CHAPTER 2:
WATER RESOURCES

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This chapter describes the availability of water resources in the vicinity of the Reservation. These resources include aquifers **(Section 2.1),** springs **(Section 2.2)**, and streams **(Section 2.3)**.

2.1 AQUIFERS

This chapter begins by describing aquifers that underlie the Reservation. An overview is provided first, followed by more detailed descriptions for six separate aquifers:

- Alluvial/Colluvial Aquifer
- Bidahochi Aquifer
- Toreva (T) Aquifer
- Dakota (D) Aquifer
- Navajo (N) Aquifer
- Coconino (C) Aquifer.

Aquifer descriptions include their occurrence, flow direction, and natural recharge and discharge. The D and N Aquifers have been the most heavily utilized in the region and are discussed here in more detail. For these aquifers, data are also presented on their estimated groundwater in storage and for the N Aquifer, aquifer properties and measured hydrologic impacts are also discussed.

2.1.1 Overview

Figure 2-1 is a stratigraphic column that shows the sequence of aquifers beneath the Reservation and their associated geologic strata. The shallowest aquifer occurs near surface in unconsolidated deposits of alluvium and colluvium. The C Aquifer is the deepest and occurs locally at depths of several thousand feet in limestone and sandstone. The Bidahochi, T, D, and N Aquifers are encountered at intermediate depths.

The lateral extent of these aquifers is shown in **Figure 2-2**. Only the C Aquifer is encountered beneath the entire Reservation but, as indicated above, it is several thousand feet deep. The D and N Aquifers are found beneath all but the far southwestern portions of the Reservation, whereas the Bidahochi and T Aquifers are only encountered in the southeast and northeast, respectively. The Alluvial/Colluvial Aquifer is limited to areas of the Reservation along washes and at the base of some slopes.

Figures 2-3 and **2-4** illustrate the expected water level after 100 days of continuous pumping in wells drilled on the Reservation with yields of at least 25 gpm and 500 gpm, respectively. **Figure 2-3** indicates that wells yielding at least 25 gpm could be completed across most of the Reservation, but pumping levels would be variable, ranging from less than 100 feet below ground surface in some areas and up to 2,000 feet in others. **Figure 2-4** indicates that wells yielding at least 500 gpm could only be completed in the northeastern portion of the Reservation. Pumping levels for these wells would be expected to range from 300 feet up to 2,000 feet below ground surface.

A conceptual hydrologic model of the region is provided in **Figure 2-5**. The model shows how water is recharged to, and discharged from, three Reservation aquifers (Alluvial/Colluvial, D, and N). The model also shows the flow of water between the aquifers. Further discussion of these processes is provided below.

2.1.2 Alluvial/Colluvial Aquifer

Occurrence

Some of the unconsolidated sediments recently deposited along drainages and at the base of slopes are saturated and form local aquifers. These unconfined aquifers are relatively thin and of limited aerial extent, but can locally contain sand and gravel beds that are more permeable than the underlying bedrock (Cooley and others, 1969). Combined, the shallow aquifers are referred to here as the Alluvial/Colluvial Aquifer (**Figure 2-2**).

Flow Direction

Water in the Alluvial/Colluvial Aquifer generally flows from higher to lower ground elevations, following the surface topography of the Reservation.

Natural Recharge and Discharge

Recharge to the Alluvial/Colluvial Aquifer comes from direct precipitation, infiltration of streamflow, and discharge from adjacent bedrock springs. Discharge from the Alluvial/Colluvial

Aquifer can occur as baseflow to streams, evapotranspiration by riparian vegetation, spring discharge, and underflow. **Figure 2-6** shows the location of recent and historic perennial stream reaches on the Reservation that are fed by baseflow, and **Appendix B, Figure B-5** shows where ADWR mapped riparian vegetation on the Reservation in 2005.

2.1.3 Bidahochi Aquifer

Occurrence

The Bidahochi Aquifer is encountered beneath a relatively small area in the southeastern portion of the Reservation (**Figure 2-2**). The aquifer is generally unconfined and comprised of Tertiary-age volcanic and sedimentary rocks including basalt, rhyolitic ash, mudstone, and sandstone (**Figure 2-1**). The main water-bearing unit locally is associated with breccia-filled volcanic pipes (Farrar, 1980).

