# COMPETITIVE GROUNDWATER USAGE FROM THE NAVAJO SANDSTONE

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## ABSTRACT

Groundwater modeling is used to theoretically relate mining pumpage of the Navajo Sandstone to declines in the potentiometric surface at Navajo and Hopi Indian community, domestic, and stock usage locations. The shallow wells on top of Black Mesa are shown to be part of a perched water table condition which is dependent upon the hydraulic conductivity of an aquatard known as the Mancos Shale. The isolation of the aquatard allows the shallow wells to be treated as a problem separate from that of the artesian and recharge areas. Computer modeling of the groundwater system is concerned only with those Indian wells which directly tap the Navajo Sandstone in either artesian or free water table areas. The computer simulation developed is a modified version of the basic artesian aquifer routine used by the Illinois State Water Survey. Computer results correspond with the low percentage of storage withdrawal calculated for the artesian area under Black Mesa.

## INTRODUCTION

Projections of future energy demands have resulted in the planned construction of coal-fired power generation plants in the "Four Corners" region of the Southwest (Arizona, New Mexico, Colorado, and Utah). A simulation of the effects of these power developments including physical, economic, and social variables is in progress at the University of Arizona under a grant from the Ford Foundation. The simulation effort has a two year duration with computer modeling consuming most of the first year and a workshop involvement with selected interest groups some time during the second year. The project emphasizes simulation as a decision and management tool and is presently nearing completion of the first year.

The objective of the Four Corners Program is to provide conflicting interest groups with an understanding of the long term consequences of various alternative plans proposed as solutions to coal-fired power developments in the Four Corners region. The enumeration of alternative plans is called a decision space, and the range of corresponding results is called an effects space. A number of computer simulation models link the decisions and effects. Figure 1 shows a conceptual block diagram of the simulation model. By virtue of the intended application, the simulation includes human participants; however, only the major section classifications (i.e., managerial, social, economic, and physical) have been diagrammed.

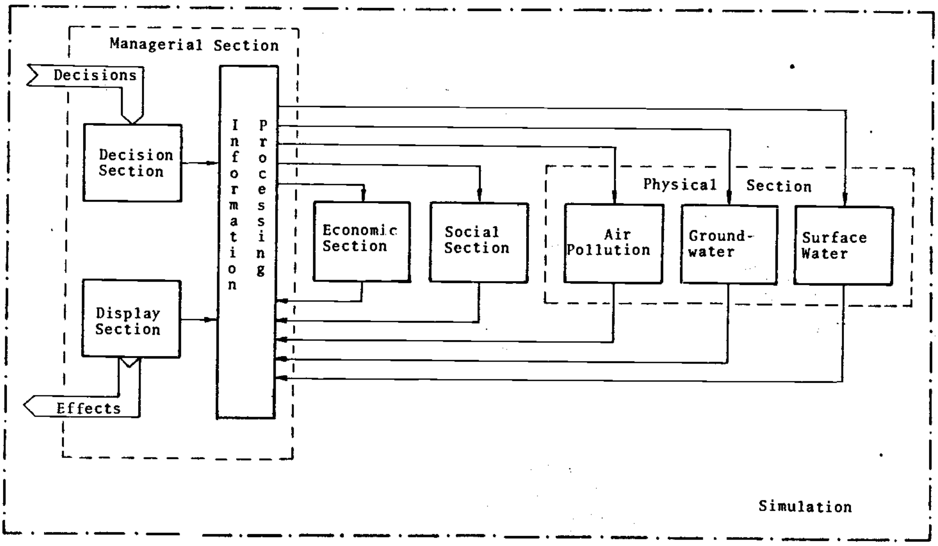


Figure 1. Conceptual Block Diagram of the Simulation.

A portion of the physical section of the simulation is concerned with the development of groundwater resources for strip mining on Black Mesa and the associated slurry transportation of coal to the Mohave power plant and, potentially, the Southern Nevada plant. The impacts of slurry pumping upon the local environment has been discussed in subjective terms by Budnik (1972, p. 102) and Clemmer (1970, pp. 5-11). The effects of slurry pumpage upon water interests of the Navajo and Hopi Indians are examined in this paper from a theoretical viewpoint with the aid of simulation model results.

