ABSTRACT

As populations grow in the arid southwestern United States and desert bedrock aquifers are increasingly targeted for future development, understanding and quantifying the spatial variability of net infiltration and recharge becomes critically important for inventorying ground-water resources and mapping contamination vulnerability. A Geographic Information System (GIS)-based model utilizing readily available soils, topographic, precipitation, and outcrop data has been developed for predicting net infiltration to exposed and soil-covered areas of the Navajo Sandstone outcrop of southwestern Utah. The Navajo Sandstone is an important regional bedrock aquifer. The GIS model determines the net-infiltration percentage of precipitation by using an empirical equation. This relation is derived from least squares linear regression between three surficial parameters (soil coarseness, topographic slope, and downgradient distance from outcrop) and the percentage of estimated net infiltration based on environmental tracer data from excavations and boreholes at Sand Hollow Reservoir in the southeastern part of the study area.

Processed GIS raster layers are applied as parameters in the empirical equation for determining net infiltration for soil-covered areas as a percentage of precipitation. This net-infiltration percentage is multiplied by average annual Parameter-elevation Regressions on Independent Slopes Model (PRISM) precipitation data to obtain an infiltration rate for each model cell. Additionally, net infiltration on exposed outcrop areas is set to 10 percent of precipitation on the basis of borehole net-infiltration estimates. Soils and outcrop net-infiltration rates are merged to form a final map.

Areas of low, medium, and high potential for ground-water recharge have been identified, and estimates of net infiltration range from 0.1 to 66 millimeters per year (mm/yr). Estimated net-infiltration rates of less than 10 mm/yr are considered low, rates of 10 to 50 mm/yr are considered medium, and rates of more than 50 mm/yr are considered high. A comparison of estimated net-infiltration rates (determined from tritium data) to predicted rates (determined from GIS methods) at 12 sites in Sand Hollow and at Anderson Junction indicates an average difference of about 50 percent. Two of the predicted values were lower, five were higher, and five were within the estimated range. While such uncertainty is relatively small compared with the three order-of-magnitude range in predicted net-infiltration rates, the net-infiltration map is best suited for evaluating relative spatial distribution rather than for precise quantification of recharge to the Navajo aquifer at specific locations. An important potential use for this map is land-use zoning for protecting high net-infiltration parts of the aquifer from potential surface contamination.

INTRODUCTION

The Navajo Sandstone is a fine-grained, well-sorted eolian sandstone of the Colorado Plateau Glen Canyon Formation, which covers a large part of the southwestern United States (Robson and Banta, 1995). Because of its relatively high permeability and thickness (as much as 600 m), it forms a major regional aquifer (Cordova and others, 1972; Hurlow, 1998) and is the primary source of ground water for southwestern Utah, the warmest and driest part of the state where water demand is high because of rapid population growth (Heilweil and others, 2000). Within Washington County, the Navajo Sandstone receives the majority of net infiltration and recharge along the exposed and soil-covered outcrop areas (fig. 1). Because of both the recent increase in ground-water development and urban growth into areas with exposed or soil-covered sandstone in western Washington County, a tool is needed for evaluating both water-resources availability and aquifer susceptibility to surface contamination.

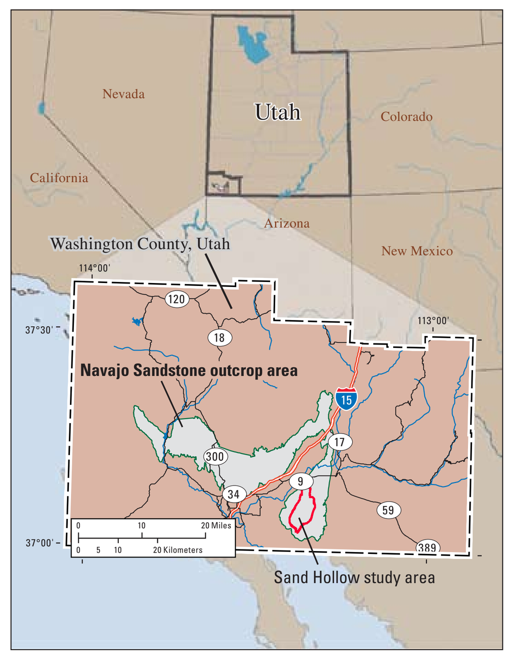

Figure 1. Location of the Navajo Sandstone outcrop area in western Washington County, Utah.

