water resources, and the scarcity of hydrologic information is a problem. The small amount of hydrologic information available for the upper Ash Creek drainage basin results in a hydrologic conceptualization that is irresolute. Existing wells, which mostly tap the basin-fill deposits, vary widely in yield, presumably because of the variability in the hydraulic conductivity of the saturated deposits. A group of more recently drilled wells on the southwest side of the drainage basin is finished in igneous rocks commonly exposed in the Pine Valley Mountains. A few of these wells can be pumped at several thousand gal/min with only a small decline in water level. Other wells finished in the same igneous rocks have low yields. These differences are thought to be caused by heterogeneity and anisotropy from the varying density and connectivity of fractures. Both properties are difficult to quantify and to map.

Ground water from the Navajo Sandstone and the Kayenta Formation has been extensively developed in certain areas along the formation outcrops; however, hydrologic data are not available for many other parts of the outcrops, or where the formations are buried in the north part of the study area. Also, fracturing within these formations, which is extremely variable throughout the study area and strongly affects the movement of ground water, is not well defined. Therefore, the conceptualization of how the hydrologic system functions is not well understood.

Development of an accurate ground-water budget is needed to improve the understanding of the ground-water systems. Ground-water recharge from precipitation, from infiltration beneath streams, from irrigated fields, and possibly from overlying or underlying formations, make up the inflow components of a ground-water budget. However, these components are not well understood or quantified for the upper Ash Creek drainage basin ground-water system for the aquifers of the Navajo Sandstone and Kayenta Formation. Some components of ground-water discharge, such as well pumpage, spring discharge, and discharge to streams can be fairly accurately quantified. However, other discharge components, including evapotranspiration and subsurface outflow to adjacent aquifers, cannot be accurately determined.

Description of the Study Area

The central Virgin River basin study area is in the southwestern corner of Utah, generally west of the Hurricane Fault (fig. 1). The area encompasses about 1,070 mi^2 along the transition between the complexly faulted and folded formations of the Basin and Range Physiographic Province and the gently dipping formations of the Colorado Plateau Physiographic Province, as described by Fenneman (1931). The study area is defined on the west and north sides by the drainage divide between the Virgin and Santa Clara River basins and adjacent drainage basins along the Beaver Dam Mountains, Bull Valley Mountains, Pine Valley Mountains, and Harmony Mountains; the boundary on the east is generally the Hurricane Cliffs, except for a small part of the Markagunt Plateau farther east; the boundary on the south is the Utah-Arizona State line (Cordova and others, 1972). Most of the study area is characterized by sedimentary formations of Mesozoic age, igneous rocks of Tertiary age, and alluvial and basalt-flow deposits of Quaternary age (pl. 1).

The 134 mi^2 upper Ash Creek drainage basin is defined as the surface-water drainage basin that drains into Ash Creek Reservoir, which is located 21 mi south of Cedar City and just west of Interstate 15 (fig. 1). The northern study area boundary divides the internal drainage of the Great Basin from the Virgin River part of the Colorado River drainage basin. The position of the surface-water divide is about 1.5 mi north of Kanarraville, Utah. The ground-water divide in the unconsolidated alluvium, which is roughly coincident with the surface-water divide, can shift slightly with variations in the location and amount of both recharge and pumpage. Topographically, the upper Ash Creek drainage basin consists of gently sloping lowland valley areas that are nearly encircled by the Harmony Mountains to the north, the Pine Valley Mountains to the southwest, and the Markagunt Plateau to the east. The Hurricane Fault zone trends north-northeast near the eastern edge of the upper Ash Creek basin, just east of Interstate 15. A narrow but thick deposit of unconsolidated alluvium has accumulated along the trace of the Hurricane Fault and connects the upper Ash Creek drainage basin northward with the southern end of Cedar Valley (pl. 1).

Within the study area, the Navajo Sandstone has an outcrop area of about 220 mi^2. The Kayenta Formation has an outcrop area of about 35 mi^2. Both formations are buried toward the north by overlying formations for an additional 500 mi^2 within the study area. The formations are absent in the southern part of the study area because of erosion. The outcrops extend from the Hurricane Fault on the east to the Bull Valley Mountains on the west (fig. 1) and vary in altitude from about 2,900 ft to 5,300 ft. In the western part of the study area is the Gunlock Fault, across which the Navajo Sandstone and Kayenta Formation are vertically offset from their southernmost erosional extents to where these formations become buried adjacent to Gunlock Reservoir (pl. 1).