## SITUATION

Black Mesa, Arizona, is the location of low sulfur, bituminous coal deposits contracted for use at the Navajo and Mohave power generation facilities. At full operation, both facilities will consume a daily total of 39,000 tons of coal -- 23,000 tons at the Navajo plant and 16,000 tons at the Mohave plant (Environmental Statement, Navajo Project, p. 79). The 35 year contractual supply agreements are held by Peabody Coal Company. Navajo and Hopi Indian Tribes have leased 64,858 acres of Black Mesa to Peabody Coal although the company anticipates mining only 14,000 acres to meet the 35 year supply agreements. For the duration of Indian leases, the Environmental Statement, Navajo Project (p. 79) states:

> "The terms of the mining leases is for 10 years and so long thereafter as coal is produced in paying quantities, with land and specified improvements to be returned to Tribal ownership."

Transportation of the strip mined coal from Black Mesa to the distant facilities has prompted the use of a slurry pipeline. The pipeline is approximately 275 miles in extent linking the coal deposits with the Mohave facility near Bullhead City, Arizona. The slurry is a 50 percent mixture by weight of coal particles and water and travels in the pipeline at a velocity of about 5 miles per hour (Environmental Statement, Navajo Project, p. 87). A 78 mile rail line is planned for the other link from Black Mesa to the Navajo facility near Page, Arizona. Figure 2 shows the location of Black Mesa with respect to the Indian reservations, state lines, and the community of Page. Bullhead City is located off the map to the southwest near the intersection of Arizona, California, and Nevada.

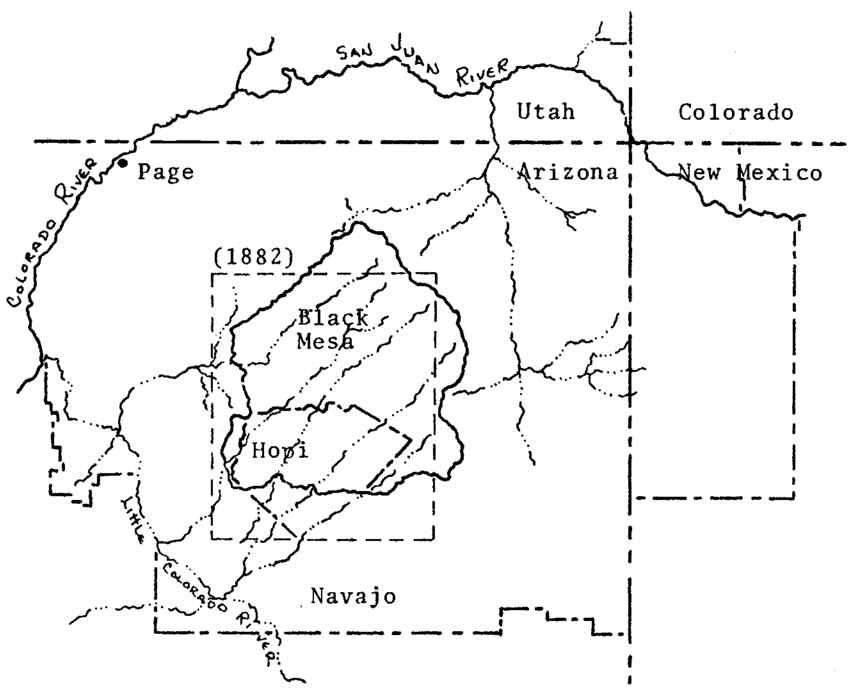


Figure 2. Location of Black Mesa on Navajo and Hopi Indian Reservation lands. (Dotted lines show Navajo-Hopi joint use area from 1882)