Flow Direction

ADWR does not have data on the direction of flow in the Bidahochi Aquifer beneath the Reservation.

Natural Recharge and Discharge

Most recharge to the Bidahochi Aquifer probably occurs from direct precipitation, where the Tertiary rocks are exposed at or near ground surface (ADWR, 1989). Discharge probably occurs largely as leakage to underlying aquifers and as underflow that leaves the Reservation. ADWR did not identify any Reservation springs that discharge water from this aquifer, and there are no reported perennial stream reaches in the area of the Reservation where it is encountered.

2.1.4 T Aquifer

Occurrence

The T Aquifer is encountered beneath the northeastern portion of the Reservation (**Figure 2-2**) and comprised of sandstone units within the Cretaceous-age Mesa Verde Group. These units include the Yale Point Sandstone and sandstones of the Wepo and Toreva Formations (**Figure 2-1**). Although confined conditions occur locally, the aquifer is generally unconfined and often consists of perched water-bearing zones formed above relatively low permeability coal, siltstone, and mudstone layers. Water levels in the T Aquifer vary both vertically and horizontally and wells completed in the aquifer may yield water from several, separate zones (Levings and Farrar, 1977).

Flow Direction

ADWR does not have data on the direction of flow in the T Aquifer, but it is expected to be complex due to the occurrence of perched water-bearing zones.

Natural Recharge and Discharge

Most recharge to the T Aquifer probably occurs from direct precipitation where units of the Mesa Verde Group are exposed at or near ground surface. Some recharge to the aquifer may also occur via leakage from the overlying Bidahochi Aquifer in areas where it present. Discharge probably occurs largely from springs, baseflow to streams, and as underflow. Leakage to the underlying D Aquifer is probably limited by several hundred feet of Mancos Shale.

Perennial stream reaches in the headwaters of Moenkopi Wash are believed to have been fed by the T Aquifer (**Figure 2-6**). This reach was observed near the beginning of the 20th century during a wet period and is currently intermittent (ADWR, 2008p). The quantity of underflow that potentially leaves the Reservation from the T Aquifer has not been determined.

2.1.5 D Aquifer

Occurrence

The D Aquifer extends beneath all but the southwestern portion of the Reservation (**Figure 2-2**), and is comprised of a series of Cretaceous- and Jurassic-age sandstones. The Dakota Sandstone is the most important water-bearing unit, with water also obtained from the Entrada Sandstone and sandstones of the Morrison and Carmel Formations (**Figure 2-1)**. The sandstones are separated by mudstone and siltstone layers and are locally discontinuous (Cooley and others, 1969).

The D Aquifer is generally thickest (up to 1,300 feet) near its center and thins to the southeast (700 feet) and northwest (100 feet) (Lopes and Hoffman, 1997). It is confined by mudstone and gypsum beds of the overlying Mancos Shale (Cooley and others, 1969).

Flow Direction

Water in the D Aquifer currently flows under pressure from an elevation of about 6,200 feet just east of the Reservation to an elevation of about 5,300 feet to the southwest (**Figure 2-7**). Flows are locally restricted where the sandstone units are folded or pinch out (Cooley and others, 1969).

Natural Recharge and Discharge

The total recharge to the D Aquifer has been estimated at 5,392 AFA (GeoTrans and Waterstone, 1999). Most of this recharge probably occurs outside of the Reservation along the eastern slope of Black Mesa, where units of the aquifer outcrop (Lopes and Hoffman, 1997). Recharge may also occur locally along ephemeral washes where these units are at or near ground surface. The age of water from the D Aquifer water is estimated to range from 4,000 to 11,000 years old near the main recharge area and up to 33,000 years old downgradient (Truini and Longsworth, 2003).

The D Aquifer discharges water via springs, leakage to the underlying N Aquifer, baseflow to streams and as underflow along the Hopi Washes. Leakage of water from the D Aquifer to the N aquifer has apparently been occurring for thousands of years, with the area of greatest leakage in the southeastern portion of the Reservation. In this area, the N Aquifer is relatively thin and the difference in predevelopment water levels between the D and N Aquifers is small (Truini and Longsworth, 2003).