At the latitude of the study area (about 37˚15 N), the effects of both the subtropical and polar jet streams influence the local climate. Also, a large variation in precipitation within the study area results from the large variation in altitude. During 1947-97, precipitation at St. George (altitude 2,820 ft) averaged about 8 in/yr, while the precipitation at New Harmony (altitude 5,290 ft) averaged about 17.8 in/yr. Average precipitation (1961-90) was about 23 in/yr at the highest altitude in the Harmony Mountains (about 8,400 ft), about 30 in/yr at the highest altitude of the Pine Valley Mountains (about 10,400 ft), and about 33 in/yr at the highest altitude of the Markagunt Plateau (about 8,000 ft) (fig. 2). Most of the precipitation in the study area occurs from December through March, although substantial precipitation also can occur from August through November and is related to a monsoonal weather pattern that brings warm, moist air northward from the Gulf of Mexico. The monthly distribution of precipitation at St. George and New Harmony is shown in figure 3.

Previous Investigations

Several reports have been written describing the geology and hydrology of the central Virgin River basin study area. Most recently, Hurlow (1998) did an extensive geologic compilation, as well as field work, to delineate the structure, lithology, and fractures of the Navajo Sandstone, as well as the structure and lithology of basin fill and older consolidated-rock formations along the Ash Creek drainage basin. Cordova, Sand-