The objective of this study was to develop a map showing the spatial distribution of net infiltration. Net infiltration is defined as subsurface moisture penetration beneath the root zone, below which water removal by evapotranspiration becomes insignificant. Under relatively stable long-term (decadal) precipitation conditions and for relatively homogeneous aquifers such as the Navajo aquifer, it is assumed that net infiltration continues downward through the vadose zone and crosses the water table to become aquifer recharge. Previous studies by Danielson and Hood (1984) and Freethey (1993), along with recent studies at the Sand Hollow study area (fig. 1), have resulted in a conceptual understanding of processes controlling net infiltration to the exposed or soil-covered Navajo Sandstone outcrop areas (Heilweil and Solomon, 2004; Heilweil and others, 2006; Heilweil and others, 2007). Net infiltration was determined to be controlled primarily by four factors: (1) precipitation, (2) soil coarseness, (3) topographic slope, and (4) downgradient distance from exposed outcrop. Other factors, such as soil thickness and the density of vertical fractures in soil-covered sandstone, were evaluated but shown to not substantially control net infiltration.

A Geographic Information System (GIS)-based model for estimating net infiltration to outcropping and soil-covered areas of the Navajo Sandstone was developed on the basis of an empirical equation derived from a least squares linear regression of soils, topography, and outcrop data with estimated net-infiltration ratios along about 3,000 linear meters of excavations in the Sand Hollow study area (Heilweil and others, 2007). These estimated net-infiltration ratios for Sand Hollow were developed from correlations between (1) vadose-zone solute accumulations (chloride, specific conductance) in the excavations, (2) vadose-zone solute accumulations at borehole sites, and (3) tritium-based net-infiltration rates obtained from these same boreholes. The net-infiltration ratios were then multiplied by average annual Parameter-elevation Regressions on Independent Slopes Model (PRISM) precipitation data, resulting in net-infiltration rates. Heilweil and others (2007) provide a more complete documentation of these methods.

The purpose of this report is to apply these same GIS-based techniques for generating a net-infiltration map for the entire exposed or soil-covered Navajo Sandstone outcrop area of western Washington County. The exposed and/or soil-covered extent of the Navajo Sandstone in western Washington County was determined previously (Freethey, 1993; Heilweil and others, 2000). The net-infiltration map presented here indicates areas of high recharge. Such information may be useful for addressing future water-resource development. Another potential application is land-use zoning, including the protection of high net-infiltration parts of the aquifer from potential surface contamination. Potential contaminant sources include septic systems, agricultural pesticides and fertilizers, and contaminant spills associated with highway transport and pipelines.

METHODS

Estimated precipitation data for the study area are based on 30-year (1971-2000) average annual PRISM data (Spatial Climate Analysis Service, 2004). The PRISM approach uses weather station and elevation data to create modeled monthly and annual precipitation raster layers by using weighted weather station climate data and linear elevation regressions in an iterative process. The available station data may not necessarily represent conditions for the surrounding locations; therefore the linear regression is modified for each model cell to reflect changes in climate and elevation. Because of its small scale (4-km^2 grid cells), the original PRISM precipitation grid was too coarse for the detailed net-infiltration calculations of this study. Therefore, the PRISM data were resampled at a larger scale (0.25-km^2 grid cells) and filtered using a GIS focal neighborhood function to refine the distribution of precipitation, based on mean values in a neighborhood of cells (McCoy and others, 2001). These resampled PRISM average annual precipitation values ranged from 185 to 429 mm/yr (fig. 2a). A total of about 160 million m^3 (130,000 acre-ft) of annual precipitation is estimated to fall on the exposed and soil-covered Navajo Sandstone outcrop area of western Washington County. In order to estimate the spatial distribution of net-infiltration rates, a GIS grid of approximately 6.8 million 9.3-m^2 cells was constructed to represent the 590-km^2 (227-mi^2) area of exposed and soil-covered Navajo Sandstone outcrop area of western Washington County.

For soil-covered areas, separate GIS layers for soil coarseness, land-surface elevation, and bedrock outcrop data were developed to calculate net-infiltration ratios for each cell with the following equation from Heilweil and others (2007):

$$R = 0.178(A) + 1.74x10^{-4}(B) + 1.07(C) - 0.0273(A^2) - 2.06x10^{-6}(B^2) - 3.14(C^2)$$

where:

R is net-infiltration ratio,
A is soil grain size, as the percent coarser than 0.15 mm,
B is downgradient distance from sandstone outcrop, in meters, and
C is topographic slope, in percent.

