Dissolved-Solids Sources and Transport in the Virgin River Basin in Utah, Arizona, and Nevada with Emphasis on Dissolved Solids Discharged from Pah Tempe Springs

Prepared in cooperation with the Bureau of Reclamation and the Colorado River Basin Salinity Control Forum

Administrative Report 2008

U.S. Department of the Interior
U.S. Geological Survey

Contents

Dissolved-Solids Sources and Transport in the Virgin River Basin in Utah, Arizona, and Nevada with Emphasis on Dissolved Solids Discharged from Pah Tempe Springs

Steven J. Gerner[1]

Executive Summary

Dissolved-solids concentrations increase in the Virgin River through depletion of dilute inflow or accretion of dissolved solids in ground-water discharge or surface runoff. Concentrations are further increased through evaporation in streams and reservoirs, and transpiration by phreatophyte and riparian vegetation. This degradation of Virgin River water affects the suitability of the water for municipal, industrial, and agricultural use in downstream basins. In June 1974, Congress enacted the Colorado River Basin Salinity Control Act which authorized planning reports on specific salinity-control units. The La Verkin Springs unit, which dealt with the discharge of dissolved solids from Pah Tempe Springs to the Virgin River, was one of these units.

Pah Tempe Springs, also known as Dixie Hot Springs or La Verkin Springs, are located along the Virgin River where the river cuts through Timpoweap Canyon in Washington County, Utah. These springs are recognized as a major source of dissolved solids (salt) discharging to the Virgin River. The average discharge and annual salt load from the springs were reported to be about 11.5 cubic feet per second and 109,000 tons per year, respectively, prior to 1984, and were determined by the current U.S. Geological Survey (USGS) study to be about 11.1 cubic feet per second and 98,800 tons per year, respectively, during 1994–2005. Both the discharge and salt load have varied substantially during 1985–2005. The effect of removing these dissolved solids from the Virgin River was studied by the Bureau of Reclamation (BOR) during the 1970s and 1980s. Their studies concluded that removing most of the salt discharged from Pah Tempe Springs from the Virgin River would reduce the salt load in the Virgin River at Littlefield, Arizona by 52,000 tons per year initially and 86,000 tons per year after 22 years. Consequently, a reduction in dissolved-solids concentration of 5.4 to 8.7 milligrams per liter would occur in the Colorado River at Imperial Dam. For the current USGS study, the model used in the 1983–84 BOR La Verkin Springs study was calibrated with streamflow and dissolved-solids concentration data for 1992–2006. The updated model shows that removing the salt discharged from Pah Tempe Springs from

[1] Hydrologic Technician, U.S. Geological Survey, Utah Water Science Center, 2329 Orton Circle, Salt Lake City, Utah 84119 (E-mail: sjgerner@usgs.gov).

the Virgin River would result in an initial reduction in the dissolved-solids load in the Virgin River at Littlefield, Arizona, of 72,000 tons per year. Additional reductions are possible, but their determination is dependent on additional studies of the hydrology of Littlefield Springs.

The transport of dissolved solids in the Virgin River during a recent period (1992–2006) was substantially different than that determined by BOR for the period prior to 1971. Streamflow in the Virgin River was generally larger, and dissolved-solids loads were generally smaller. For example, the dissolved-solids load in the Virgin River at Littlefield, Arizona was estimated to be 28 percent less during 1992–2006 than the average prior to 1971 as determined by BOR (494,000 tons per year). The development and use of infrastructure associated with Quail Creek and Sand Hollow Reservoirs has affected the transport of water and dissolved solids in the basin. Additionally, the discharge of water and dissolved solids from the Saint George Regional Water Reclamation Facility has been increasing and is partially responsible for eliminating periods of no flow in the Virgin River near Saint George during 1992–2006. The estimated flow and dissolved solids contributed to the Virgin River from Littlefield Springs prior to 1980 and during 1992–2006 are similar; however, a more recent conceptual model proposed for the source of water and dissolved solids discharged at Littlefield Springs is contrary to assumptions made during the original BOR La Verkin Springs studies.

Introduction

Pah Tempe Springs, also known as Dixie Hot Springs or La Verkin Springs, are located along approximately 2,000 feet of the Virgin River where the river cuts through Timpoweap Canyon (fig. 1, table 1 [all figures and tables are presented in the back of the report]) in Washington County, Utah. The springs issue from multiple vents in fractured Permian-age Toroweap Limestone in the river bed and on either bank. Pah Tempe Springs are recognized as a substantial localized source of dissolved solids (salt) discharging to the Virgin River, which is a tributary to the Colorado River at Lake Mead. Discharge from the springs has been reported to be about 11.5 cubic feet per second (ft^3/s) with an average dissolved-solids concentration of 9,650 milligrams per liter (mg/L) and an annual dissolved-solids load of about 109,000 tons per year (tons/yr) (Bureau of Reclamation, 1981).

The La Verkin Springs Unit studies were conducted by the Bureau of Reclamation (BOR) beginning in the early 1970s for the purpose of studying desalinization of Pah Tempe Springs discharge. These studies found that a desalinization project, although technically feasible, would be less economical than other salt-mitigation projects in the Upper Colorado River Basin. A report released by BOR as part of the study concluded that the actual reduction in dissolved solids discharged to Lake Mead as a result of the project was not certain (Bureau of Reclamation, 1981). Most of this uncertainty was because of questions related to the hydrogeology of the Virgin River Basin. Specifically, there were uncertainties in salinity[2] reduction that were related to the source of water to Littlefield Springs and the effects of using the more dilute water generated by the project for irrigation on gypsiferous soils near Saint George, Utah (Bureau of Reclamation, 1981). The

[2] The term “salinity”, as used in this report, is synonymous with dissolved solids.

possibilities of more dilute water leaching out additional salts from beneath irrigated lands or better quality water being lost to a deep underlying aquifer resulted in reduced confidence in the effectiveness of the project. The desalinization project was put on hold until it was re-studied in 1983. The second study of the La Verkin Springs Unit was based on the analysis of hydrologic and chemical data from the previous study but focused on determining the economic viability of other desalinization methods. Preliminary findings from the 1983 study indicated that the project would not have been cost effective at that time (Bureau of Reclamation, 1984b).

The collection and interpretation of hydrologic data in the Virgin River Basin for resource assessment and water-project development has been ongoing since 1984. Hence, there is a large body of knowledge on the hydrology of the basin to assess the impact of removing dissolved solids discharged from Pah Tempe Springs. Water management and use in the Virgin River Basin also has changed during the last several decades as resource managers have tried to balance the use of water supporting agriculture with providing additional supplies to support urban growth in the area and still protect the aquatic habitat. These changes have included converting some agricultural water supplies to public and industrial uses; changes in diversion points, water use patterns, and water quantities withdrawn from the Virgin River; implementation of managed recharge and aquifer storage; and implementation of prescribed instream flows in some reaches of the river system.

The Colorado River Basin Salinity Control Forum has asked the U.S. Geological Survey (USGS) to review existing data and studies pertaining to dissolved solids in the Virgin River and determine if the overall transport of dissolved solids in the river has changed substantially since the period prior to the early 1980s, which is the period associated with BOR La Verkin Springs Unit studies. The current USGS study can be used to determine if any changes in hydrology and dissolved-solids transport in the Virgin River Basin warrant additional studies related to removal of dissolved solids discharged from Pah Tempe Springs.

Approach

For the current USGS study, existing data and prior studies related to streamflow and dissolved-solids transport in the Virgin River Basin were acquired from various Federal, State, and local agencies to determine streamflow and dissolved-solids loads for selected sites throughout the basin and to develop a general conceptual model of the transport of dissolved solids in the Virgin River Basin from Virgin, Utah to Lake Mead, Nevada. The conceptual model describes hydrologic and salinity conditions in the Virgin River Basin that generally correspond to the period 1992 to 2006. Next, streamflow and dissolved-solids loads and concentrations for selected sites in BOR La Verkin Springs Unit studies (Bureau of Reclamation, 1981 and 1984a) were compared to values determined for 1992–2006. This comparison provides a basis for assessing if the salinity load values from the original studies reflect more recent conditions. Additionally, streamflow and dissolved-solids loads and concentrations determined for 1992–2006 were applied to the salinity model used in BOR La Verkin Springs Unit studies to determine changes in salinity loads following the implementation of a salinity reduction project that would be based on removal of salt discharged from Pah Tempe Springs using reverse osmosis and brine disposal. This application provided an estimate of salinity reduction in the Virgin River at Littlefield, Arizona, based on past project proposals and more recent conditions. Finally, some of the general changes in Virgin River Basin hydrology that have occurred since about 1970 and the effect these changes have had on dissolved-solids transport in the river are discussed.

The S-PLUS LOAD ESTimator (S-LOADEST) computer program (Dave Lorenz, U.S. Geological Survey, written commun., 2005) was used for estimating dissolved-solids loads in the Virgin River Basin at monitoring sites for the period 1992–2006 using daily mean streamflow values from USGS stream gages and infrequent measurements of dissolved-solids concentrations with associated values of instantaneous streamflow. The S-LOADEST program is a menu-driven version of the LOADEST FORTRAN program of Runkel and others (2004) and uses measurements of constituent concentration and streamflow to develop a regression model for estimating dissolved-solids loads from a time series of streamflow. Most dissolved-solids concentration values used to calibrate the model were from water samples collected by the Utah Department of Environmental Quality (UDEQ). These values were obtained from the U.S. Environmental Protection Agency Modernized Storage and Retrieval (STORET) Data Warehouse (U.S. Environmental Protection Agency, 2008). Additional dissolved-solids concentration values for water samples collected by USGS personnel were obtained from the USGS National Water Information System: Web Interface (NWISWeb) (U.S. Geological Survey, 2007). For some sites, few dissolved-solids concentration values were available; however, there were specific-conductance values in the STORET or NWIS databases that were used as a surrogate to determine dissolved-solids concentrations for input values in the S-LOADEST models. The streamflow component of the dissolved-solids load estimate at some sites that had not been monitored by a USGS streamflow gage was determined for 1992-2006 using monthly streamflow estimates from the Virgin River Daily Simulation Model (VRDSM) (Nathan Kennard, Utah Division of Water Rights, written commun., March 2008). The VRDSM, developed by the Utah Division of Water Resources, is calibrated with gage data to simulate monthly streamflow in the river system from the Virgin River at Virgin streamgage to the Utah/Arizona state line (fig. 2).

Summary of the La Verkin Springs Unit Study Findings

Beginning in 1972, the discharge of dissolved solids from Pah Tempe Springs and the control of that discharge were studied by BOR as part of the Colorado River Water Quality Improvement Program. The 1974 Colorado River Basin Salinity Control Act, Public Law 93-320, authorized the construction, operation, and maintenance of works in the Colorado River Basin to control the salinity of water delivered to the lower Colorado River Basin states (Arizona, Nevada, and California) and Mexico. Title II of the Salinity Control Act authorized several specific salinity control units upstream from Imperial Dam[3] to meet the objectives and standards set by the Clean Water Act. In 1980, Public Law 96-375 authorized feasibility studies on 10 units including the La Verkin Springs Unit. The La Verkin Springs Unit studies determined the annual dissolved-solids loads in the Virgin River at selected sites and in water discharged from Pah Tempe Springs. On the basis of these data, a plan was formulated for removing the dissolved solids originating from Pah Tempe Springs from the Colorado River system. However, the plan

---

[3] Imperial Dam is located in California on the Colorado River approximately 20 miles north of Yuma, Arizona.

was not considered to be cost effective relative to other projects in the Upper Colorado River Basin. In 1981, BOR suspended further studies of the La Verkin Springs Unit and prepared a concluding report (Bureau of Reclamation, 1981).

Specific conclusions of the 1972–81 studies were:

1. Pah Tempe Springs discharged approximately 109,000 tons of salt per year to the Virgin River. These dissolved solids were estimated to have been contributing about 11 mg/L to the concentration of dissolved solids in the Colorado River below Imperial Dam. This contribution was about 1.4 percent of the 1940–80 average annual dissolved-solids concentration (780 mg/L [Bureau of Reclamation, 2008]) in the Colorado River below Imperial Dam.
2. The most viable plan identified for mitigating the salt discharge to the Virgin River from Pah Tempe Springs was to capture the spring flow, desalt the water using a membrane desalting plant, precipitate salt from the brine in solar evaporation ponds, and dispose of the salt under earth cover. Implementation of this plan was estimated to reduce the salinity of the Colorado River at Imperial Dam by an average of approximately 8.4 mg/L during the projected 50-year period of operation.
3. This plan was too costly for the project to be authorized. In addition, there were uncertainties identified in the hydrosalinity model that translated into uncertainties in the economic analysis. These uncertainties included the potential for increased dissolution of salts from soil and rocks by more dilute water (as a result of project implementation) being applied for irrigation downstream of Pah Tempe Springs. Additionally, project implementation would reduce the dissolved-solids concentration of water lost from the Virgin River at the head of the Virgin River Gorge and potentially increase the dissolution of salts from rocks as water moved along flow paths to the discharge point at Littlefield Springs. Given these uncertainties, the economics of the desalinization project could be less favorable than those projected in the report.

An additional study of the La Verkin Springs Unit conducted by BOR in 1983–84 was done in response to requests by the State of Utah and the Washington County Water Conservancy District (WCWCD), which considered using alternative methods for desalinization based on a proposal for total evaporation of Pah Tempe Springs discharge in clay-lined ponds. This method was thought to be a cost effective alternative for mitigating the discharge of salts from Pah Tempe Springs. The BOR updated the hydrologic assumptions from the 1972–81 studies and indexed the cost of previously identified alternatives to 1983 (Bureau of Reclamation, 1984a).

The hydrosalinity analysis for the 1983–84 study introduced the question of whether the source of Littlefield Springs was in fact Virgin River streamflow lost near the head of the Virgin River Gorge near Saint George, Utah. Estimates of the reduction in dissolved-solids concentration in the Colorado River at Lake Mead were prepared on the basis of two scenarios: the discharge from Littlefield Springs was entirely from water lost upstream in the Virgin River, or the discharge from Littlefield Springs was unrelated to water lost from the Virgin River upstream.

Specific conclusions of the 1983–84 study were:

1. A re-analysis of hydrologic data resulted in a revised estimate for the reduction in salinity of the Colorado River at Imperial Dam from the operation of a La Verkin Springs Unit desalinization plant during a 50-year period. The estimated reduction in concentration was changed from 7 mg/L after 5 years of operation and 11 mg/L after 22 years of operation to 5.4 mg/L after 5 years of operation and 8.7 mg/L after 22 years of operation (Bureau of Reclamation, 1984b).
2. Four additional alternatives using total evaporation processes for removing salts from Pah Tempe Springs discharge were investigated. None of the previous alternatives or alternatives using total evaporation was found to be cost effective.

Both the 1972–81 and 1983–84 BOR studies recommended that further study and planning relative to the La Verkin Springs Unit be suspended until technological advances or other factors warrant reconsideration.

The project evaluations completed in 1981 and 1984 for the La Verkin Springs Unit used the “future effects equation” detailed in the Colorado River Basin Progress Report no. 11 (U.S. Department of the Interior, 1983). This simple equation was derived from the Colorado River Simulation System that was in its infancy at the time. Contained in this equation was a coefficient of 1.01, which was applied to every 10,000 tons of dissolved solids removed from the Colorado River in the basin upstream of Parker Dam[4], to calculate the amount of reduction in dissolved-solids concentration achieved at Imperial Dam. Cost effectiveness[5] was determined for the seven alternatives explored in the re-analysis of the La Verkin Springs Unit, concluded in 1984 (Bureau of Reclamation, 1984b). The reduction in concentration determined for the project alternatives varied from 4.1 to 5.3 mg/L and the cost effectiveness (in 1983 dollars) varied from $1.9 to $2.7 million annually for each mg/L of salinity reduction (assuming a 50-year project life).

Comparison of Hydrosalinity Values Reported in the La Verkin Springs Unit Studies with Conditions during 1992–2006

The conclusions drawn from BOR La Verkin Springs Unit studies were based on the assumption that the dissolved-solids loads determined during those studies represented average conditions. Using newer modeling tools and more recent data, the present USGS study determined estimates of dissolved-solids loads during 1992–2006 for many sites on the Virgin River and its tributaries, and these values were compared to those previously determined by BOR in the La Verkin Springs Unit studies.

---

[4] Parker Dam spans the Colorado River between California and Arizona, 17 miles northeast of Parker, Arizona.

[5] Cost effectiveness is expressed in terms of annual equivalent cost per milligram per liter of salinity reduced at Imperial Dam on the Colorado River.

Generally, the average daily streamflow at sites on the Virgin River was larger during water years[6] (WYs) 1992–2006 than during the periods studied by BOR, but dissolved-solids loads were smaller. For example, in the Virgin River near Saint George, Utah (site GS13, fig. 1), the average daily streamflow was 138 ft^3/s for WYs 1951–56 (a time of drought) and 220 ft^3/s for WYs 1992–2006 (a time that averaged near normal precipitation) (tables 2 and 3). The average annual dissolved-solids load in the Virgin River at Littlefield, Arizona (site GS16, fig. 1), was reported by BOR (1984a) to be 494,000 tons/yr, but was determined to be 357,000 tons/yr during 1992–2006.

Average daily streamflow in the Virgin River above Pah Tempe Springs (downstream of the Quail Creek diversion dam) was estimated to be 73 ft^3/s during 1992–2006 (Nathan Kennard, Utah Division of Water Rights, written commun., 2008), slightly less than the 81 ft^3/s reported by BOR (1984a); however, the value determined by BOR was unaffected by diversion of water to Quail Creek and Sand Hollow Reservoirs. In addition, average annual dissolved-solids loads were substantially different: 56,300 tons/yr determined by BOR (1984), and 24,900 tons/yr (56 percent less) during 1992–2006.

The BOR estimate of average annual dissolved-solids load discharged from Pah Tempe Springs to the Virgin River was slightly higher than the estimate determined for this study (106,000 and 98,800 tons/yr, respectively). If this discharge was treated and water lost in the process was replaced by water stored in Quail Creek Reservoir, BOR estimated that the average annual dissolved-solids load in the Virgin River near Saint George[7] would be reduced by 92,000 tons/yr (Bureau of Reclamation, 1984a). In their assessment, BOR made the following assumptions:

1. Discharge from Pah Tempe Springs would be collected and desalinated by reverse osmosis.
2. The desalinization process would have a water recovery rate of 73 percent.
3. The treated water would be returned to the river and have a dissolved-solids concentration of 284 mg/L.
4. The water lost from the Virgin River as a result of desalinization-plant brine disposal would be replaced by water stored in Quail Creek Reservoir.