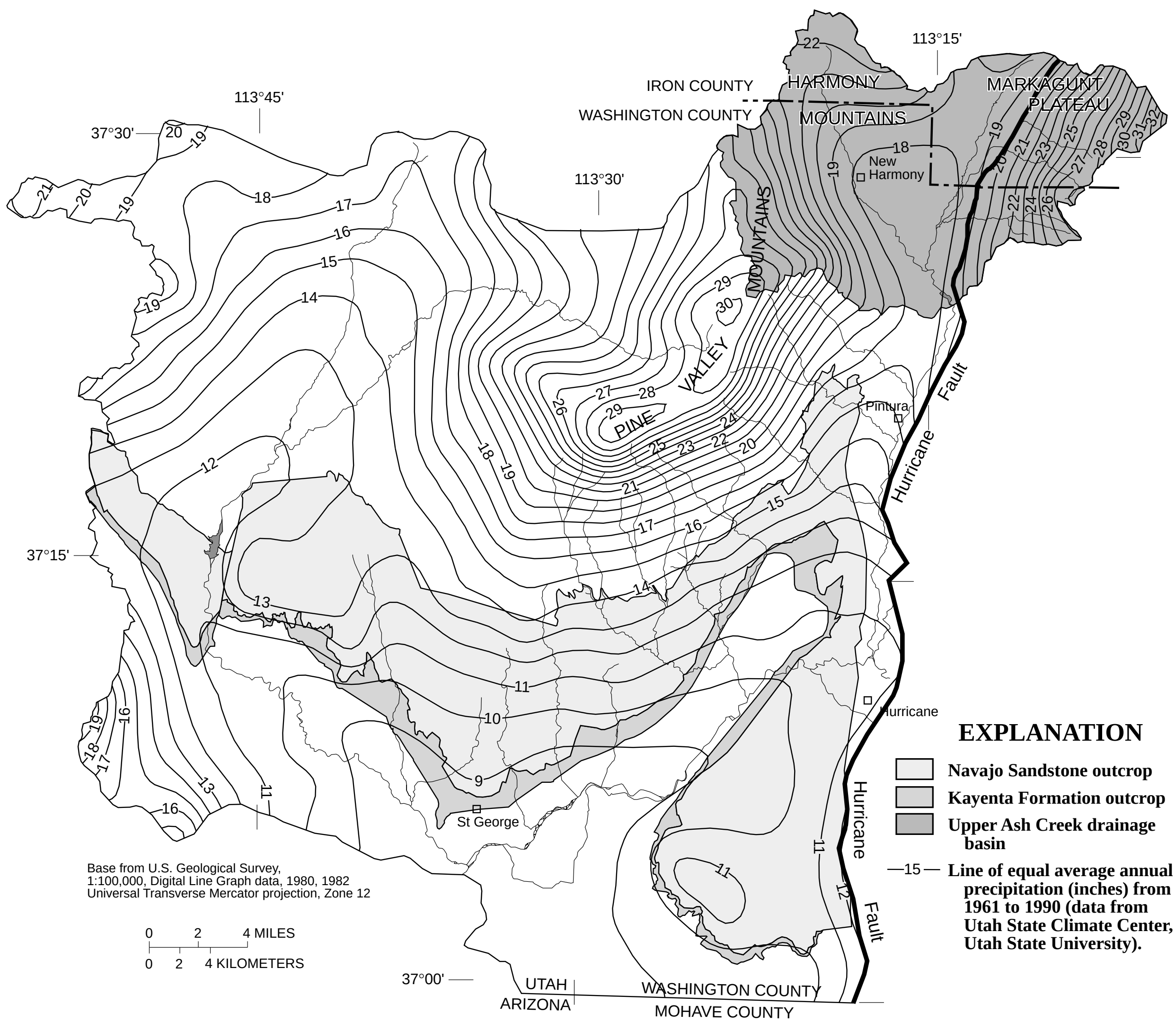

Figure 2. Average annual precipitation contours for the central Virgin River basin study area, Utah, 1961-90.

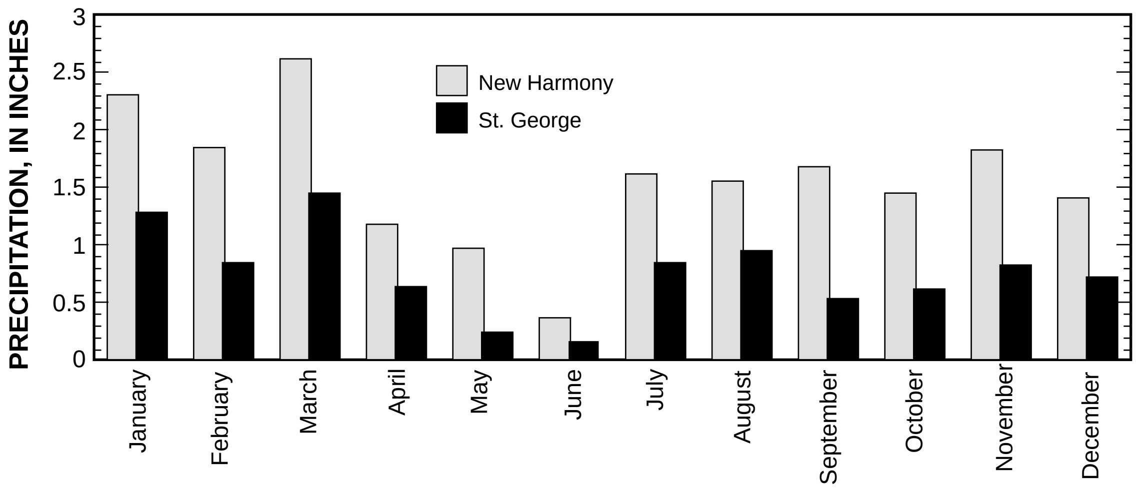

Figure 3. Monthly average precipitation at St. George and New Harmony, Utah, based on data from 1980 to 1989.

berg, and McConkie (1972) described the hydrogeology of both the unconsolidated and consolidated-rock aquifers, including aquifer properties and ground-water budgets. A follow-up study by Cordova (1978) provides a more detailed investigation of ground-water conditions in the Navajo Sandstone within the study area, including aquifer testing and the compilation of a hydrologic budget. A report by Budding and Sommer (1986) describes an assessment of the low-temperature geothermal potential of the Santa Clara River and Virgin River Valleys in Washington County, including extensive water-chemistry data. Clyde (1987) compiled and summarized hydrologic information for both the central Virgin River and upper Virgin River drainage basins. Herbert (1995) described a seepage study of a section of the Virgin River within Washington County. Jenson, Lowe, and Wireman (1997) provided a detailed hydrologic analysis of Sheep Spring near Santa Clara. Cook (1960) presented an overview of the geology of Washington County and a more-detailed description (Cook, 1957) of the geology of the Pine Valley Mountains. Spencer Reber (written commun., 1994) wrote a number of unpublished reports for the municipalities of St. George, Washington, and Leeds, including detailed geologic maps and cross sections. With regard to geohydrology of the upper Ash Creek drainage basin, Thomas and Taylor (1946) and Bjorklund, Sumsion, and Sandberg (1978), as part of their overall hydrologic study of the more populated Cedar City and Parowan Valleys, briefly described ground-water occurrence and use near Kanarraville, Utah.