These net-infiltration ratios were then multiplied by average precipitation rates (in mm/yr) for each cell, resulting in estimated net-infiltration rates (in mm/yr). To ensure an accurate cell-by-cell combination of the raster data, common analysis environmental parameters were configured in ArcInfo GRID for resolution and geographic extent. The appropriate cell sizes, analysis window, and mask were configured before data processing.

Soil Survey Geographic Database (SSURGO) soil maps (Mortensen and others, 1977) and recent field mapping and aerial photograph interpretation (Sutcliffe, 2005) provided the basis for the GIS soil-coarseness layer. The SSURGO data were produced by the Natural Resource Conservation Service (NRCS) and are composed of large scale (1:12,000 to 1:63,360) soil-map units. Soil-particle-size distributions provided with the SSURGO data did not coincide with the soil-coarseness parameter required for the net-infiltration model. Therefore, the SSURGO data were supplemented by laboratory analysis of particle-size distributions to determine the soil fraction greater than 0.15 mm for each of the 40 unique soil types in western Washington County. This coarseness parameter was then joined to the SSURGO data layer for the study area. Soil fractions ranged from 1.8 to 75 percent coarser than 0.15 mm for the 40 different soil types (fig. 2b, table 1). The soils polygon data were then rasterized, resulting in a GIS layer of values for the soil-coarseness parameter.

A U.S. Geological Survey National Elevation Dataset, one-third arc second (10 m) Digital Elevation Model (DEM) (National Center for Earth Resources Observation & Science, 1999) was used to calculate topographic slope for each cell. The DEM data were hydraulically conditioned; artificial sinks and peaks were filled or leveled to remove inaccuracies resulting from errors in the creation of the DEM (McCoy and others, 2001). Slopes for each 9.3-m^2 cell for the soil-covered parts of the study area were calculated as rise over run from the hydraulically conditioned DEM by using a three-cell by three-cell neighborhood surrounding each elevation cell. The resulting GIS layer for the topographic-slope parameter has values ranging from about 0 to 30 percent (fig. 2c). On the basis of field observations, areas with slopes of greater than 30 percent are assumed to be sandstone outcrops.

Exposed sandstone areas were extracted from the soils coverage to make a separate GIS raster layer for calculating values for the downgradient distance from outcrop. Surface-water flow paths from all outcrop areas were determined with a downgradient influence algorithm (Tarboton, 1997) that calculates flow direction as the path from each GIS cell to its steepest downgradient neighboring cell. The downgradient influence flow paths (fig. 2d) were calculated by applying the downgradient influence algorithm only to flowpaths originating from outcrop areas. These flow paths show where runoff from exposed sandstone would flow during precipitation events in order to account for the higher net-infiltration rates that would occur at locations of soil-covered sandstone because of this ephemeral surface-water flow. The resulting GIS raster layer is a grid of distance values from outcrop areas to each soil cell along a downgradient flow path. A maximum value of 200 m is used for this downgradient distance-from-outcrop parameter, on the basis of solute distribution patterns in the Sand Hollow excavations (Heilweil and others, 2007).

The three processed GIS raster data layers (soil coarseness, topographic slope, and downgradient distance from outcrop) were applied as parameters in the empirical equation (Heilweil and others, 2007, eq. 4) by using the Map Algebra computational programming language (McCoy and others, 2001) to determine net-infiltration ratios for soil-covered areas. These net-infiltration ratios were then multiplied by the modified 30-year average annual PRISM data to obtain net-infiltration rates for each soil-covered cell in the study area (77 percent of the study area).

For areas of exposed sandstone outcrop (18 percent of the study area), a constant net-infiltration ratio of 0.10 (10 percent of the average annual PRISM precipitation) was used. This outcrop net-infiltration ratio was estimated from the tritium-based net-infiltration data from Sand Hollow and previous Navajo Sandstone infiltration studies near the Dirty Devil River (Danielson and Hood, 1984).