Given these same assumptions and utilizing the average annual conditions determined for 1992–2006, the reduction in the dissolved-solids load in the Virgin River near Saint George was estimated to be 95,000 tons/yr. This is a conservative estimate, given that new technologies have been developed that have increased the efficiency and economy of desalinization plants (U.S. Department of the Interior, 2003).

---

[6] A water year begins October 1st and ends September 30th. The water year is designated by the year in which it ends. For example, October 1, 2006 to September 30, 2007 is the 2007 water year.

[7] The exact location of the BOR site—Virgin River near Saint George—is unclear. It represents the "*midpoint of the study area*" and related data are used to determine dissolved solids gained from intervening flow and lost from seepage. The most appropriate site to use for determining these same values for 1992–2006 is Virgin River near Bloomington, Utah (site GS12, fig. 1). Consequently, values referenced to Virgin River near Saint George for 1992–2006 in this discussion were generally derived from values determined for the USGS site—Virgin River near Bloomington, Utah.

The average streamflow in the Virgin River near Saint George determined by BOR was much smaller than the streamflow determined for 1992–2006 (138 ft^3/s and 220 ft^3/s, respectively); however, the dissolved-solids load determined by BOR was much larger. The BOR used data from 1951–56 to determine the streamflow and dissolved-solids load in the Virgin River near Saint George, but used data from 1941–70 for determining streamflow and dissolved-solids loads in the Virgin River upstream of Pah Tempe Springs and at Littlefield, Arizona. The use of data from different periods seems to have had considerable influence on the estimates determined by the BOR for intervening streamflow and associated dissolved-solids loads in the Virgin River upstream and downstream of Saint George. The average daily streamflow calculated as part of the current USGS study for the Virgin River between Pah Tempe Springs and the Virgin River near Saint George for WYs 1992–2006 was much larger than the streamflow previously determined by BOR (1984a) (136 ft^3/s and 46 ft^3/s, respectively); however, the average annual dissolved-solids load was much smaller (90,300 tons/yr and 127,000 tons/yr, respectively).

Estimates of streamflow and dissolved-solids load lost from the Virgin River by streambed infiltration in the vicinity of Saint George that were presented in BOR study reports are much larger than those determined for the present USGS study. On the basis of data presented in Trudeau and others (1983), the BOR estimate of average daily streamflow lost in this reach (60 ft^3/s) was assumed to be the same as the flow being discharged from Littlefield Springs. Using data from USGS streamflow gages, the current USGS study found that the average daily amount of streamflow lost in this reach during 1992–2006 was about 31 ft^3/s. The difference between the BOR estimate of the average annual dissolved-solids load lost in this reach from seepage, presented in the 1983–84 report, and the estimate for 1992–2006 is large (126,000 tons/yr versus 39,900 tons/yr, respectively). Because recent data show that substantially smaller amounts of dissolved solids have been lost annually to seepage in this reach than previously estimated, the amount of dissolved solids derived from Pah Tempe Springs that is lost to seepage in this reach is also much smaller. Thus, the initial impact of reducing salt discharge from Pah Tempe Springs would be larger downstream of the Virgin River Gorge than was previously estimated.

Estimates of the average amount of water and dissolved solids discharged from Littlefield Springs that were presented by BOR and those that were determined for this study were similar (60 ft^3/s and 56 ft^3/s; 172,000 and 158,000 tons/yr, respectively). However, estimates of the amount of water and dissolved solids added to the Virgin River between Saint George and Littlefield that are not associated with Littlefield Springs were very different. In the La Verkin Springs Unit study, BOR determined that, on average, 78 ft^3/s of water and 158,000 tons/yr of dissolved solids were added in this reach. Data from 1992–2006 show that, on average, 28 ft^3/s of water and 24,500 tons of dissolved solids were added annually in this reach. This difference is directly related to the value determined for the average annual dissolved-solids load in the Virgin River at Littlefield, Arizona (site GS16, fig. 1). The BOR La Verkin Springs studies presented a much larger load than that determined for 1992–2006 (494,000 and 357,000 tons/yr, respectively). Because the 1992–2006 average is very similar to the average of the annual salinity loads subsequently reported by BOR for this site for 1940–2003 (355,000 tons/yr) and 1940–70 (359,000 tons/yr) (Bureau of Reclamation, 2008), it is likely that the load estimate for the Virgin River at Littlefield reported in the La Verkin Springs Unit studies is much too large.

If the dissolved solids discharged from Pah Tempe Springs were removed as described in the 1983–84 study, BOR determined that there would be an initial reduction in the annual dissolved-solids load in the Virgin River at Littlefield of about 52,000 tons/yr. On the basis of the estimated travel time required for influent Virgin River water to be discharged at Littlefield Springs, an additional reduction of 34,000 tons/yr was anticipated to begin 22 years later. However, based on data from 1992–2006, the initial annual reduction in the Virgin River dissolved-solids load at Littlefield, Arizona, would be about 72,000 tons/yr. Additional reductions would occur as more dilute water was lost through seepage from the Virgin River downstream of Saint George and subsequently discharged back to the river from Littlefield Springs. The timing and magnitude of these additional reductions are uncertain. New interpretations of the tritium analyses done by Trudeau (1983) indicate that the travel time of influent Virgin River water that may discharge from Littlefield Springs could be much less than the 22 years assumed in BOR studies (Cole and Katzer, 2000).

The precipitation that occurs in the Virgin River Basin has a direct effect on streamflow and dissolved-solids transport in the basin. As such, precipitation could be a significant factor affecting the results of the hydrosalinity analyses included in BOR La Verkin Springs studies and in the present USGS study. As shown in table 4 and figure 3, the average annual precipitation that occurred during 1942–70 (Utah Climate Center, 2008), was less than the long-term average (includes all water years during 1942–2006 for which precipitation data were available) at selected precipitation-monitoring sites. Less-than-normal precipitation may have affected BOR study results; however, differences among these periods are not statistically significant. The average annual precipitation that occurred during 1992–2006 was greater than the long-term average at Zion National Park, La Verkin, and Saint George. Greater-than-normal precipitation may have affected the results of the present USGS study; however, differences among these periods are also not statistically significant. Hence, differences in the amount of precipitation that occurred in each of the periods studied probably are not the only factor contributing to the differences in streamflow and in dissolved-solids loads identified in this report.

Conceptual Model of Dissolved-Solids Sources and Transport in the Virgin River Basin

Sources

Most of the dissolved solids in the Virgin River are derived from natural sources, such as geology, soils, and geothermal activity. Anning and others (2007) found that high salt-yielding Mesozoic sedimentary rocks, such as those in the Chinle and Moenkopi Formations, and high and medium salt-yielding Paleozoic and Precambrian sedimentary rocks, such as the Callville and Redwall Limestones, were the most significant sources of dissolved solids in the Lower Colorado-Lake Mead hydrologic accounting unit (which includes the Virgin River Basin). Precipitation runoff on the more easily weathered rock types found in the basin, such as some shale and limestone, can transport large amounts of sediment and dissolved solids to lakes and streams (Utah Department of

Environmental Quality, 2004). Additionally, because of high evaporation rates in the Virgin River Basin, salts accumulate in the upper layers of soil and can be transported to streams in runoff.

Ground water discharging to the Virgin River and its tributaries is a substantial source of dissolved solids. For example, the Navajo Sandstone is a large water-bearing formation that crops out in areas north and west of Saint George and has relatively low concentrations of dissolved solids (less than 500 mg/L) in ground water in the upper units and higher concentrations of dissolved solids (500 to 1,360 mg/L) in ground water in the lower units (Cordova, 1978). The Muddy Creek Formation discharges substantial amounts of water to the Virgin River downstream of the Virgin River Gorge (Dixon and Katzer, 2002). West of Beaver Dam Wash, the concentration of dissolved solids in water from this formation is generally less than 500 mg/L; however, the dissolved-solids concentration in water from the Muddy Creek Formation near the Virgin River east of Beaver Dam Wash is generally greater than 1,500 mg/L (Holmes and others, 1997). Pah Tempe and Littlefield Springs are examples of fairly localized, yet large naturally occurring sources of dissolved solids. A substantial portion of the ground water discharged from these springs may come from deeper aquifers underlying the Virgin River Basin (Dutson, 2005).

Anthropogenic sources of salinity, such as agricultural irrigation returns, disturbed land, and urban and agricultural runoff also contribute dissolved solids to the Virgin River. The application of irrigation water in excess of crop needs results in deep percolation of this water and leaching of salt from the soil profile and bedrock formations. Dissolved solids are added to, and concentrated in, water used for municipal supply which is discharged from various wastewater-treatment facilities including the Saint George Regional Water Reclamation Facility (SGWRF).

Dissolved-Solids Concentrations and Transport

Dissolved-solids concentrations in the Virgin River generally increase from the headwaters to its terminus; however, dissolved-solids loads in the river may increase or decrease because of flow alterations associated with irrigation diversions and reservoir management (table 2). In the Virgin River at Virgin, Utah (site GS1, fig. 1), dissolved-solids concentrations generally are less than 570 mg/L (the 90^{th} percentile of daily mean dissolved-solids concentrations). Not far downstream of Virgin, a substantial portion of the water and dissolved solids in the Virgin River is diverted into the Quail Creek pipeline at the Quail Creek diversion dam (figs. 1 and 2). This water is conveyed to the La Verkin and Hurricane areas for irrigation, back to the river through the Pah Tempe hydropower plant, to Sand Hollow Reservoir (site S8, fig. 1), or to Quail Creek Reservoir (sites S5-7, fig. 1). Water from Sand Hollow Reservoir and Quail Creek Reservoir is used for public supply, irrigation, and for generating hydropower. Dissolved-solids loads downstream of the Quail Creek diversion dam are increased substantially by inflow from Pah Tempe Springs. Downstream of the springs, inflows from tributaries, including Ash and La Verkin Creeks, contribute water and dissolved solids to the Virgin River, but generally dilute the dissolved-solids concentration in the river. Water that is returned to the Virgin River from the Quail Creek pipeline and Quail Creek Reservoir to meet the Saint George and Washington Canal (SGWC) water right also dilutes the dissolved-solids concentration in the Virgin River downstream of Pah Tempe Springs.

A large portion of the water and dissolved solids in the Virgin River is diverted into the SGWC (site GS9, fig. 1) at the diversion dam near Washington, Utah (fig. 1). Dissolved solids are added to the river in runoff and seepage from the irrigated acreage served by the SGWC. Additional salts are dissolved from the soil and rock underlying this and other agricultural areas in the Virgin River Basin by deeply percolated irrigation water (water applied in excess of crop needs). These dissolved solids are transported in ground water which discharges to the Virgin River from seeps and drains. Flow from Fort Pearce Wash to the Virgin River is naturally ephemeral, and flow from the Santa Clara River is highly regulated, resulting in periods with no inflow to the Virgin River. However, these sub basins contributed about 10 percent of the estimated average annual dissolved-solids load in the Virgin River near Bloomington, Utah (site GS11, fig. 1), which is just downstream of the confluences of these streams with the Virgin River.

Treated water discharged from the SGWRF contributes dissolved solids to the Virgin River in a reach immediately downstream of Saint George (fig. 1). The dissolved-solids load from the SGWRF is about 5 percent of the total estimated dissolved-solids load in the Virgin River near the Utah/Arizona state line. There are minor seepage losses of water and dissolved solids in the reach between Bloomington and the Utah/Arizona state line.

The Virgin River flows into the Virgin River Gorge near the Utah/Arizona state line and loses some water and dissolved solids through seepage from the river channel as the river crosses several fault zones in the upper part of the gorge. Near the downstream end of the Virgin River Gorge and just upstream of Littlefield, Arizona, ground water discharges as seeps and springs in the Littlefield Springs complex, which contributes substantial amounts of water and dissolved solids to the Virgin River. Additional water and dissolved solids are contributed to the Virgin River in ephemeral runoff from Beaver Dam Wash and runoff from the Beaver Dam and Virgin Mountains.

In the lower part of the Virgin River Basin, from near the mouth of the Virgin River Gorge in Arizona to Lake Mead in Nevada, water and dissolved solids are diverted from the river for agricultural and municipal purposes, primarily near the towns of Littlefield, Mesquite, Bunkerville, and Riverside. Additionally, an estimated 70,000 acre-feet (ac-ft) (Cole and Katzer, 2000) of water is lost from the river in this reach through evapotranspiration. Some water and most of the dissolved solids diverted from the river probably return to the river in irrigation return flow and ground-water seepage; however, the transport of dissolved solids in the lower Virgin River Basin is not well documented. The Virgin River and its load of dissolved solids finally discharge to Lake Mead on the Colorado River.

Hydrologic Changes in the Virgin River Basin since 1983 and their Effect on Transport of Dissolved Solids in the Virgin River

The present USGS study determined the hydrologic and salinity conditions that existed during 1992–2006 at many Virgin River sites. These conditions were compared to those presented in BOR La Verkin Springs studies reports for periods prior to 1984.

The most substantial anthropogenic changes to Virgin River hydrology have occurred in the Utah reach of the river. Current (2008) routing of water (and dissolved solids) through the Utah reach of the Virgin River from Virgin, Utah to the Utah/Arizona state line, is shown in the VRDSM diagram (fig. 2). The following discussion will describe hydrologic changes that have occurred in reaches from Virgin, Utah, to Lake Mead, Nevada and the possible effects these changes have had on salinity loads.

Virgin to Bloomington, Utah

Streamflow routing in the reach of the Virgin River between the USGS streamgage near Virgin (site GS1, fig. 1) and the gage near Bloomington, Utah (site GS12, fig. 1) has undergone many changes since BOR La Verkin Springs Unit studies were completed in the early 1980s. The largest impacts to flow in the Virgin River have resulted from the development of the Quail Creek diversion, pipeline, and reservoir. The rerouting of irrigation flows to Hurricane and La Verkin through the Quail Creek pipeline has left just a small habitat maintenance flow in Timpoweap Canyon upstream of the Pah Tempe Springs inflow (fig. 2, Q2) during base-flow periods.

The flow in the Virgin River at Virgin, Utah (site GS1, fig. 1) was similar during WYs 1941–70 and 1992–2006 (fig. 4A). In the La Verkin Springs Unit studies, BOR proposed a 950 ft^3/s design capacity for a structure intended to divert Virgin River water around a Pah Tempe Springs collector dam and predicted the structure's capacity would be exceeded about 2 percent of the time, based on Virgin River streamflow during WYs 1910–1970. During 1992–2006, the same design capacities were exceeded less than 2 percent of the time because of the increased diversion of water from the Virgin River at the Quail Creek diversion.

The annual dissolved-solids loads in the Virgin River at Virgin, Utah are much less variable than at sites downstream (fig. 5). From 1992 through 2006 the average annual dissolved-solids load in the Virgin River at Virgin, Utah was 64,900 tons/yr. More than 60 percent of this load was diverted into the Quail Creek pipeline.

Quail Creek Diversion Dam, Pipeline, and Reservoir

During 1983–85, the Quail Creek diversion dam, pipeline, and reservoir were constructed. The facility became fully operational in 1987. Up to 170 ft^3/s of water from the Virgin River can be diverted into a 66-inch (in.) pipeline; however, an estimated average annual diversion of 117 ft^3/s was determined for 1992–2006 using the VRDSM (Nathan Kennard, Utah Division of Water Rights, written commun., March 2008). The La Verkin and Hurricane Canal Companies hold water rights that are now satisfied through discharges from the Quail Creek diversion pipeline (Cory Cram, Washington County Water Conservancy District, oral commun., January 22, 2008). Additionally, water from the pipeline can be diverted through the Hurricane (Pah Tempe) hydropower plant and back to the Virgin River, depending on the demand for power and the need for additional water in the reservoir. Water is also diverted from the pipeline to Sand Hollow Reservoir. The remaining water is transported nearly 9 miles (mi) to Quail Creek Reservoir (figs. 1 and 2). Water in the reservoir is mostly used for public supply in Washington County; however, some water is released to the Virgin River to satisfy the SGWC water right. The reservoir has a capacity of 40,300 ac-ft, and the average dissolved-solids concentration in water samples collected by UDEQ from Quail Creek

Reservoir during 1990–2005 was 608 mg/L (U.S. Environmental Protection Agency, 2008).

Sand Hollow Reservoir and Proposed Lake Powell Pipeline

Sand Hollow Reservoir, located approximately 10 mi east of Saint George, is an off-channel reservoir that has a storage capacity of 50,000 ac-ft and provides surface-water storage and artificial recharge to the underlying aquifer. The reservoir receives water from the Virgin River via a 60-in. pipeline connected to the Quail Creek pipeline. Construction began during 2000 and was completed in 2002. The reservoir began filling in April 2002 and was full in May 2006. Water in the reservoir is mostly used for public supply in Washington County, Utah.

In order to meet future water demands in southern Utah, construction of a pipeline from Lake Powell to Sand Hollow Reservoir has been planned and studied. The pipeline would originate at Lake Powell, near the Glen Canyon Dam[8], and would deliver water to Sand Hollow Reservoir. The proposed Lake Powell pipeline would include about 120 mi of 66-in. pipe and would deliver 70,000 ac-ft of water to Washington County. Deliveries of Colorado River water to Sand Hollow Reservoir are estimated to begin in 2020 (Utah Division of Water Resources, http://www.water.utah.gov/LakePowellPipeline/Timeline/default.asp). The median dissolved-solids concentration of this water is likely to be about the same as that in the Colorado River at Lees Ferry, about 520 mg/L (Anning and others, 2007). Some increase in Virgin River streamflows and dissolved-solids loads, most likely in the river reach downstream of the Saint George area, would probably occur as a result of importing and using this water in the Virgin River Basin.

Conservation Flows Associated with Threatened and Conservation-Species Fish

Conservation streamflows in specific reaches of the Virgin River generally provide continuous flow in the river whereas, historically, the river was dry in these reaches part of the year because of irrigation diversions. The introduction of conservation streamflows on specific reaches of the Virgin River has not only provided additional habitat for target fish species but has increased the amount of dissolved solids transported by the Virgin River during base-flow periods.