Water for the slurry pipeline is obtained from groundwater pumpage of the Navajo Sandstone aquifer. Six production wells owned by Peabody Coal presently extend from the surface of Black Mesa to depths ranging from 3535 feet to 3737 feet.[1] The Navajo Sandstone is the fourth member, numbered in ascending order, of the N-multiple-aquifer system (Southwest Energy Study, Appendix D, p. 51). The N-multiple-aquifer system demonstrates artesian conditions under Black Mesa and water table (unconfined) conditions in associated recharge or outcrop areas. As of 1961, a field inventory of reservation groundwater supplies resulted in the tabulation of 1248 drilled wells, 537 dug wells, and 955 springs (Cooley, et al., p. A4). A large portion of the Indian wells do not directly tap the Navajo Sandstone aquifer. For example, Indian wells in the Mesaverde formation (upper 600 to 800 feet) of Black Mesa are more than 1700 feet above the Navajo Sandstone in the vicinity of the Peabody Coal mining site.

## MODEL OBJECTIVE

The objective of the groundwater model is to relate aquifer withdrawals by Peabody Coal to possible declines in the potentiometric surface of the Indian domestic and stock usage areas. Three main areas are of interest, they are:

1. Shallow Indian wells on top of Black Mesa.
2. Indian artesian wells tapping the Navajo Sandstone.
3. Indian wells in the recharge area of the Navajo Sandstone.

## DECISION SPACE

Pumping rates and pumping durations for the Peabody Coal wells define the decision space of the groundwater model. Pumping rates of 2,000 gallons per minute and 4,000 gallons per minute are selected. The lower rate reflects current activities. The higher rate represents a speculation that the Southern Nevada plant might be built and might be supplied by a slurry pipeline in whole or in part. The observation time horizon is 55 years, and the pumping duration is 35 years. The effects space is the variation in potentiometric surface as a result of the decision space for the three areas defined by the model objective. Other parameters are changed for a sensitivity analysis of aquifer characteristics.

## AQUIFER PROPERTIES

The Navajo Sandstone, Coconino Sandstone, and the De Chelly Sandstone are the principal water bearing aquifers located on reservation lands. Productivity of the water bearing units is low, and few wells are used for irrigation purposes. Typical pumping rates corresponding to various

[1]E. H. McGavock, well schedules, U.S.G.S., Flagstaff, Arizona.

water uses include 1-5 gallons per minute for stock and domestic windmills, 5-100 gallons per minute for municipal and institutional wells, and less than 200 gallons per minute for the few industrial wells (Cooley, et al., 1969, p. A48). The aquifers are generally separated by thick layers of sandy siltstone; siltstone, and mudstone which form confining layers or aquatards.

## NAVAJO SANDSTONE

The Navajo Sandstone occupies the west and northwest portion of reservation lands. It is dissected by the San Juan River and roughly bounded by the Colorado and Little Colorado Rivers (Harshbarger, et al., 1957, p. 21). The Navajo Sandstone is wedge shaped varying in thickness from 1,400 feet in the northwest corner of the reservation to 15 feet near Chinle (eastward), 192 feet at Second Mesa (southeastward), and 525 feet at Tuba City (southward). The sandstone is characterized by large-scale crossbeds believed to be the result of wind deposition. About 98 percent of the sandstone is quartz grains. Hydraulic properties for the Navajo Sandstone obtained from pump tests and drill-core samples are summarized in Table 1 (Cooley, et al., 1969, p. A46).

Table 1 Hydraulic Properties of the Navajo Sandstone Aquifer

| Parameter | Range |
|---|---|
| Porosity (%)[1] | 25-35 |
| Specific Retention (%)[1] | 3-8 |
| Specific Yield (%)[1] | 18-29 |
| Permeability (gal/day/sq ft)[1] | 3-494 |
| Transmissivity (gal/day/ft)[2] | 450-3800 |
| Coefficient of Storage[3] | .005 |

[1]Hydrologic laboratory tests on 24 samples.

[2]Computed from three pump tests.

[3]Computed from one pump test.

