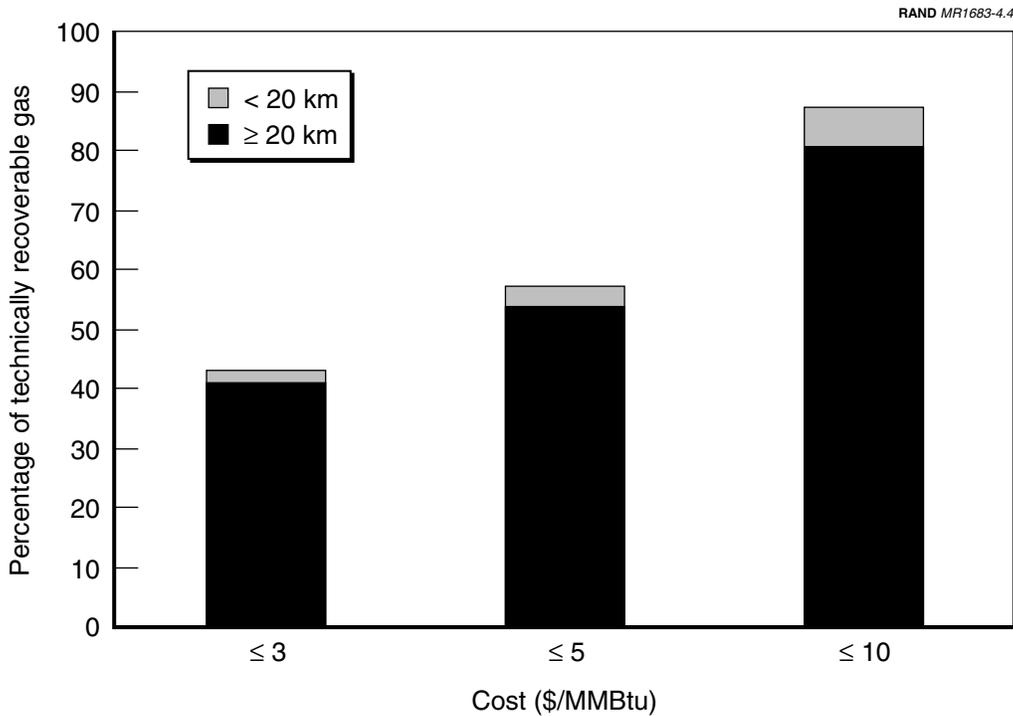

Figure 4.4—Proximity to Human Settlements Overlay Results

WATER QUALITY

Water quality is an important issue associated with gas and oil resource extraction and production. In Wyoming, approximately 65 percent of the population is served by surface water systems and the remainder is served by groundwater systems (U.S. Environmental Protection Agency, 2001). Agricultural and livestock operations also depend on water of sufficient quality. Contamination of water supply systems, ero-

sion and runoff into surface waters, and contamination of groundwater are among the potential risks associated with gas and oil production. In this analysis, we consider these risks as they relate to surface and groundwater quality.

Surface Water Quality

One measure of the potential risk of gas and oil production is the potential for runoff from a storm event or from surface discharge of fluids. Access to drilling areas, equipment staging, and rig set-up involve potential disturbance of vegetation and soils. This disturbance may lead to increased soil erosion and increased nutrient runoff and sedimentation of nearby and downstream waters. The potential for surface water contamination from runoff is correlated with a number of factors including slope, soil type, and type of vegetation cover (Lee, 1980).

Areas of lower slope, more permeable (sandy and gravelly) soils, and thicker undisturbed plant cover generally are associated with less runoff into surface waters. Greater slope, heavy clay soils, shallow soils over bedrock, and sparse vegetation often are associated with greater runoff potential. Although all of these factors correlate with runoff, we use slope as an important indicator of runoff potential.

Surface Slope. Using Bureau of Land Management lease stipulations (Potential Gas Committee, 2001; Advanced Resources International, Inc., 2001) and personal communication with Bureau of Land Management scientists[11] for guidance, we assume that unmitigated developments on slopes greater than 25 percent (approximately 14 degrees) are more likely to be associated with erosion. Additional mitigation measures are often required at slopes steeper than approximately 40 percent, so we also consider another slope cutoff at 40 percent (approximately 22 degrees) to further differentiate the land. Thus, we consider three bins for runoff and erosion potential due to varied slope:[12]

- Less than 25 percent,
- 25 to 40 percent, and
- Greater than 40 percent.