The U.S. Fish and Wildlife Service designated 87.5 mi of the Virgin River and its flood plain as critical habitat for two endangered fishes, the woundfin and Virgin River chub. The designation includes the mainstem Virgin River in southwestern Utah, northwestern Arizona, and southeastern Nevada, and extends from the confluence of La Verkin Creek, Utah, downstream to Halfway Wash, Nevada (U.S. Fish and Wildlife Service, 2000). In addition, *Virgin spinedace* were recognized in 1979 as a threatened species by the scientific community. Populations of *Virgin spinedace* currently exist in the mainstem of the Virgin River and eleven of its tributaries; however, the largest populations occur in the upper mainstem above the Quail Creek diversion. Small populations exist in Ash Creek, La Verkin Creek, and the lower mainstem below Pah Tempe Springs. *Virgin spinedace* are not listed as ‘threatened’ because of a Conservation

[8] Glen Canyon Dam is located on the Colorado River at Page, Arizona.

Agreement that provides a mechanism to significantly reduce or eliminate the threats that warrant listing (Lentsch and others, 2002).

The WCWCD maintains a 3 ft^3/s minimum streamflow in Timpoweap Canyon below the Quail Creek diversion. This action has restored approximately 2.8 mi of *Virgin spinedace* habitat (Lentsch and others, 2002). The conservation flows in Timpoweap Canyon provide sustained flow in the canyon and assist the transport downriver of dissolved solids discharged from Pah Tempe Springs. Approximately 3 ft^3/s of water are released from Gunlock Reservoir to the Santa Clara River to maintain streamflow conditions and support native fisheries in this reach. However, a substantial portion of this flow is lost because of evapotranspiration above the confluence with the Virgin River. Consequently, the conservation flow from Gunlock Reservoir does not affect the transport of dissolved solids in the Virgin River. A minimum release of 5 to 10 ft^3/s of water is anticipated in the near future to maintain flow past the SGWC diversion. This conservation flow may result in a relatively small amount of additional transport of dissolved solids from Pah Tempe Springs past the SGWC diversion during the irrigation season and during base-flow periods.

Pah Tempe Springs

Measurements of Pah Tempe Springs discharge and dissolved-solids concentrations have been made periodically since about 1960 (table 5). For the hydrosalinity analysis presented in the 1983–84 BOR La Verkin Springs Unit report, the discharge from Pah Tempe Springs was determined to be 10.9 ft^3/s with a dissolved-solids concentration of 9,920 mg/L and an annual dissolved-solids load of about 106,000 tons (U.S. Department of the Interior, 1984a). Since 1984, the dissolved-solids concentration in water from Pah Tempe Springs has varied from 7,350 to 9,640 mg/L (as determined from water samples or measurements of specific conductance), and discharge from the springs has ranged from 9.1 to 20 (estimated) ft^3/s. Consequently, estimates of dissolved-solids loads discharged from the springs have ranged from 86,300 to 151,000 tons/yr. The larger discharge value and lower dissolved-solids concentrations observed during 1985–86 were the result of a portion of the Virgin River being diverted into a sinkhole in the streambed immediately upstream of Pah Tempe Springs (Everitt and Einert, 1994) and contributing extra water to the spring flow. This sinkhole was filled, and discharge and dissolved-solids concentrations from Pah Tempe Springs returned to near the historical averages.

It appears that discharge and dissolved-solids concentrations from Pah Tempe Springs have been more variable since 1985. Most of the dissolved-solids concentration values for Pah Tempe Springs that have been published since 1982 have been estimates derived from specific-conductance measurements using an applied coefficient of 0.73. For purposes of determining more recent discharge and dissolved-solids concentrations from Pah Tempe Springs, values from 1994 to 2005 were used. The average discharge during this period was 11.1 ft^3/s, the average dissolved-solids concentration was 9,040 mg/L, and the average dissolved-solids load was 98,800 tons/yr (table 5). Additional measurements of Pah Tempe Springs discharge, specific conductance, and dissolved-solids concentration are needed for determining the current dissolved-solids load discharging from the springs and for identifying seasonal variations.

A total maximum daily load (TMDL) for dissolved solids in the Virgin River has been prepared for UDEQ and approved by the Environmental Protection Agency (Utah Department of Environmental Quality, 2004). The Virgin River TMDL established a dissolved-solids concentration of 2,360 mg/L as the natural background level downstream of Pah Tempe Springs. This site-specific criterion is related to the beneficial uses of water in the Virgin River below Pah Tempe Springs to the Utah/Arizona state line and is based on conditions that include the impacts of the Quail Creek diversion on salinity in the river. If streamflows in the Virgin River were not diverted at the Quail Creek diversion, the “natural” concentration would be considerably lower.

Saint George and Washington Canal

The Saint George and Washington Canal Company holds the largest (86 ft^3/s) and oldest (1870) water right in the Virgin River Basin (Washington County Water Conservancy District, 2006). Because of this water right, an average of 24 ft^3/s is diverted from the Quail Creek diversion dam pipeline through the Pah Tempe hydropower plant and back to the river. Additionally, releases from Quail Creek Reservoir are made (an average of 11.5 ft^3/s, from VRDSM estimate) to supplement diversions from the Virgin River to the SGWC (fig 3).

The average annual flow in the SGWC during 1965–85 was 33,000 ac-ft (46 ft^3/s) (Utah Division of Water Rights, 2008). Diversion into the canal increased substantially between 1985 and 1986 when winter water (November-March) began being diverted. Average annual flow in the canal during 1988–2004 was 42,700 ac-ft (59 ft^3/s). The increased diversion into the canal has affected the routing of some of the dissolved-solids in the Virgin River Basin. In addition, canal leakage of winter water and the resulting deep percolation of that water have likely resulted in increased dissolution of dissolved solids from soils and rock surrounding the canal. During 1992–2006, the estimated average annual dissolved-solids load in water diverted into the canal was 84,700 tons. The dissolved-solids load in return flow and seepage in this reach of the river amounted to about 111,000 tons, as determined from residuals after other dissolved-solids sources had been accounted for (table 2). In 2004, the canal company began installing a 63-in. high-density polyethylene pipe to replace the concrete-lined canal and completed the project in 2007. The pipeline is about 8.6 mi long and will reduce seepage by about 4,400 ac-ft per year (ac-ft/yr) (Washington County Water Conservancy District, 2007). Reduced seepage from the canal (and less deep percolation of that seepage) could result in a smaller dissolved-solids load reaching the Virgin River from ground-water seepage in the reach adjacent to and downstream of the Washington agricultural area.

Bloomington, Utah to Utah/Arizona State Line

Several investigators, particularly Trudeau and others (1983) and Cole and Katzer (2000) have documented historic measurements that were made between 1952 and 1976 that indicated a streamflow loss of between 10 and 108 ft^3/s from the Virgin River in the reach from approximately Bloomington, Utah to the Utah/Arizona state line. When these losses occur, they affect the transport time and possibly the fate of dissolved solids (some of which are contributed by Pah Tempe Springs) that are transported in this flow. Cole and Katzer (2000) studied flow in this reach of the river during 1998–99 and found that there was no loss of streamflow at that time. They concluded that the losses previously reported may have resulted from streamflow infiltration into the ground-water system through the underlying carbonate rock, as evidenced by sinkholes in Big Round Valley. Cole and Katzer did not offer a specific reason why the river is no longer losing water in this manner, but it is possible that lateral shifting of the channel has resulted in less exposure to these sinkholes and thus, less infiltration of Virgin River streamflow.

The Virgin River between the Utah/Arizona state line and Bloomington, Utah has a shifting sand channel that makes it difficult to accurately determine daily streamflow values. In fact, the daily mean streamflow records determined for USGS gages on this reach of the Virgin River are generally rated 'fair', meaning that 95 percent of the values are judged to be within 15 percent of the true value. An analysis of water loss from the Virgin River in this reach was conducted for the current USGS study using daily mean streamflow paired values from the USGS Virgin River near Bloomington streamgage (site GS12, fig. 1), and the Virgin River near Saint George streamgage (site GS13, fig. 1). Only daily values that were closely associated with instream streamflow measurements were used in this analysis.

To determine which daily mean streamflow pairs were appropriate to use in this analysis, paired streamflow measurements were identified that fit the following criteria:

1. The measurements were made during January-February, or October-December.
2. The measurements in each pair were not made more than 5 days apart.
3. The measured streamflow was less than 250 ft^3/s.
4. The streamflow measurements were made during WYs 1992–2006.

Twenty-nine measurement pairs were identified using these criteria. The seasonal periods were chosen to reduce the effect of evapotranspiration on observed differences in flow. The measurements were limited to streamflows less than 250 ft^3/s because the differences in streamflow were expected to be less than 8 ft^3/s. Next, daily streamflow values were identified that included the day of the measurements, and the two days prior to and following the day of the measurements (if they were made on the same day) or a 5-day period that bracketed the midpoint between the measurements. Because rapidly changing flow in the river likely has a large effect on streamflow differences between sites in this reach, the maximum percent difference in flow during each period was determined for both sites. If the difference exceeded 35 percent, that period was not used in the final analysis. The final data set included 84 paired daily values. Because the SGWRF outflow occurs downstream of the gage near Bloomington, the average daily streamflow from the SGWRF for the appropriate month was added to daily streamflow from the Virgin River near Bloomington. The average difference in streamflow (the loss of streamflow between the Virgin River near Bloomington streamgage and the Virgin River near Saint George streamgage), as determined from these paired daily values, was 6.7 +/- 3.0 ft^3/s (fig. 6). Additionally, the loss of flow in this reach appears to be generally related to streamflow because losses are usually larger when streamflow in the Virgin River is more than about 120 ft^3/s (fig. 7). The average loss of flow in the Virgin River determined from this analysis was about 12 ft^3/s when the streamflow in the river at the streamgage near Bloomington, Utah was at least 120 ft^3/s. Some of the losses in this reach are attributable to evapotranspiration that may be as much as 4 ft^3/s (Devitt and others, 1998); however, some of these losses may be offset by return flow from the Bloomington Canal of as much as 3.2 ft^3/s (Cole and Katzer, 2000).

Saint George Regional Water Reclamation Facility

The SGWRF began discharging treated water to the Virgin River in 1990. The facility had an original design capacity of 5 million gallons per day (MGD) (7.7 ft^3/s) but was upgraded in 1994 to a capacity of 8.5 MGD (13.2 ft^3/s) and then upgraded again in 1999 to a capacity of 17 MGD (26.3 ft^3/s). The treatment plant serves Saint George, Ivins, Santa Clara, and Washington, Utah. Two outfall points, a 27-in. pipe and a 48-in. pipe, discharge on the north bank of the Virgin River near Saint George approximately 1.5 mi southwest of where the Virgin River crosses under Interstate 15 (Utah Department of Environmental Quality, 2006). The mean daily discharge to the Virgin River from the SGWRF was 5.8 ft^3/s during WY 1990, then increased to 10.1 ft^3/s in WY 1996, and increased again to 14 ft^3/s during WY 2007 (Ben Ford, City of Saint George Water Services Department, written commun., 2007). The overall trend in discharge from WY 1992 to WY 2006 showed an increase; however, discharge from the SGWRF was relatively steady during WYs 1997–2004, about 8,000 ac-ft/yr (fig. 8).

The average dissolved-solids concentration of discharge from the SGWRF, as determined from water samples collected at the plant outfall by the Utah Department of Environmental Quality during WYs 1990–2006 (U.S. Environmental Protection Agency, 2008) was 1,210 mg/L. However, there is a significant difference ($p < 0.01$) in the average dissolved-solids concentration during WYs 1991–1998 (1,250 mg/L) and WYs 1999–2006 (1,160 mg/L). Average annual dissolved-solids loads discharged from the SGWRF were estimated using monthly discharge from the SGWRF and a 3-year moving average dissolved-solids concentration calculated from values in the STORET database (U.S. Environmental Protection Agency, 2008). The estimated annual dissolved-solids load discharged from the SGWRF during 1990–2005 ranged from 6,650 tons during WY 1990 to 16,000 tons during WY 2005 and averaged 11,600 tons/yr during WYs 1990–2005 (fig. 8).

Water discharged from the SGWRF provides additional flow in the Virgin River that transports dissolved solids downstream through the Virgin River Gorge. There was no flow in the Virgin River at Saint George slightly more than 20 percent of the time during WYs 1951–56 (fig. 4C), a period of state-wide drought in Utah. However, there were no days without flow in the river during WYs 1992–2006 even with the drought conditions that occurred during 2000–04. This may be attributable, in part, to water discharged from the SGWRF.

The Saint George Water Reuse Project, which treats and recycles discharge from the SGWRF, became operational in June 2007. During June to October 2007, the reclamation facility was able to reclaim 1,121 ac-ft of water. An agreement is in place to deliver 2,000 ac-ft/yr of reuse water to the Shivwits Band of the Paiute Tribe (Utah Division of Water Resources, 2005). The SGWRF has future plans to reuse as much as 11,200 ac-ft of water discharged from the treatment plant per year; however, the Utah State Engineer has limited the amount of reuse water to 6,496 ac-ft/yr. Reuse of water from the SGWRF will probably reduce the amount of water in the Virgin River downstream of Saint George that is available to transport dissolved solids, although this reduction would only be noticeable during periods of base flow.

Utah/Arizona State Line to the Narrows

Flow in some reaches of the Virgin River, particularly between the USGS gage near Bloomington and the USGS gage above the Narrows near Littlefield, Arizona, is intermittent during most years. The hydrosalinity analysis performed by BOR for the La Verkin Unit studies utilized data from the 1951–56 WYs, a period of drought. During this period there were 464 days (21 percent of the total) of no flow in the Virgin River near Saint George. During WYs 1992–2006 there were no days where the daily mean streamflow in the Virgin River was less than 4 ft^3/s, and 90 percent of the mean daily streamflow values during this period were 24 ft^3/s or greater (fig. 4C); transport of dissolved solids past the Utah/Arizona state line may be less impeded by lack of flow than during some previous periods. During WYs 1999–2006 there were 90 days (3.1 percent of the total) when there was no flow at the USGS streamgage Virgin River above the Narrows near Littlefield, Arizona (site GS14, fig. 1). Nearly all of these no-flow days were during June, July, and August.

Evapotranspiration contributes to flow losses in this reach, but flow losses result mainly from seepage into the streambed. Much of this seepage is theorized to follow flow paths defined by fault zones until it is ultimately discharged in the general vicinity of the Narrows, and from Littlefield Springs in particular (Cole and Katzer, 2000). Cole and Katzer (2000) measured an average loss in this reach of about 27 ft^3/s. Utilizing mean monthly streamflow records for the USGS Virgin River streamflow gage near Saint George, Utah (site GS13, fig. 1) and the USGS streamflow gage above the Narrows near Littlefield, Arizona (site GS14, fig. 1) for WYs 1998–2006, an average loss for this reach was calculated (fig. 9). These monthly values include several outliers where large gains or losses were calculated for specific months. These are probably the result of localized storms (large gains) or possibly errors in the estimated record (large losses). Monthly values less than the 10^{th} percentile and greater than the 90^{th} percentile were trimmed from the dataset and an average loss of 24.2 +/- 2.3 ft^3/s in this reach for WYs 1998–2006 was computed. When the average monthly loss between sites was compared to the average monthly streamflow of the Virgin River near Saint George, Utah, there was no statistically significant correlation.

At the two USGS gaging stations that bound this reach, there were very few pairs of instantaneous streamflow measurements made that met the criteria established in the previous section for identifying periods with higher quality daily streamflow values from which to compute reach losses. In addition, there is about a half day of streamflow travel time between the gages. Consequently, the alternative method used to compute streamflow losses explained in the previous section was not appropriate for this reach.

The Narrows to Littlefield, Arizona

The Virgin River generally gains water from ground water discharged to the river between the USGS gages above the Narrows and near Littlefield, Arizona (sites GS13 and 14, respectively, fig. 1). The largest source of ground-water discharge to the Virgin River in this reach is from Littlefield Springs (fig. 1, table 2).

Littlefield Springs

Littlefield Springs is a complex of springs discharging to the Virgin River along a 6-mi reach immediately upstream of Littlefield, Arizona (Trudeau and others, 1983; Geological Society of America, 2002). The origin and quantity of water discharged from these springs are very important considerations for determining the routing of dissolved solids from Pah Tempe Springs. In addition, economic analyses of Pah Tempe Springs salt-mitigation projects hinge, in part, on these characteristics.

The source of Littlefield Springs discharge has been the focus of previous investigations. Trudeau and others (1983) concluded that 82 percent of the discharge from the springs was from Virgin River influent in the reach near and directly downstream of Saint George. The other 18 percent was from infiltration of precipitation. A comparison of the major-ion composition of water samples collected from wells in the Virgin River Gorge and reported by Towne (1999) and the major-ion composition of water samples collected from the Virgin River by the Utah Department of Environmental Quality suggests that the discharge from Littlefield Springs is a combination of Virgin River influent and ground water in the Littlefield and Virgin Basin alluvial aquifers (fig. 10).

Discharge

Previous investigations have estimated discharge from Littlefield Springs using synoptic measurements upstream and downstream of the springs (Trudeau, 1983; Cole and Katzer, 2000). There is uncertainty associated with these estimates relative to the travel time of water in the Virgin River. Since the USGS established a gage on the Virgin River above the Narrows near Littlefield, Arizona (site GS14, fig. 1) in 1998, discharge can be determined for Littlefield Springs on the basis of comparisons of flow in the Virgin River at Littlefield, Arizona (site GS16, fig. 1) and in the Virgin River above the Narrows near Littlefield, Arizona (site GS14, fig. 1). As a result of the drought in the southwestern United States that began in 1999, there was a period of WYs (2001–2005) in which very few high-flow events occurred in the Virgin River Gorge, and the streamflow at site GS16 could generally be characterized as being an aggregate of the flow at site GS14, the flow from Littlefield Springs, and the flow from Beaver Dam Wash (site GS15). To determine the average discharge from Littlefield Springs, the monthly average streamflow of Beaver Dam Wash (at site GS15) and the Virgin River above the Narrows near Littlefield, Arizona during October 2000 to September 2005 was subtracted from the monthly average streamflow of the Virgin River near Littlefield, Arizona for the same period. The result is the monthly average discharge from Littlefield Springs to the Virgin River (fig. 11). Using monthly averages for this analysis has the advantage over using daily values because it eliminates most of the variability that may be due to the travel time of water in the river. These results indicate that the average discharge from Littlefield Springs during WYs 2001–05 varied from 29 ft^3/s to 90 ft^3/s and averaged 56 +/- 2.6 ft^3/s ($p = 0.05$). This value is less than the estimated 65 ft^3/s reported by Trudeau and others (1983) but is near the 60 ft^3/s at the higher end of the 95-percent confidence interval used in the 1983–84 BOR water/salt balance calculations (Bureau of Reclamation, 1984a). The discharge from Littlefield Springs, as determined by Cole and Katzer (2000) from seepage runs conducted between August 1998 and September 1999, ranged from 10 to 69 ft^3/s. They showed that the mean 7-day low flow during 1930–2000 at site GS16 (which presumably represents discharge from Littlefield Springs) was quite variable; however, the median 7-day low flow was 57 ft^3/s. Although discharge from Littlefield Springs has been quite variable during short periods (days to several years), over longer periods (such as the 30- to 50-year life of a project mitigating dissolved solids from Pah Tempe Springs) discharge from the springs has been consistent at about 55 to 60 ft^3/s.