Water from the D Aquifer is also discharged on the Reservation as baseflow to streams and as underflow (Cooley and others, 1969). Perennial stream reaches historically observed along Dinnebito and Jeddito Washes are believed to have been fed by the D Aquifer (**Figure 2-6)**. During dry periods, discharge from the D Aquifer probably still occurs along these and the other Hopi washes as recharge to underlying alluvial aquifers. The quantity of D Aquifer water that potentially leaves the Reservation as underflow along the washes has not been determined. However, it has been estimated that a relatively large quantity of water in the alluvial aquifer is consumed locally by riparian vegetation (see **Appendix B, Figure B-5**).

Water in Storage and Well Yields

ADWR (1989) estimated the total volume of water stored in the D Aquifer at 15 million acre-feet.[1] The estimate applies to the entire LCR watershed and includes Navajo lands outside of the Reservation. More than half of the total D Aquifer water appears to be stored beneath the Reservation. The actual yield of most D Aquifer wells on the Reservation is believed to be less than 1.25 gpm (DBSA, 2000), although yields up to 20 to 25 gpm are reported in the region (ADWR, 1989 and Farrar, 1980).

2.1.6 N Aquifer

Occurrence

The N Aquifer extends beneath all but the southwestern portion of the Reservation (**Figure 2-2**), and is comprised of a series of Jurassic-age sandstones. The Navajo Sandstone is the primary water-bearing unit, with water also obtained from underlying sandstones in the Lukachukai Member of the Wingate Sandstone (**Figure 2-1**).

In the vicinity of the Reservation, the N Aquifer is generally thickest (up to 1,000 feet) in the northwest and thins to between 200 and 400 feet in the east and west and less than 200 feet in the south (**Figure 2-8**). It is confined over much of this area by siltstone and mudstone of the Carmel Formation. Unconfined conditions occur in a recharge area to the north, a discharge area to the west, and in the southeast where the N Aquifer is relatively thin and receives leakage from the D Aquifer (**Figure 2-9**).

Flow Direction

Figure 2-9 shows the general direction of groundwater flow in the N Aquifer prior to 1972, when substantial development of the aquifer began. Water levels were highest in the Shonto area, north of the Reservation, and reached an elevation of over 6,500 feet. From there, groundwater flowed to the south and west with elevations dropping to less than 4,800 feet near Moenkopi, and flowed to the northeast with elevations dropping to less than 5,000 feet.

[1] It is important to note that not all groundwater in storage is recoverable. Significant percentages of estimated volumes of stored groundwater may remain after it is no longer practicable to pump from an aquifer.

Across much of this area, water in the N Aquifer occurred under confined conditions with water levels in wells rising as much as 1,800 feet above the top of the Navajo Sandstone. Along the aquifer margins, the groundwater was unconfined with water levels in wells at or below the top of the aquifer (Brown and Eychaner, 1988). These conditions generally still occur today, although industrial and municipal pumping has locally altered water levels and associated flow directions by forming drawdown cones around well sites.

Natural Recharge and Discharge

Recharge to the N Aquifer is estimated to range from 2,600 and 20,248 AFA (OSM, 2008). Geochemical analysis and groundwater flow and transport modeling suggest that N Aquifer recharge was 50% lower from 6,000 to 11,000 years ago and 2 to 3 times higher from 11,000 to 31,000 years ago. Variations in recharge are explained by effects from glacial and post-glacial periods (Zhu and others, 1998).

Water is discharged from the N Aquifer via springs, baseflow to streams, and as underflow along the Hopi Washes. Perennial and intermittent stream reaches historically and currently observed along Moenkopi, Dinnebito, and Polacca Washes are also believed to have been fed by the N Aquifer (**Figure 2-6**). The aquifer also discharges to alluvial aquifers that underlie the Hopi Washes, although the quantity of this water that leaves the Reservation as underflow has not been determined. A relatively large quantity of water from the alluvial aquifer (from 23,200 to 56,550 acre-feet) has been estimated to be consumed each year by riparian vegetation (see **Appendix B, Figure B-5**). A portion of this likely originates from the N Aquifer.

Aquifer Properties

Figure 2-10 shows the variability in the estimated hydraulic conductivity of the N Aquifer in the vicinity of the Reservation. The hydraulic conductivity is estimated to range from 0.1 to 1.8 feet/day with the highest values in the southwest and near the center of the area. These values were input to a United States Geological Survey (USGS) groundwater flow model and are based on long-term (over 6-year) aquifer tests conducted in the PWCC well field and 40 other short-term aquifer and well tests.