The spatial distribution of surface slope according to these bins is shown in Map 4.5 in the maps section.

Overlay results indicate that only about 4 percent of the gas at any cost is on lands with slopes greater than 40 percent (Table 4.3). Areas with slopes between 25 and 40 percent similarly contain about 4 percent of the gas, whereas more than 90 percent is

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[11]Keith Andrews, Bureau of Land Management, Pinedale Field Office, personal communication, August 2002.

[12]We used a dataset representing slope for Wyoming that is based on a 90 meter digital elevation model, and resampled over 100 meter grid cells. Results of analysis at this resolution may underestimate runoff and erosion potential (e.g., gully erosion) because of topographic variation at a smaller than 1:250:000 scale.

on lands with slopes less than 25 percent. Overlay results for gas at different costs are shown in Figure 4.5.

Table 4.3

Natural Gas at Different Costs from USGS-Based Scenario Having Different Values of Water Quality Measures

	Cost ($/MMBtu)						
	≤3		≤5		≤10		
	% of ERR	% of TRR	% of ERR	% of TRR	% of ERR	% of TRR	% of TRR
Environmental Measure							
Surface slope							
> 40%	4	2	4	3	4	4	4
25–40%	4	2	4	2	4	4	4
< 25%	91	39	91	52	91	80	91
Sum	100	43	100	57	100	87	100
Aquifer recharge rate							
≥ 2 inches/year	9	4	9	5	9	8	9
< 2 inches/year	91	39	91	52	91	79	91
Sum	100	43	100	57	100	87	100
Depth to groundwater							
< 16 feet	9	4	10	6	12	10	12
16–56 feet	42	18	41	23	42	37	43
> 56 feet	49	21	49	28	46	40	45
Sum	100	43	100	57	100	87	100

NOTES: % of ERR = [economically recoverable gas at listed price with specified value of environmental measure]/[economically recoverable gas at listed price]. % of TRR = [economically recoverable gas at listed price with specified value of environmental measure]/[technically recoverable gas]. Sums may differ slightly from totals because of rounding.
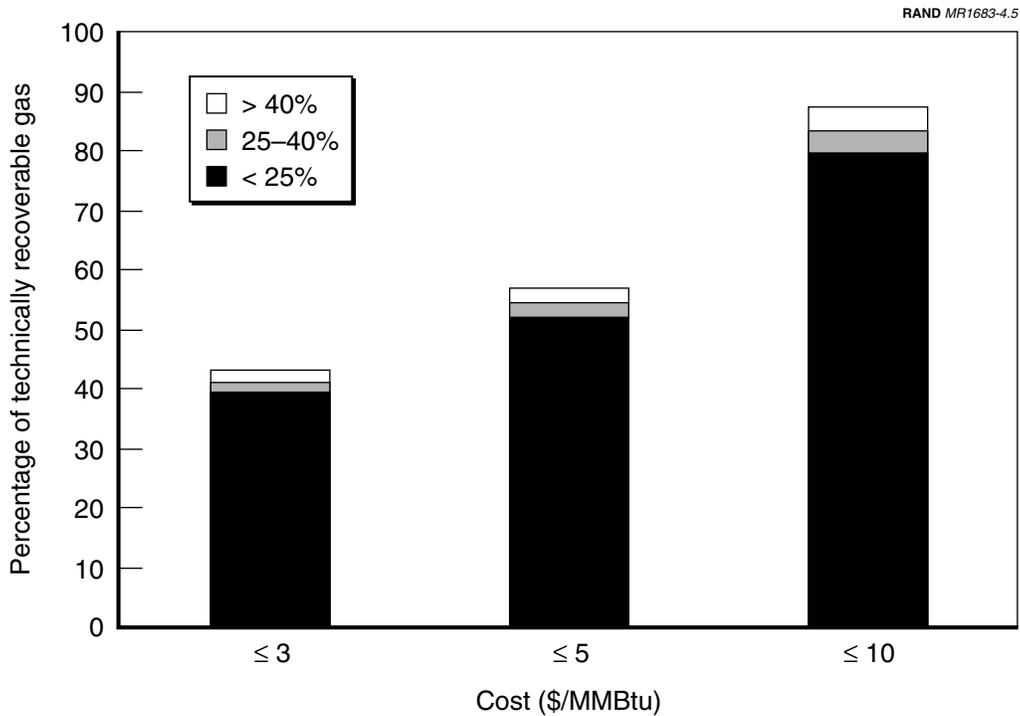