If the total streamflow estimated to be lost in the reach upstream of the gage on the Virgin River above the Narrows (about 24 ft^3/s) is discharged from Littlefield Springs as proposed by Trudeau and others (1983) and Cole and Katzer (2000), about 32 ft^3/s are unaccounted for and must originate from other sources. Cole and Katzer (2000) estimated the average ground-water inflow to the Virgin River between Bloomington, Utah and Littlefield, Arizona was 30,000 ac-ft/yr (41 ft^3/s). Discharge of water from Littlefield Springs could account for almost 80 percent of this.

If water lost from the Virgin River near Saint George is partly the source of water for Littlefield Springs then the travel time of this water from seepage loss to eventual ground-water discharge is important with respect to the transport of dissolved solids. If the dissolved solids discharged from Pah Tempe Springs were removed from the Virgin River, the dissolved-solids concentration in water from Littlefield Springs would be expected to improve after a period of time equal to the ground-water travel time between water lost to seepage near Saint George and water discharged from Littlefield Springs. Trudeau and others (1983) determined from tritium concentrations in water from Littlefield Springs that this travel time was more than 22 years. Cole and Katzer (2000) re-interpreted these data and determined that the travel time of influent river water from near Saint George to Littlefield Springs was less than 22 years and possibly a lot less.

There are two diversions that result in water bypassing the USGS gage at Littlefield, Arizona. About 1 ft^3/s is diverted from Beaver Dam Wash and 2 to 3 ft^3/s are diverted from a spring on the east side of the Virgin River into the Littlefield irrigation ditch. This water is used for irrigation downstream from the Littlefield gage (Geological Society of America, 2002).

Dissolved-Solids Concentration and Load

There have not been many recent determinations of the dissolved-solids concentration in water from Littlefield Springs. Trudeau and others (1983) reported an average dissolved-solids concentration of 2,940 mg/L for these springs and Towne (1999) reported dissolved-solids concentrations that averaged 2,870 mg/L in water from wells in the Littlefield aquifer, which is a probable source of Littlefield Springs. This second value was used to compute an annual dissolved-solids load of about 158,000 tons from the springs. Dissolved solids contributed through seepage in the reach upstream of the gage on the Virgin River above the Narrows may account for about 40,000 tons of the dissolved solids discharged annually from Littlefield Springs. The remaining 118,000 tons of dissolved solids discharged from the springs are probably derived from alluvial-fan deposits and limestone formations that make up the aquifer in the Littlefield area.

Littlefield, Arizona to Lake Mead, Nevada

The La Verkin Springs Unit studies assumed that reductions in dissolved solids from Pah Tempe Springs that were realized at Littlefield, Arizona, would also be realized downstream at the mouth of the Virgin River at Lake Mead; however, the study reports included a caveat that some of the streamflow in the Virgin River downstream of Littlefield was diverted for agricultural irrigation. There have been intermittent streamflow and dissolved-solids concentration data collected in this reach of the Virgin River by various organizations but there has been a paucity of data collected since 1991, so determining a comparable set of average values for streamflow, dissolved-solids concentrations, and dissolved-solids loads, such as those presented in table 4 for upstream sites, is difficult. An attempt was made to develop an S-LOADEST model for dissolved solids in the Virgin River at Riverside, Nevada by using periodic dissolved-solids concentration data collected by the Nevada Division of Environmental Protection (U.S. Environmental Protection Agency, 2008) and assigning the mean daily streamflow on the day of collection to those samples. Daily streamflow values for the Virgin River at Riverside, Nevada are available for the 1993–95 WYs and these values were regressed against mean daily values for the Virgin River at Littlefield to simulate a complete record for the Riverside gage for 1992–2006 (fig. 12). The resulting values showed a streamflow loss of 25,000 ac-ft/yr and a loss of 23,000 tons/yr in dissolved solids. This apparent loss is less than 7 percent of the total annual load estimated to be in the Virgin River at Riverside and may be within the error of the estimated annual dissolved-solids loads at Littlefield and Riverside.

A synoptic measurement of flow and specific conductance by the USGS during February 2003 (Beck and Wilson, 2006) showed a streamflow loss of about 50 ac-ft/day in this reach and a loss of about 34 tons/day in dissolved solids, as determined by applying a 0.73 coefficient to specific-conductance values to estimate dissolved-solids concentrations. The dissolved-solids losses were relatively small—less than 4 percent of the instream values.

A study by Westenburg (1995) estimated the annual load of dissolved solids discharged from the Virgin River to Lake Mead to be 710,000 tons, on the basis of periodic data collected from the Virgin River above Halfway Wash, near Riverside, Nevada, (a site about 8 mi upstream of Lake Mead) during 1978–86. Westenburg estimated the dissolved-solids load in the Virgin River at Littlefield to be 640,000 tons/yr for this same period, indicating an accretion of 70,000 tons/yr in this reach. Even though this was a period of above-average precipitation, these values for annual dissolved-solids loads seem very high; however, they indicate a net increase in dissolved solids in this reach.

Dixon and Katzer (2002) developed a water budget for the lower Virgin River Basin, the contributing basin for the reach between Littlefield and Lake Mead. Results of this study indicated that the largest source of water to the Virgin River downstream of Littlefield was ground-water discharge (55,000 ac-ft/yr) and the largest loss of streamflow was from evapotranspiration (70,000 ac-ft/yr). The study also showed a net loss in streamflow of 48,000 ac-ft/yr between Littlefield and Lake Mead.

Currently (2008 WY), there is a USGS streamgage at both ends of the reach between Littlefield and Lake Mead. It would be very beneficial to future salinity studies in the basin if continuous specific-conductance data were collected at these gages and periodic water samples were collected and analyzed for concentrations of dissolved solids. The resulting data then could be used to calculate daily and annual dissolved-solids loads and thus, determine gains or losses given current conditions.

Conclusions

The Bureau of Reclamation (BOR) La Verkin Springs Unit studies that were concluded in 1984 included a hydrosalinity model for the Virgin River based on data collected prior to about 1971. Since then, there have been some changes in streamflow in the Virgin River Basin that have affected the transport of dissolved solids in the river. For example, the development and use of infrastructure associated with irrigation and public supply in the Virgin River Basin, particularly the operation of Quail Creek Reservoir, has affected the amount and travel time of water and dissolved solids transported in the Virgin River. Additionally, the discharge of water and dissolved solids from the Saint George Regional Water Reclamation Facility (SGWRF) has been increasing and is partially responsible for eliminating periods of no flow in the Virgin River near Saint George. There is evidence that seepage from the Virgin River in the vicinity of the upper Virgin River Gorge is currently less than it was prior to 1971, resulting in more water and dissolved solids being transported directly in surface water from the upper to the lower Virgin River Basin. Understanding these and other changes is useful for interpreting the differences in the transport of dissolved solids in the Virgin River before and after about 1971.

During the 1980s, BOR determined that building and operating a desalinization plant or evaporation ponds to remove dissolved solids from the Virgin River that had been discharged from Pah Tempe Springs was not cost effective. In addition, uncertainties in the transport of dissolved solids through the Virgin River Gorge, and the dissolution of additional dissolved solids that may result by irrigating with the more dilute water that would result from implementing a Pah Tempe desalinization project, made achieving a predicted dissolved-solids concentration reduction at Imperial Dam appear risky.

The streamflow and dissolved-solids load values presented in BOR La Verkin Springs Unit studies were assumed to represent long-term averages. However, average streamflow and dissolved-solids loads determined for 1992–2006 show that this assumption may not be valid. The BOR determined that removing most of the dissolved solids discharged from Pah Tempe Springs would result in an initial reduction of 52,000 tons/yr in the dissolved-solids load in the Virgin River at Littlefield, Arizona. By using similar computation methods applied to data from 1992–2006, the dissolved-solids load reduction was estimated to be 72,000 tons/yr. Additional reductions in load are possible if influent Virgin River water is a partial source of water for Littlefield Springs. The occurrence of these additional reductions is related to the travel time of the influent Virgin River water discharged from Littlefield Springs.

Measurements of discharge, specific conductance, and dissolved-solids concentration in outflow from Pah Tempe Springs varied substantially during 1985–2005. The estimated annual dissolved-solids load discharged from the springs based on data from 1994 to 2005 is 98,800 tons, which is slightly less than the 106,000 tons reported in the La Verkin Springs Unit concluding reports.

Discharge from the SGWRF provides additional flow in the Virgin River that transports dissolved solids downstream through the Virgin River Gorge. The average daily discharge from the SGWRF increased from 5.8 ft^3/s during WY 1990 to 14 ft^3/s during WY 2007 and should continue to increase to the plant capacity of about 26 ft^3/s as the Saint George area population increases. Prior to 1971 there were many days without flow in the Virgin River near Saint George; however, during WYs 1992–2006 there was continuous flow—even with the drought conditions that occurred during 2000–04. This likely is attributable to discharge from the SGWRF.

The average loss of streamflow in the Virgin River between Bloomington, Utah and the Narrows in the Virgin River Gorge was substantially less during 1992–2006 (31 ft^3/s) than was estimated by BOR for the period prior to 1979 (60 ft^3/s). This difference has been attributed by some investigators to be the result of less seepage of Virgin River water into sinkholes in the Big Round Valley reach of the river, and consequently, less Virgin River seepage (and dissolved solids) for discharge from Littlefield Springs.

Although the discharge and associated dissolved-solids load from Littlefield Springs estimated by BOR and determined for 1992–2006 for this study are similar, the sources of water and dissolved solids discharged from the springs is not certain. Recently, alternative interpretations of the data used by BOR to estimate spring sources and their age have been proposed, which are compelling given the apparent change in the rate of seepage from the Virgin River in the upper Virgin River Gorge.

The amount of dissolved solids received by, diverted to, and transported in various reaches of the Virgin River during 1992–2006 (as determined in the current study) were substantially different than those prior to about 1971 (as determined in the La Verkin Springs Unit studies). However, additional data collection and interpretation are needed to verify these results and provide a more accurate hydrosalinity model on which to base the implementation of salinity-reduction projects in the Virgin River Basin. Further studies could include the following components:

1. **Determine the current discharge, dissolved-solids concentration, and dissolved-solids load in water discharged to the Virgin River from Pah Tempe Springs and the seasonal variation in discharge** by conducting tracer-dilution streamflow measurements and collecting water samples to be analyzed for major ions.

2. **Determine the amount and variation of seepage losses occurring in the Virgin River reach between Bloomington, Utah, and the USGS streamflow gage above the Virgin River Gorge Narrows** by conducting seasonal seepage studies in this reach.

3. **Determine if replacing water discharged to the Virgin River from Pah Tempe Springs with more dilute water from Quail Creek Reservoir will affect the dissolution of solids in soil and rock if that water is diverted downstream for irrigation.** Analytical results from additional water samples collected from diversions and drains in the agricultural areas should be input to a geochemical model such as PHREEQC (a

USGS computer program for simulating chemical reactions and transport processes).

4. **Determine the source of water for Littlefield Springs and the approximate age of water discharged from the springs** through analysis of stable and radioisotopes and noble gases in water samples collected from the Virgin River, Littlefield Springs, and ground water in the Littlefield area. Additionally, these data might be used to develop a mixing model that would better determine the contributions of the various components of flow to Littlefield Springs.

5. **Acquire additional data for calibrating Virgin River dissolved-solids load models, particularly in the lower Virgin River Basin,** by periodic specific-conductance measurements and collection of water samples to be analyzed for major ions and dissolved-solids concentrations at all sites where a USGS streamflow gage is located.

References

Anning, D.W., Bauch, N.J., Gerner, S.J., Flynn, M.E., Hamlin, S.N., Moore, S.J., Schaefer, D.H., Anderholm, S.K., and Spangler, L.E., 2007, Dissolved solids in basin-fill aquifers and streams in the Southwestern United States: U.S. Geological Survey Scientific Investigations Report 2006-5315, 336 p.

Beck, D.A., and Wilson, J.W., 2006, Discharge and physical-property measurements from Virgin River Narrows, Arizona, to Lake Mead, Nevada, February 12, 2003: U.S. Geological Survey Scientific Investigations Report 2005-5286, 10 p., accessed April 1, 2008 at *http://pubs.water.usgs.gov/sir2005-5286*

Blackett, R.E., 1994, Low-temperature thermal water in Utah—A compilation of data for thermal wells and springs through 1993: Utah Geological Survey Open File Report 311, 33 p. plus appendices.

Budding, K.E., and Sommers, S.N., 1986, Low-temperature geothermal assessment of the Santa Clara and Virgin Valleys, Washington County, Utah: Utah Geological and Mineral Survey Special Studies 67, 34 p.

Bureau of Reclamation, 1973, La Verkin Springs Unit, Utah – Feasibility report, Colorado River water quality improvement program, Point Source Division, July 1973, Appendix A - Water supply, 99 p.

Bureau of Reclamation, 1981, La Verkin Springs Unit, Utah – Concluding report, Colorado River water quality improvement program, Point Source Division, 25 p.

Bureau of Reclamation, 1984a, La Verkin Springs Unit (Utah) – Composite of reports, 1983–84 La Verkin Springs study: Bureau of Reclamation, Lower Colorado Region, variously paged.

Bureau of Reclamation, 1984b, La Verkin Springs Unit (Utah) – Preliminary findings report: Bureau of Reclamation, Lower Colorado Region, 12 p.

Bureau of Reclamation, 2008, Digital data: accessed May 27, 2008 at *http://www.usbr.gov/uc/progact/salinity/excel/CRBannual_salinity_data.xls*

Cole, Erin, and Katzer, Terry, 2000, Analysis of gains and losses in Virgin River flow between Bloomington, Utah and Littlefield, Arizona: Southern Nevada Water Authority, Las Vegas, Nevada, 31 p. plus appendices.

Cordova, R.M., 1978, Ground-water conditions in the Navajo Sandstone in the central Virgin River Basin, Utah: Utah Department of Natural Resources Technical Publication No. 61, 66 p.

Devitt, D.A., Sala, A., Smith, S.D., Cleverly, J., Shaulis, L.K., and Hammett, R., 1998, Bowen ratio estimates of evapotranspiration for *Tamarix ramosissima* stands on the Virgin River in southern Nevada: Water Resources Research, v. 34, no. 9, p. 2407-2414.

Dixon, G.L., and Katzer, Terry, 2002, Geology and hydrology of the lower Virgin River Valley in Nevada, Arizona, and Utah: Southwest Geology, Inc., Blackfoot, Idaho, and Cordilleran Hydrology, Inc., Reno, Nevada; report prepared for the Virgin Valley Water District.

Dutson, S.J., 2005, Effects of Hurricane Fault architecture on groundwater flow in the Timpoweap Canyon of southwestern Utah: Department of Geology, Brigham Young University, unpublished Master's thesis, 57 p.

Everitt, Ben, and Einert, Martin, 1994, The 1985 slug test of Pah Tempe Springs, Washington County, Utah, *in* Blackett, R.E., and Moore, J.N., eds., Cenozoic geology and geothermal systems of southwestern Utah: Utah Geological Association Publication 23, p. 189-194.

Geological Society of America, 2002, Hydrology and ground-water conditions of the Tertiary Muddy Creek Formation in the lower Virgin River Basin of southeastern Nevada and adjacent Arizona and Utah: Field trip guide book, 315 p.

Holmes, W.F., Pyper, G.E., Gates, J.S., Schaefer, D.H., and Waddell, K.M., 1997, Hydrology and water quality of the Beaver Dam Wash area, Washington County, Utah, Lincoln County, Nevada, and Mohave County, Arizona: U.S. Geological Survey Water-Resources Investigations Report 97-4193, 71 p.

Lentsch, L.D., Perkins, M.J., Maddux, Henry, and Hogrefe, T.C., 2002, *Virgin spinedace* conservation strategy: Utah Department of Natural Resources, Division of Wildlife Resources, Publication No. 02-22, accessed June 2008 at *http://wildlife.utah.gov/pdf/virgspin.pdf*

Mundorff, J.C., 1970, Major thermal springs of Utah: Utah Geological and Mineral Survey Water Resources Bulletin 13, 60 p.

Runkel, R.L., Crawford, C.G., and Cohn, T.A., 2004, Load Estimator (LOADEST): A FORTRAN program for estimating constituent loads in streams and rivers: U.S. Geological Survey Techniques of Water-Resources Investigations, book 4, chap. A5, 69 p.

Sandberg, G.W. and Sultz, L.G., 1985, Reconnaissance of the quality of surface water in the upper Virgin River basin, Utah, Arizona, and Nevada, 1981-82: Utah Department of Natural Resources Technical Publication 83, 69 p.

Towne, D.C., 1999, Ambient groundwater quality of the Virgin River Basin: A 1997 baseline study: Arizona Department of Environmental Quality Open-File Report 99-4, 98 p.

Trudeau, D.A., Hess, J.W., and Jacobson, R.L., 1983, Hydrology of the Littlefield Springs, Arizona: Ground Water, v. 21, no. 3, p. 325-333.

U.S. Department of the Interior, 1983, Quality of water—Colorado River Basin: Bureau of Reclamation, Upper Colorado Region, Salt Lake City, Utah, Progress report no. 11.