Figure 2-11 shows how the transmissivity of the N Aquifer varies over the same model area**.** Transmissivity is a measure of an aquifer's ability to transmit water and is the product of its hydraulic conductivity and saturated thickness. Transmissivity is an important factor in evaluating well yields and, in general, aquifers with higher transmissivities may sustain higher pumping rates. The transmissivity of the N Aquifer, as modeled by the USGS, ranges from 20 to over 1,000 $feet^2$/day. The highest transmissivity values are located in the north where PWCC completed its well field in the N Aquifer.

As described earlier, water in the N Aquifer is encountered under both unconfined and confined conditions. Specific yield is a measure of the amount of water that an unconfined aquifer releases from storage when its water level declines. For confined aquifers, storage coefficient is a measure of the amount of water that is released from storage with a decrease in artesian pressure. In the vicinity of the Reservation, specific yield and storage values for the N Aquifer are reported to range from 0.1 to 0.15 and from 0.00022 to 0.0008, respectively (Eychaner, 1983). A practical implication of this is the relatively large drawdowns that have been measured in several wells completed in confined portions of the N Aquifer where storage coefficients are comparatively low. For a given pumping rate and aquifer transmissivity, water levels decline more quickly in wells with lower specific yield and storage coefficient values.

Yields of wells completed in the N Aquifer range from less than 5 gpm to over 300 gpm (Farrar, 1979 and 1980), with some wells in the PWCC leasehold yielding over 500 gpm. Pumping rates for municipal wells completed on the Reservation in the N Aquifer are reported to range from 8.5 to 121 gpm (Tetra Tech, 2006).

Water in Storage

The USGS estimates the volume of groundwater stored in their modeled area of the N Aquifer (**Figure 2-8**) as 180 million acre-feet (Eychaner, 1983). Other models, such as the PWCC model, simulate different sized areas and make different assumptions about aquifer thickness which result in different estimates of groundwater in storage.

The N Aquifer has been the most heavily developed of the region's six aquifers. In addition to Hopi municipal pumping, the Navajo and PWCC have several wells completed in the N Aquifer for municipal and industrial use, respectively. **Table 2-1** lists the total and average annual withdrawals from these wells since 1965, and **Figure 2-12** shows well locations and withdrawals for 2011. Over 243,660 acre-feet of water have been pumped from the N Aquifer over the period from 1965 to 2011 (Macy and Unema, 2014). From 1965 through 2005, PWCC industrial withdrawals averaged 3,453 AFA and comprised approximately 63% of the N Aquifer withdrawals. Since the closing of the Black Mesa Mine in 2005, PWCC industrial withdrawals now average 1,255 AFA and make up only approximately 30% of the total N Aquifer withdrawals. Withdrawals for municipal use by the Navajo and Hopi now comprise 70% of the total N Aquifer withdrawals.

Macy and Unema (2014) estimate that total withdrawals from other wells completed in the N and D Aquifer are less than 1% of the total municipal and industrial withdrawals from the N Aquifer. These other wells are used for stock and domestic purposes and their flows are generally not monitored.

Measured Hydrologic Impacts from Development

Figure 2-13 shows the water level change measured by the USGS in several N Aquifer wells since aquifer development began during the early 1970s. Between 1965 and 2012, water levels generally dropped in the confined portion of the aquifer, but were little changed in the unconfined portion. The median water level change over this period was -39.1 feet for 18 wells completed in the confined aquifer and -2.1 feet for 16 wells completed in the unconfined aquifer (Macy and Unema, 2014). The largest declines were measured at municipal pumping centers and near the PWCC leasehold. A municipal well (PM2) near Keams Canyon showed a water-level decline of 205.5 feet, a USGS monitoring well (BM2) northeast of the leasehold showed a change of -91.6 feet, and a USGS monitoring well (BM6) between the leasehold and municipal well showed a change of -151.0 feet.

Once operation of the Black Mesa Mine ceased in December 2005, water levels in two N Aquifer observation wells on the leasehold rose substantially (**Figure 2-14**). Between 2002 and 2005, PWCC estimated that the static water level depth was about 1,150 feet in observation well NAVOBS3 and about 1,344 feet in observation well NAVOBS6. Due to a decrease in pumping, water levels in these wells rose by over 100 feet during the two year period.