Figure 4.5—Surface Slope Overlay Results

Groundwater Quality

The process of drilling requires passage of formation fluids and process additives near and through groundwater aquifers above deeper gas and oil resources. Resource production, particularly coalbed methane production, can also generate large volumes of potentially hazardous formation fluids. Formation fluids may be discharged at the surface or reinjected into deep groundwater basin—the difference between these two methods has great implications for risk to surface or groundwater systems. In the Greater Green River Basin, reinjection is expected to predominate, and the risk of contaminating surface waters or initial groundwater aquifers is considerably less than if water were discharged at the surface. However, our methodology was derived with the intention of applying it to multiple basins. Thus, some measures, such as one assessing groundwater quality, which may not be critical in the Greater Green River Basin, may be more relevant in other basins.

Several types of groundwater vulnerability assessment models exist, including overlay and index methods, methods employing process-based simulation models, and statistical models (National Research Council, 1993). DRASTIC, one of the best-known index models, for example, considers measures of depth to groundwater, recharge rates, soils and aquifer media, and hydraulic conductivity and ranks areas based on weighted vulnerability scores. However, the DRASTIC method relies on judgment in proper weighting of parameters, which is often a source of debate. In our analysis, we do not combine measures in an attempt to comprehensively model groundwater vulnerability but instead focus on two measures—aquifer recharge rate and depth to groundwater—that generally correlate with an aquifer's potential risk of contamination from surface discharge (Johnston, 1988).

Aquifer Recharge. Recharge describes the infiltration of surface water into the soil and its percolation through the soil and unsaturated geologic material into the groundwater. It is measured as a flow rate and is expressed as an amount of water infiltrating to the water table in an area per unit of time (inches per year). Aquifer recharge varies according to amount of rainfall as well as soil and aquifer properties that characterize the unsaturated zone beneath the surface and above the water table (Johnston, 1988).

Recharge represents a primary transport mechanism of potential contaminants from the ground surface into the aquifer. In general, the more water available to recharge, the more susceptible the groundwater is to potential contamination.[13]

Recharge varies considerably across the study area, with relatively low recharge across much of the arid basin. Recharge across the basin is higher in areas character-ized by certain surface water features (sluggish streams, lakes, and wetlands) and also increases dramatically with elevation in the mountainous areas. Review of

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[13]Note that there is a higher recharge rate where recharge begins to dilute contaminants, resulting in an inverse relationship between recharge and potential groundwater contamination; this dilution is not considered likely under natural conditions of the semiarid Wyoming landscape (Knight, 1994).

recharge data, which range from 0 to 58 inches per year, shows that three-quarters of the state of Wyoming (excluding Yellowstone National Park) is characterized by aquifer recharge of less than two inches per year.[14] We divide the data set into two groups on the basis of this third quartile score:

- Less than 2 inches per year, and

- Greater than 2 inches per year.

The spatial distribution of aquifer recharge according to these bins is shown in Map 4.6 in the maps section.