Similar to the ratio used in the exposed sandstone areas, a constant net-infiltration ratio of 0.10 (10 percent of the average annual PRISM precipitation) was used for areas of basalt-boulder colluvium (5 percent of the study area). A net-infiltration ratio of 0.10 is larger than what would be calculated on the basis of soil coarseness of the sand/silt fraction of the basalt-boulder colluvium. This larger ratio is justified, however, because it was observed that runoff from the basalt boulders during periods of intense precipitation provides focused infiltration to the surrounding soils. Use of only direct infiltration of precipitation for the fine colluvial soils would result in an underestimate of net infiltration. The colluvium, however, was not considered an outcrop area for the calculation of downgradient influence.

Ultimately, these net-infiltration rates for the exposed and soil-covered areas of the Navajo Sandstone were merged to produce a net-infiltration map of the entire study area. These methods do not account for focused infiltration along ephemeral or perennial streams, which were previously estimated within the study area by Heilweil and others (2000).

ESTIMATED (TRITIUM-BASED) NET-INFILTRATION RATES

The empirical relation between the three primary controlling parameters (soil coarseness, topographic slope, and downgradient distance from outcrop) and net-infiltration ratios was based on vadose-zone environmental tracers in excavations and boreholes. Table 2 provides the estimated net-infiltration rates for the 11 borehole sites in Sand Hollow. Rates range from 1-3 mm/yr to 50-64 mm/yr. In order to evaluate the accuracy of using this empirical relation for predicting net infiltration to the Navajo Sandstone elsewhere in western Washington County, an additional vadose-zone borehole was drilled for determining tritium-based net-infiltration rates at Anderson Junction, about 15 km north of Sand Hollow. This yielded a tritium-based net-infiltration rate of 12 to 18 mm/yr (Heilweil and others, 2007).

PREDICTED (GIS-MODEL-BASED) NET-INFILTRATION RATES

Results obtained with the GIS model predict net-infiltration rates ranging from 0.1 to 66 mm/yr (fig. 3). The average net-infiltration rate for the entire study area is about 24 mm/yr. The areas with highest net-infiltration rates (greater than 50 mm/yr) occur in coarser soils downgradient from sandstone outcrops at higher-elevation areas (receiving more precipitation). Medium net-infiltration rates (10-50 mm/yr) occur in similar upland areas with coarser soils, yet away from sandstone outcrops. The lowest net-infiltration rates (less than 10 mm/yr) occur at lower elevations beneath finer-grained soils not receiving runoff from sandstone outcrops. Total estimated net infiltration for the study area is about 0.5 m^3/s (13,000 acre-ft/yr). This does not include focused infiltration along perennial and ephemeral streams, which was previously estimated to range from 0.08 to 0.45 m^3/s (2,000 to 11,500 acre-ft/yr; Heilweil and others, 2000). The source of this streamflow is primarily from precipitation in the Pine Valley Mountains above the outcrop area. The estimated net infiltration of 0.5 m^3/s is within the previously reported range of 0.3 to 0.9 m^3/s (8,000 to 23,000 acre-ft/yr; Heilweil and others, 2000). Dividing the estimated total annual precipitation of 5 m^3/s within the study area by this estimated net infiltration yields an average net-infiltration ratio of about 10 percent of precipitation.