The Navajo Sandstone in confined areas exists between the Kayenta (lower) and the Carmel (upper) Formations. The Carmel Formation ranges in thickness from 0-300 feet and is principally siltstone and some sandstone. The Kayenta Formation ranges in thickness from 0-700 feet. In the northern part of the Navajo Indian Reservation, the Kayenta is a sandstone becoming a siltstone in the southern part of the reservation (Cooley, et al., 1969, Table 3, p. A7). Information on hydrologic properties of the Carmel and Kayenta Formations is scarce; however, representative ranges of permeability (hydraulic conductivity) are listed by Walton (1970, p. 36) according to rock type. Typical permeabilities for the rock types in units of gallons per day per square foot include 0.1 - 50 for sandstone, 0.001 - 2 for clay and silt, and 0.00001 - 0.1 for shale.

## MANCOS SHALE

The aquifers of the Mesaverde Formation on top of Black Mesa are separated from other underlying aquifers by the Mancos Shale. Direct precipitation and infiltration from small ephemeral streams is the only source of recharge for the Mesaverde aquifers. The Mancos Shale is a thick aquiclude ranging in thickness from 500 to 700 feet in Black Mesa basin (Cooley, et al., 1969, p. A43). A perched water table condition exists in the Mesaverde Formation. Indian wells tapping the Mesaverde aquifers range in depth from 300 to 400 feet. In order for the slurry pumpage to affect the shallow Indian wells, the perched water table must be drained. Assuming the Mancos Shale to be free from major fractures or punctures and the cement grout around the Peabody Coal wells to be solid, the remaining means of Mesaverde drainage is by leakage through the Mancos Shale.

Leakage per unit of surface area is a function of the permeability and head differential across the Mancos Shale. Other modeling efforts for a pumping rate of 2000 gallons per minute for 30 years have theoretically obtained a 600 foot drawdown calculation for the center of slurry pumping (Southwest Energy Study, Appendix D, 1971, p. 57). Assuming the 600 foot head differential to be distributed only across the Mancos Shale, leakage velocity and travel time through the shale can be calculated with the aid of Darcy's Law. The leakage velocity ranges from 0.013 to 0.0000013 feet per day, and the associated travel times through the Mancos Shale become 126 to 1,260,000 years. Under the conditions stated above, leakage through the Mancos Shale as a result of slurry pumpage will not appreciably affect the shallow Indian wells on Black Mesa. The low permeability of the Mancos Shale, not considering the other intervening layers, effectively isolates the Mesaverde Formation from the Navajo Sandstone.

## COMPUTER MODEL

The effective use of computer models cannot be divorced from a basic understanding of the phenomena being modeled. In the case of the groundwater model, an understanding of the hydrologic system can simplify and make applicable computer programming efforts. For example, recognition of the hydraulic isolation between the Navajo Sandstone and the perched water table on top of Black Mesa reduced what was perceived as a three-dimensional modeling problem into a two-dimensional one. Thus, computer modeling of the groundwater system is concerned only with those Indian wells which directly tap the Navajo Sandstone in either artesian or free water table areas.

Initially, three computer models were considered adaptable for use; however, no models were known to exist which could simulate the Navajo Sandstone in an "off-the-shelf" capacity. Modeling considerations included (1) free water table conditions, (2) artesian head conditions, (3) wedge shaped geometry, (4) possible leakage in the artesian areas, (5) possible recharge in the unconfined areas, and (6) hydrologic stress applied through well pumping rates. Given the considerations above, modifications to each computer program available was expected. The three models were:

1. A finite difference representation of aquifer cross sections in steady-state (Freeze, 1969).
2. A finite difference representation of the free water table aquifer in the Tucson Basin (Gates, 1972).
3. A finite difference representation of a basic artesian configuration with various hydrologic options (Prickett and Lonnquist, 1971).

The Freeze model required major modifications to convert the computer program from one based upon a steady-state solution (static) to a nonsteady-state solution (dynamic).