As Table 4.3 shows, areas with recharge less than two inches per year account for 91 percent of the resource recoverable at any cost. Areas with recharge of two inches or more per year account for 9 percent of the resource. Results for different costs are shown in Figure 4.6.
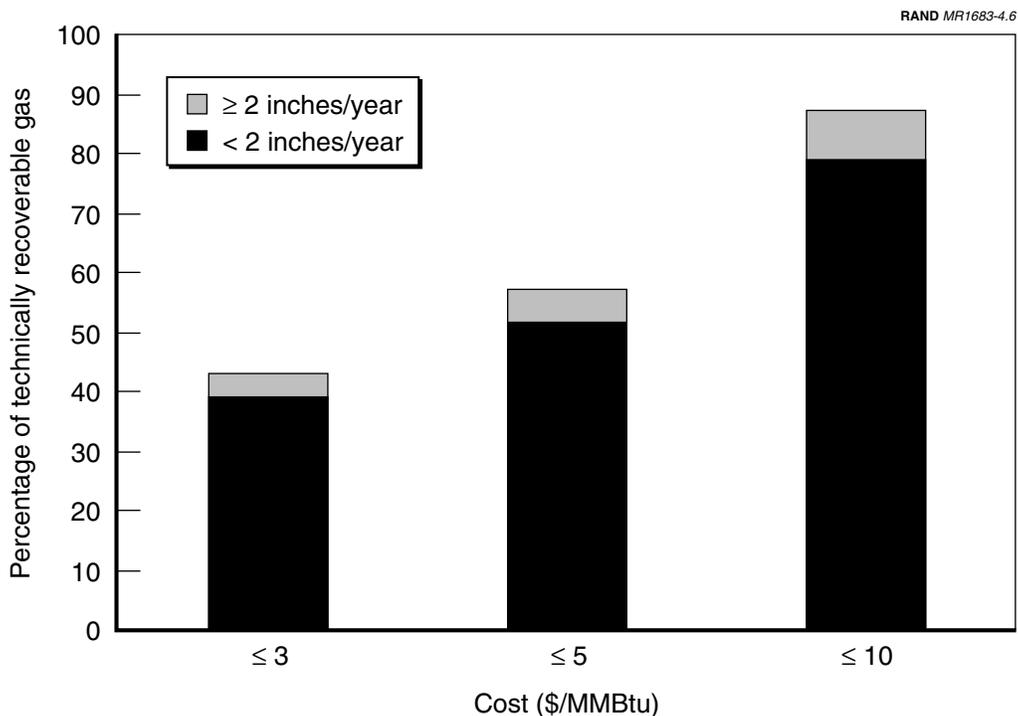

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Figure 4.6—Aquifer Recharge Rate Overlay Results

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[14]We use annual aquifer recharge data with 100 meter resolution from Munn and Arneson (1998). These data use average annual precipitation calculated by PRISM (Parameter-elevation Regressions on Independent Slopes Model) and published percolation percentages for documented soil and vegetation combinations to estimate recharge rates and classify 1:100,000-scale soil maps. PRISM is an analytical tool that uses point data, a digital elevation model, and other spatial datasets to generate gridded estimates of monthly, yearly, and event-based climatic parameters, such as precipitation, temperature, and dew point.

Depth to Groundwater. Along with the recharge rate, risk to groundwater quality may vary with depth to groundwater—shorter distances from the surface to the initial aquifer correlate with a greater risk from potential surface contamination.[15] Depth to initial groundwater in the Greater Green River Basin extends from areas where groundwater is as deep as 269 feet beneath the surface, with the distribution skewed toward shallower groundwater depths.[16] We grouped data into three bins accord-
ing to first and third quartile scores of the distribution (16 feet and 56 feet, respectively) as follows:

- Less than 16 feet,

- 16 to 56 feet, and

- Greater than 56 feet.

The spatial distribution of the depth to the initial groundwater according to these bins is shown in Map 4.7 in the maps section.

As shown in Table 4.3, lands with depths to initial groundwater of less than 16 feet account for 9–12 percent of the economically recoverable gas at any cost. Areas with depths to groundwater between 16 and 56 feet account for 42–43 percent, and areas with depths to groundwater exceeding 56 feet account for 46–49 percent of the resource. Overlay results for different costs are shown in Figure 4.7.

LEASE STIPULATIONS

In addition to the environmental measures derived for this study, we also conducted an overlay analysis for different classes of federal land lease stipulations. Recent attempts to assess energy resources in the Rocky Mountains have focused on inventorying resources subject to various legal access restrictions (lease stipulations) to resource development on federal lands (National Petroleum Council, 1999; Advanced Resources International, Inc., 2001). These studies have been controversial (e.g., Morton et al., 2002; LaTourrette et al., 2002). In their effort to identify impediments to energy development, these studies make some important assumptions that have implications for the effect of access restrictions on the available gas resource. These assumptions deal with economics, the resource base considered, restriction enforcement, technology, infrastructure, and drilling schedules. Some of these concerns

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[15]The relationship between groundwater vulnerability and depth to groundwater is complicated by the possibility of preferential pathways and differences in soil and aquifer properties. More detailed analysis would be required to refine these influences.