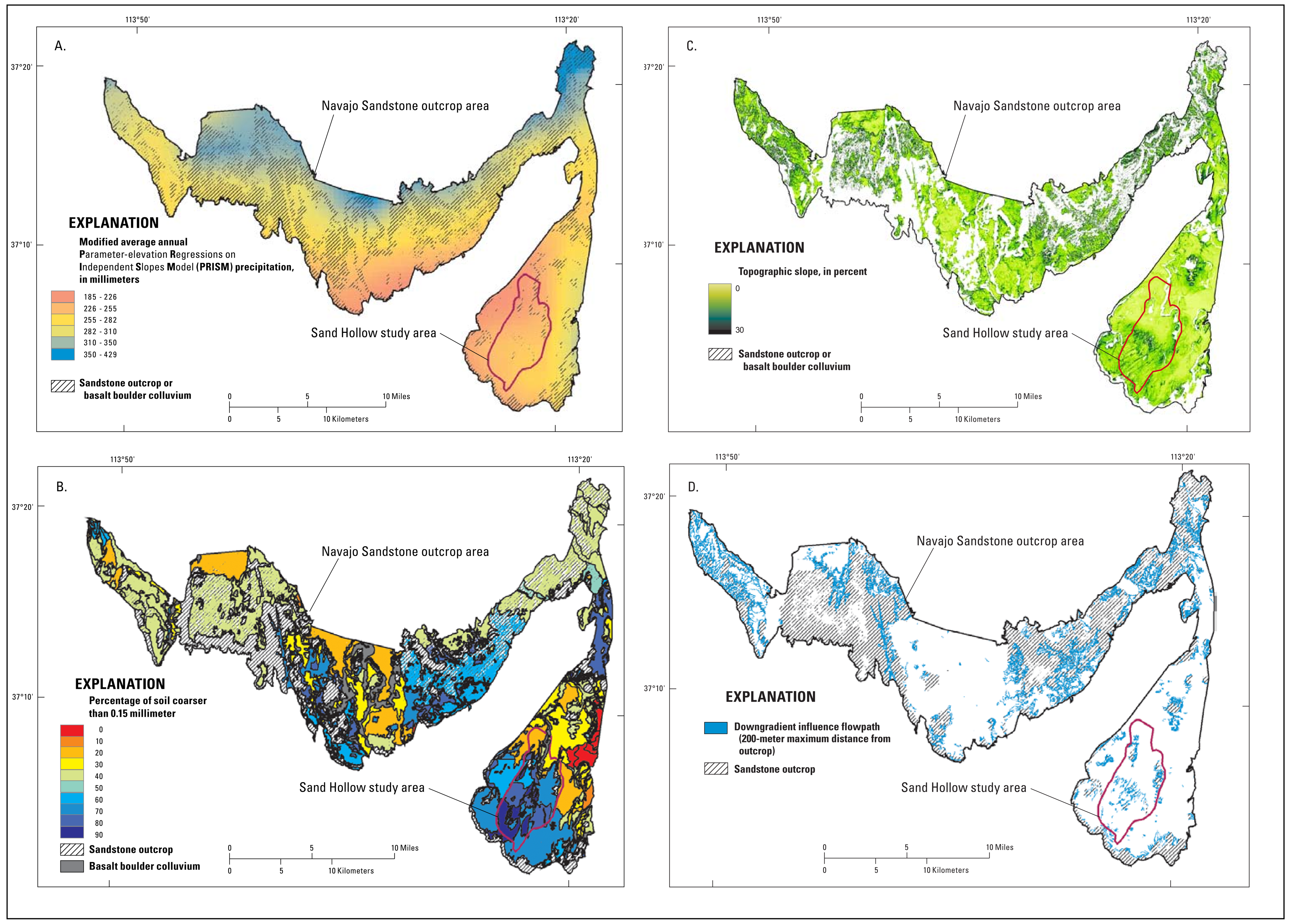

Figure 2. (a) Modified average annual PRISM precipitation, (b) soil coarseness, (c) topographic slope, and (d) downgradient influence flow paths for the Navajo Sandstone outcrop area in western Washington County, Utah.

DIFFERENCE BETWEEN ESTIMATED AND PREDICTED NET-INFILTRATION RATES

The average difference between estimated (tritium-based) and predicted (GIS-model-based) net-infiltration rates at the borehole sites in Sand Hollow and Anderson Junction is about 50 percent, and each rate individually varies from about half the estimated value at Sand Hollow borehole 9 to about double the estimated value at Sand Hollow boreholes 37, 38, and the Anderson Junction borehole (table 2). This comparison is based on the GIS-modeled value from the grid cell at the borehole location. Because the borehole diameter is much smaller (0.03 m^2) than the grid cell area of 9.3 m^2, there is a substantial difference in the representative area which is likely a large source of error. This error would be particularly pronounced at a soil-type boundary or where actual heterogeneity in soil coarseness is not accurately represented by the soil maps. Another potential source of error is the coarseness of the PRISM data, because the resampling and filtering process does not necessarily improve its accuracy. These differences, while small in comparison to the overall range in predicted net-infiltration rates of almost three orders of magnitude, indicate that the net-infiltration map is best suited for evaluating its relative spatial distribution, rather than for precise quantification of recharge to the Navajo aquifer at specific locations outside of Sand Hollow.