U.S. Department of the Interior, 2003, Desalting handbook for planners: Bureau of Reclamation, 3rd ed., accessed June 2008 at *http://www.usbr.gov/pmts/water/publications/reportpdfs/report072.pdf*

U.S. Environmental Protection Agency, 2008, Modernized Storage and Retrieval (STORET) Data Warehouse, accessed January 15, 2008 at *http://www.epa.gov/storet/dw_home.html*

U.S. Fish and Wildlife Service, 2000, Draft environmental assessment for Federal agency participation in the Virgin River Resource Management and Recovery Program, accessed February 7, 2008 at *http://www.fws.gov/mountain-prairie/NEPA/VirginRiver/pdf_files/figure3-4.pdf*

U.S. Geological Survey, 2007, National Water Information System: Web Interface (NWISWeb), data set accessed June 18, 2007 at *http://waterdata.usgs.gov/nwis/*

Utah Climate Center, 2008, Digital climate data prepared by the Utah State University, accessed January 10, 2008 at *http://climate.usurf.usu.edu/*

Utah Department of Environmental Quality, 2004, TMDL water quality study of the Virgin River watershed: Division of Water Quality, 152 p. plus appendices, accessed October 2007 *http://www.waterquality.utah.gov/TMDL/Virgin_River_Watershed_TMDL.pdf*

Utah Department of Environmental Quality, 2006, Statement of basis, Saint George City renewal permit: Discharge, biosolids, and storm water, UPDES permit number: UT0024686, accessed January 9, 2008 at *http://www.waterquality.utah.gov/PublicNotices/StGeorge_SOB_2006.pdf*

Utah Division of Water Resources, 2005, Water reuse in Utah, April 2005: Utah Department of Natural Resources, Utah State Water Plan series, accessed March 5, 2008 at *http://www.water.utah.gov/WaterReuse/WaterReuseAA.pdf*

Utah Division of Water Rights, 2008, Water diversion records, accessed January 24, 2008 at *http://www.waterrights.utah.gov/distinfo/distribution_systems.asp*

Washington County Water Conservancy District, 2006, 2006 Operational overview: accessed October 2007 at *http://wcwcd.state.ut.us/our_mission_and_info.htm*

Washington County Water Conservancy District, 2007, The Waterline Newsletter, Spring 2007, accessed March 17, 2008 at *http://wcwcd.state.ut.us/District%20Info/Waterlines/2007%20Spring.pdf*

Westenburg, C.L., 1995, Dissolved-solids contribution to the Colorado River from public lands in southeastern Nevada, through September 1993: U.S. Geological Survey Water-Resources Investigations Report 94-4210, 25 p.

Yelkin, M.A. 1996, Trace element analysis of selected springs in the Virgin River basin: Unpublished thesis, University of Nevada, Las Vegas, 155 p.

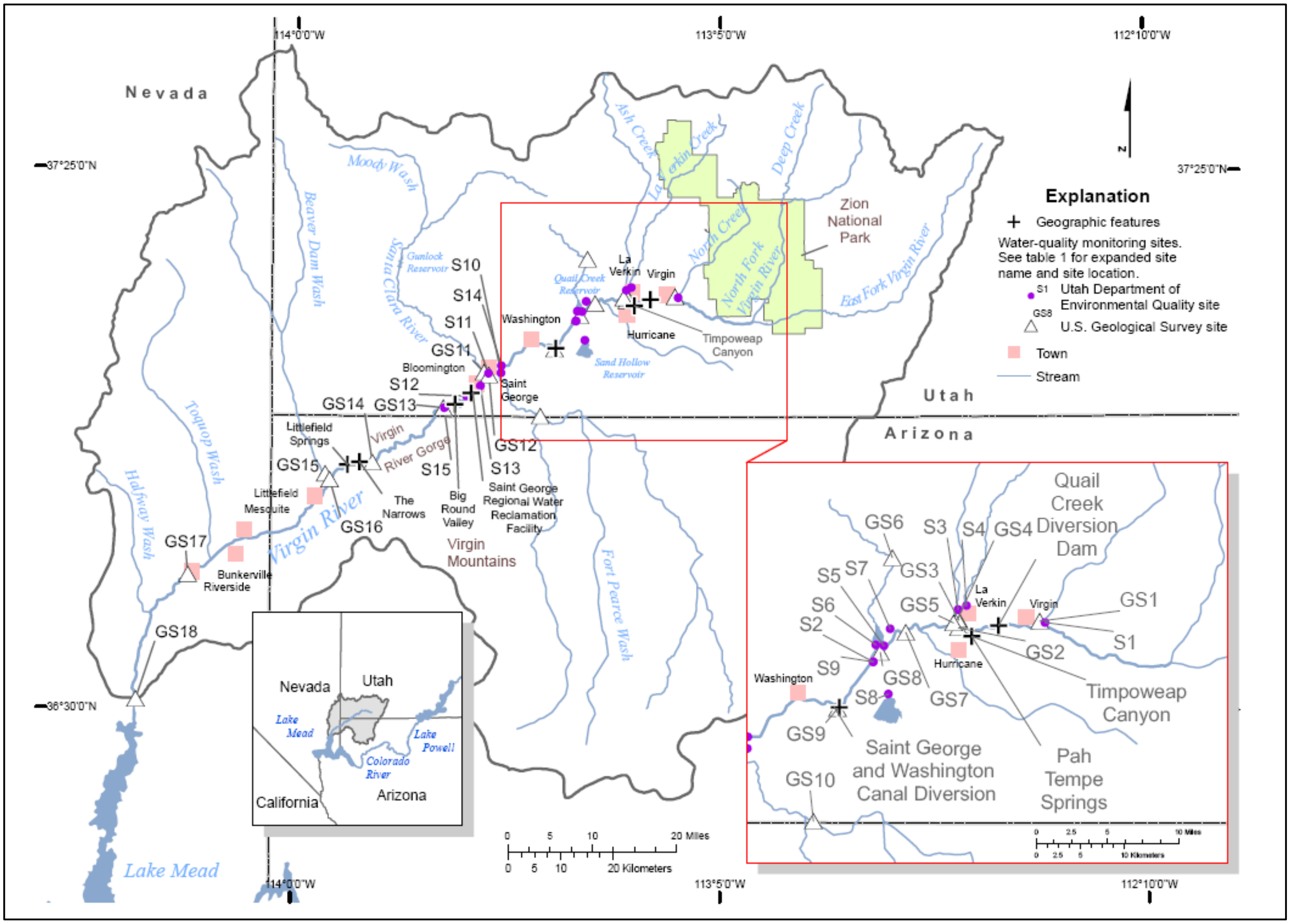

Figure 1. Geographic features and monitoring sites in the Virgin River Basin. See table 1 for expanded site name and site location.

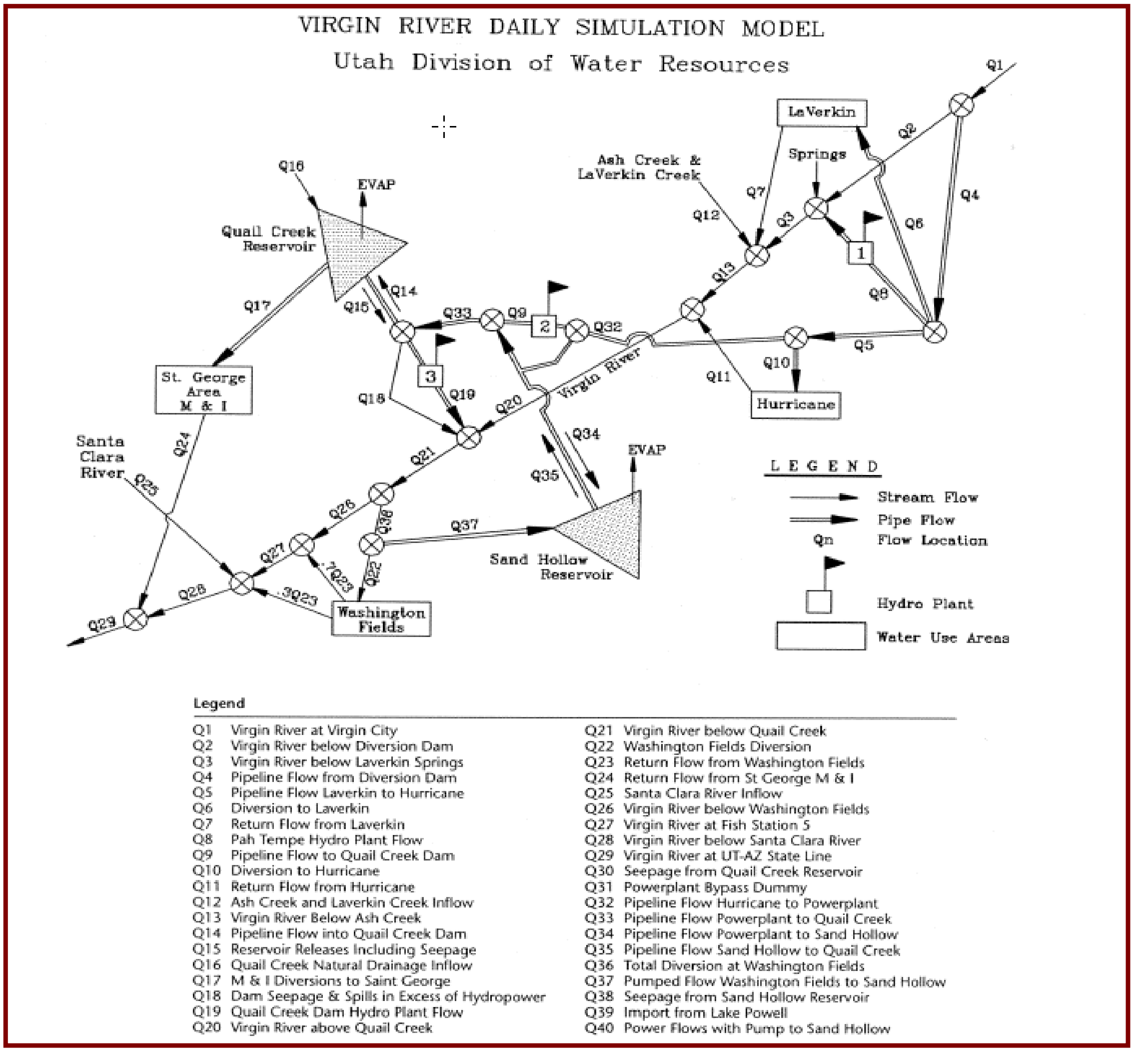

Figure 2. Utah Division of Water Resources Virgin River Daily Simulation Model flow diagram (Nathan Kennard, Utah Department of Natural Resources, Water Rights, written communication, 2008).

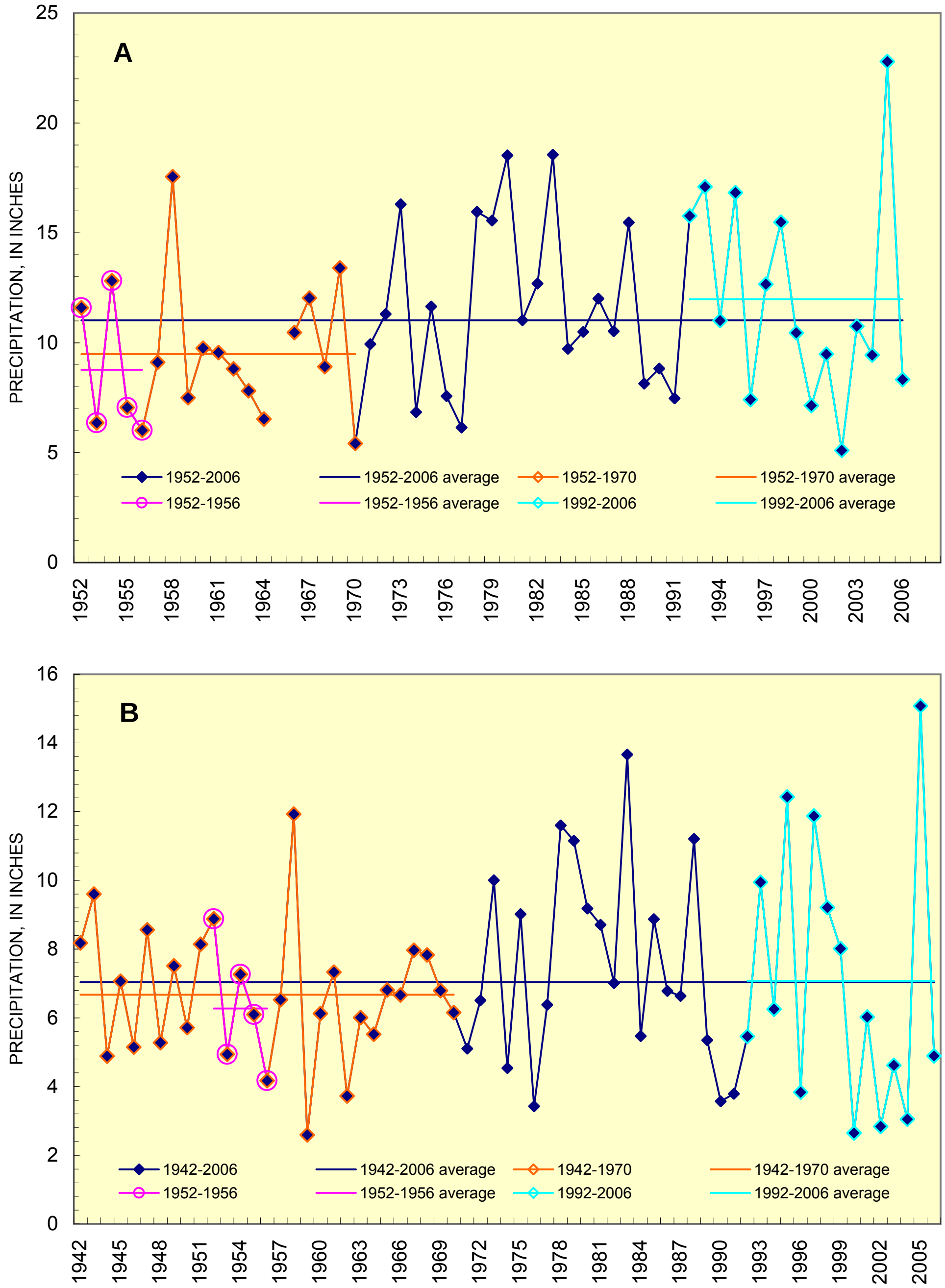

Figure 3. Annual and average annual precipitation at (A) La Verkin, Utah and (B) Saint George, Utah.

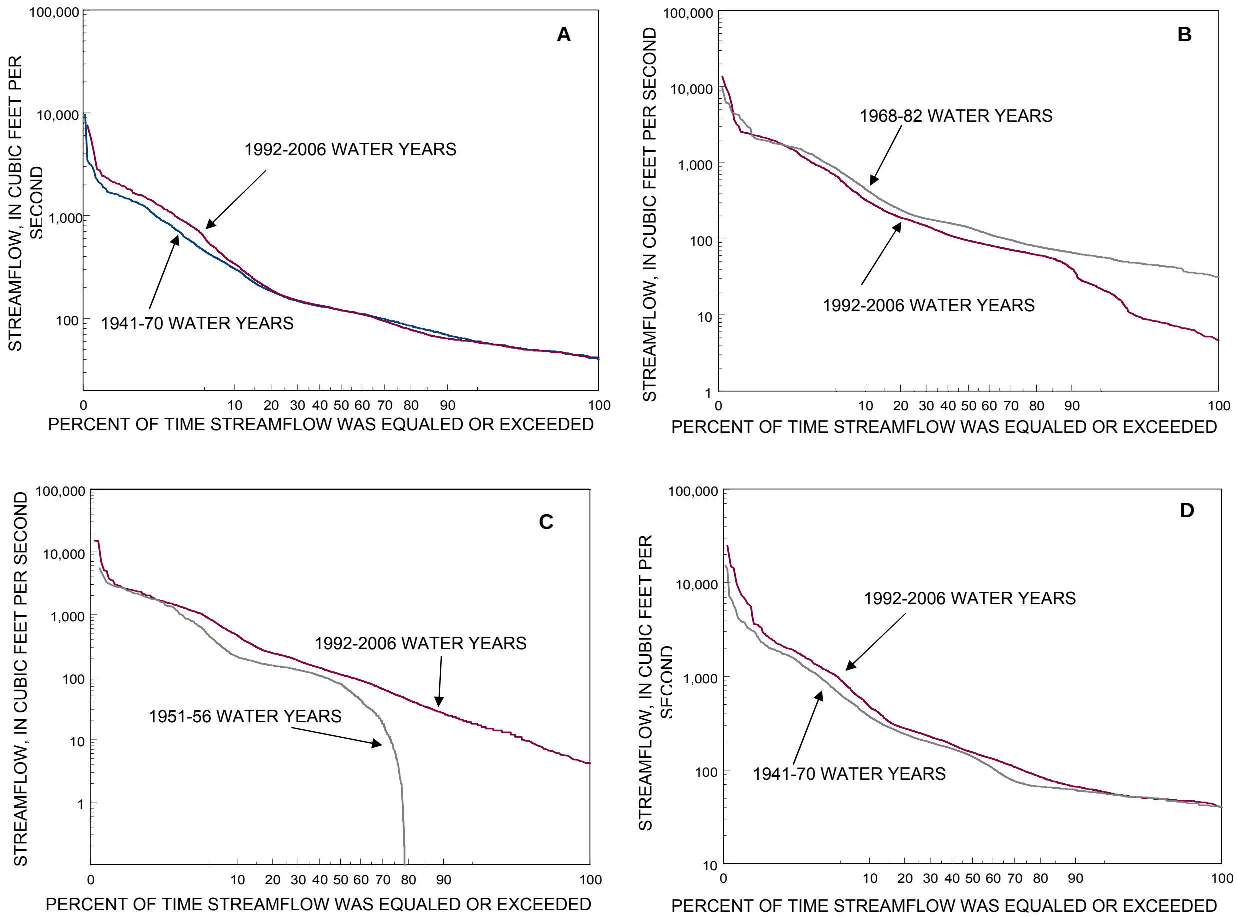

Figure 4. Streamflow duration curves for (A) Virgin River at Virgin, Utah, (B) Virgin River near Hurricane, Utah, (C) Virgin River near Saint George, Utah, and (D) Virgin River at Littlefield, Arizona.