Since the late 1980s and early 1990s, the USGS has also routinely monitored discharge from four N Aquifer springs in the vicinity of the Reservation. **Figure 2-15** shows the location of the springs and how their discharge has varied over time. Trends in measured discharges over time at the unnamed spring on Navajo land near Dennehotso and at Burro Spring do not appear to be significant (Macy and Unema, 2014). Accounting for annual and seasonal fluctuations, discharges from Moenkopi School and Pasture Canyon Springs appear to have declined by about 7 gpm, and 10 gpm, respectively. [Note that the measuring point for Pasture Canyon Springs used in the Macey and Unema study is different from the USGS gage location.]

Figure 2-15 also shows variations in the discharge along three streams and one spring believed to be fed by N Aquifer discharge. The USGS monitors flows in Moenkopi, Dinnebito and Polacca Washes on the Reservation and flows at Pasture Canyon Spring on adjoining Navajo land.

To remove potential short-term effects from snowmelt, riparian evapotranspiration, and monsoon storms, flow data collected during November through February were analyzed separately (Macy and Unema, 2014). None of the four studied sites show significant increasing or decreasing trends in discharge measurements over the period of record. For reference, **Figure 2-15** also shows annual precipitation data from a nearby meteorological station.

2.1.7 C Aquifer

Occurrence

The C Aquifer is encountered beneath the entire Reservation (**Figure 2-2**) and consists of the Permian-age Kaibab Limestone, Coconino Sandstone, and upper Supai Formation (**Figure 2-1**). It also underlies much of the LCR Basin, extending from the Mogollon Rim in the south to an area west of the LCR River and northeast into New Mexico (Hart and others, 2002). Locally, the C Aquifer is confined by the Chinle and Moenkopi Formations which restrict downward leakage from the overlying N Aquifer.

Flow Direction

Water in the C Aquifer generally flows in a west-northwest direction across the southern portion of the Reservation. C Aquifer groundwater flows beneath the central and northern parts of the Reservation reportedly are less well defined and restricted by low permeability units. Few C Aquifer wells have been completed in the vicinity of the Reservation due to poor water quality conditions and the relatively high well construction and pumping costs associated with developing this deep aquifer (Cooley and others, 1969 and Hart and others, 2002).

Natural Recharge and Discharge

The C Aquifer water beneath the Reservation is recharged nearly 100 miles to the south along the Mogollon Rim and 50 miles to the east on the Defiance Uplift (Hart and others, 2002). Blue Springs, the major discharge area in the region, is located about 40 miles west of Moenkopi along the lower LCR (**Figure 2-6**). Due to its depth, no discharge from the aquifer occurs locally.

2.2 SPRINGS

The Hopi Tribe and the United States, on behalf of the Hopi Tribe, claim the right to utilize all flows from springs on the Reservation. Further, they claim the right to make improvements, such as constructing spring boxes or pipe collection systems, to preserve each springs utility for any use including livestock, domestic, agriculture, ceremonial, religious and cultural. Neither the Hopi nor the United States claim a specific quantity for each spring since metering data or evidence of past or present flows is generally unavailable.

In their Third Amended SOCs, the Hopi and the United States claim a total of 379 springs. Both the Hopi and United States reference the same list and maps of springs as presented in Appendices 5 and 7 of the United States Third Amended SOC. GIS shapefiles depicting spring locations and other information were provided to ADWR by the United States in support of the Hopi and United States claims.

2.2.1 Evaluation of Spring Locations

ADWR conducted an evaluation to verify the presence of claimed springs within the following sources of information at the locations provided by the United States.

- Appendix D: Hopi Spring Evaluation from ADWR’s 2008 Preliminary HSR;
- USGS Topographic Series Maps (Topo Large);
- NWIS: National Water Information System (USGS Water Data);
- GNIS: Geographic Names Information System;
- Topographic Series Maps (USA Topo Maps);
- USGS Scanned Topos; and
- ESRI World Imagery and Google Earth.

ADWR considered the presence of a spring to be verified if a spring was noted as verified in Appendix D: Hopi Spring Evaluation or evidence of a spring was observed in the other maps or imagery data sources reviewed as part of this evaluation. If a spring did not meet either of these criteria, the presence of a spring was considered not verified. Information about the data sources used in this evaluation is presented below followed by ADWR's evaluation findings.