[16]We use a dataset that represents depth to initial groundwater for Wyoming (excluding Yellowstone) at 100 meter resolution and is appropriate for analysis at 1:100,000 scale (Wyoming Water Resources Center, 1997). The data were created by spherical Kriging to interpolate a smooth surface between known data points obtained from the Wyoming State Engineer's Office well permit records from the early 1900s to 1992. Quality of well data was improved by some screening procedures and the final layer was expertly reviewed, but no quality assurance procedures have been performed as of 1996. The authors of this dataset warn that it should be used with extreme caution because of inaccuracies associated with township-range locational descriptions as well as the problems inherent in the State Engineer's Office database.
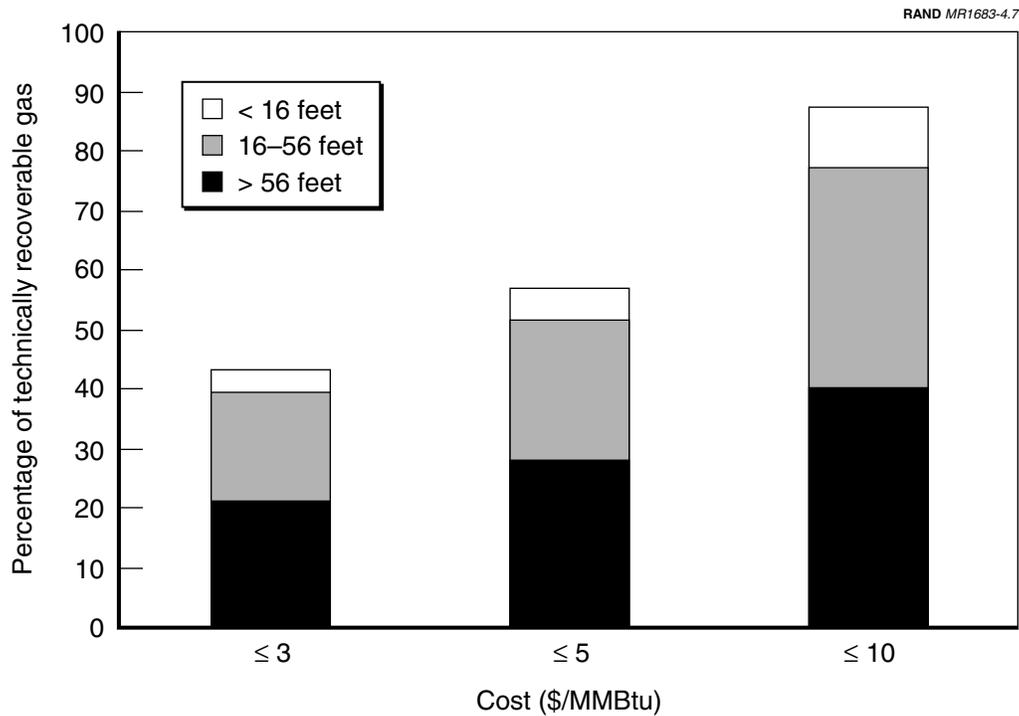
Figure 4.7—Depth to Initial Groundwater Overlay Results

have been addressed in a recently released study assessing access restrictions in five western basins, including a reanalysis of the Greater Green River Basin (U.S. Departments of Interior, Agriculture, and Energy, 2003). Overlays are presented here for the purposes of comparing results from different studies. These overlay results should be interpreted in light of the above concerns.

For this analysis we used the aggregated lease stipulation data compiled by the Department of Energy in its inventory of federal lands in the Greater Green River Basin (Advanced Resources International (ARI), Inc., 2001). GIS shape files of aggregated stipulations were overlaid with the gas distribution in the area included in the intersection of the RAND and Department of Energy study areas. Overlays were calculated for areas subject to no access, restricted access, standard lease terms, and nonfederal land. The distribution of these categories throughout the Greater Green River Basin is shown in Map 4.8 in the maps section.