LIMITATIONS OF THE MODEL

Although the extrapolation of methods developed for Sand Hollow are only validated by one additional data point (Anderson Junction), the larger Navajo Sandstone outcrop area of western Washington County has similar soils, surficial geology (a combination of exposed/soil-covered sandstone and basalt boulder colluvium), and topographic slope. Two primary differences, however, between Sand Hollow and the larger study area are annual precipitation and topographic aspect. Mean annual precipitation at Sand Hollow ranges from about 200 to 250 mm/yr, compared with 185 to 429 mm/yr for this study area (fig. 2a). The relation between precipitation and net infiltration in areas receiving either more or less precipitation than Sand Hollow could not be thoroughly investigated during this study. Although a common assumption is that net-infiltration ratios increase in wetter climates and decrease in drier climates, other regional factors likely play a role, including warm- versus cold-season precipitation, storm duration, and storm intensity. The topographic aspects within Sand Hollow generally are more northerly than those in the rest of the outcrop area. It is assumed that less net infiltration occurs on slopes with southerly aspects because of higher evaporation rates associated with increased solar radiation. Because Sand Hollow is located in a shallow basin sloping gently to the north and because excavations did not occur on south-facing slopes, this parameter could not be evaluated. Potential controlling factors for outcrop areas that were not evaluated during this study include slope, area, aspect, and fracture density. These factors would affect runoff generation on exposed outcrop and, therefore, the downgradient influence component of net infiltration. It is hypothesized that steeper, larger, north-facing outcrops with little surface fracturing would produce the most runoff. Unfortunately, there was not enough borehole and trench environmental tracer data downgradient of different outcrops in Sand Hollow to evaluate these factors.

The estimated net-infiltration rates were based on previously reported vadose-zone tritium concentrations (Heilweil and others, 2006). These tritium concentrations reflect net infiltration during the past 50 years. Longer-term historical climate records indicate that this period (the latter half of the 20th century) was wetter than normal (Gray and others, 2003, 2004), The net-infiltration rates presented here, therefore, may be somewhat higher than longer-term rates.

SUMMARY

Desert bedrock aquifers in the southwestern United States are increasingly targeted for water development. Understanding and quantifying the spatial variability of net infiltration and recharge, therefore, becomes critically important for inventorying ground-water resources and mapping contamination vulnerability. A GIS-based model utilizing soils, topographic, precipitation, and outcrop data has been developed for predicting net infiltration to the Navajo Sandstone outcrop area of western Washington County, Utah. The GIS model is based on an empirical equation derived from least squares linear regression between three surficial parameters (soil coarseness, topographic slope, and downgradient distance from outcrop) and net-infiltration ratios based on environmental tracer data from excavations and boreholes at Sand Hollow Reservoir.

Areas of low, medium, and high net infiltration have been identified, with estimated rates ranging from about 0.1 to 66 mm/yr. The highest predicted net-infiltration rates (greater than 50 mm/yr) occur in higher-elevation areas covered with coarser-grained soils and located downgradient from sandstone outcrops. Net-infiltration rates of 10-50 mm/yr generally occur in upland areas with coarser soils, yet away from sandstone outcrops. Net-infiltration rates of less than 10 mm/yr occur at lower elevations beneath finer-grained soils not receiving runoff from sandstone outcrops. The total amount of estimated net infiltration (not including infiltration along streams) for the study area is 0.5 m^3/s, or about 10 percent of the total estimated precipitation. Comparison of estimated and predicted net-infiltration rates at 12 borehole locations showed that predicted rates ranged from about one-half to about double the estimated rates. This uncertainty indicates that this net-infiltration map is useful for evaluating relative spatial distribution rather than for precise quantification of recharge to the Navajo aquifer. Further evaluation of additional parameters such as elevation, slope aspect, outcrop area, outcrop fracturing, and precipitation patterns may help improve the accuracy of this method, particularly if applied to other desert sandstone outcrop areas.

Table 1. Coarseness value of soils for the soil-covered Navajo Sandstone outcrop area in western Washington County, Utah.