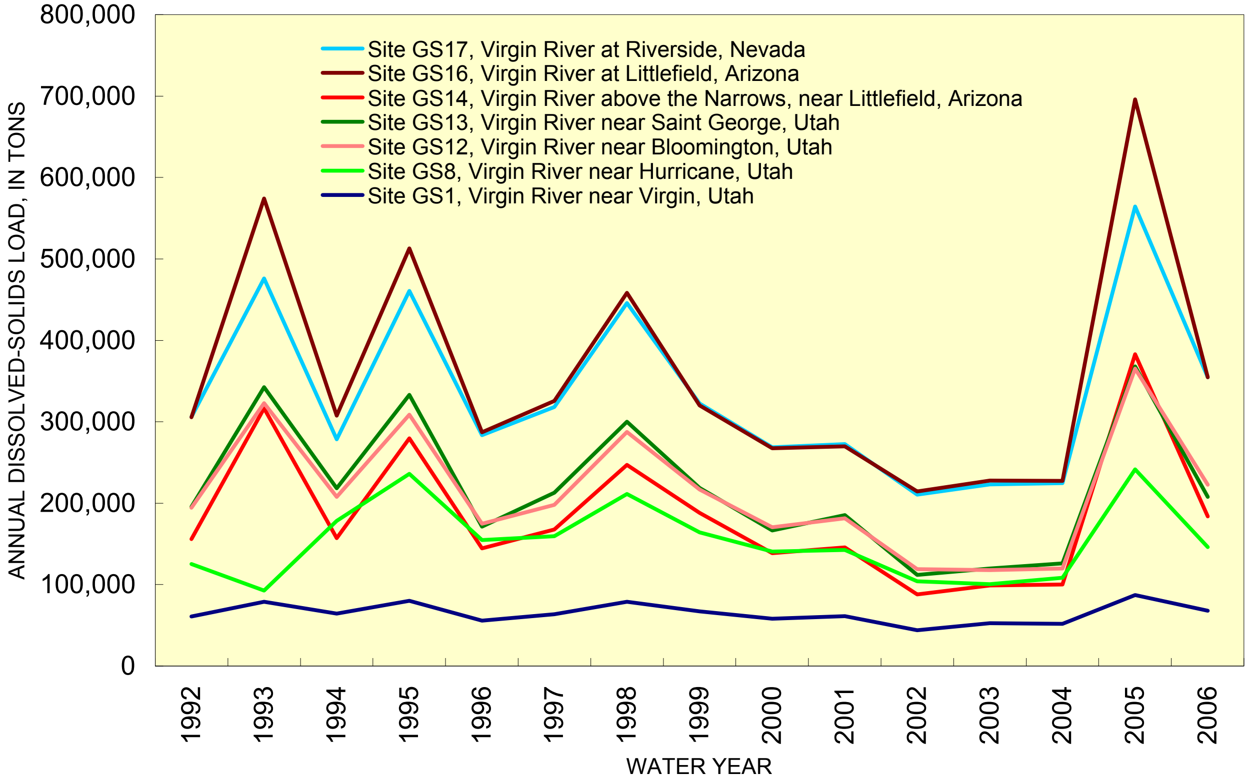

Figure 5. Annual dissolved-solids loads at selected sites in the Virgin River Basin, 1992-2006.

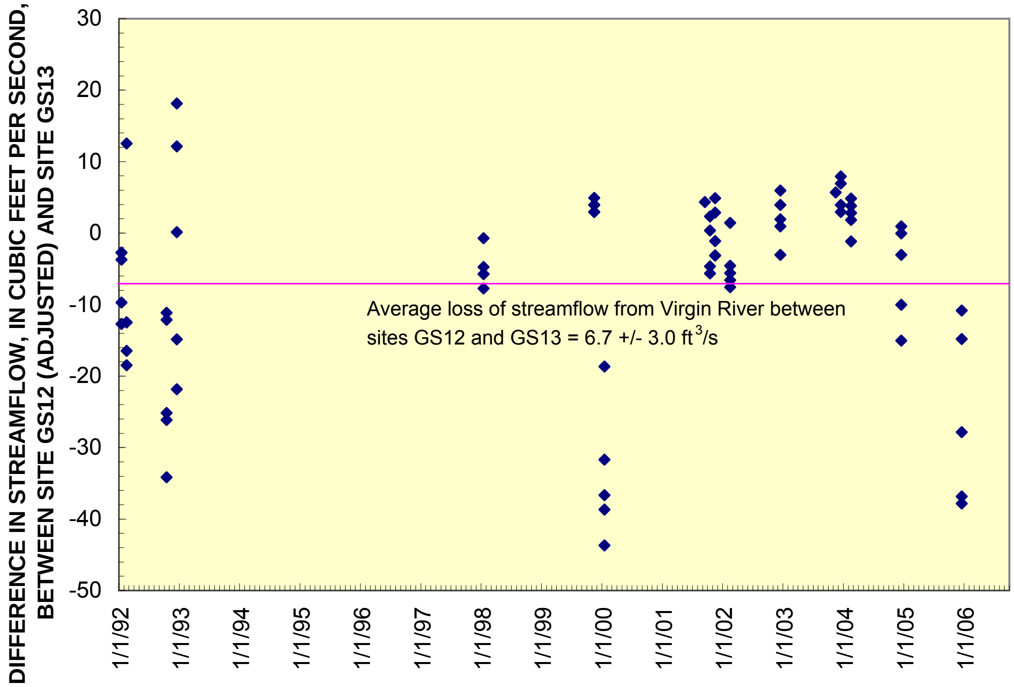

Figure 6. The difference in Virgin River daily mean streamflow measured at site GS12, the Virgin River near Bloomington, Utah (with discharge from the Saint George Regional Water Reclamation Facility added), and site GS13, the Virgin River near Saint George, Utah, for selected days during 1992-2006.

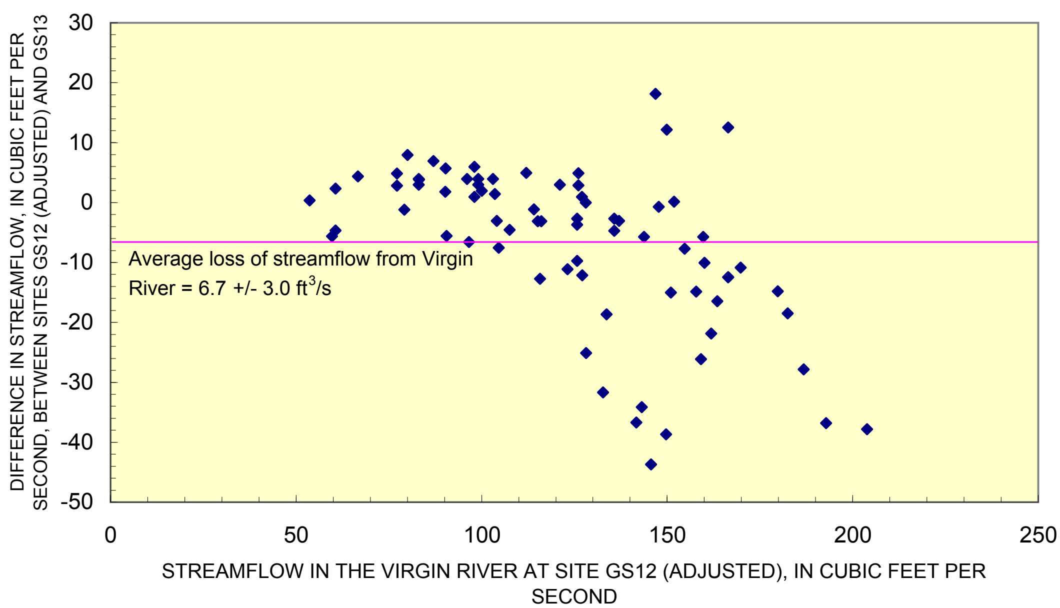

Figure 7. The relation between loss in streamflow (expressed as negative values) determined for the reach of the Virgin River between sites GS12 and GS13 and the total streamflow at site GS12 (adjusted by adding discharge from the Saint George Regional Water Reclamation Facility), for selected days during 1992-2006.

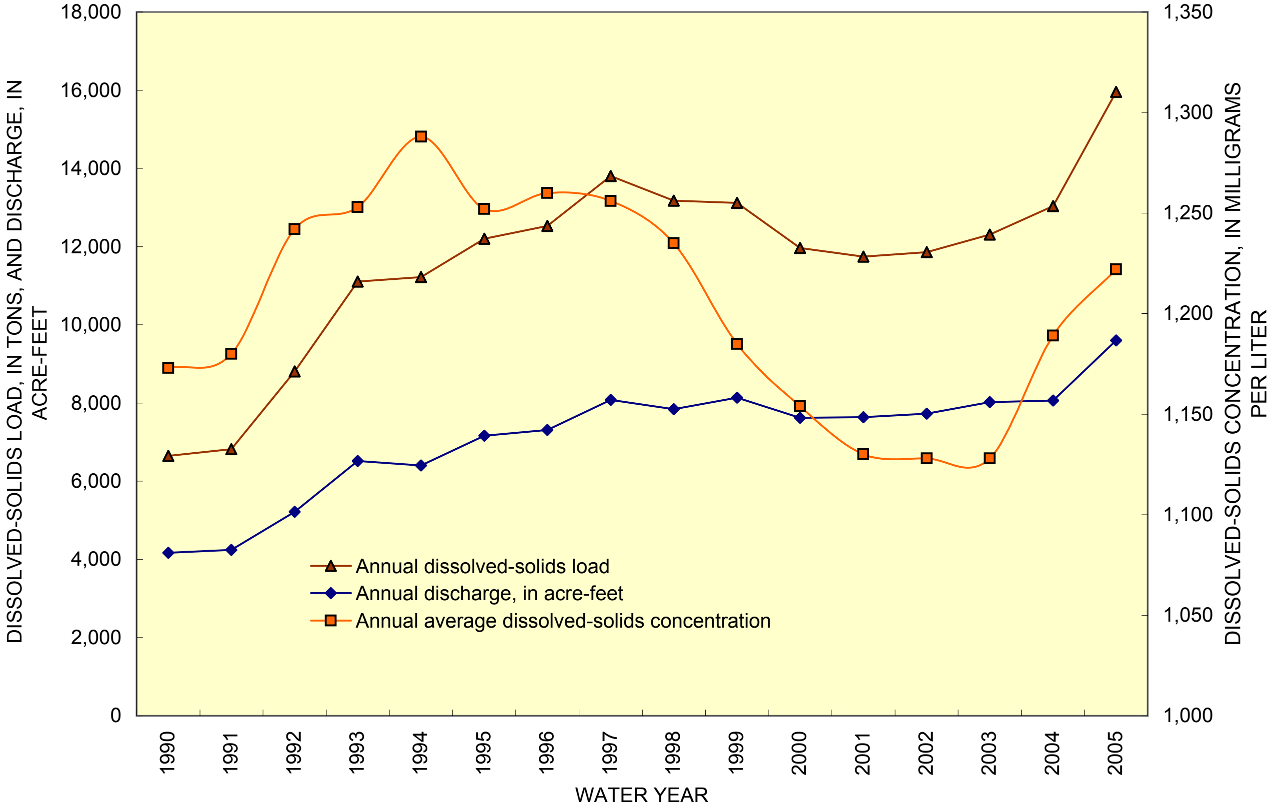

Figure 8. Annual discharge, annual dissolved-solids load, and annual average dissolved-solids concentration in outfall from the Saint George Regional Water Reclamation Facility, 1990-2005.

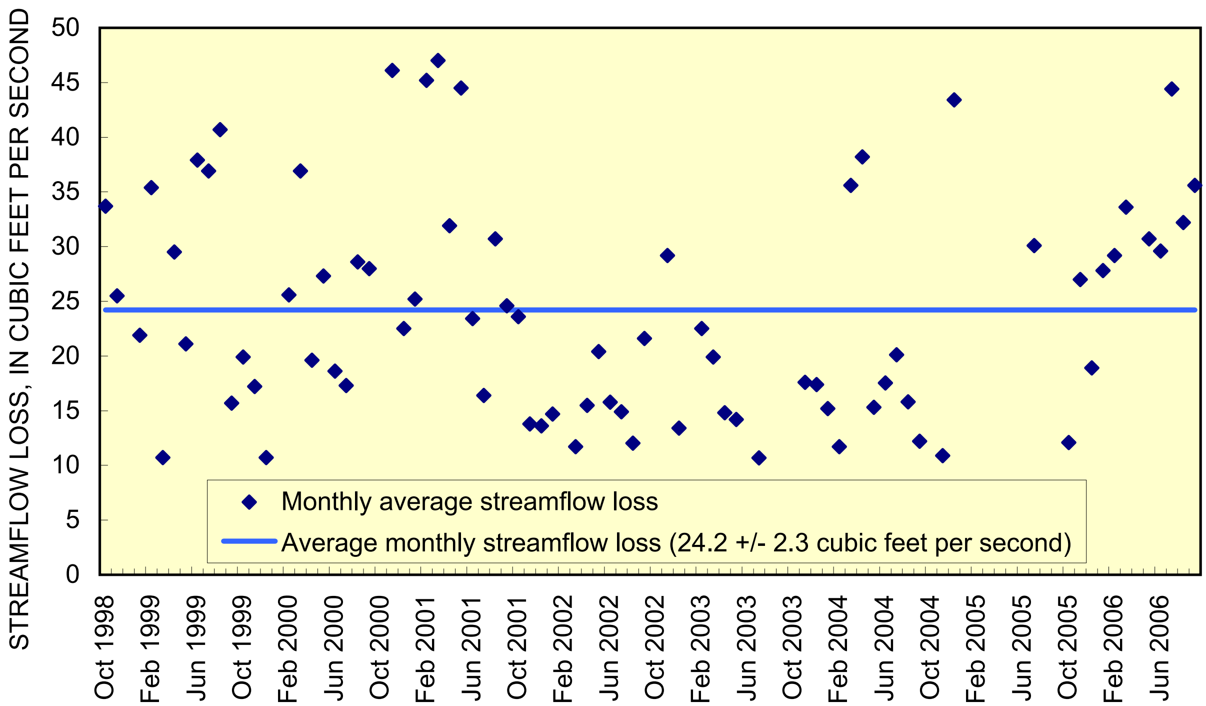

Figure 9. Monthly streamflow loss in the Virgin River between site GS13 (Virgin River near Saint George, Utah) and site GS14 (Virgin River above the Narrows, near Littlefield Arizona).

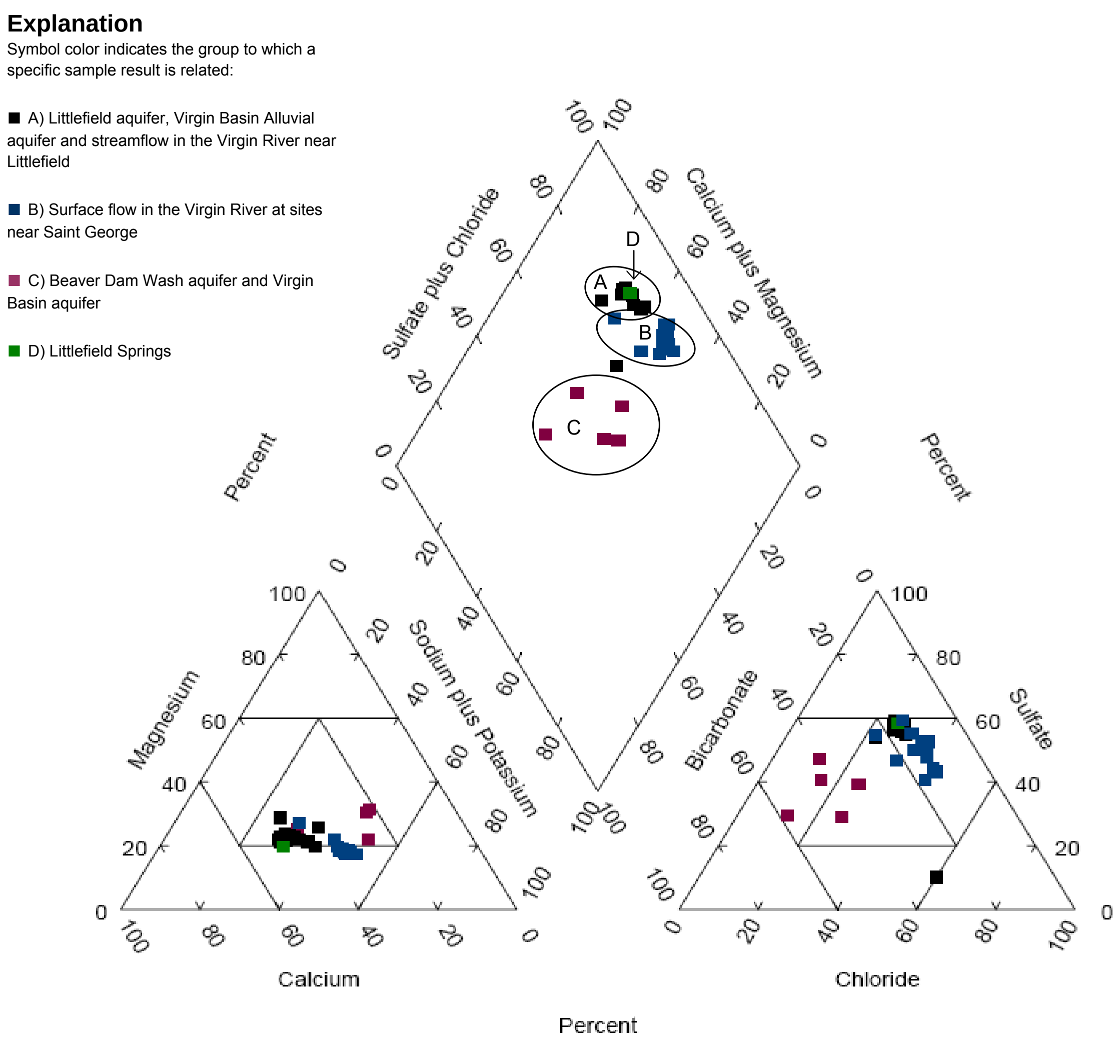

Figure 10. Relative composition of water in selected water samples from the Virgin River Basin.

