Assessments of Aquifer Sensitivity on Navajo Nation and Adjacent Lands and Ground-Water Vulnerability to Pesticide Contamination on the Navajo Indian Irrigation Project, Arizona, New Mexico, and Utah

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 02-4051

Prepared in cooperation with the

NAVAJO NATION ENVIRONMENTAL PROTECTION AGENCY PESTICIDES PROGRAM

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
Length		
inch	2.540	centimeter
inch	25.4	millimeter
foot	0.3048	meter
mile	1.609	kilometer
Area		
acre	4,047	square meter
square mile	259.0	hectare
square mile	2.590	square kilometer

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Altitude, as used in this report, refers to distance above sea level.

ASSESSMENTS OF AQUIFER SENSITIVITY ON NAVAJO NATION AND ADJACENT LANDS AND GROUND-WATER VULNERABILITY TO PESTICIDE CONTAMINATION ON THE NAVAJO INDIAN IRRIGATION PROJECT, ARIZONA, NEW MEXICO, AND UTAH

By Paul J. Blanchard

ABSTRACT

The U.S. Environmental Protection Agency requested that the Navajo Nation conduct an assessment of aquifer sensitivity on Navajo Nation lands and an assessment of ground-water vulnerability to pesticide contamination on the Navajo Indian Irrigation Project. Navajo Nation lands include about 17,000 square miles in northeastern Arizona, northwestern New Mexico, and southeastern Utah. The Navajo Indian Irrigation Project in northwestern New Mexico is the largest area of agriculture on the Navajo Nation. The Navajo Indian Irrigation Project began operation in 1976; presently (2001) about 62,000 acres are available for irrigated agriculture. Numerous pesticides have been used on the Navajo Indian Irrigation Project during its operation.

Aquifer sensitivity is defined by the U.S. Environmental Protection Agency as "The relative ease with which a contaminant [pesticide] applied on or near a land surface can migrate to the aquifer of interest. Aquifer sensitivity is a function of the intrinsic characteristics of the geologic material in question, any underlying saturated materials, and the overlying unsaturated zone. Sensitivity is not dependent on agronomic practices or pesticide characteristics." Ground-water vulnerability is defined by the U.S. Environmental Protection Agency as "The relative ease with which a contaminant [pesticide] applied on or near a land surface can migrate to the aquifer of interest under a given set of agronomic management practices, pesticide characteristics, and aquifer sensitivity conditions."

The results of the aquifer sensitivity assessment on Navajo Nation and adjacent lands indicated relative sensitivity within the boundaries of the study area. About 22 percent of the study area was not an area of recharge to bedrock aquifers or an area of unconsolidated deposits and was thus assessed to have an insignificant potential for contamination. About 72 percent of the Navajo Nation study area was assessed to be in the categories of most potential or intermediate potential for contamination. About 6 percent of the study area was assessed to have the least potential for contamination, mostly in areas where the slope of the land surface is more than 12 percent. Nearly all fields on the Navajo Indian Irrigation Project were assessed to have the most potential for contamination.

The assessment of ground-water vulnerability to pesticide contamination on the Navajo Indian Irrigation Project was based on pesticide application to various crops on part of the Navajo Indian Irrigation Project during 1997-99. The assessment indicated that ground water underlying fields of beans, wheat, barley, and alfalfa was most vulnerable to pesticide contamination; ground water underlying fields of corn and potatoes was intermediately vulnerable to pesticide contamination; and ground water underlying fields of hay was least vulnerable to pesticide contamination.

INTRODUCTION

The U.S. Environmental Protection Agency (USEPA) requested that the Navajo Nation conduct assessments of aquifer sensitivity on Navajo Nation lands and ground-water vulnerability to pesticide contamination on the Navajo Indian Irrigation Project (NIIP). The results of these assessments are necessary in order for the Navajo Nation to develop a Pesticide Management Plan as required by the USEPA. Aquifer sensitivity is defined by the USEPA as "The relative ease with which a contaminant [pesticide] applied on or near a land surface can migrate to the aquifer of interest. Aquifer sensitivity is a function of the intrinsic characteristics of the geologic material in question, any underlying saturated materials, and the overlying unsaturated zone. Sensitivity is not dependent on agronomic practices or pesticide characteristics" (U.S. Environmental Protection Agency, 1993, p. 9). Ground-water vulnerability is defined by the USEPA as "The relative ease with which a contaminant [pesticide] applied on or near a land surface can migrate to the aquifer of interest under a given set of agronomic management practices, pesticide characteristics, and aquifer sensitivity conditions" (U.S. Environmental Protection Agency, 1993, p. 9).

Navajo Nation lands include about 17,000 square miles in northeastern Arizona, northwestern New Mexico, and southeastern Utah (fig. 1). These lands consist of the contiguous Navajo Reservation, three non-contiguous reservations (the Alamo Navajo Reservation, the Cañoncito Navajo Reservation, and the Ramah Navajo Reservation), and, in northwestern New Mexico, land purchased by the Navajo Nation and land allotments to individual Navajo Tribal members. Land ownership in northwestern New Mexico is mixed: in addition to Navajo Tribal members, other land owners include the U.S. Government, the State of New Mexico, and non-Navajo people.

The largest area of agriculture on Navajo Nation lands is the NIIP in northwestern New Mexico (fig. 1), which is operated by the Navajo Agricultural Products Industries (NAPI). All cropland on this project is irrigated. The NIIP began operation in 1976; presently (2001) about 62,000 acres are available for irrigated agriculture. Numerous pesticides have been used on the NIIP during its operation.

In addition to the NIIP, at least 11 community irrigation systems have been operated or are under consideration on the Navajo Nation. There is no known documentation of pesticide sales or use regarding these community irrigation systems, but pesticide use on these systems is reported to be minimal. Each of these systems typically includes less than 5,000 acres.

Purpose and Scope

This report has three purposes. The first is to describe the methods developed and used to assess aquifer sensitivity on Navajo Nation and adjacent lands and ground-water vulnerability to pesticide contamination on the NIIP. The second purpose is to present the results of these assessments. The third purpose is to provide assessment tools that the Navajo Nation can use with minor modification to assess aquifer sensitivity at specific locations and ground-water vulnerability under differing agricultural practices.

Methods development included locating sources of and obtaining, reviewing, and assessing available data and electronic databases on geology, precipitation, soils, topography, hydrologic characteristics in the study area, and pesticide characteristics and use of pesticides on the NIIP. Subsequently, each database that was evaluated to be useful for conducting the assessments was modified as necessary and converted into a geographic information system (GIS) coverage. These coverages included geology (areas of unconsolidated deposits and areas where bedrock aquifers are recharged), precipitation, soil properties, slope of the land surface, stream courses, and pesticide use on part of the NIIP. The assessments consisted of assigning ratings or scores to values of the characteristics represented on the GIS coverages, overlaying the GIS overages, and combining the scores from each contributing coverage.

Lands assessed included the contiguous Navajo Indian Reservation; the non-contiguous Alamo, Cañoncito, and Ramah Navajo Reservations; non-Navajo lands between and (or) adjacent to the reservations; and lands of mixed ownership in northwestern New Mexico. These lands are referred to in this report as the “Navajo Nation study area.” All lands in northwestern New Mexico were assessed, regardless of ownership. The entire area under consideration in this study included about 21,500 square miles.

Geohydrologic Setting

The Navajo Nation study area is part of the Colorado Plateaus Physiographic Province (Fenneman, 1931), which is characterized by thick sequences of sedimentary rocks with deep canyons downcut into the sedimentary strata. The strata typically are flat lying or dipping at a low angle. These flat-lying or nearly flat-lying strata are interrupted by broad anticlinal, synclinal, and monoclinal folds and, locally, by intrusive and extrusive igneous rocks.

The United States has been divided into 15 ground-water regions (Heath, 1984), and the entire study area is within the Colorado Plateau and Wyoming Basin Region. The Colorado Plateau and Wyoming Basin Region is described as being typically composed of thin, patchy, and rocky soils overlying sedimentary strata and having sparse vegetation.