Results of the overlay analysis are presented in Table 4.4 and Figure 4.8. Our analysis shows that about 11 percent of the potential gas resources is on land classified as no access and 30 percent of the gas is on land subject to restricted access. The remainder is on land subject to standard lease terms or not federally owned. Compared to results presented in Advanced Resources International (2001), our results show that a higher fraction of the gas is subject to standard lease terms and a lower fraction is subject to access restrictions or no access. Both analyses use the same distribution of lease stipulations, so the discrepancy reflects differences in the gas re-

Table 4.4

**Percentage of Technically Recoverable Gas from USGS-Based
Scenario Subject to Different Categories of Lease Stipulations**

Stipulation Category[a]	This Study	This Study, Federal Land Only	ARI (2001)
No access[b]	11	17	30
Restricted access[c]	30	44	39
Standard lease terms	59[d]	40	32

[a]Distribution of stipulations is taken from Advanced Resources International , Inc. (2001).

[b]No access includes no access statutory, no access administrative, and no surface occupancy categories.

[c]Restricted access includes all timing lease stipulations and controlled surface use categories.

[d]Includes gas on nonfederal land.
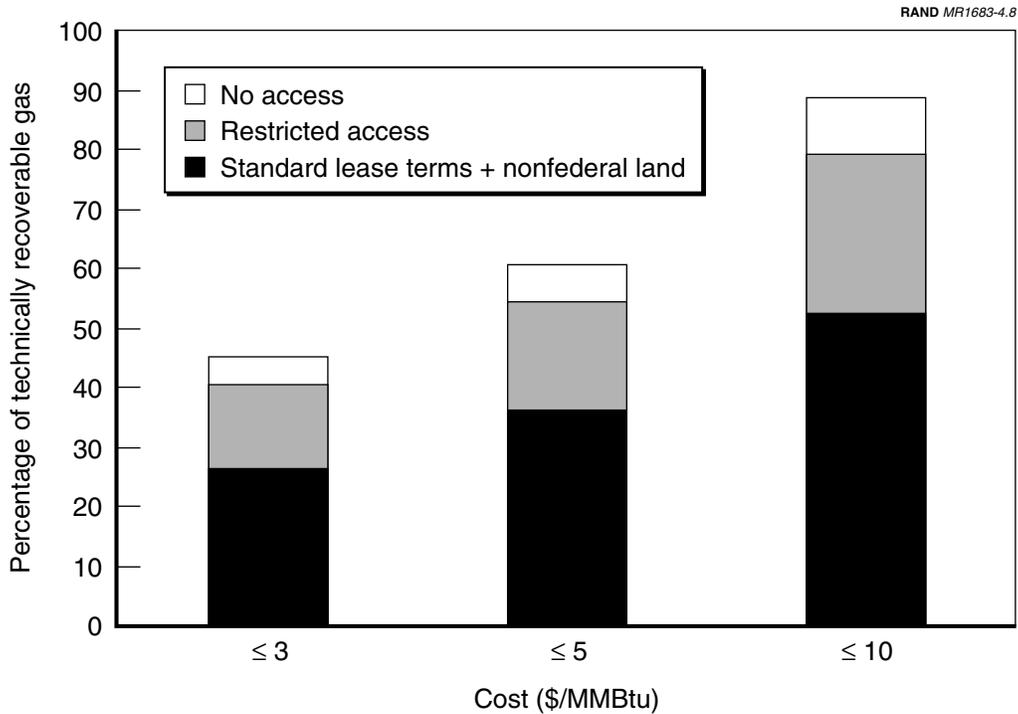

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Figure 4.8—Lease Stipulation Category Overlay Results

source base and spatial distribution used in each analysis. Some of these differences stem from using different data sources and allocation procedures. In addition, the results presented in this report differ in that they include proved reserves, reserve appreciation, and gas underlying nonfederal lands, which are not included in Advanced Resources International (2001). Nonfederal lands are generally considered accessible to industry, so we include nonfederal lands with the standard lease terms category. Including them increases the fraction of resources subject to standard lease terms and decreases the fraction of resources subject to access restrictions.