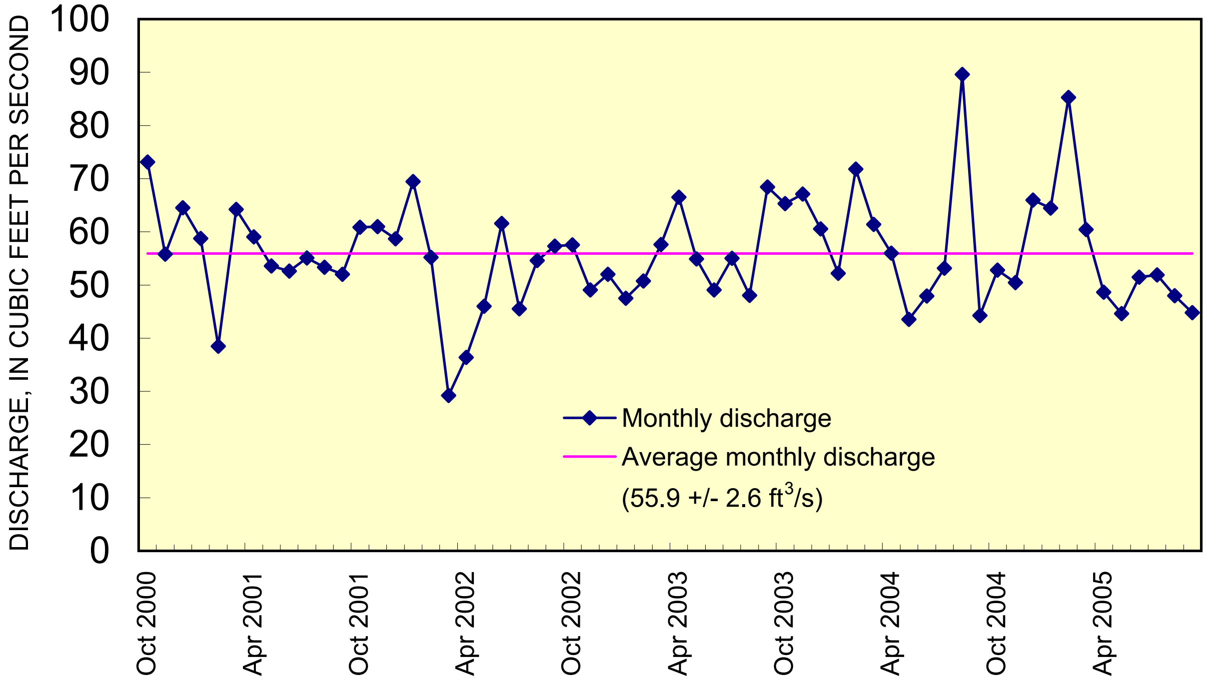

Figure 11. Monthly discharge from Littlefield Springs [calculated as the difference in streamflow at site GS15, the Virgin River above the Narrows (plus discharge from Beaver Dam Wash) and site GS16, Virgin River near Littlefield, Arizona] during water years 2001-2005.

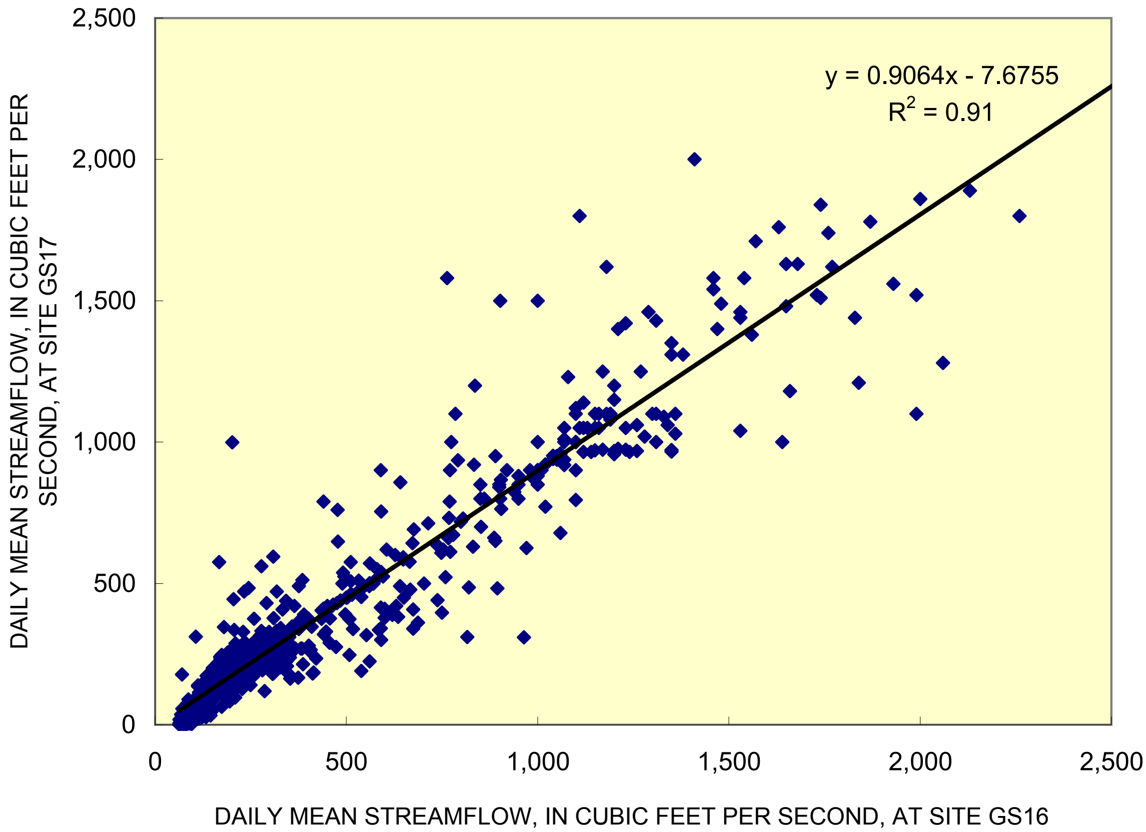

Figure 12. Relation between daily mean streamflow in the Virgin River at site GS16, Virgin River at Littlefield, Arizona, and daily mean streamflow at site GS17, Virgin River at Riverside, Nevada, October 1992-September 1995.

Table 1. Location of selected sites in the Virgin River Basin, Utah, Arizona, and Nevada.
[USGS, U.S. Geological Survey; UDEQ, Utah Department of Environmental Quality; NDEP, Nevada Division of Environmental Protection]

Organization	Short site name	Site number	Site name	Latitude[1]	Longitude[1]
Data associated with the following sites are available from the U.S. Geological Survey National Water Information System (NWIS)					
USGS	GS1	09406000	Virgin River at Virgin, Utah	37.2041	–113.1808
USGS	GS2	09406100	Virgin River above La Verkin Creek near La Verkin, Utah	37.1969	–113.2853
USGS	GS3	09406150	La Verkin Creek near La Verkin, Utah	37.2047	–113.2850
USGS	GS4	09407800	Ash Creek near La Verkin, Utah	37.2055	–113.2869
USGS	GS5	09407810	Virgin River below Ash Creek, near La Verkin, Utah	37.2019	–113.2916
USGS	GS6	09408000	Leeds Creek near Leeds, Utah	37.2675	–113.3708
USGS	GS7	09408135	Virgin River above Quail Creek, near Hurricane, Utah	37.1925	–113.3533
USGS	GS8	09408150	Virgin River near Hurricane, Utah	37.1722	–113.3861
USGS	GS9	09408175	Saint George and Washington Canal near Washington, Utah	37.1150	–113.4408
USGS	GS10	09408195	Fort Pearce Wash near Saint George, Utah	37.0016	–113.4688
USGS	GS11	09413000	Santa Clara River at Saint George, Utah	37.0753	–113.5930
USGS	GS12	09413200	Virgin River near Bloomington, Utah	37.0705	–113.5827
USGS	GS13	09413500	Virgin River near Saint George, Utah	37.0144	–113.6805
USGS	GS14	09413700	Virgin River above the Narrows, near Littlefield, Arizona	36.9211	–113.8319
USGS	GS15	09414900	Beaver Dam Wash at Beaver Dam, Arizona	36.9019	–113.9336
USGS	GS16	09415000	Virgin River at Littlefield, Arizona	36.8916	–113.9244
USGS	GS17	09415190	Virgin River at Riverside, Nevada	36.7289	–114.2275
USGS	GS18	09415250	Virgin River above Lake Mead, near Overton, Nevada	36.5161	–114.3350
Data associated with the following sites are available from the U.S. Enviromental Protection Agency STOrage and RETrieval system (STORET)					
UDEQ	S1	4950890	North Creek above confluence with Virgin River	37.2028	–113.1744
UDEQ	S2	4950300	Virgin River below Hot Springs	37.1628	–113.3947
UDEQ	S3	4950710	Ash Creek above Virgin River	37.2156	–113.2864
UDEQ	S4	4950770	La Verkin Creek at U17 crossing	37.2197	–113.2752
UDEQ	S5	4950350	Quail Creek Reservoir above Dam 001	37.1789	–113.3811
UDEQ	S6	4950360	Quail Creek Reservoir above Dike 002	37.1797	–113.3917
UDEQ	S7	4950370	Quail Creek Reservoir North End 003	37.1961	–113.3733
UDEQ	S8	5951000	Sand Hollow Reservoir 001	37.1304	–113.3773
UDEQ	S9	4950320	Virgin River at U15 crossing west of Hurricane	37.1628	–113.3947
UDEQ	S10	4950180	Fort Pearce Wash above confluence with Virgin River	37.0744	–113.5561
UDEQ	S11	4950090	Santa Clara River above Virgin River	37.0738	–113.5828
UDEQ	S12	4950060	St. George WWTP New Plant	37.0350	–113.6306
UDEQ	S13	4950120	Virgin River At Bloomington crossing below St. George WWTP	37.0522	–113.6000
UDEQ	S14	4950200	Virgin River SE of St. George at creek crossing	37.0864	–113.5558
UDEQ	S15	4950020	Virgin River below First Narrows	37.0150	–113.6783
NDEP	S16	NV13-010-T-004	Virgin River at Riverside	36.7326	–114.2192

[1]Horizontal coordinate information are in decimal degrees referenced to the North American Datum of 1983 (NAD83).

Table 2. Streamflow and dissolved solids at selected locations and in selected reaches, Virgin River Basin, Utah, Arizona, and Nevada, water years 1992-2006. Values in red represent streamflow and dissolved solids diverted from the Virgin River.

[USGS, United States Geological Survey; STORET, U.S. Environmental Protection Agency Modernized STORage and RETrieval Data Warehouse; UDWR VRDSM, Utah Division of Water Resources Virgin River Daily Simulation Model; UDEQ, Utah Department of Environmental Quality; —, not applicable or not computed; NWIS, National Water Information System ; S-LOADEST, S-PLUS Load estimator computer program; LOWESS, locally-weighted scatter-plot smooth; SGWRF, Saint George Regional Water Reclamation Facility; AZDEQ, Arizona Department of Environmental Quality; NDEP, Nevada Division of Environmental Protection]

Site designation									
USGS	STORET	UDWR VRDSM	Site Name	Average daily streamflow or discharge, in cubic feet per second	Average annual runoff, in acre-feet	Average annual dissolved-solids load, in tons	Average daily dissolved-solids concentration, in milligrams per liter	Average flow-weighted dissolved-solids concentration, in milligrams per liter	Dissolved-solids load per acre-foot of runoff, in tons
09406000	4950850	Q1	Virgin River at Virgin, Utah	190	138,000	64,900	481	347	0.5
—	—	Q4	Quail Creek Pipeline Diversion	117	84,700	40,000	—	347	0.5
—	—	Q2	Virgin River below Quail Creek Diversion Dam	73	52,800	24,900	—	—	0.5
—	—	—	Pah Tempe Springs	11.1	8,040	98,800	9040	—	12.3
—	—	Q8	Pah Tempe Hydroplant ouflow	24	17,400	8,200	—	347	0.5
—	—	Q15	Quail Creek Reservoir releases	11.5	8,320	6,880	608	—	0.8
—	—	—	Unaccounted for inflow 1	65.4	47,400	27,200	—	—	—
09408150	4950320	—	Virgin River near Hurricane, Utah	185	134,000	166,000	1,440	912	1.2
09408175	—	Q36	Saint George and Washington Canal	60	43,400	84,700	1,450	1,430	2.0
—	—	Q26	Virgin River below Saint George and Washington Canal	125	90,500	81,300	—	661	0.9
—	—	—	Return flow and seepage 1	69	49,900	111,000	—	1,630	2.2
09408195	4950180	—	Fort Pearce Wash near Saint George, Utah	4	2,900	4,490	2,090	1,140	1.5
09413000	4950090	Q25	Santa Clara River at Saint George, Utah	22	15,900	17,600	1,940	813	1.1
09413200	4950120	—	Virgin River near Bloomington, Utah	220	159,000	214,000	1,810	988	1.3
09413200	4950060	—	Saint George Regional Water Reclamation Facility	10.6	7,670	11,900	1,210	1,140	1.6
—	—	—	Loss 1	6.7	4,850	7,900	—	1,200	—
—	—	—	Unaccounted for inflow 2	4	2,590	—	—	—	—
09413500	4950020	—	Virgin River near Saint George, Utah	220	159,000	218,000	1,700	1,010	1.4
—	—	—	Loss 2	24.2	17,500	32,000	—	1,340	—
—	—	—	Unaccounted for inflow 3	10.8	7600	—	—	—	—
09413700	—	—	Virgin River above the Narrows, near Littlefield, Arizona	185	134,000	186,000	1,740	1,020	1.4
—	—	—	Littlefield Springs	56	40,500	158,000	—	2,870	3.9
—	—	—	Unaccounted for inflow 4	32	23,100	13,000	—	—	—
09415000	—	—	Virgin River at Littlefield, Arizona	273	198,000	357,000	1,840	1,330	1.8
	—	—	Loss 3	34	25,000	23,000	—	—	—
09415190	—	—	Virgin River at Riverside, Nevada	239	173,000	334,000	2,220	1,420	1.9

[1]S-LOAD ESTimator (S-LOADEST) is a Fortran load estimation program developed by Runkel and others (2004) and later modified to be used with S-PLUS programming (S-PLUS LOADEST).

[2]Towne, D.C., 1999, Ambient groundwater quality of the Virgin River Basin: A 1997 baseline study: Arizona Department of Environmental Quality OFR 99-4, 98 p.

Table 2. Streamflow and dissolved solids at selected locations and in selected reaches, Virgin River Basin, Utah and Arizona, water years 1992-2006. Values in red represent streamflow and dissolved solids diverted from the Virgin River.—Continued

Site Name	**Computation methods**
Virgin River at Virgin, Utah	Average daily mean streamflow 1992-2006, from NWIS. Dissolved-solids load (1992-2006) from S-LOADEST calculation. Average daily dissolved-solids concentration from average daily S-LOADEST calculation. S-LOADEST model was calibrated using dissolved-solids concentration and specific-conductance values from water samples collected during 1990-1997 by USGS personnel.
Quail Creek Pipeline Diversion	Streamflow estimates were derived from the VRDSM (Nathan Kennard, Utah Division of Water Rights, written communication, March 2008). Dissolved-solids concentration was assumed to be the same as the flow-weighted value determined for the Virgin River at Virgin, Utah.
Virgin River below Quail Creek Diversion Dam	Streamflow and load estimates were determined as the difference between those at the Virgin River at Virgin, Utah and those diverted at the Quail Creek Diversion Dam.
Pah Tempe Springs	Discharge and load estimates were determined from the average discharge and dissolved-solids concentration for measurements made during 1994-2005.
Pah Tempe Hydroplant outflow	Streamflow estimates were derived from the Virgin River Daily Simulation Model. Dissolved-solids concentration was assumed to be the same as the flow-weighted value determined for the Virgin River at Virgin, Utah.
Quail Creek Reservoir releases	Discharge estimates were derived from the Virgin River Daily Simulation Model (Nathan Kennard, Utah Division of Water Rights, written communication, 2008). Dissolved-solids concentration was estimated as the average concentration in water samples collected by UDEQ from three sites in Quail Creek Reservoir during 1990-2005.
Unaccounted for inflow 1	Residual that accounts for the difference in streamflow and dissolved-solids load between Virgin River below Quail Creek Diversion Dam and Virgin River near Hurricane. This residual includes streamflow and dissolved solids from canal return flow and seepage, Ash and La Verkin Creeks, small and ephemeral tributaries, and error associated with estimated flow and loads.
Virgin River near Hurricane, Utah	Average daily mean streamflow 1992-2006, from NWIS. Dissolved-solids load (1992-2006) from S-LOADEST calculation. Average daily dissolved-solids concentration from average daily S-LOADEST calculation. S-LOADEST model was calibrated using dissolved-solids concentration and specific-conductance values from water samples collected during 1990-2001 by UDEQ.
Saint George and Washington Canal	Average daily mean streamflow 1993-2003, from NWIS. Average daily dissolved-solids concentration estimated from average daily specific conductance and a coefficient of 0.68 based on the average dissolved-solids concentration/specific-conductance ratio of water samples collected at the Virgin River near Hurricane, Utah. A LOWESS smooth applied to specific-conductance data was used to estimate missing daily specific-conductance values.
Virgin River below Saint George and Washington Canal	Streamflow and dissolved-solids load estimates determined as the difference between that at the Virgin River near Hurricane and that diverted to the Saint George and Washington Canal.
Return Flow and seepage 1	Residual that accounts for the difference in streamflow and dissolved-solids load between Virgin River below Saint George and Washington Canal Diversion and Virgin River near Bloomington after accounting for inflow from the Santa Clara River and Fort Pearce Wash. This residual includes streamflow and dissolved solids from canal return flow and seepage, and includes errors associated with estimated streamflow and dissolved-solids loads in this reach.
Fort Pearce Wash near Saint George, Utah	Average daily mean discharge 1992-2006, from NWIS. Dissolved-solids load (1992-2006) from S-LOADEST calculation. Average daily dissolved-solids concentration from average daily S-LOADEST calculation. S-LOADEST model was calibrated using dissolved-solids concentration and specific-conductance values from water samples collected during 1996-2005 by UDEQ.
Santa Clara River at Saint George, Utah	Average daily mean streamflow 1992-2006, from NWIS. Dissolved-solids load (1992-2006) from S-LOADEST calculation. Average daily dissolved-solids concentration from average daily S-LOADEST calculation. S-LOADEST model was calibrated using dissolved-solids concentration and specific-conductance values from water samples collected during 1990-2005 by UDEQ.
Virgin River near Bloomington, Utah	Average daily mean streamflow 1992-2006, from NWIS. Dissolved-solids load (1992-2006) from S-LOADEST calculation. Average daily dissolved-solids concentration from average daily S-LOADEST calculation. S-LOADEST model was calibrated using dissolved-solids concentration and specific-conductance values from water samples collected during 1990-2006 by UDEQ.
Saint George Regional Water Reclamation Facility	Average annual dissolved-solids loads discharged from SGWRF were estimated based on annual average daily discharge and a 3-year moving average dissolved-solids concentration of water samples collected by UDEQ personnel.