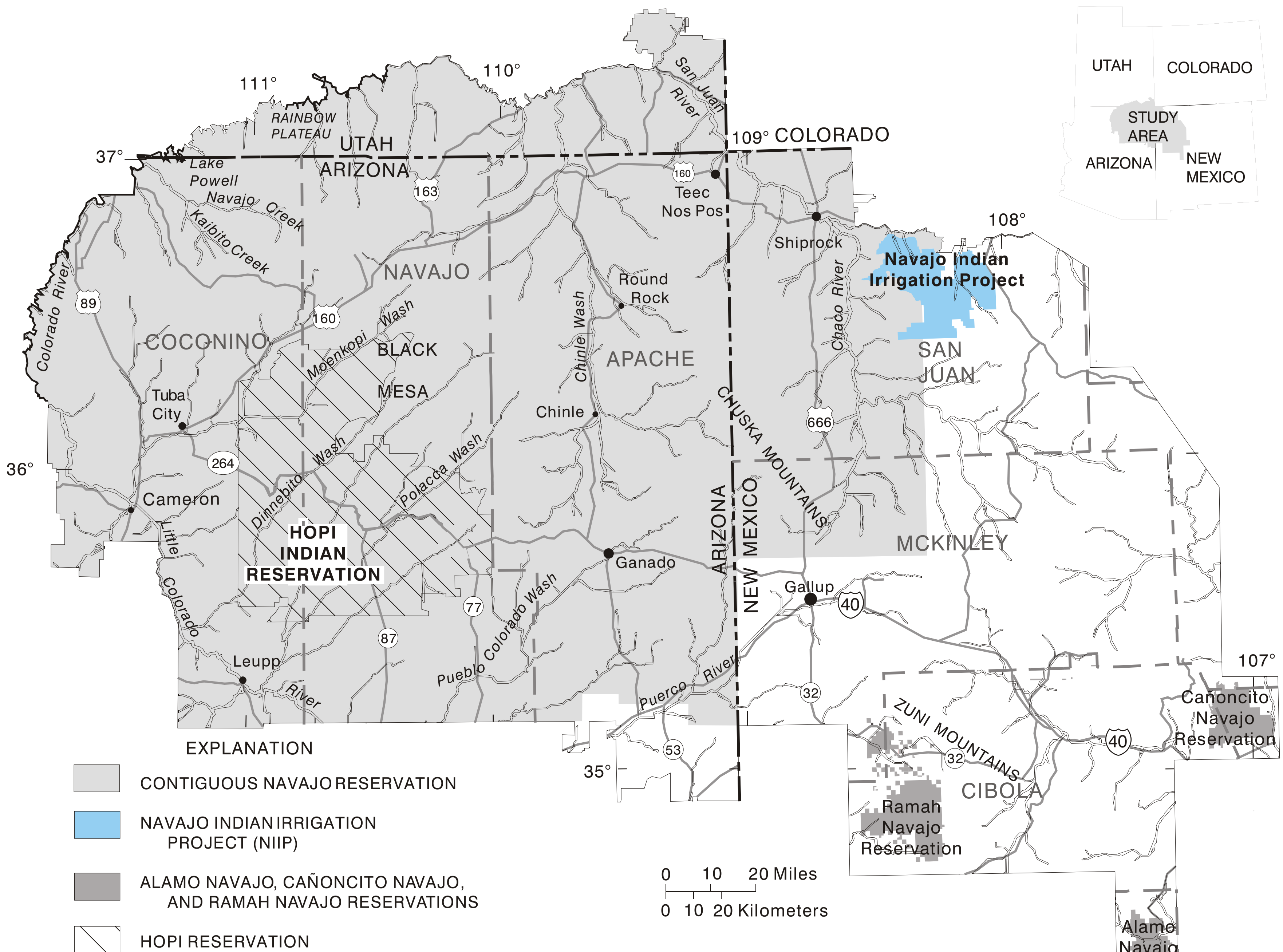

Figure 1. Navajo Nation study area.

Ground water is in shallow, unconfined, unconsolidated aquifers and in underlying bedrock aquifers, which may be either confined or unconfined. Aquifers in unconsolidated deposits are in alluvium and terrace deposits along drainages, in eolian deposits in upland areas, and in landslide deposits along the margins of upland areas. Areas within the approximate boundaries of the contiguous Navajo Reservation that are unconsolidated deposits and (or) are recharge areas to bedrock aquifers are identified in figure 2 as areas having significant potential to facilitate contamination of ground water.

In the areas identified as having significant potential to facilitate contamination of ground water (fig. 2), the land surface and underlying aquifers are hydrologically connected; therefore, in these areas the quality of ground water can be affected by human activities at land surface, including agriculture. Agricultural chemicals applied at land surface can be transported downward to the ground-water system by infiltration and percolation of precipitation or irrigation water.

Review of Selected, Previously Used Assessment Methods

The USEPA has compiled information on 11 aquifer sensitivity assessment methods and 22 ground-water-vulnerability assessment methods (U.S. Environmental Protection Agency, 1993). Aquifer sensitivity methods are described by the USEPA as the most appropriate screening tool of large areas, and ground-water-vulnerability methods are described by the USEPA as the most appropriate for use at the field or plot level.

The most well-known and commonly used method to assess aquifer sensitivity is a system that assigns ratings and weights to hydrogeologic factors titled “DRASTIC: a standardized system for evaluating ground-water pollution potential using hydrogeologic settings” (Aller and others, 1985). DRASTIC is an acronym for factors that are considered by the method: depth to ground water, recharge, aquifer media, soil media, topography, impact of the vadose zone, and hydraulic conductivity of the aquifer. Aller and others (1985) also developed agricultural DRASTIC to be used when considering the potential effects of agriculture on underlying ground water. Slightly different weights have been assigned to soil media, topography, impact of the vadose zone, and hydraulic conductivity of the aquifer in agricultural DRASTIC.

DRASTIC and agricultural DRASTIC specify ratings weights for each of the seven factors. Each factor is divided into ranges of values, and ranges are assigned a rating from 1 to 10. For example, recharge, in inches per year, is divided into five ranges: 0 to 2, 2 to 4, 4 to 7, 7 to 10, and more than 10, and these ranges are assigned ratings of 1, 3, 6, 8, and 9, respectively. The weight of each factor depends on its relative significance. In agricultural DRASTIC, depth to water and soil media were assigned a weight of 5; recharge and impact of the vadose zone were assigned a weight of 4, aquifer media and topography were assigned a weight of 3, and conductivity was assigned a weight of 2.

Several States and at least one private entity have conducted aquifer sensitivity assessments using the DRASTIC method (Soller, 1992). Soller compared the results of DRASTIC and several other assessment methods at the county level in the Midwest. Soller commented that data required by the DRASTIC assessment method typically are not available or are inadequate, especially for depth to ground water, recharge, and hydraulic conductivity. Soller also reported that in areas where data were inadequate and standard values were used instead of real data, the assignment of standard values varied considerably with different investigators. This variability adversely affected comparability between areas investigated by different individuals. Soller recommended that the DRASTIC method be modified to include only characteristics for which adequate data are available.

An example of a modified DRASTIC method is that used in the Denver Basin by Hearne and others (1995) to determine sensitivity of the uppermost ground water in the greater Denver, Colorado, area. This study covered about 2,500 square miles. Characteristics assessed included depth to ground water, soil media, topography of the land surface, and geohydrologic unit (impact of the vadose zone) but did not include recharge, aquifer media, or hydraulic conductivity. Aquifer media and hydraulic conductivity of the aquifer, however, address the fate of water and its solutes within the saturated zone rather than in the overlying unsaturated zone. Recharge was generally considered to be in the lowest category of recharge defined by Aller and others (1985); variation of recharge in the study area was not quantified. Ratings for selected characteristics developed by Aller and others (1985) and Hearne and others (1995) are listed in table 1.

Table 1. Ratings and weights of selected factors that contribute to potential for contamination

[Rating, potential for contamination, ranging from 1 to 10; weight, comparative potential for contamination among factors; >, greater than; <, less than]

Depth to water (feet)	Rating	Annual recharge (inches)	Rating	Slope of land surface (percent)	Rating
		Aller and others, 1985			
0 to 5	10	>10	9	0 to 2	10
5 to 10	9	7 to 10	8	2 to 6	9
15 to 30	7	4 to 7	6	6 to 12	5
30 to 50	5	2 to 4	3	12 to 18	3
50 to 75	3	0 to 2	1	>18	1
75 to 100	2				
>100	1				
Weight = 5		Weight = 4		Weight = 3	
		Hearne and others, 1995			
<5	10			<6	10
5 to 20	9			6 to 12	5
>20	7			>12	3

The resulting map contained 158 “vulnerability response units,” with each response unit appearing in 1 to 92 areas on the map. Hearne and others (1995) labeled these areas as “vulnerability response units” even though no agronomic management practices or pesticide characteristics were included in the assessment. According to USEPA definitions (U.S. Environmental Protection Agency, 1993, p. 9), these units would be called “sensitivity response units.”

Ground-water-vulnerability assessment methods were subdivided by the USEPA (1993) into computer simulation methods (15 studies), pesticide leaching methods (5 studies), and pesticide loading methods (2 studies). Computer simulation methods typically require programming expertise and computers containing large amounts of memory, each of which may limit their use by the general population. Therefore, these methods were not considered for this study. Pesticide leaching methods typically evaluate pesticide properties. Three of the methods compiled by the USEPA (1993) also incorporate soil, hydrogeologic, and (or) climate characteristics. None consider pesticide application amounts.

One of the two pesticide loading methods simply adds a pesticide application amount to the aquifer sensitivity assessment. The other pesticide loading method, relative aquifer vulnerability evaluation (RAVE) (DeLuca and Johnson, 1990), includes irrigation practices, frequency of pesticide application, and a relative pesticide leaching potential based on the sorption coefficient and half-life of the applied pesticide. RAVE was developed and is used by the Montana Department of Agriculture and is intended for onsite determinations.

AQUIFER SENSITIVITY ON NAVAJO NATION AND ADJACENT LANDS

This section describes development of the assessment method and the results of the assessment of aquifer sensitivity on Navajo Nation and adjacent lands. Development included selecting characteristics to include in the assessment method and sources of data used to describe these characteristics, developing a method to combine data describing each characteristic, and interpreting the results of this combination.

Method Developed for Assessment of Aquifer Sensitivity

The Navajo Nation study area, because of its size and relative isolation, typically is lacking in detailed information regarding geology, soils, and hydrology that is required to use a rigorous scoring method such as DRASTIC. For example, soil surveys have been conducted on only small parts of the Navajo Nation. Although 965 data points are available regarding depth to ground water, the data were still too sparse (on average, one data point for about every 20 square miles) to determine areas of relative potential to facilitate contamination. The method developed for this study, therefore, required optimal use of limited data. Characteristics for which data were considered adequate included geology within the approximate boundaries of the contiguous Navajo Reservation only (impact of the vadose zone), precipitation (a surrogate for recharge), soil properties, slope of the land surface (topography), and location of stream courses.

Aquifer media and hydraulic conductivity of the aquifer (Aller and others, 1985) address the fate of water and its solutes within the saturated zone rather than in the overlying unsaturated zone. Although the definition of aquifer sensitivity includes characteristics of saturated materials (U.S. Environmental Protection Agency, 1993), these factors, along with hydraulic gradient, describe the direction and rate of the movement of water and its solutes once they have entered the aquifer. Therefore, they are important for assessing where the solutes can be expected to travel. The emphasis of this assessment of aquifer sensitivity, however, is to assess the relative protection the overlying material affords the aquifer. Aquifer media and hydraulic conductivity of the aquifer, therefore, were not considered in this assessment.