## SELECTION CRITERIA

The groundwater model selected for use is a modified version of the basic two-dimensional, simulation program developed by the Illinois State Water Survey (Prickett and Lonnquist, 1971). The simulation mathematics utilize finite difference equations developed from the physical considerations of Darcy's Law and the conservation of mass. This simulation program was selected as the basic building block of the groundwater model for the following reasons:

1. Characterization potential as related to the physical problem.
2. Time scheduling requirements of the modeling effort.
3. Excellent documentation of the computer program.
4. Modification potential of the computer program.

## FINAL MODEL

Figure 3 shows the final model grid for Black Mesa using 2 mile, nodal spacings. The grid is composed of 34 columns and 39 rows. Aquifer pumpage for most computer calculations utilize five Peabody Coal wells with location coordinates as shown. The pumpage effects at four points surrounding the Peabody wells is monitored. Three of the monitor points exhibit artesian conditions while Shonto is an unconfined aquifer location. In general, the nodal points within the perimeter of Black Mesa are assigned artesian properties, and the nodal points outside the mesa perimeter are designated as free water table. The hatched area in the upper left corner is the major recharge surface for the 66 by 76 mile section of Navajo Sandstone.

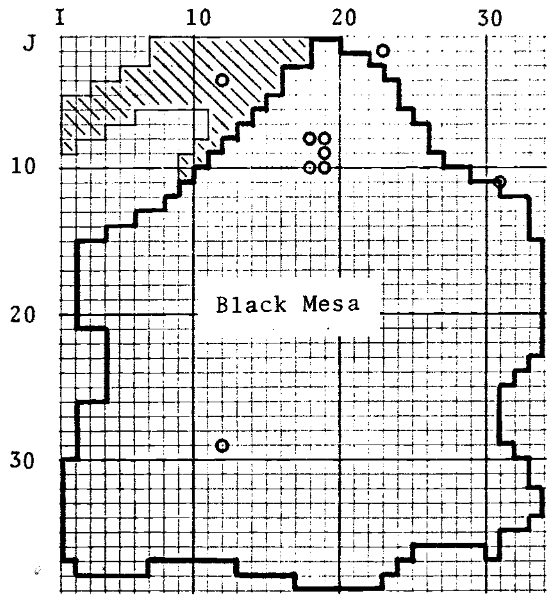


Figure 3 Final Model Grid

| Interest Point | (I,J) Coordinates |
|---|---|
| Peabody Coal Well #2 | (18,8) |
| Peabody Coal Well #6 | (19,8) |
| Peabody Coal Well #5 | (19,9) |
| Peabody Coal Well #3 | (19,10) |
| Peabody Coal Well #4 | (18,10) |
| Shonto | (12,4) |
| Chilchinbito | (23,2) |
| Rough Rock | (31,11) |
| Oraibi | (12,29) |

The calibration of a simulation model for groundwater is generally based upon point source information in some historic sequence. A sufficiency of data in an historic sense is immediately lacking, and calibration of the present groundwater model in the traditional manner is not possible. However, the model will be used to access future effects based upon differential head changes in the potentiometric surface rather than accurate location of head elevations.

## MODEL RESULTS

The theoretical effects of slurry pumping on the potentiometric surface at Chilchinbito, Rough Rock, Oraibi, and Shonto are tabulated in Table 2. The largest drawdown effects are obtained at Chilchinbito, the closest artesian location to the Peabody Coal wells. The following is a list of assumptions used in the model computations:

1. Recharge is zero.
2. Leakage is zero.
3. Total observation time is 55 years.
4. Slurry pumpage time is 35 years.
5. Slurry pumpage rates are either 2000 or 4000 gallons per minute (5 wells @ 400 gpm or 8 wells @ 500 gpm).