Appendix D: Hopi Spring Evaluation (ADWR, 2008p)

This document presented an inventory of springs on the Reservation and ADWR's evaluation of the claimed springs. ADWR used topographic maps, published reports, ADWR ground inspection, and/or supporting evidence from the Hopi to verify both claimed and unclaimed springs.

USGS Topographic Series Maps (Topo Large)

USGS Topo Large is a web based dynamic topographic map service that combines the best available data (Boundaries, Elevation, Geographic Names, Hydrography, Land Cover, Structures, Transportation, and other themes) that make up The National Map. Contours generated for the US Topo product are visible along with other data at scales of 1:13,500 and larger. This product is designed to provide a seamless view of the data in a geographic information system (GIS) accessible format, closely resembling the US Topo product at large scales.

NWIS: National Water Information System (USGS Water Data)

The USGS has collected water-resources data at approximately 1.5 million sites in all 50 States, the District of Columbia, Puerto Rico, the Virgin Islands, Guam, American Samoa and the Commonwealth of the Northern Mariana Islands. The types of data collected are varied, but generally fit into the broad categories of surface water and groundwater. Surface water data, such as gage height (stage) and streamflow (discharge), are collected at major rivers, lakes, and reservoirs. Groundwater data, such as water level, are collected at wells and springs.

GNIS: Geographic Names Information System

The Geographic Names Information System (GNIS), developed by the USGS in cooperation with the U.S. Board on Geographic Names, contains information about physical and cultural geographic features in the United States and associated areas, both current and historical (not including roads and highways). The database holds the federally recognized name of each feature and defines the location of the feature by state, county, USGS topographic map, and geographic coordinates.

Other feature attributes include names or spellings other than the official name, feature designations, feature class, historical and descriptive information. The database assigns a unique feature identifier, a random number that is a key for accessing, integrating, or reconciling GNIS data with other datasets. The GNIS is the United States' official repository of domestic geographic feature names information.

ESRI Topographic Series Maps (USA Topo Maps)

This map presents land cover imagery for the world and detailed topographic maps for the United States. The map includes the National Park Service (NPS) Natural Earth physical map at 1.24 km per pixel for the world at small scales, i-cubed eTOPO 1:250,000-scale maps for the contiguous United States at medium scales, and National Geographic TOPO! 1:100,000 and 1:24,000-scale maps (1:250,000 and 1:63,000 in Alaska) for the United States at large scales. The TOPO! maps are seamless, scanned images of USGS paper topographic maps.

Scanned Topos

A digital raster graphic (DRG) is a scanned image of a USGS standard series topographic map, including all map collar information. The image inside the map neat line is georeferenced to the surface of the earth and fit to the Universal Transverse Mercator projection. The horizontal positional accuracy and datum of the DRG matches the accuracy and datum of the source map. The map is scanned at a minimum resolution of 250 dots per inch.

Utilizing the data sources described above, ADWR was able to verify the presence of 316 or about 83% of the 379 claimed springs. ADWR was unable to verify 63 claimed springs, or about 17% of the total. Of the 63 unverified springs, ADWR was not able to locate 41 springs at the claimed location during field investigations on the Reservation in 2005. ADWR was unable to verify the remaining 22 springs using the data sources listed above or due to lack of access during the 2005 field investigations. **Table 2-2** provides information on the 63 springs that were not verified during ADWR's evaluation.

2.2.2 Characteristics

Where known, water sources for most springs on and near the Reservation are from the T Aquifer (103 springs) and N Aquifer (82 springs). Other water sources include the alluvial aquifer (25 springs), colluvial aquifer (23 springs), spring (travertine) deposits (7 springs), and the D Aquifer (5 springs) (ADWR, 2008p). Some form of development was noted at 83 spring sites during ADWR's 2005 field investigations. The most common improvements were troughs (44 springs) and spring boxes (22 springs).

2.2.3 Discharge

ADWR found or collected discharge data for 208 springs (ADWR, 2008p). Measured discharges totaled from 360 to 1,103 gpm and were greatest from the N Aquifer (207 to 777 gpm) and T Aquifer (99 to 202 gpm). Discharge measurements for each individual spring ranged from 0 to 326 gpm.