The largest limitation of the method developed for assessment of aquifer sensitivity on Navajo Nation and adjacent lands is the lack of adequate information to describe depth to the uppermost ground water throughout the study area. The rating for depth to water is included in table 1 to demonstrate its importance regarding potential for contamination. Aller and others (1985) and Hearne and others (1995) indicated a rating of 10 where ground water is within 5 feet of land surface; Aller and others (1985) indicated a rating of 1 where ground water is more than 100 feet below land surface. Depth to the uppermost ground water in the study area ranges from less than 10 feet along some stream courses to more than 1,300 feet in the northwestern part of the study area.

In addition to the lack of adequate information needed to describe depths to ground water throughout the study area geographically, the available depth-to-water data do not reliably indicate depth to the uppermost ground water. An example is on the north part of Black Mesa (fig. 1) where wells that supply a coal slurry operation penetrate several aquifers prior to accessing a deep, confined aquifer because the deep, confined aquifer provides the large quantity of water required by the slurry. The overlying aquifers are capable of supplying only much smaller quantities of water. Depth to water in the deep, confined aquifer is more than 700 feet. The uppermost ground water, however, is as shallow as 10 feet.

Geology

Cooley and others (1969) identified areas within the approximate boundaries of the contiguous Navajo Reservation where consolidated rocks are recharged and where unconsolidated deposits are at the surface. Unconsolidated deposits included alluvium, eolian deposits, terrace deposits, and landslide deposits.

In this assessment, geology served as a surrogate for impact of the vadose zone (Aller and others, 1985) and was described in terms of potential to facilitate contamination of ground water. Two categories were used, significant and insignificant, and were assigned numerical values of 1 and 0, respectively. Within the approximate boundaries of the contiguous Navajo Reservation, areas identified by Cooley and others (1969) where consolidated rocks are recharged and where unconsolidated deposits are at land surface were assigned to the category significant potential to facilitate contamination of ground water and assigned a numerical value of 1. The remaining areas within the approximate boundaries of the contiguous Navajo Reservation were assigned to the category insignificant potential to facilitate contamination of ground water and assigned a numerical value of 0. These areas are shown in figure 2.

The part of the study area that extends beyond approximately the eastern and southeastern boundaries of the contiguous Navajo Reservation was not included in the analysis of Cooley and others (1969), and areas of recharge to consolidated rocks and areas of unconsolidated deposits therefore were not identified beyond these boundaries. Regarding geology, the potential to facilitate contamination of ground water in this part of the study area has been identified in figure 2 as undetermined. In order to not underestimate the potential of this part of the study area to facilitate contamination, however, it was included in the category significant potential to facilitate contamination and assigned a numerical value of 1 (fig. 2).

Precipitation

Because precipitation provides the solvent (water) in which contaminants are transported from land surface to an underlying aquifer, larger precipitation amounts typically increase the potential for contaminants to infiltrate the land surface and move downward toward underlying aquifers. In this assessment, precipitation was used as a surrogate for recharge. Actual recharge, however, typically is a small percentage of precipitation.

The percentage of precipitation that becomes recharge has been estimated by several investigators. Eychaner (1983) estimated recharge to be 1 to 3 percent of precipitation on and north of Black Mesa, respectively. In eastern Colorado, two estimates of the percentage of annual precipitation that becomes annual recharge were 4 percent (Erker and Romero, 1967) and less than 10 percent (Hurr and others, 1975).

The **P**arameter-Elevation **R**egressions on **I**ndependent **S**lopes **M**odel (PRISM) database, developed by Oregon State University, was used to provide precipitation data for this assessment (Daly and Taylor, 1998). Using this model, Daly and Taylor estimated annual precipitation in the study area to range from 5 to 35 inches. By using 10 percent as the maximum percentage of precipitation that becomes recharge (Hurr and others, 1975), estimated recharge in the study area would range from 0.5 to 3.5 inches. This range is within the two smallest (0 to 2 inches and 2 to 4 inches) of five categories described by Aller and others (1985). The five categories of recharge described in DRASTIC (Aller and others, 1985) exceed the range of recharge in the study area because DRASTIC was designed for use throughout the United States.

In this assessment, precipitation was divided into three categories to determine relative potential to facilitate contamination of ground water: least, intermediate, and most, having corresponding numerical values of 1, 2, and 3, respectively. Precipitation was categorized as follows: less than 8 inches, “least potential to facilitate contamination”; 8 to 16 inches, “intermediate potential to facilitate contamination”; and more than 16 inches, “most potential to facilitate contamination.” The potential for precipitation to facilitate contamination of ground water throughout the study area is shown in figure 3.

Soil Properties

Texture, infiltration rate, drainage, and organic content are principal soil properties that control the potential for contaminant movement from land surface through soils to underlying geologic materials. Soil texture controls hydraulic conductivity, the rate at which water and the solutes it contains move through the soil. Fine-grained soils (silts and clays) also have sorption sites to which contaminants can attach. Infiltration rate controls the amount of water entering the soil from land surface. Drainage rate controls the time that water and its solutes are in contact with the soil prior to leaving the soil. Organic material can decrease the amount of pesticides in solution by microbial activity and sorption. A soil that has a coarse-grained texture, a high infiltration rate, a low organic content, and is well drained has a larger potential for contaminant delivery from land surface to the underlying geologic material than a soil that has a fine-grained texture, a low infiltration rate, a high organic content, and is poorly drained.

The **STAT**e **S**oil **G**e**O**graphic (STATSGO) database was created by the U.S. Department of Agriculture, Natural Resources Conservation Service (1994) and subsequently was modified for ease of use on U.S. Geological Survey (USGS) computer systems (Schwarz and Alexander, 1995). The STATSGO database was digitized at a scale of 1:250,000 and was designed to be used at the multicounty, State, and regional level.

The STATSGO database contains a calculated classification of soils called hydrologic group, which was used in this assessment. Characteristics combined to create hydrologic group (class) include texture, infiltration rate, and drainage classification (Schwarz and Alexander, 1995). Class 1 soils are sands and gravels having high infiltration rates and are well drained to excessively drained. Class 2 soils are moderately coarse grained, have moderate infiltration rates, and are moderately well drained to well drained. Class 3 soils are moderately fine to fine grained or have layers that impede downward movement of water, have low infiltration rates, and are poorly drained. Class 4 soils are high in clay content and have low infiltration rates, may be underlain by a confining layer, and are very poorly drained.

In the STATSGO database, a soil hydrologic group (1, 2, 3, or 4) was assigned to each component of a soil mapping unit. A weighted average of these values was then calculated to determine a soil hydrologic group score for each mapping unit. These values ranged from 1 to 4.

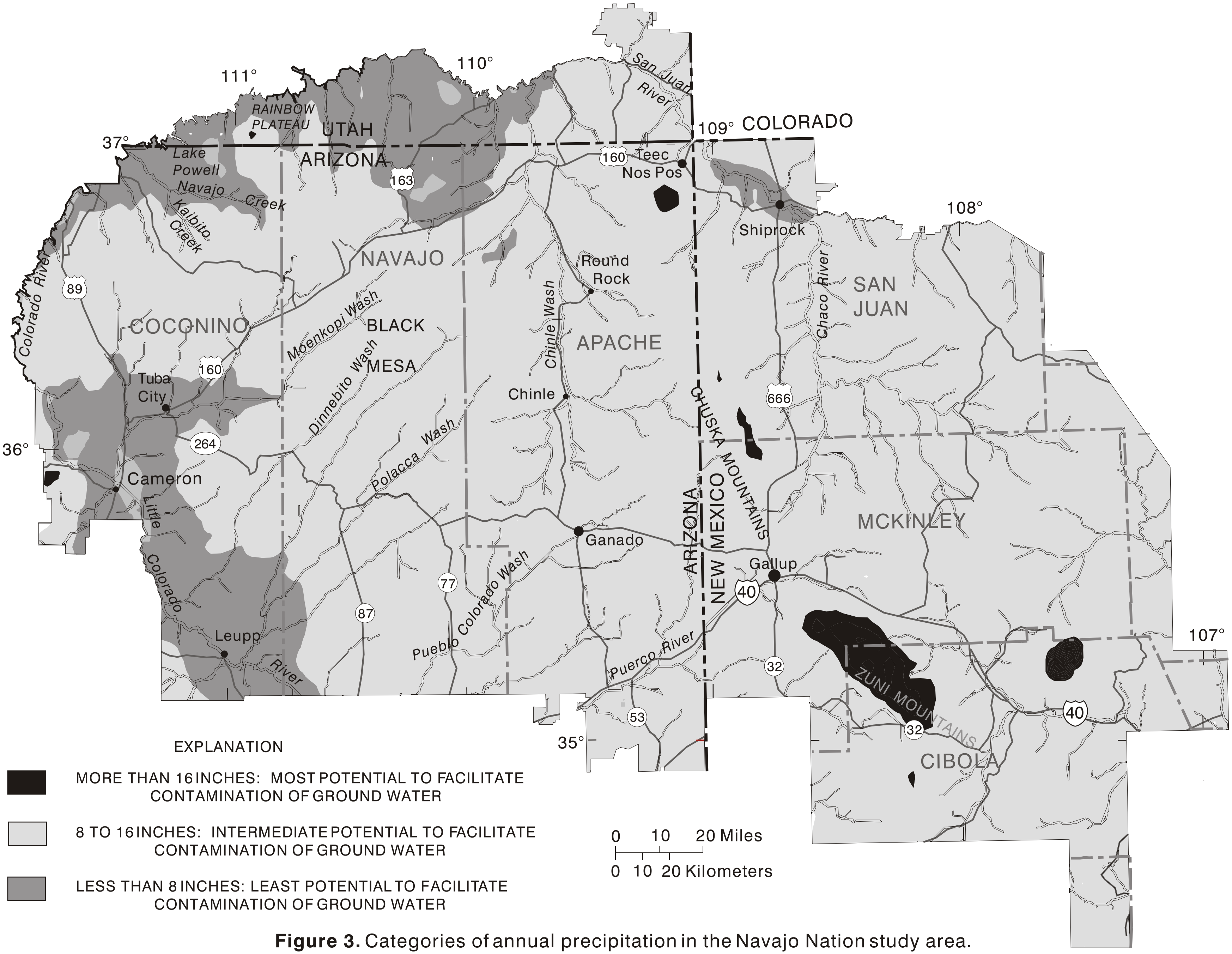

Figure 3. Categories of annual precipitation in the Navajo Nation study area.