Table 2. Streamflow and dissolved solids at selected locations and in selected reaches, Virgin River Basin, Utah and Arizona, water years 1992-2006. Values in red represent streamflow and dissolved solids diverted from the Virgin River.—Continued

Site Name	Computation methods
Loss 1	Streamflow is the average difference in discharge (the loss of flow between Bloomington and the Utah/Arizona state line, as determined from selected paired daily mean values.The estimated average dissolved-solids load is calculated as the difference between the estimated load at the Virgin River at Saint George (plus the dissolved-solids load discharged from SGWRF) and the Virgin River near Bloomington.
Unaccounted for inflow 2	Residual streamflow that may represent the total error associated with flow estimates for the Virgin River near Saint George, the Virgin River near Bloomington and SGWRF, and flow losses in between.
Virgin River near Saint George, Utah	Average daily mean streamflow 1992-2006, from NWIS. Dissolved-solids load (1992-2006) from S-LOADEST calculation. Average daily dissolved-solids concentration from average daily S-LOADEST calculation. S-LOADEST model was calibrated using dissolved-solids concentration and specific-conductance values from water samples collected during 1992-2006 by UDEQ.
Loss 2	Streamflow is the average difference in monthly mean daily discharge (1992-2006) between Virgin River at Saint George and Virgin River above the Narrows. Concentration is undetermined. The estimated average dissolved-solids load is calculated as the difference between the estimated load at the Virgin River above the Narrows and the Virgin River at Saint George.
Unaccounted for inflow 3	Residual streamflow that may represent the total error associated with flow estimates for the Virgin River near Saint George, the Virgin River above the Narrows, and flow losses in between.
Virgin River above the Narrows, near Littlefield, Arizona	Average daily mean streamflow, from NWIS (1999-2006) and regression with Virgin River near Littlefield (1992-1998). Dissolved-solids load from S-LOADEST calculation (1999-2006) and regression with load at Virgin River near Littlefield. Average daily dissolved-solids concentration from average daily S-LOADEST calculation. S-LOADEST model was calibrated using estimates of dissolved-solids concentration from specific-conductance values measured during 1999-2006 by USGS personnel and a coefficient of 0.69 based on the average ratio of dissolved-solids concentration to specific-conductance values of water samples collected from the Virgin River at Saint George, Utah.
Littlefield Springs	Discharge is the average difference in monthly mean daily discharge between the Virgin River near Littlefield, Arizona (with the monthly mean daily discharge at Beaver Dam Wash [at USGS site 09414900] subtracted) and the Virgin River above the Narrows near Littlefield, Arizona during October 1999 to September 2004. Dissolved-solids concentration is the average value measured in water samples collected from the Littlefield aquifer by AZDEQ personnel (Towne, 1999). Dissolved-solids load estimate is calculated as (discharge x concentration x 0.002697 x 365).
Unaccounted for inflow 4	Residual streamflow and dissolved-solids load are from mountain runoff and ephemeral stream discharge and includes errors associated with estimated discharge and dissolved-solids loads in this reach.
Virgin River at Littlefield, Arizona	Average daily mean streamflow 1992-2006, from NWIS. Dissolved-solids load (1992-2006) from S-LOADEST calculation. Average daily dissolved-solids concentration from average daily S-LOADEST calculation. S-LOADEST model was calibrated using dissolved-solids concentration and specific-conductance values from water samples collected during 1992-2006 by UDEQ.
Loss 3	Loss is the difference between upstream and downstream sites; the causes are undefined, but may be due to seepage or irrigation diversion.
Virgin River at Riverside, Nevada	Average daily mean streamflow (1992-2006) determined from regression with Virgin River at Littlefield using data from 1993-95 water years. Average daily dissolved-solids concentration from average daily S-LOADEST calculation. S-LOADEST model was calibrated using dissolved-solids concentration from water samples collected during 1997-2005 by NDEP. No streamflow was measured when these samples were collected so the daily mean streamflow at USGS site 09415190 on the day of sample collection was assigned.

Table 3. Streamflow, dissolved-solids concentrations, and dissolved-solids loads as reported for the La Verkin Springs Unit salinity studies and as determined for the same locations during 1992-2006. The upper half of the table contains estimates which include natural flow from Pah Tempe Springs. The lower half of the table contains estimates assuming most of the dissolved solids discharged from Pah Tempe Springs were removed from the basin.

[BOR, Bureau of Reclamation; SGWRF, Saint George Regional Water Reclamation Facility]

Site	Average daily streamflow, in cubic feet per second		Average dissolved-solids concentration, in milligrams per liter		Average annual dissolved-solids load, in tons	
	La Verkin Springs Unit data	Values determined from 1992-2006 data	La Verkin Springs Unit data[1]	Values determined from 1992-2006 data[2]	La Verkin Springs Unit data	Values determined from 1992-2006 data
The following values are estimates based on conditions prior to 1984 (La Verkin Springs Unit) and during 1992-2006.						
Virgin River above Pah Tempe Springs	81	73	703	347	56,300	24,900
Pah Tempe Springs replacement and desalting plant water	10.9	11.1	9,920	9,040	106,000	98,800
Intervening flow (Pah Tempe Springs to near Saint George)	46	136	2,800	675	127,000	90,300
Virgin River near Saint George	138	220	2,130	988	290,000	214,000
Infiltration loss	60	31	2,130	1,310	126,000	39,900
Intervening flow between the Virgin River near Saint George and Virgin River near Littlefield	78	28	2,050	889	158,000	24,500
Littlefield Springs	60	56	2,920	2,870	172,000	158,000
Virgin River at Littlefield, Arizona	216	273	2,320	1,330	494,000	357,000
The following values are estimates of discharge, and dissolved solids based on the assumption that the dissolved solids from Pah Tempe Springs were removed by reverse osmosis (as described in Bureau of Reclamation, 1984) and water lost in the process was replaced from Quail Creek Reservoir.						
Virgin River above Pah Tempe Springs	81	73	703	347	56,300	24,900
Pah Tempe Springs replacement and desalting plant water	10.9	11.1	705	376	7,560	4,060
Intervening flow (Pah Tempe Springs to near Saint George)	46	136	2,800	675	127,000	90,200
Virgin River near Saint George	138	220	1,460	549	198,000	119,000
Infiltration loss	60	31	1,460	549	86,200	16,800
Intervening flow between the Virgin River near Saint George and Virgin River near Littlefield	78	28	2,050	889	158,000	24,500
Littlefield Springs	60	56	2,920	2,870	172,000	158,000
Virgin River at Littlefield, Arizona	216	273	2,080	1,060	442,000	285,000

[1]Dissolved-solids concentration values are generally the arithmetic mean of individual sample values.

[2]Dissolved-solids concentration values are generally flow-weighted averages calculated as [average annual dissolved-solids load ÷ average daily discharge ÷ 0.002697 ÷ 365].

[3]Bureau of Reclamation, 1984, La Verkin Springs Unit (Utah)–Composite of reports, 1983–84 La Verkin Springs Study: Bureau of Reclamation, Lower Colorado Region

Table 3. Streamflow, dissolved-solids concentrations, and dissolved-solids loads as reported for the La Verkin Springs Unit salinity studies and as determined for the same locations during 1992-2006. The upper half of the table contains estimates which include natural flow from Pah Tempe Springs. The lower half of the table contains estimates assuming most of the dissolved solids discharged from Pah Tempe Springs were removed from the basin.—Continued

Site	Remarks	
	La Verkin Springs Unit data	Values determined from 1992-2006 data
The following remarks are associated with table values based on conditions prior to 1984 (La Verkin Springs Unit) and during 1992-2006.		
Virgin River above Pah Tempe Springs	Values from BOR La Verkin Springs Unit studies. These values were determined from discharge and water-quality data for 1941-70.	Streamflow and load estimates were determined as the difference between those at the Virgin River at Virgin, Utah and those diverted at the Quail Creek Diversion Dam. Concentration value is flow-weighted average.
Pah Tempe Springs replacement and desalting plant water	Values from BOR La Verkin Springs Unit studies.	Discharge and dissolved-solids values were determined as the average of measurements made during 1994-2005.
Intervening flow (Pah Tempe Springs to near Saint George)	Calculated as [Virgin River near Saint George – (Virgin River at Virgin + Pah Tempe Springs)]	Calculated as [Virgin River near Saint George – (Virgin River at Virgin + Pah Tempe Springs)]
Virgin River near Saint George	Values from BOR La Verkin Springs Unit studies. These values were determined from discharge and water-quality data for 1951-56.	Average daily mean streamflow 1992-2006, from NWIS. Dissolved-solids load (1992-2006) from S-LOADEST calculation. Concentration value is flow-weighted average. S-LOADEST model was calibrated using dissolved-solids concentration and specific-conductance values from water samples collected during 1992-2006 by UDEQ.
Infiltration loss	Values from BOR La Verkin Springs Unit studies. Discharge assumed to be the same as that from Littlefield Springs. Dissolved-solids concentration assumed to be the same as in Virgin River near Saint George.	Streamflow losses were determined seperately for the reach between gages at the Virgin River near Bloomington and the Virgin River at Saint George and then downstream to the USGS gage at the Virgin River above the Narrows near Littlefield, Arizona. The estimated average dissolved-solids load is calculated as the difference between the estimated load at the Virgin River at Saint George (plus the dissolved-solids load discharged from SGWRF) and the Virgin River near Bloomington and between Virgin River at St. George and Virgin River above the Narrows.
Intervening flow between the Virgin River near Saint George and Virgin River near Littlefield	Calculated as [Virgin River near Littlefield – (Virgin River near Saint George – Infiltration loss + Littlefield Springs)]	Calculated as [Virgin River near Littlefield – (Virgin River near Saint George – Infiltration loss + Littlefield Springs)]
Littlefield Springs	Values from BOR La Verkin Springs Unit studies.	Discharge of Littlefield Springs determined as difference in discharge at Virgin River gages at Littlefield and above the Narrows, 2000-04.
Virgin River at Littlefield, Arizona	Values from BOR La Verkin Springs Unit studies. These values were determined from discharge and water-quality data for 1941-70.	Average daily mean streamflow 1992-2006, from NWIS. Dissolved-solids load (1992-2006) from S-LOADEST calculation. Concentration value is flow-weighted average. S-LOADEST model was calibrated using dissolved-solids concentration and specific-conductance values from water samples collected during 1992-2006 by UDEQ.
The following remarks are related to table values that are estimates of discharge and dissolved solids based on the assumption that the dissolved solids from Pah Tempe Springs were removed by reverse osmosis (as described in Bureau of Reclamation, 1984) and water lost in the process were replaced from Quail Creek Reservoir.		
Virgin River above Pah Tempe Springs	Values from BOR La Verkin Springs Unit studies. These values were determined from discharge and water-quality data for 1941-70.	Streamflow and load estimates were determined as the difference between those at the Virgin River at Virgin, Utah and those diverted at the Quail Creek Diversion Dam.
Pah Tempe Springs replacement and desalting plant water	Values determined in the 1984 La Verkin Springs Unit study ([3]Bureau of Reclamation, 1984)	Discharge is the aggregate of water discharged from the treatment plant and supplemental water from Quail Creek Reservoir.
Intervening flow (Pah Tempe Springs to near Saint George)	Values from BOR La Verkin Springs Unit studies.	Same as original values
Virgin River near Saint George	Values determined in the 1984 La Verkin Springs Unit study (Bureau of Reclamation, 1984)	Streamflow and dissolved-solids values were determined as [Virgin River above Pah Tempe Springs + Pah Tempe Springs + intervening flow]. Concentration value is flow-weighted average.
Infiltration loss	Values determined in the 1984 La Verkin Springs Unit study (Bureau of Reclamation, 1984)	Streamflow was assumed to be the same as original value. Dissolved-solids concentration was assumed to be the same as in the Virgin River near Saint George. Dissolved-solids load determined from discharge and dissolved-solids concentration values.
Intervening flow between the Virgin River near Saint George and Virgin River near Littlefield	Values from BOR La Verkin Springs Unit studies	Same as original values
Littlefield Springs	Values determined in the 1984 La Verkin Springs Unit study. (Bureau of Reclamation, 1984)	Discharge of Littlefield Springs determined as difference in discharge at Virgin River USGS streamflow gages at Littlefield and above the Narrows, 2000-04.
Virgin River at Littlefield, Arizona	Values determined in the 1984 La Verkin Springs Unit study (Bureau of Reclamation, 1984).	Streamflow was assumed to be the same as original value. Dissolved-solids load was calculated as [Virgin River near Saint George – infiltration loss + intervening flow + Littlefield Springs]. Concentration value is flow-weighted average.

Table 4. Average precipitation at selected sites in or near the Virgin River Basin (Data are from Utah Climate Center, 2008).

	Average annual precipitation, in inches		
Site	1942-70	1992-2006	long-term average[1]
Zion National Park	14.0	16.0	15.1
La Verkin	9.5[2]	12.0	11.0
Saint George	6.7	7.1	7.0

[1]The long-term average includes all water years during 1942-2006 for which precipitation data are available.

[2]Includes only water years 1952-1970

Table 5. Selected measurements of discharge, specific conductance, and dissolved solids, Pah Tempe Springs, near La Verkin, Utah. Values in red itallics are estimated or calculated from reference data.

[—, not reported or not calculated]

Date	Discharge, in cubic feet per second	Specific conductance, in microsiemens per centimeter at 25 degrees Celsius	Dissolved-solids concentration, in milligrams per liter	Dissolved-solids load, in tons per year	Dissolved-solids concentration/specific-conductance ratio	Reference	Remarks
08/31/60	10.0	13,500	9,390	*92,400*	0.70	Mundorf, 1970	none
03/25/66	10.0	—	9,523	—	—	Mundorf, 1970	none
05/25/05	11.5	—	9,650	—	—	Bureau of Reclamation, 1973	none
08/25/81	11.0	13,000	9,660	*104,600*	0.74	Sandberg and Sultz, 1985	none
05/05/82	11.0	12,600	9,840	*106,600*	0.78	Sandberg and Sultz, 1985	none
09/22/82	—	15,400	—	—	—	Sandberg and Sultz, 1985	none
10/01/85	*20.0*	*10,500*	*7,665*	*150,900*	*0.73*	Everitt and Einert, 1994	Estimated discharge. Sinkholes in the river diverted Virgin River flow to the subsurface resulting in additional spring flow.
02/06/86	10.7	—	7,388	*77,800*	—	Budding and Sommer, 1986	none
02/20/86	—	10,200	7,500	—	0.74	Everitt and Einert, 1994	none
03/14/86	—	10,100	*7,350*	—	*0.73*	Everitt and Einert, 1994	none
09/22/87	18.0	11,420	*8,340*	*147,800*	*0.73*	Everitt and Einert, 1994	none
09/19/87	15.1	11,700	*8,540*	*126,900*	*0.73*	Everitt and Einert, 1994	none
09/26/89	12.3	13,200	*9,640*	*116,700*	*0.73*	Everitt and Einert, 1994	none
10/02/91	12.8	13,000	*9,490*	—	*0.73*	Everitt and Einert, 1994	none
09/30/92	15.0	12,800	*9,340*	*137,900*	*0.73*	Everitt and Einert, 1994	none
02/07/94	—	11,000	9,075	—	0.83	Blackett, 1994	none
09/28/94	12.8	12,100	*9,075*	*114,300*	*0.75*	Utah Department of Natural Resources, 1994	none
07/18/95		10,670	—	—	—	Yelkin, 1996	none
02/20/02	10.1	—	—	—	—	Utah Department of Natural Resources, 2002	none
03/01/03	9.1	14,470	9,630	*86,300*	0.67	Dutson, 2005	Dissolved-solids concentration is average of values from multiple springs. Discharge is sum of multiple measurements made at low flow throughout the reach containing springs.
08/22/05	12.4	11,200	*8,400*	*102,500*	*0.75*	Utah Department of Natural Resources, 2005	Four cubic feet per second of flow was discharging from pipes immediately downstream of the pipeline crossing.

Blackett, R.E., 1994, Low-temperature thermal water in Utah—A compilation of data for thermal wells and springs through 1993: Utah Geological Survey Open File Report 311, 33 p. plus appendices

Budding, K.E. and Sommer, S.N., 1986, Low-temperature geothermal assessment of the Santa Clara and Virgin River valleys, Washington County, Utah: Utah Department of Natural Resources Special Studies 67, 34 p., 1 plate

Bureau of Reclamation, 1973, La Verkin Springs Unit, Utah, Feasibility Report, Colorado River water quality improvement program, Point Source Division, July 1973, Appendix A - Water supply, 99 p.

Dutson, S.J. 2005, Effects of Hurricane fault architecture on groundwater flow in the Timpoweap Canyon of southwestern: Unpublished M.S. Thesis, Brigham Young University, Provo, Utah, 57 p.

Everitt, Ben, and Einert, Martin, 1994, The 1985 slug test of Pah Tempe Springs, Washington County, Utah, *in* Blackett, R.E., and Moore, J.N., editors, Cenozoic geology and geothermal systems of southwestern Utah: Utah Geological Association Publication 23, p.

Mundorff, J.C., 1970, Major thermal springs of Utah: Utah Geological and Mineral Survey Water Resources Bulletin 13, 60 p.

Sandberg, G.W. and Sultz, L.G., 1985, Reconnaissance of the quality of surface water in the upper Virgin River basin, Utah, Arizona, and Nevada, 1981-82: Utah Department of Natural Resources Technical Publication 83, 69 p.

Utah Department of Natural Resources, 1994, Flow and conductivity measurements of La Verkin Springs: Division of Water Resources, unpublished memorandum, 2 p.

Utah Department of Natural Resources, 2002, Virgin River at Pah Tempe Springs measurements: Division of Water Resources, unpublished memorandum, 3 p.

Utah Department of Natural Resources, 2005, Virgin River at Pah Tempe Springs measurements: Division of Water Resources, unpublished memorandum, 3 p.

Yelkin, M.A., 1996, Trace element analysis of selected springs in the Virgin River basin: Unpublished M.S. Thesis, University of Nevada, Las Vegas, 155 p.

Gerner—Dissolved-Solids Sources and Transport in the Virgin River Basin in Utah, Arizona, and Nevada
with Emphasis on Dissolved Solids Discharged from Pah Tempe Springs—Administrative Report 2008