Scope of study

The purpose of the study was to assess the quantity of ground water in the central Virgin River basin and to document, to the closest extent possible, direction and rate of movement of ground water through the aquifer systems. In general, the approach of this study was to (1) compile available geologic information on the various aquifer formations; (2) collect additional hydrologic, geologic, and chemical data, where possible and practical; (3) formulate hydrologic conceptualizations of ground-water movement through the principal aquifers; (4) develop computer simulations representing the aquifers to test various alternative hydrologic conceptualizations; (5) compare model-computed results with measured hydrologic data to determine how confidently the models can be used as tools for the management of ground-water resources; and (6) determine which additional data collection would be most helpful in refining present hydrologic conceptualizations. Water chemistry was also investigated when it could be used to aid in the analysis of recharge, ground-water movement, and discharge. Generally, well and spring locations within the study area were selected on the basis of proximity to municipalities, depth to water, quality of water, and natural factors such as topography and surface recharge. Thus, more information is available for certain parts of the aquifers, which allows for more detailed hydrologic analyses in those areas. Conversely, only a small amount of information is available regarding ground-water conditions in many parts of the upper Ash Creek drainage basin ground-water system and the Navajo and Kayenta aquifers.

Purpose and Scope of Report

The purpose of the report is to document the findings of the study, which include descriptions of the geohydrologic framework, analyses of the chemical and isotopic character of the ground water, and conceptual and mathematical representation of three separate aquifer systems in the study area. This report describes the geohydrology of the upper Ash Creek drainage basin ground-water system and the aquifers within the central Virgin River basin formed by the Navajo Sandstone and the Kayenta Formation. The Navajo Sandstone and the Kayenta Formation are two of the formations that make up the principal regional aquifer of the Colorado Plateau, the Glen Canyon aquifer. For this report they will be referred to individually as the Navajo aquifer and the Kayenta aquifer. Information was compiled and analyzed regarding their lateral and vertical extents, hydraulic properties, ground-water budgets, and directions of ground-water flow.

In addition to the data provided by previous investigations, hydrologic data collected for this study included water level measurements in wells, discharge measurements from pumping wells and springs, discharge measurements in streams, aquifer testing, and the collection of water samples for the analysis of general chemistry, stable and radioactive isotopes, dissolved gases, and chlorofluorocarbons (Wilkowske and others, 1998). Water levels were measured in about 30 wells in the upper Ash Creek drainage basin and in about 80 wells in the Navajo and Kayenta aquifers to determine the configuration of water-level contours (Wilkowske and others, 1998, tables 1 and 2). Most of the municipal well pumpage information was available from the Utah Division of Water Rights and private well owners; however, power consumption and discharge were measured at 14 irrigation wells in the Navajo and Kayenta aquifers southwest of Hurricane and at 8 irrigation wells in the upper Ash Creek drainage basin to estimate annual average rates of ground-water discharge (Wilkowske and others, 1998, table 1). Surface-water discharge was measured at 58 sites in the study area to determine the relative amount of stream loss and gain and the locations where these losses and gains occur (Wilkowske and others, 1998, table 6). Four aquifer tests were conducted at wells that pump water from the Navajo Sandstone and one aquifer test was conducted at a well that pumps water from the igneous rocks in the upper Ash Creek drainage basin.

Field and laboratory analyses were done on ground- and surface-water samples, not to characterize water quality, but to evaluate surface- and ground-water relations and to get a sense of how water enters, moves through, and leaves the ground-water systems of interest. Specific conductance, water temperature, and pH were measured at many of the surface water and ground-water sites inventoried to determine the range and the areal and temporal trends of the values (Wilkowske and others, 1998, tables 3, 4, 5, 6). Water samples for general chemistry were collected at 7 wells, in addition to a compilation of 113 previously reported analyses (Wilkowske and others, 1998, table 4). Thirty-four samples were analyzed for the stable isotopes of oxygen and hydrogen; 25 water samples and 2 rock samples were analyzed for strontium isotopes; and 2 water samples were analyzed for the radioactive isotope of hydrogen (tritium) (Wilkowske and others, 1998, table 5). Water samples from 36 sites were analyzed for chlorofluorocarbons and 6 samples were analyzed for dissolved gases (Wilkowske and others, 1998, table 5).

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GEOHYDROLOGIC FRAMEWORK

The central Virgin River basin study area is located at the transition zone between the Basin and Range and the Colorado Plateau Physiographic Prov-