Organic content in soils was not included in the determination of hydrologic group (Schwarz and Alexander, 1995). Data describing organic material, however, were included in the STATSGO database and were evaluated as part of this assessment. Soil organic content was less than 2 percent in all soils throughout the study area. Therefore, microbial activity and sorption were considered to be minimal, and all soils were assessed to be in the category most potential to facilitate contamination regarding soil organic content. Because the entire area was assessed to have the same potential to facilitate contamination and, therefore, to have little relative difference throughout the area, no value for organic content was included in the assessment.

In this assessment, soil properties also were described in terms of potential to facilitate contamination of ground water. Three categories were used: least, intermediate, and most, having corresponding numerical values of 1, 2, and 3, respectively. Categories of hydrologic group were: more than 3, least potential to facilitate contamination; 2 to 3, intermediate potential to facilitate contamination; and less than 2, most potential to facilitate contamination. The potential for soils to facilitate contamination of ground water throughout the study area is shown in figure 4.

Slope of the Land Surface

The slope of the land surface affects the ability of precipitation to infiltrate soils and geology. Precipitation falling on a nearly flat land surface remains nearly stationary, maximizes the time available for infiltration because of storage time on the land surface, and therefore maximizes the potential for infiltration. Conversely, precipitation falling on a steep land surface has little storage time on the land surface and will begin moving downslope as soon as the precipitation rate exceeds the infiltration capacity of the upper soil layer. The potential for infiltration, therefore, is minimized.

In this assessment, USGS digital elevation models (DEM's) were used to determine slope of the land surface, and slope of the land surface was described in terms of potential to facilitate contamination of ground water. Three categories were used: least, intermediate, and most, having corresponding numerical values of 1, 2, and 3, respectively. Slopes of more than 12 degrees were considered to have the least potential to facilitate contamination; slopes of 6 to 12 degrees were considered to have intermediate potential to facilitate contamination; and slopes of less than 6 degrees were considered to have the most potential to facilitate contamination. These categories of land-surface slope are similar to those of Aller and others (1985) and Hearne and others (1995) (table 1). The potential for slope of the land surface to facilitate contamination of ground water throughout the study area is shown in figure 5.

Stream Courses

Flood plains and terraces bordering streams typically are areas of the most potential to facilitate contamination of ground water compared to surrounding areas because shallow ground water is stored in and moves through these deposits. These deposits most often have a sandy texture and a corresponding high infiltration rate and low organic content. Underlying bedrock may perch water in these deposits because of its lower infiltration rate, or the water may recharge an underlying aquifer.

In several locations, flood-plain deposits were not identified in the STATSGO database because of their small geographical area. Stream courses throughout the study area, therefore, were identified using DEM's. Strahler fourth-order and higher stream courses (Strahler, 1963, p. 504) were generated using the ARC/INFO grid module. Areas identified by this procedure were categorized as having the most potential to facilitate contamination and were assigned a numerical score of 9.

Although actual precipitation may be less than 16 inches on the stream course, runoff following precipitation typically concentrates in stream courses. Soils on flood plains and terraces bordering streams typically are composed of materials that place them in hydrologic group 1, and the topography of stream courses typically is nearly flat, both parallel and perpendicular to the stream. Stream courses are shown in figures 1 through 6.

Conducting the Assessment: Combining Characteristics

The aquifer sensitivity assessment was conducted by overlaying GIS coverages of geology, precipitation, soil properties, and slope. For each geographic area (GIS polygon) in the combined coverage, the scores for precipitation, soil properties, and slope were summed and then multiplied by the score for geology (either 0 or 1) to determine the final

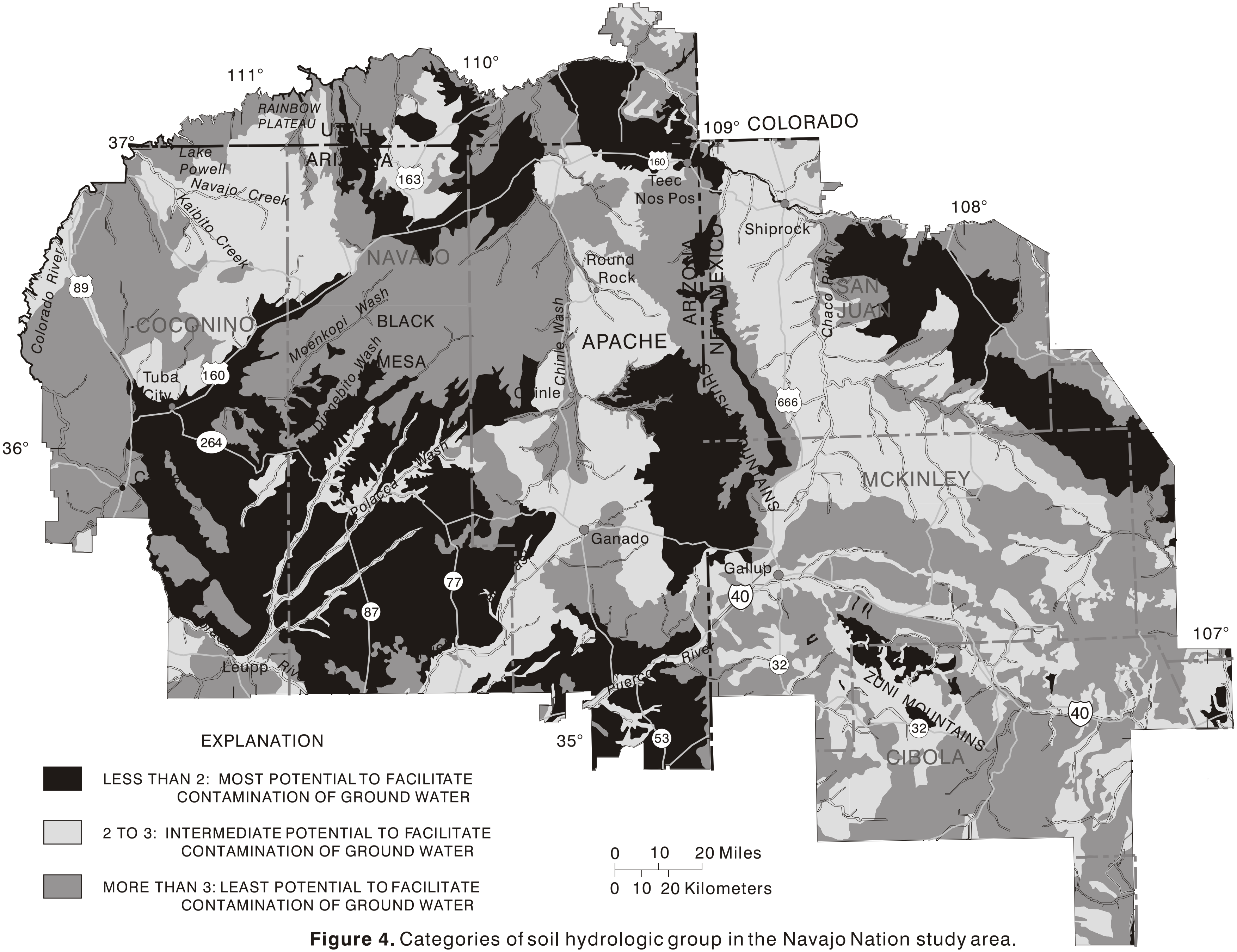

Figure 4. Categories of soil hydrologic group in the Navajo Nation study area.