Table 2 Theoretical Effects of Slurry Pumping on the Potentiometric Surfaces at Various Locations (drawdown in feet)

| | Years | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Locations Pump Rate | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 55 |
| Chilchinbito | | | | | | | | | | | |
| Q = 2000 gpm | 17 | 31 | 39 | 43 | 46 | 49 | 52 | 36 | 24 | 18 | 16 |
| Q = 4000 gpm | 30 | 56 | 70 | 79 | 85 | 91 | 96 | 68 | 45 | 33 | 27 |
| Rough Rock | | | | | | | | | | | |
| Q = 2000 gpm | 4 | 10 | 16 | 20 | 23 | 25 | 27 | 24 | 18 | 14 | 10 |
| Q = 4000 gpm | 9 | 21 | 32 | 41 | 47 | 52 | 56 | 48 | 37 | 27 | 21 |
| Oraibi | | | | | | | | | | | |
| Q = 2000 gpm | 1 | 4 | 8 | 12 | 16 | 18 | 20 | 20 | 18 | 14 | 10 |
| Q = 4000 gpm | 2 | 9 | 18 | 28 | 35 | 41 | 45 | 43 | 38 | 29 | 21 |
| Shonto | | | | | | | | | | | |
| Q = 2000 gpm | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Q = 4000 gpm | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Peabody Well No. 5 | | | | | | | | | | | |
| Q = 400 gpm | 406 | 491 | 521 | 535 | 543 | 548 | 553 | 148 | 65 | 36 | 24 |
| Q = 500 gpm | 708 | 875 | 937 | 965 | 981 | 992 | 1001 | 296 | 132 | 74 | 49 |

Note: Pump 35 years, stop, T = 2000 gpdpf, SC(WT) = 0.15, and SC(A) = 0.0002.

## SENSITIVITY ANALYSIS

Aquifer parameters were varied to determine ranges and characteristics of influence in potentiometric contours. Storage coefficient for the artesian conditions and aquifer transmissivity were of central interest. While most calculations used an artesian storage coefficient of 0.0002, the effects of changing the value one order of magnitude above and below this nominal choice was examined. A larger storage coefficient of 0.002 generally produced a reduction in drawdown and a time delay in the observation of slurry pumping effects at Chilchinbito, Rough Rock, and Oraibi. A smaller storage coefficient of 0.00002 produced a small increase in peak drawdown for the 35 year pumping period; however, the theoretical drawdowns had a sharper initial response reaching a stable reduction rate over most of the pumping period.

Variations in transmissivity,through aquifer geometry were accomplished by varying the aquifer thickness for a single value of permeability. The general wedge shape of the Navajo Sandstone in an east-west direction was used. Correspondingly, the greatest effect in potentiometric contours is observed at Rough Rock where the aquifer becomes thin. For the wedge geometry, two values of permeability were used -- 3 gallons per day per square foot and 30 gallons per day per square foot. The lower value of permeability is the low end of the hydraulic property range shown in Table 1. An increase in permeability by one order of magnitude decreases the peak drawdown and generally smoothes the observed pumping effects. The range of theoretical effects from low to high drawdowns as a result of the slurry pumping and sensitivity analysis are shown in Table 3.

Table 3 Range of Theoretical Effects for Slurry Pumping on the Potentiometric Surfaces at Various Locations (drawdown in feet)

| | Years | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Locations | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 55 |
| Chilchinbito | | | | | | | | | | | |
| Low Drawdown | 0 | 2 | 6 | 8 | 9 | 11 | 12 | 8 | 7 | 6 | 6 |
| High Drawdown | 37 | 56 | 70 | 79 | 85 | 91 | 96 | 68 | 45 | 33 | 29 |
| Rough Rock | | | | | | | | | | | |
| Low Drawdown | 0 | 0 | 0 | 1 | 2 | 4 | 7 | 5 | 4 | 3 | 3 |
| High Drawdown | 17 | 22 | 32 | 41 | 47 | 52 | 56 | 48 | 37 | 27 | 21 |
| Oraibi | | | | | | | | | | | |
| Low Drawdown | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 2 | 2 |
| High Drawdown | 13 | 19 | 20 | 28 | 35 | 41 | 45 | 43 | 38 | 29 | 21 |
| Shonto | | | | | | | | | | | |
| Low Drawdown | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| High Drawdown | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 |
| Peabody Well No. 5 | | | | | | | | | | | |
| Low Drawdown | 52 | 56 | 57 | 58 | 59 | 60 | 61 | 10 | 7 | 6 | 5 |
| High Drawdown | 708 | 875 | 937 | 965 | 981 | 992 | 1001 | 296 | 204 | 148 | 111 |