The N Aquifer discharges water to several springs located along Pasture Canyon, upstream of the villages of Upper Moenkopi and Lower Moenkopi. Most spring flow occurs in the upper portion of the canyon and, since August 2004, the USGS has continuously monitored the combined discharge of the springs at its Pasture Canyon gage (**see Table 2-3 and Figure 2-6**). Before installing the gage, the USGS had measured a total spring discharge of greater than 300 gpm in this area, although measurements have generally been lower and some were apparently affected by irrigation diversions. The earliest measurements were made during 1908 and 1948 when total discharges of 224 and 210 gpm were recorded, respectively (Brown and Halpenny, 1948). Between 1948 and 1954, 13 discharge measurements were reported and averaged 177 gpm (Chambers & Campbell, 1962). The average annual flow from Pasture Canyon Springs over the period of record from 2004 to present is 226 AFA, which is equivalent to 140 gpm.

2.3 STREAMS

The Reservation is drained by five major washes – Jeddito (Jadito) Wash, Polacca Wash, Oraibi Wash, Dinnebito Wash, and Moenkopi Wash. Locations of the Hopi Washes and USGS stream gages are shown in **Figure 2-6**. Streamflow data collected from the gages are summarized in **Table 2-3** and include the identification number, contributing drainage area, period of record, number of daily mean flow measurements taken, annual and seasonal flow statistics, typical flow durations, and streamflow regimes (perennial, intermittent, and ephemeral).

2.3.1 Streamflow Monitoring

Streamflow monitoring began in the mid-1990s in four of the Hopi Washes (Dinnebito, Jeddito, Oraibi, and Polacca). Monitoring ceased in Jeddito Wash in 2005 and in Oraibi Wash in 2013. Streamflows in Moenkopi Wash have been continuously monitored since the 1920s, and gages along Coal Mine Wash and two of its tributaries were monitored from the late 1970s through the early 1980s. Coal Mine Wash drains part of the PWCC leasehold and is a tributary to Moenkopi Wash.

Based on available USGS data, median streamflows in the Hopi Washes have ranged from a low of 145 AFA in Jeddito Wash to a high of about 10,600 AFA in Moenkopi Wash. Measured flows at these gages have been highly variable from year to year, with maximum annual flows exceeding minimum annual flows by a factor of between 6 and 22. On average, the majority (over 50%) of annual streamflow volumes have occurred during the summer in response to monsoon storms. Streamflows have usually been lowest in the spring when precipitation is also at its lowest and evapotranspiration (ET) of riparian vegetation begins.

Several hydrologic factors may affect Reservation streamflows. In addition to storm runoff and ET, factors include snowmelt, baseflow (groundwater inflow), transmission losses, and well pumpage. Storm runoff, snowmelt and baseflow can result in streamflow gains while ET, transmission losses, and well pumpage can result in streamflow losses.

2.3.2 Streamflow Regimes

Median daily flows were used to identify recent streamflow regimes at the gage sites. Available data presented in **Table 2-3** indicate that perennial flows occur along sections of Dinnebito and Polacca Washes, intermittent flows occur along Moenkopi Wash, and ephemeral flows occur along Jeddito and Oraibi Washes. It was assumed that streamflows at the gages were ephemeral if the percentage of days each year with measurable flow was typically less than 10% and intermittent if this percentage was 10% or greater but less than 100% (perennial).

Figure 2-6 shows the recent streamflow regimes based on gage data as well as historic perennial stream reaches on and near the Reservation. Maps of the latter were published in 1916, 1942 and 1969 and generally coincide with the recent intermittent and perennial streamflow regimes. One notable exception is a relatively long perennial reach identified along Jeddito Wash on the 1942 and 1969 stream maps. Recent (1993-2005) streamflow data indicates this reach of Jeddito Wash has become ephemeral.

Ephemeral stream reaches generally occur within smaller watersheds or on larger streams where baseflow contributions are minimal. Runoff is relatively low and infrequent in these reaches and results mainly from stormflow during the late summer and early fall. Intermittent reaches can occur where adjacent aquifers supply baseflow that exceeds alluvial aquifer outflows on a seasonal basis, or where tributary surface flows are significant. At higher elevations, intermittent reaches can experience runoff from snowmelt during the late winter and early spring while at lower elevations most runoff comes from summer and fall storms. Perennial reaches in the area occur immediately downstream of springs and seeps where groundwater inputs exceed ET and transmission losses.