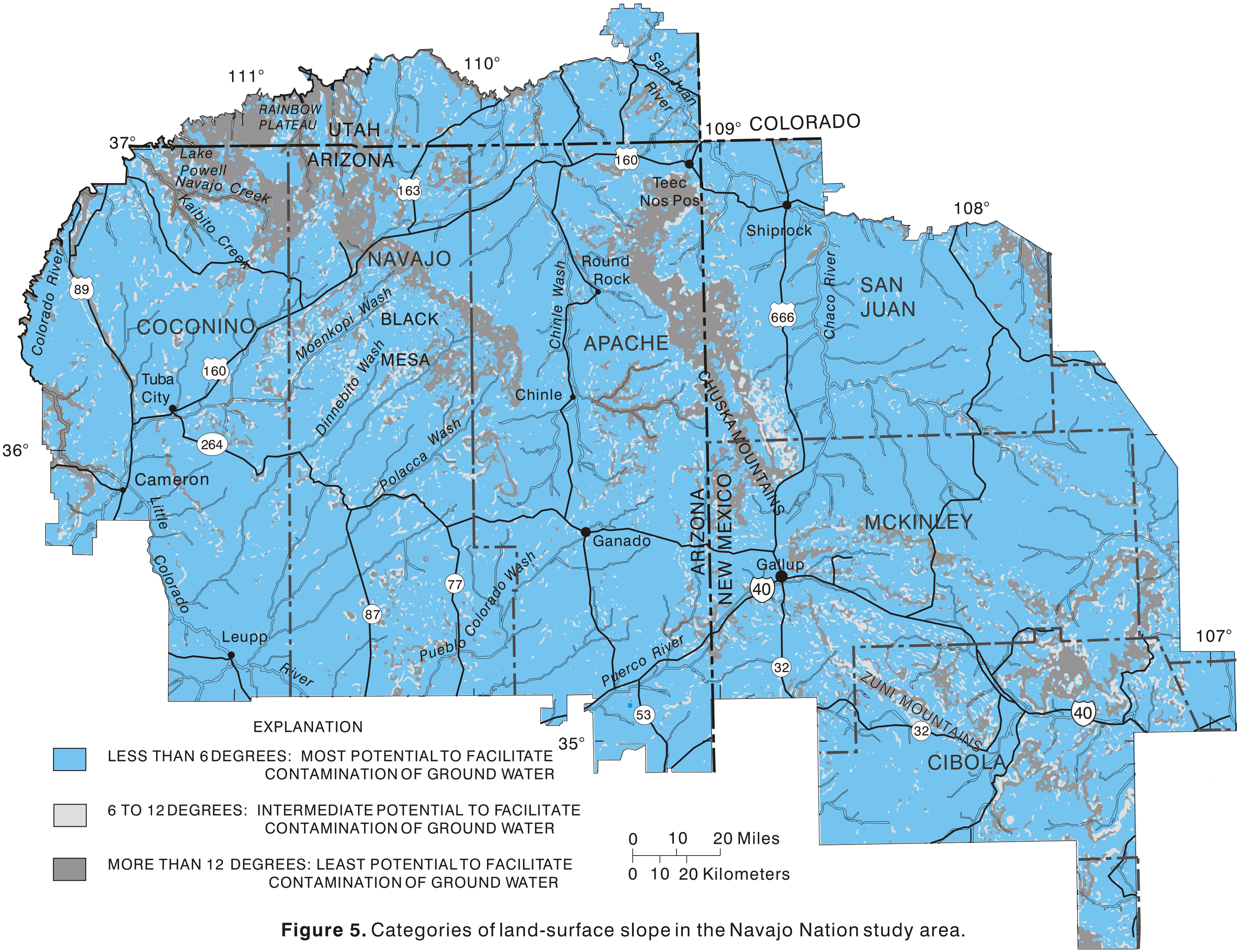

Figure 5. Categories of land-surface slope in the Navajo Nation study area.

score. Scores for polygons within the boundaries of the contiguous Navajo Reservation that were neither areas of recharge to bedrock aquifers nor areas of unconsolidated deposits were zero (geology score = 0). Scores for polygons that were areas of recharge to bedrock aquifers and (or) areas of unconsolidated deposits ranged from 3 where the least potential to facilitate contamination occurred for precipitation, soil properties, and slope to 9 where the most potential to facilitate contamination occurred for these characteristics. No scores were greater than 0 or less than 3. Stream courses were the exception to this assessment method; they were assigned a score of 9.

Finally, the aquifer sensitivity assessment was completed by converting the numerical scores to categories of "potential for contamination." These categories are defined as: 0, insignificant potential; at least 3 but less than 5, least potential; 5 to 7, intermediate potential; and more than 7, most potential for contamination.

The resulting score for any area within the boundaries of the study area is comparable to that of any other area and indicates relative potential to facilitate contamination. The resulting scores, however, are not comparable to any other assessment conducted either within or beyond the boundaries of this study, unless the same data sources and the same assessment method are used.

Results of Assessment of Aquifer Sensitivity

Results of the assessment of aquifer sensitivity on Navajo Nation and adjacent lands are shown in figure 6. The results indicated that about 22 percent of the study area has an insignificant potential for contamination, being neither bedrock recharge areas nor areas of unconsolidated deposits. The results indicate potential for contamination based on actual precipitation conditions (fig. 3). If this assessment method were used to determine the potential for contamination of an existing or proposed irrigated-agriculture project, it would need to be modified to adjust precipitation to the category most potential to facilitate contamination. This adjustment would account for the increased potential recharge resulting from irrigation.

About 71 percent of the Navajo Nation study area was assessed to be in the categories most potential (more than 40 percent) or intermediate potential (more than 31 percent) for contamination (fig. 6). About 6 percent of the study area was assessed to be in the category least potential for contamination, generally in areas where the slope of the land surface is greater than 12 percent (fig. 5). In the northwestern part of the study area near Navajo Creek and the Rainbow Plateau, precipitation is less than 8 inches; this also contributes to parts of this area being in the category least potential for contamination (figs. 3 and 6).

Nearly all the NIIP (about 96 percent) was assessed to be in the category most potential for contamination; the remaining 4 percent of the NIIP was assessed to be in the category intermediate potential for contamination (fig. 7). The areas of intermediate potential for contamination are on the periphery of the NIIP and along small areas of Gallegos Canyon, Ojo Amarillo Canyon, and an unnamed drainage west of Ojo Amarillo Canyon. Following an adjustment for precipitation to account for the effects of irrigation, all irrigated fields except a small part of one field along Ojo Amarillo Canyon were assessed to be in the category most potential for contamination.

GROUND-WATER VULNERABILITY TO PESTICIDE CONTAMINATION ON THE NAVAJO INDIAN IRRIGATION PROJECT

This section describes the method developed for assessment of ground-water vulnerability to pesticide contamination on the NIIP. Subsequently, it describes the results of the assessment and additional applications of the method.

Method Developed for Assessment of Ground-Water Vulnerability

To quantitatively determine ground-water vulnerability on the NIIP or how the application of pesticides to a particular field affects underlying ground water, the concentration of each pesticide in ground water underlying that field would need to be determined. In the absence of available laboratory-determined concentrations of pesticides in ground water underlying the NIIP, the vulnerability of ground water was determined by using leachability data for pesticides typically applied to each crop. Pesticide

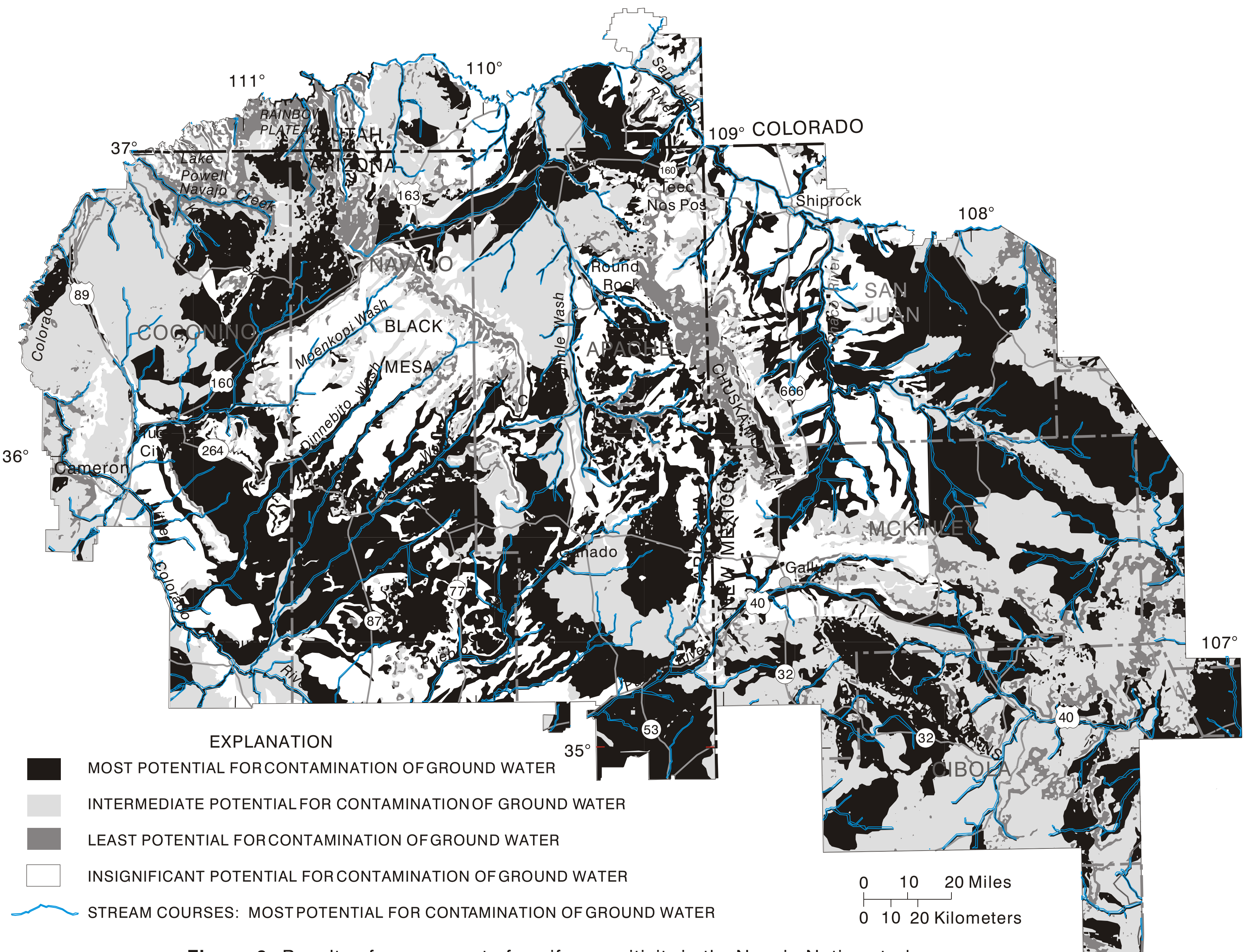

Figure 6. Results of assessment of aquifer sensitivity in the Navajo Nation study area.