## VOLUME USAGE

Although a measure of potentiometric surface effects was the desired goal, some simple static calculations add to an appreciation of the problem scope. Assume recharge and leakage to be zero and consider only the artesian area under Black Mesa. For an average aquifer thickness of 400 feet, a specific yield of 0.2, and a surface area of 2.1 million acres, the volume of water in the Navajo Sandstone (Black Mesa only) is calculated to be 168 million acre-feet. The Southwest Energy Study estimates present water pumpage from the Navajo Sandstone to be 3,264 acre-feet per year (Appendix D, p. 56). Over a 35 year period and at a constant pumping rate, the accumulated pumpage amounts to 114,240 acre-feet. The percentage of volume of water pumped over a 35 year period to the volume of water within the aquifer is calculated to be 0.07 percent. If variable ranges and calculation errors either increased the volume of pumpage by one order of magnitude or decreased the volume of aquifer storage by one order of magnitude, the percentage of volume usage would remain less than 1 percent.

## CONCLUSIONS

Slurry pumping in the Navajo Sandstone is effectively isolated from the shallow wells on Black Mesa by the Mancos Shale and other intervening rock layers. Assuming no abnormal leakage paths, the mining withdrawals will not appreciably affect Indian wells located in the Mesaverde formation. Computer modeling has provided theoretical drawdown estimates for locations in the artesian and unconfined areas of the Navajo Sandstone. Since a variety of aquifer conditions are possible, ranges of drawdown are listed for the Indian communities of Chilchinbito, Rough Rock, Oraibi, and Shonto. The drawdowns vary from zero to less than 20 percent of the artesian head elevation above the Navajo Sandstone aquifer in confined areas. Similar modeling results were obtained for the Southwest Energy Study (Appendix D, 1971, p. 57). The volume of storage removal at a projected usage rate of 3,264 acre-feet per year for 35 years is significantly less than 1 percent of the water resources under Black Mesa.

## REFERENCES CITED


Budnik, Dan, "Black Mesa: Progress Report on an Ecological Rape," Art In America, Vol. 60, July-August, 1972, pp. 98-105.

Clemmer, Richard O., "Economic Development vs. Aboriginal Land Use: An Attempt to Predict Culture Change on an Indian Reservation in Arizona," unpublished paper, the University of Illinois, Urbana, August, 1970.

Cooley, M. E. et al., Regional Hydrogeology of the Navajo and Hopi Indian Reservations, Arizona, New Mexico and Utah, Geological Survey Professional Paper 521-A, Washington: Government Printing Office, 1969.

Freeze, R. A., Theoretical Analysis of Regional Groundwater Flow, Inland Waters Branch, Department of Energy, Mines and Resources, Scientific Series No. 3, Ottawa: Queen's Printer for Canada, 1969.

Gates, Joseph S., "Worth of Data Used in Digital-Computer Models of Ground-Water Basins," unpublished Ph.D. dissertation, University of Arizona, 1972.

Harshbarger, J. W., C. A. Repenning, and J. W. Irwin, Stratigraphy of the Uppermost Triassic and the Jurassic Rocks of the Navajo Country, Geological Survey Professional Paper 291. Washington: Government Printing Office, 1957.

Prickett, T. A., and C. G. Lonnquist, Selected Digital Computer Techniques for Groundwater Resource Evaluation, Illinois State Water Survey, Bulletin 55, Urbana: The State of Illinois, 1971.

U.S. Department of Interior, Geological Survey, Southwest Energy Study, Appendix D, Report of the Water Resources Monitoring Group, Unofficial Preliminary Draft, Washington: Geological Survey, December, 1971.

U.S. Department of Interior, Bureau of Reclamation, Final Environmental Statement, Navajo Project, Springfield, Virginia: National Technical Information Service, February 1972.

Walton, William C., Groundwater Resource Evaluation, New York: McGraw-Hill Book Company, 1970.