Our analysis shows that approximately 31 percent of the technically recoverable gas in the Greater Green River Basin underlies nonfederal lands. Recalculating our overlays using only federal lands moves the results closer to those of Advanced Resources International (Table 4.4).[17]

UNCERTAINTY IN OVERLAY RESULTS

Uncertainties in the overlay results are difficult to estimate because the uncertainties in the input data are poorly constrained. Uncertainty derives from two sources: the positional uncertainty in the gas and environmental measure distributions and uncertainty in the data values assigned to each point. The effect of the positional uncertainty can be qualitatively evaluated by comparing the results of overlays of a single environmental measure distribution with the various gas distributions generated at different costs. In terms of the relative proportion of gas in different environmental bins, overlay results for gas distributions generated at different costs agree to within 5 percent (% of ERR in Tables 4.1–4.3). This suggests that variations in the locations of data elements do not significantly affect the overlay results.

In principle, the environmental measure distributions could be perturbed by an estimated uncertainty to determine the sensitivity of the overlay results to the data values. The extent to which the overlay results differed from the overlay with the initial distribution would then give an estimate of the sensitivity. However, because no uncertainty estimates were provided for the data values of the input environmental data, we were unable to estimate the effect they may have on the overlay results. Although the environmental data may be the best available, we can suggest only that results are preliminary and are to be used for general strategic guidance purposes.

SUMMARY

The overlay results shown provide estimates of the amount of resource that satisfies different levels of both economic and environmental criteria and are summarized in Tables 4.1–4.3. In general, we find that relatively small fractions of the technically or economically recoverable natural gas in the Greater Green River Basin occur in areas of relatively higher potential environmental concern with respect to the environmental measures we considered. For the ecological measures, 18 percent of the economically recoverable natural gas is in areas with predicted species richness above the median value and 11 percent is in aquatic or riparian areas. Less than 8 percent of the gas occurs within close proximity of human settlements. Of the water quality measures, only 8 percent occurs in areas with slopes greater than 25 percent, and ar-

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[17]The government's inventory of natural gas subject to various lease stipulations has been revised in the recently released Energy Policy and Conservation Act (EPCA) study (U.S. Departments of Interior, Agriculture, and Energy, 2003). That study finds that 10 percent, 29 percent, and 61 percent of the gas in the Greater Green River Basin is subject to no access, restricted access, and standard lease terms, respectively. The EPCA study results cannot be compared to the overlay results presented in this report because they are based on different distributions of lease stipulations. The differences between the results of the initial Department of Energy study (Advanced Resources International, Inc., 2001) and the EPCA study stem from a number of changes in the approaches used, such as including proved reserves and using a different geographic area.

eas with high aquifer recharge rates and shallow groundwater contain 9 percent and 12 percent, respectively, of the gas in the basin. From 14 to 64 percent of the gas is located in buffer zones around sensitive species observed locations, making this measure outstanding in having a relatively higher fraction of gas in the potentially more sensitive bin.

The interpretation of the environmental measures is less straightforward than the results of the economic analysis, in terms of both the relative importance of the different values of a single measure and the relative importance of the different measures. As discussed above, we have endeavored to select an appropriate suite of environmental measures and to bin values of those measures in meaningful ways. We do not attempt to integrate the separate measures into a single index. For our purposes, it was important to use environmental measures consisting of only professionally reviewed, publicly available data from reliable sources. Combining these data into an integrated index could provide the appearance of simplicity and allow easy ranking of areas, but in reality such an approach would introduce new assumptions and uncertainties, potentially undermining the reliability of any index. Note also that the bin values assigned for the various measures are not necessarily based on established significance thresholds. Setting such thresholds is a task best left to agency discretion and more thorough scientific research than is possible within the scope of this study.

We therefore present the results of the overlay analysis with the environmental measures as an example of how our proposed methodology can be used. Our intention is to develop a systematic framework with which to examine the effect of various environmental measures on the resource assessment. Given this framework, different stakeholders can approach the problem with measures and bins of interest and assess the resources accordingly.