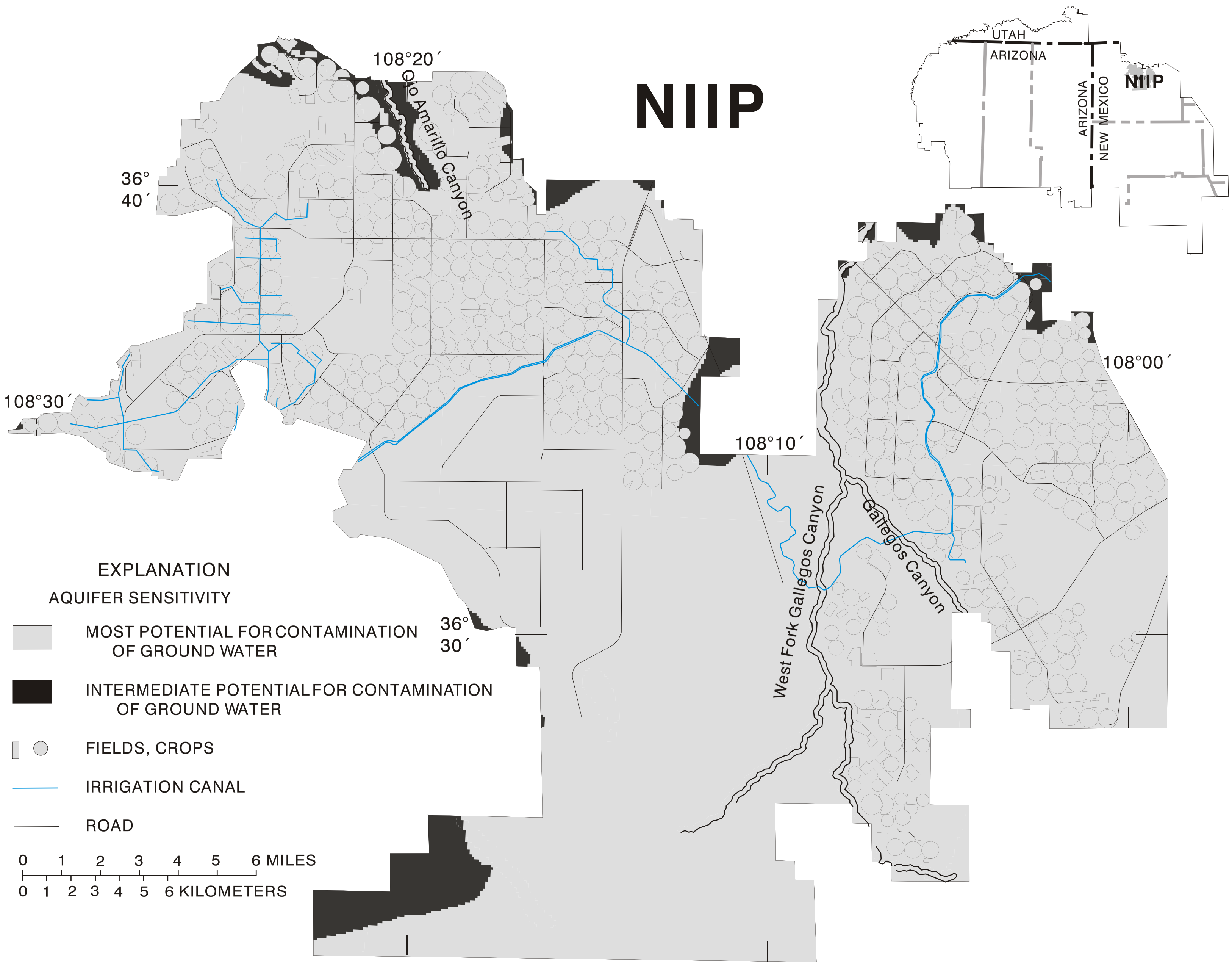

Figure 7. Results of assessment of aquifer sensitivity on the Navajo Indian Irrigation Project (NIIP).

application data for the 1997-99 growing seasons on block I of seven blocks on the NIIP were obtained from the NAPI (James Dangler, written commun., 2000), and pesticide leachability data were obtained from the Montana Department of Agriculture (DeLuca and Johnson, 1990; Donna Rise, written commun., 2001). The location of block I fields is shown in figure 8.

The following steps were conducted to prepare available pesticide application data for use in the ground-water vulnerability assessment. First, for the 1997-99 growing seasons, fields in block I of the NIIP were categorized by crop. The number of fields that were planted in each crop during the 3-year period were: beans, 57; corn, 45; potatoes, 37; wheat, 37; hay (fields used for grazing), 16; barley, 8; and alfalfa, 6. Second, the number of fields on which each pesticide was used on each crop during 1997-99 was summed (table 2).

Pesticides used during 1997-99 were then divided into two groups: those “typically applied” and those “not typically applied” to each crop (table 2). Pesticides that were applied to 40 percent or more of fields planted in a particular crop were considered to be “typically applied” to that crop. The difference was characteristically large between the percentage of fields on which pesticides in the “typically applied” group were applied (43 to 100 percent) and the percentage of fields on which pesticides in the “not typically applied” group were applied (2.2 to 35 percent). These percentages are listed in table 3.

Oregon State University has determined ground-water ubiquity scores for nearly all the pesticides applied to block I of the NIIP during 1997-99 (Donna Rise, written commun., 2001). Ground-water ubiquity scores are determined by the equation:

$$\text{Ground-water ubiquity score} = (\log t)(4 - \log Koc)$$

where t = pesticide half-life, and
Koc = pesticide sorption coefficient.

The Montana Department of Agriculture has assigned descriptive terms, called relative pesticide leaching potentials, to ranges of ground-water ubiquity scores to provide pesticide users a tool with which to compare potential effects of pesticides on shallow ground water (DeLuca and Johnson, 1990; Donna Rise, written commun., 2001). These terms and their respective ground-water ubiquity scores are: extremely low, less than 0.1; very low, 0.1 to 1.0; low, 1.0 to 2.0; moderate, 2.0 to 3.0; high, 3.0 to 4.0; and very high, more than 4.0. In this assessment, crops were ranked by the number of typically applied pesticides that had (1) a very high relative pesticide leaching potential, then by the number of typically applied pesticides that had (2) a high relative pesticide leaching potential, and then by the number of typically applied pesticides that had (3) a moderate relative pesticide leaching potential.

Typically, a ground-water vulnerability assessment is a combination of the results of an aquifer sensitivity assessment and agricultural practices. Because the results of the aquifer sensitivity assessment were the same on all fields of the NIIP and, therefore, had no relative difference throughout the NIIP, the results of the ground-water vulnerability assessment were used independently.

Results of Assessment of Ground-Water Vulnerability

The results for crops ranked by the number of typically applied pesticides are listed in table 4. The relative vulnerability of ground water to contamination by pesticides underlying fields on the NIIP, based on crops grown on each field in 2000, is shown in figure 9. This relative vulnerability of ground water is based on expected pesticide applications to each crop.

One pesticide typically applied to beans, wheat, barley, and alfalfa had a very high relative pesticide leaching potential. Fields planted in these crops in 2000 were identified, and ground water underlying these fields was considered most vulnerable to pesticide contamination.

No pesticide typically applied to corn and potatoes had a very high relative pesticide leaching potential, but two pesticides typically applied to corn and one pesticide typically applied to potatoes had high relative pesticide leaching potentials. Fields planted in these crops in 2000 were identified, and ground water underlying these fields was considered intermediately vulnerable to pesticide contamination.

No pesticide typically applied to hay had either a very high or a high relative pesticide leaching potential, but two pesticides typically applied to hay had a moderate relative pesticide leaching potential. Fields planted in hay in 2000 were identified, and ground water underlying these fields was considered least vulnerable to pesticide contamination.