Soil symbol[1]	Soil name	Percent coarser[2] than 0.15 millimeter	Percent of total area
BED	Bermesa fine sandy loam	26.9	1.31
BF	Bermesa–Rock land association	14.8	.24
CSE	Curhollow gravelly fine sandy loam	39.8	.49
DU	Dune land	75.0	.99
EB	Eroded land-Shalet complex	3.6	.98
HbC	Harrisburg fine sandy loam	20.4	2.30
HD	Harrisburg-Rock land association	35.0	.40
JaB	Junction fine sandy loam	1.8	.37
JaC	Junction fine sandy loam	47.8	.34
MAE	Magotsu-Pastura complex	19.1	13.40
MFD	Mespun fine sand	35.3	9.65
MFD-JnRO	Mespun-Rock outcrop complex	35.5	9.08
MOG	Motoqua-Rock outcrop complex	17.0	.24
NaC	Naplene silt loam	9.0	.62
NEF	Nehar very stony sandy loam	39.3	3.20
PED	Pastura-Esplin complex	27.3	.56
PnC	Pintura loamy fine sand	60.9	.33
PoD	Pintura loamy fine sand, hummocky	60.9	4.39
PTE	Pintura-Toquerville complex	73.4	3.17
PTE-JnRO	Pintura-Toquerville-Rock outcrop complex	73.4	.90
RaC	Redbank fine sandy loam	56.3	.41
Sc	St. George silty clay loam	1.8	.57
TBF	Tobish very cobbly clay loam	20.0	.34
Tc	Tobler fine sandy loam	36.3	1.05
To-JkuRO	Toquerville-Rock outcrop complex, Kayenta	57.0	.21
To-JnRO	Toquerville-Rock outcrop complex, Navajo	57.0	5.23
VHD	Veyo-Curhollow complex	47.7	.88
VPD	Veyo-Pastura complex	13.3	2.83
WBD	Winkel gravelly fine sandy loam	21.5	3.07
WCF	Winkel-Rock outcrop complex	32.5	.58
BB	Badland	bedrock	3.68
CI	Cinder land	bedrock	.26
JkuRO	Kayenta Formation	bedrock	.49
JnRO	Navajo Sandstone	bedrock	6.54
LA	Lava flows	bedrock	.43
RO	Rock land	bedrock	.24
RP	Rock land, stony	bedrock	.40
RT	Rock outcrop	bedrock	1.97
RU	Rough broken land	bedrock	3.90
SY	Stony colluvial land	bedrock	11.34

[1]Soil symbol is from Soil Survey Geographic Database (SSURGO) soil maps (Mortensen and others, 1977) and recent field mapping and aerial photo interpretation (Sutcliffe, 2005).

[2]Coarseness analysis was done by the Bureau of Reclamation Lower Colorado Soils Laboratory using the procedures outlined in Bureau of Reclamation (1990a, 1990b); percent coarser than 0.15 millimeter is based on #100-sieve size.

Table 2. Estimated (tritium-based) and predicted (GIS-model-based) net-infiltration rates for borehole sites in the Navajo Sandstone outcrop area in western Washington County, Utah.

Borehole site[1]	Estimated range[2] of tritium-based net-infiltration rates, in millimeters per year	Predicted GIS-based net-infiltration rate, in millimeters per year	Lower, higher, or within estimated range
Sand Hollow 9	50-64	25	lower
Sand Hollow 44	29-39	35	within
Sand Hollow 43	23-31	21	lower
Sand Hollow 35	23-29	26	within
Anderson Junction	12-18	30	higher
Sand Hollow 50	8-12	19	higher
Sand Hollow 37	3-7	11	higher
Sand Hollow 2	2-6	4	within
Sand Hollow 27	2-6	20	higher
Sand Hollow 12	2-4	4	within
Sand Hollow 39	2-4	4	within
Sand Hollow 38	1-3	4	higher

[1]Borehole site location shown in Heilweil and others (2007).

[2]The range of values denotes the uncertainty reported in Heilweil and others (2006).

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CONVERSION FACTORS

Multiply	By	To obtain
Length		
millimeter (mm)	0.03937	inch (in.)
centimeter (cm)	0.394	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
Area		
square kilometer (km^2)	0.386	square mile (mi^2)
square meter (m^2)	10.76	square foot (ft^2)
Volume		
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
Flow rate		
cubic meter per second (m^3/s)	70.07	acre-foot per day (acre-ft/d)
millimeter per year (mm/yr)	0.03937	inch per year (in/yr)

DATUMS

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88). Altitude, as used in this report, refers to distance above the vertical datum.

U.S. DEPARTMENT OF THE INTERIOR
DIRK KEMPTHORNE, Secretary
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Net-Infiltration Map of the Navajo Sandstone Outcrop Area in Western Washington County, Utah

By

Victor M. Heilweil and Tim S. McKinney

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For additional information write to:
U.S. Geological Survey
Director, USGS Utah Water Science Center
2329 W. Orton Circle
Salt Lake City, UT 84119-2047
Email: GS-W-UTpublic-info@usgs.gov
URL: http://ut.water.usgs.gov/

For more information about the USGS and its products:
Telephone: 1-888-ASK-USGS
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