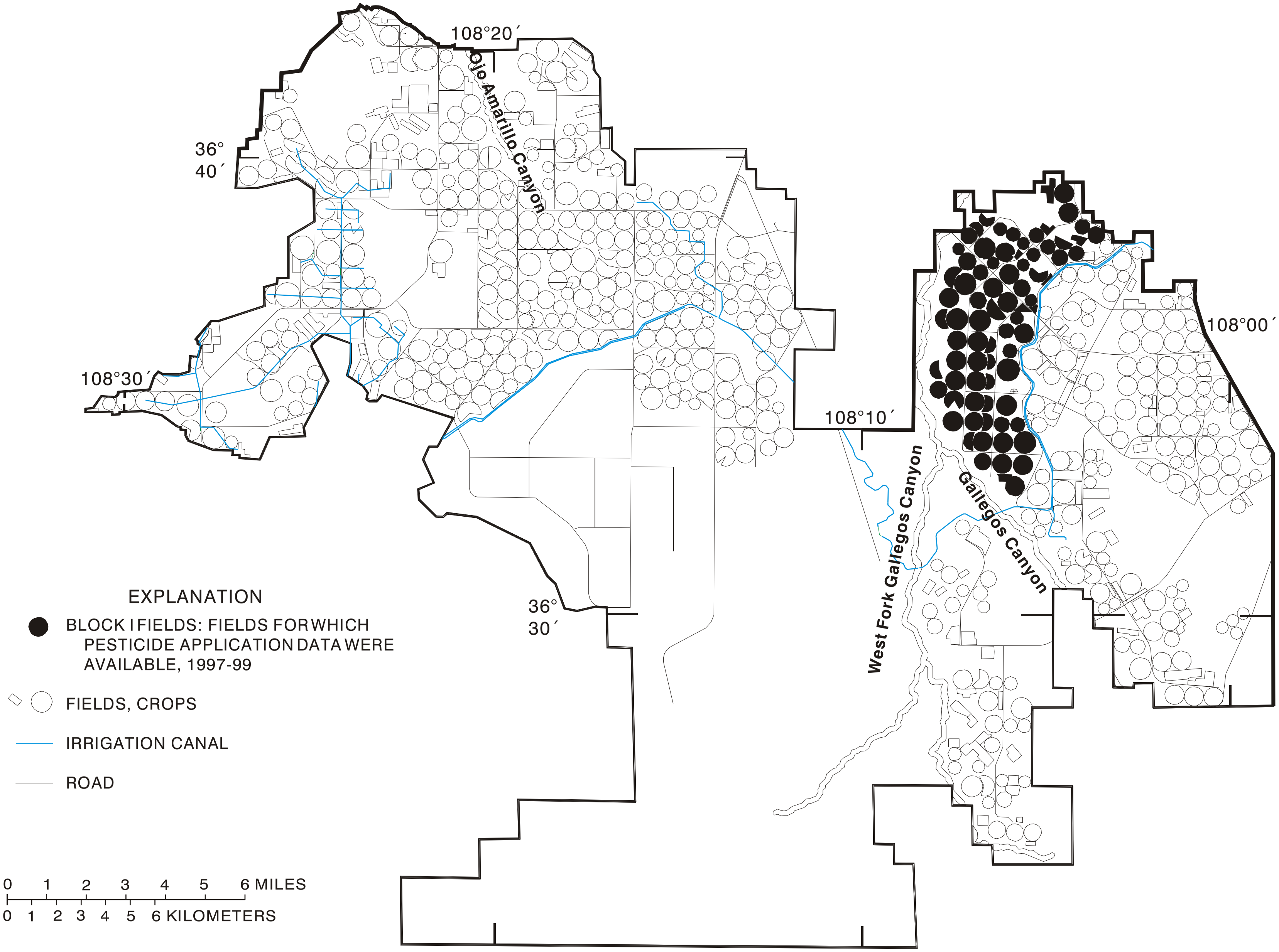

Figure 8. Navajo Indian Irrigation Project fields for which pesticide application data are available, 1997-99.

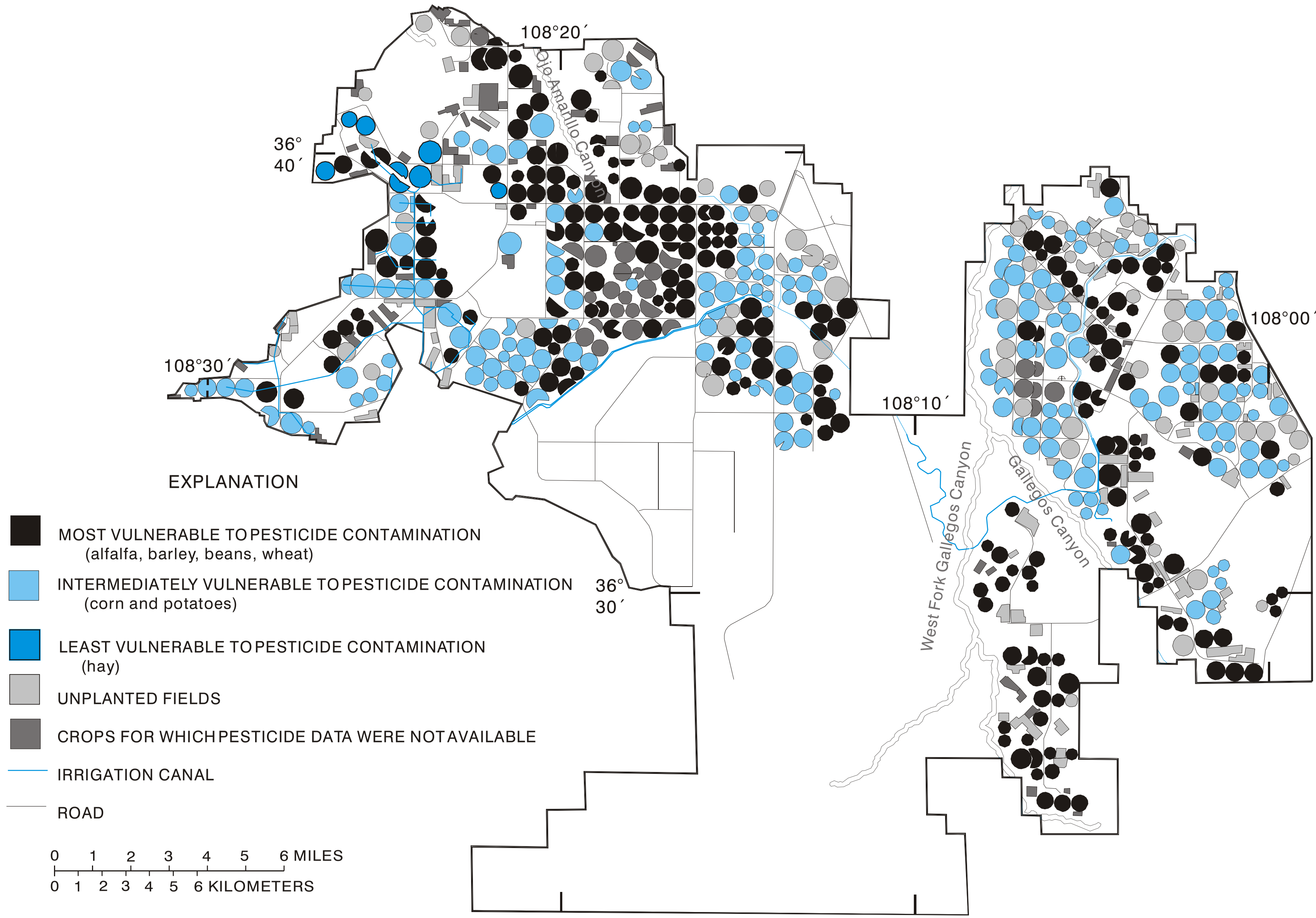

Figure 9. Results of assessment of ground-water vulnerability to pesticide contamination on the Navajo Indian Irrigation Project, 2000.

Table 2. Relative pesticide leaching potential of pesticides and number of fields in block I of the Navajo Indian Irrigation Project on which each pesticide was applied, 1997-99

[Pesticide, trade or commonly accepted product name; typically used pesticides are in bold type. Relative pesticide leaching potential: Montana Department of Agriculture pesticide leachability classification system of very high, high, moderate, low, very low, and extremely low leachability (DeLuca and Johnson, 1990)]

Pesticide	Relative pesticide leaching potential	1997	1998	1999	Total
Pesticide applications to alfalfa (1 pesticide typically applied to fields of alfalfa)					
Velpar	**Very high**	**2 of 2**	**2 of 2**	**2 of 2**	**6 of 6**
Zinc Phosphide	Low	0	0	**2**	2
Zorial Rapid 80	Low	0	**1**	0	1
Pesticide applications to barley (3 pesticides typically applied to fields of barley)					
Amine, 2,4-D	**Moderate**	**8 of 8**	0 of 0	0 of 0	**8 of 8**
Banvel	**Very high**	**8**	0	0	**8**
Penncap-M	**Very low**	**8**	0	0	**8**
Pesticide applications to beans (6 pesticides typically applied to fields of beans)					
Basagran	High	0 of 14	8 of 43	0 of 0	8 of 57
Dual/Dual II[1]	**High**	**10**	**21**	0	**31**
Frontier 6.0	Undetermined	0	**20**	0	20
Frontier 7.5	Undetermined	0	2	0	2
Gramoxone Extra	**Extremely low**	0	**25**	0	**25**
Kocide 2000	Low	0	4	0	4
Poast	Low	4	0	0	4
Pursuit	**Very high**	0	**42**	0	**42**
Roundup Ultra	Very low	0	4	0	4
Rovral 4FL	**Low**	0	**42**	0	**42**
Sonalan HFP	Very low	10	0	0	10
Thiodan 3EC	Extremely low	0	11	0	11
Topsin M 70 W	**Very low**	0	**42**	0	**42**
Zinc Phosphide	**Low**	0	**27**	0	**27**
Pesticide applications to corn (3 pesticides typically applied to fields of corn)					
Accent SP	Very high	1 of 17	0 of 5	4 of 23	5 of 45
Asana XL	Very low	1	1	0	2
Atrazine 4L	High	1	0	4	5
Basis Gold	High	1	0	0	1
Beacon	**High**	**8**	0	**16**	**24**
Bladex 90DF	**Low**	**16**	**5**	1	**22**
Buctril 4EC	Very low	0	0	**14**	14
Clarity	Undetermined	2	1	4	14
Dual II/Dual II Magnum[2]	**High**	**16**	**5**	**11**	**32**
Glyfos	Very low	6	0	0	6
Lannate LV	High	2	0	1	3
Penncap-M	Very low	1	0	0	1
Roundup Ultra	Very low	0	0	4	4
Zinc Phosphide	Low	6	0	0	6

Table 2. Relative pesticide leaching potential of pesticides and number of fields in block I of the Navajo Indian Irrigation Project on which each pesticide was applied, 1997-99--Concluded

Pesticide	Relative pesticide leaching potential	1997	1998	1999	Total
Pesticide applications to hay (2 pesticides typically applied to fields of hay)					
Amine 4	**Moderate**	**7 of 14**	0 of 0	0 of 2	**7 of 16**
Amine 2,4-D	**Moderate**	**7**	0	0	**7**
LV-6 Ester Weed Kill	Low	0	0	**2**	2
Pesticide applications to potatoes (8 pesticides typically applied to fields of potatoes)					
Asana XL	**Very low**	**26 of 29**	**4 of 5**	**3 of 3**	**33 of 37**
Bravo Weather Stik	Low	0	0	**3**	3
Bravo Zinc	**Low**	**25**	**3**	**0**	**28**
Bravo ZN	Low	0	0	3	3
Diquat	**Extremely low**	**26**	**3**	**3**	**32**
Dithane-DF	**Low**	**27**	**3**	0	**30**
Eptam 7E	**Low**	**27**	**4**	**3**	**34**
Glyfos	Very low	1	0	0	1
Kocide-DF	Low	3	0	0	3
Manzate 75DF	Low	0	0	**3**	3
Matrix	Low to high	4	**2**	**3**	9
Penncozef 75DF	Low	0	**2**	0	2
Poast	Low	1	0	0	1
Ridomil Bravo 81W	**Low**	**16**	0	0	**16**
Ridomil Gold Bravo	Low	0	**4**	0	4
Ridomil Gold MZ	Low	0	0	3	3
Trifluralin 4EC	**Very low**	**26**	0	0	**26**
Trifluralin HF	Very low	0	0	**3**	3
Trilin	Very low	0	**2**	0	2
Trilin 5	Very low	0	**2**	0	2
Turbo 8E	**High**	**19**	0	0	**19**
Turbo 8EC	High	0	**2**	0	2
Pesticide applications to wheat (4 pesticides typically applied to fields of wheat)					
Accent SP	Very high	0 of 5	0 of 4	1 of 28	1 of 37
Amine 2,4-D	**Moderate**	**5**	0	**12**	**17**
Banvel*L	**Very high**	**5**	**4**	**26**	**35**
Clarity	Undetermined	0	0	1	1
Dual II Magnum	High	0	0	2	2
Lorsban 4ESG	Very low	0	**4**	0	4
Nufos 4E-SG	**Very low**	0	**4**	**22**	**26**
Roundup Ultra	Very low	0	0	1	1
Weedar 64	**Moderate**	0	**4**	**15**	**19**

[1]Dual used on 10 fields in 1997; Dual II used on 21 fields in 1998.
[2]Dual II applied to 16 fields in 1997 and 5 fields in 1998; Dual II Magnum applied to 11 fields in 1999.

Table 3. Range of percentage of fields on which "typically applied" and "not typically applied" pesticides were used for each crop grown in block I of the Navajo Indian Irrigation Project, 1997-99

[Crop: number in parentheses, number of fields planted in specified crop in block I of the Navajo Indian Irrigation Project during 1997-99; --, not applicable]

Crop	Range of percentage of fields on which "typically applied" pesticides were used	Range of percentage of fields on which "not typically applied" pesticides were used
Alfalfa (6)	100	16 - 33
Barley (8)	100	--
Beans (57)	44 - 74	3.5 - 35
Corn (45)	49 - 71	2.2 - 31
Hay (16)	44	12
Potatoes (37)	43 - 92	2.7 - 24
Wheat (37)	46 - 95	2.7 - 11

Table 4. Ground-water vulnerability and crop ranking based on number of typically applied pesticides having very high, high, and moderate relative pesticide leaching potential

[Relative pesticide leaching potential: Montana Department of Agriculture pesticide classification system of very high, high, moderate, low, very low, and extremely low relative pesticide leaching potential (DeLuca and Johnson, 1990)]

Ground-water vulnerability	Crop	Number of typically applied pesticides having very high, high, or moderate relative pesticide leaching potential		
		Very high	High	Moderate
High	Beans	1	1	0
	Wheat	1	0	2
	Barley	1	0	1
	Alfalfa	1	0	0
Moderate	Corn	0	2	0
	Potatoes	0	1	0
Low	Hay	0	0	2

This assessment method can be combined with the cropping plan for any year, whether it is a past year, the present year, or a future year, to assess ground-water vulnerability to pesticide contamination in that year. The results can be used to adjust the number of fields planted in each crop to optimize the combination of economic and environmental benefits. The results also can be used to locate crops whose typical pesticide applications make underlying ground water most vulnerable to pesticide contamination in the least environmentally sensitive areas, such as project drains and natural drainages, to decrease the potential effects of pesticides on fish, birds, and other fauna.

SUMMARY AND CONCLUSIONS

The USEPA requested that the Navajo Nation conduct an assessment of aquifer sensitivity on Navajo Nation lands and an assessment of ground-water vulnerability to pesticide contamination on the NIIP. Navajo Nation lands include about 17,000 square miles in northeastern Arizona, northwestern New Mexico, and southeastern Utah. The NIIP, in northwestern New Mexico, is the largest area of agriculture on the Navajo Nation. The NIIP began operation in 1976; presently (2001) about 62,000 acres are available for irrigated agriculture. Numerous pesticides have been used on the NIIP during its operation.

Aquifer sensitivity is defined by the USEPA as "The relative ease with which a contaminant [pesticide] applied on or near a land surface can migrate to the aquifer of interest. Aquifer sensitivity is a function of the intrinsic characteristics of the geologic material in question, any underlying saturated materials, and the overlying unsaturated zone. Sensitivity is not dependent on agronomic practices or pesticide characteristics." Ground-water vulnerability is defined by the USEPA as "The relative ease with which a contaminant [pesticide] applied on or near a land surface can migrate to the aquifer of interest under a given set of agronomic management practices, pesticide characteristics, and aquifer sensitivity conditions."

The Navajo Nation study area includes about 21,500 square miles, and because of its size and relative isolation, is lacking in detailed information regarding geology, soils, and hydrology that typically is used to conduct an aquifer sensitivity assessment. Characteristics for which data were considered adequate included geology (within the approximate boundaries of the contiguous Navajo Reservation only), precipitation, soil properties, slope of the land surface, and location of stream courses.

Geology within the approximate boundaries of the contiguous Navajo Reservation was divided into areas of significant potential to facilitate contamination of ground water and insignificant potential to facilitate contamination of ground water. Areas within the approximate boundaries of the contiguous Navajo Reservation where consolidated rocks are recharged and (or) where unconsolidated deposits are at land surface were considered to have significant potential to facilitate contamination of ground water. All other areas within the approximate boundaries of the contiguous Navajo Reservation were considered to have an insignificant potential to facilitate contamination of ground water. No data-defining areas of recharge to bedrock aquifers or areas of unconsolidated deposits were available for the part of the study area south and southeast of the approximate boundaries of the contiguous Navajo Reservation. Therefore, regarding geology, the potential to facilitate contamination in this part of the study area was identified as undetermined. In order to not underestimate the potential of this part of the study area to facilitate contamination, however, its potential was estimated to be significant, and it was assigned a numerical value of 1.

Precipitation, soil properties, and slope of the land surface were evaluated regarding potential to facilitate contamination of underlying ground water. Each of these characteristics was subdivided into three categories: least, intermediate, and most potential to facilitate contamination.

Stream courses typically receive runoff from their surrounding drainage during and following precipitation. Deposits in them typically are coarse grained, have a high infiltration rate, low organic content, and are well drained; slope of the land surface typically is nearly flat. Therefore, stream courses were considered to be in the category most potential to facilitate contamination of ground water with regard to precipitation, soil properties, and the slope of the land surface.

The assessment of aquifer sensitivity on Navajo Nation and adjacent lands was conducted by first converting the areas of least, intermediate, and most potential to facilitate contamination of ground water to the respective numerical values of 1, 2, and 3 in the GIS coverages of precipitation, soil properties, and slope of the land surface. For the GIS coverage of geology, the category insignificant potential to facilitate contamination of ground water was assigned a score of 0, and the category significant potential to facilitate contamination of ground water was assigned a score of 1. GIS coverages for precipitation, geology, soil properties, and slope of the land surface were overlaid, and the numerical values for each GIS polygon in the resulting coverage were summed and then multiplied by the score for geology (0 or 1). All stream courses received a score of 9. Finally, the scores were converted to potentials for contamination as follows: 0, insignificant; at least 3 but less than 5, least; 5 to 7, intermediate; and more than 7, most.

Results of the assessment indicated that about 22 percent of the study area was in the category insignificant potential to facilitate contamination. About 72 percent of the study area was assessed as being in the categories most or intermediate potential for contamination. About 6 percent of the study area was assessed to be in the category least potential for contamination, typically in areas where the slope of the land surface is more than 12 percent.

About 96 percent of the NIIP was assessed to be in the category most potential for contamination; the remaining 4 percent of the NIIP was assessed to be in the category intermediate potential for contamination. All irrigated fields except a small part of one field along Ojo Amarillo Canyon were assessed to be in the category most potential for contamination.

The assessment of aquifer vulnerability to pesticide contamination on the NIIP was based on the relative pesticide leaching potential of pesticides typically applied to each crop. First, pesticides typically applied to each crop were determined. Second, the relative pesticide leaching potential was assigned to each typically applied pesticide. Third, crops then were ranked by the number of typically applied pesticides that had (1) a very high relative pesticide leaching potential; then by the number of typically applied pesticides that had (2) a high relative pesticide leaching potential; and then by the number of typically applied pesticides that had (3) a moderate relative pesticide leaching potential.

The results of this assessment indicated relative ground-water vulnerability to pesticide contamination under all fields on the NIIP. Ground water underlying fields planted in alfalfa, barley, beans, and wheat was considered most vulnerable; ground water underlying fields planted in corn and potatoes was considered intermediately vulnerable; and ground water underlying fields planted in hay was considered least vulnerable to pesticide contamination. These categories of vulnerability were substituted for the respective crops in the NIIP 2000 cropping plan, and a GIS coverage was created that shows relative ground-water vulnerability to pesticide contamination under all fields on the NIIP for 2000.

The results of this assessment of ground-water vulnerability to pesticide contamination on the NIIP show relative vulnerability for 2000. This assessment method can be combined with the cropping plan for any year, whether it is a past year, the present year, or a future year, to assess ground-water vulnerability to pesticide contamination in that year. The results can be used to adjust the number of fields planted in each crop to optimize the combination of economic and environmental benefits. The results also can be used to locate crops whose typically applied pesticides make underlying ground water most vulnerable away from the most environmentally sensitive areas, such as project drains and natural drainages, to decrease the potential effects of pesticides on fish, birds, and other fauna.

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