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Middle Rio Grande Water Budget - Draft

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Middle Rio Grande Water Assembly Water Budget Task Force

Dedication

This report is dedicated to Frank Titus, Ph.D. Dr. Titus led the Middle Rio Grande Water Assembly's "El Grupo Tecnico" in preparing the first water budget for the basin that was published in 1999 (MRGWA, 1999). Dr. Titus was leading the team to update this budget but passed away before it could be completed. Through decades of private and public work he gained a reputation as a thoughtful but forceful advocate for rational and hydrologically defensible planning and administration of the state's most precious resource. In his own words, Frank wanted "New Mexico to grow, but to keep looking like New Mexico."

Introduction

The challenges of meeting the water needs of the Middle Rio Grande basin become greater each year due to the combined effects of increasing demands of water for our towns, industries and farms coupled with a decreased supply due to the effects of a multi-year drought. In addition to these immediate challenges is the expected decrease in annual water supply as a result of a warming climate (Llewellyn et al., 2013). Therefore, it is likely that the impacts of increased demand and reduced supply will result in more frequent and more significant shortages in the near future.

Although there has been a great improvement in measuring precipitation, surface and ground water diversions in the Middle Rio Grande (MRG) basin in the past two or three decades, there is still a large amount of uncertainty in how water is used, especially in those components of the hydrologic cycle that are difficult or impossible to measure. These include evaporation from the river and reservoirs, evapotranspiration from crops and riparian vegetation, and ground water recharge from agricultural fields, stream beds and canals. This lack of quantitative information introduces difficulty in management of MRG water resources. Perhaps more importantly, the complexity of the MRG hydrologic cycle and the uncertainty in how water is distributed and used makes it very difficult to understand by elected and appointed officials, and especially the general public.

One method of improving the understanding of water flows and uses within the basin is to develop a budget that shows water sources and sinks for the MRG hydrologic system, as well as how water moves through the basin from surface water to ground water and back. This report describes a water budget for the MRG watershed for three different time periods; 1975 to 1997, 2000 to 2012 and 2008 to 2012. The objective of this report is to provide an analysis that identifies the major sources of water supply in the MRG basin, provide quantitative estimates of anthropogenic and natural uses of the water, summarize the interaction between surface and ground water resources, and provide quantitative estimates of water losses from the basin in the form of evaporation from surface water and evapotranspiration (ET) from vegetation. These estimates were developed using URGSiM which is a hydrologic model of the Rio Grande Basin in New Mexico that was originally developed by researchers at Sandia National Laboratories

(USBOR, 2013). URGSiM uses a systems dynamics approach to account for all flows and reservoirs (both surface and ground water) on a monthly time step.

Basin Description

A map of the Rio Grande from its headwaters in CO to Ft. Quitman, TX where it disappears in all but the wettest years is presented in Figure 1. The portion of the basin referred to as the Middle Rio Grande has had different delineations in different studies. For purposes of this report, the MRG basin is that part of the river between Cochiti Reservoir and the spillway at Elephant Butte Dam, the same boundaries as considered in the 1999 water budget by the Middle Rio Grande Water Assembly (MRGWA, 1999). The MRG basin has about 180 mi of the Rio Grande flowing through it. The total drainage area is about 15,200 mi^2. Major gaged tributaries to the Rio Grande in the MRG below Cochiti dam are Jemez river, Galisteo Creek, North Diversion Channel, South Diversion Channel and Rio Puerco. Other ungaged tributaries contribute to the flow of the Rio Grande during heavy rain storms such as Calabacitas Arroyo, Abo Arroyo, Rio Salado and Brown Arroyo.

Cochiti Reservoir (storage capacity = 582,019 AF) and Elephant Butte (storage capacity = 1,999,600 AF) are the only two reservoirs in the MRG basin with permanent pools of water (www.fws.gov/southwest/mrgbi/Resources/Dams). Although Cochiti Reservoir has an appreciable capacity, the enabling legislation and subsequent operating rules allow the reservoir to operate only as flood control structure. The reservoir's permanent pool consists of San-Juan Chama (SJC) water and maintained at 1,200 acres surface area (approximate volume = 50,000 AF) using SJC water. Native Rio Grande water is bypassed to the safe channel capacity (currently about 7,000 cfs) Elephant Butte Reservoir located at the terminus of the MRG basin stores native water for users in the Lower Rio Grande basin below the dam and it is the delivery point for New Mexico under the Rio Grande Compact (RGC). In addition, Elephant Butte Reservoir stores SJC water for MRG water users that can be used by exchange.

There are numerous dams for flood and sediment control including Jemez Canyon Dam (capacity = 102,700 AF), Galisteo Dam (capacity = 88,900 AF) as well as many smaller dams operated by flood control and irrigation districts; none have a permanent pool of water and do not retain water for longer than 96 hours.

Major water users in the MRG basin are irrigators served by the Middle Rio Grande Conservancy District (MRGCD), the Albuquerque Bernalillo County Water Utility Authority (ABCWUA), the City of Rio Rancho and Bosque del Apache National Wildlife Refuge.

The MRGCD diverts water for agricultural use from four diversion dams on the main stem of the river in the MRG basin. Angostura near the town of Algodones, Isleta diversion dam on the Isleta Pueblo, and San Acacia north of Socorro. The ABCWUA diverts water for municipal uses from a variable height dam (often referred to as an inflatable dam) and a horizontal well collector system beneath the river bed near Alameda river crossing in Albuquerque for non-potable uses.

The USGS maintains several gaging stations on the main stem of the Rio Grande between Otowi and EB dam. The Otowi gage located near the NM State Highway 502 bridge on San Ildefonso Pueblo land north of Santa Fe. This gage is the NM Index Gage that determines the required deliveries of water to the lower Rio Grande and TX under the Rio Grande Compact. Besides its importance under the Compact, index flows at Otowi Gage provide a long term historic record of the amount of water supply for the MRG basin. The index flows at this gage represent the natural river flows, often referred to as native flows, excluding the influence of trans-basin diversions and upstream reservoir operations in New Mexico. Figure 2 provides a plot of Rio Grande index flows at the Otowi Gage.

Table 1 summarizes the annual average flows at select locations along the Rio Grande for the period of records. In order to illustrate the high variability of flows in the river, it also presents data for Q_{10}, the low flow that, over a long period of record, occurs 10% of the time. The ratio Q_{10}/Q_{avg} represents the ratio of these low flows to average flows. For example, the average river flow at Albuquerque is 944.9 KAF/yr but over the long term, 1 year out of 10 will have a flow of 436.5 KAF/yr or less. Flows of major tributaries to the Rio Grande are summarized in Table 2. Note that the flows from the ABCWUA Southside Water Reclamation Plant contribute 59.6 KAF/yr of water to the river and this discharge constitutes the third largest tributary to the river.

Figure 3 presents the historic record of precipitation in northern NM climate region 5 which encompasses the northern mountains of the Rio Grande watershed, the river's headwaters. This figure shows both the annual as well as decadal variations in precipitation. More importantly, selection of the period of 1972 to 1997 as done by the MRGWA (1999) includes two of the wettest decades of the last 100 years.

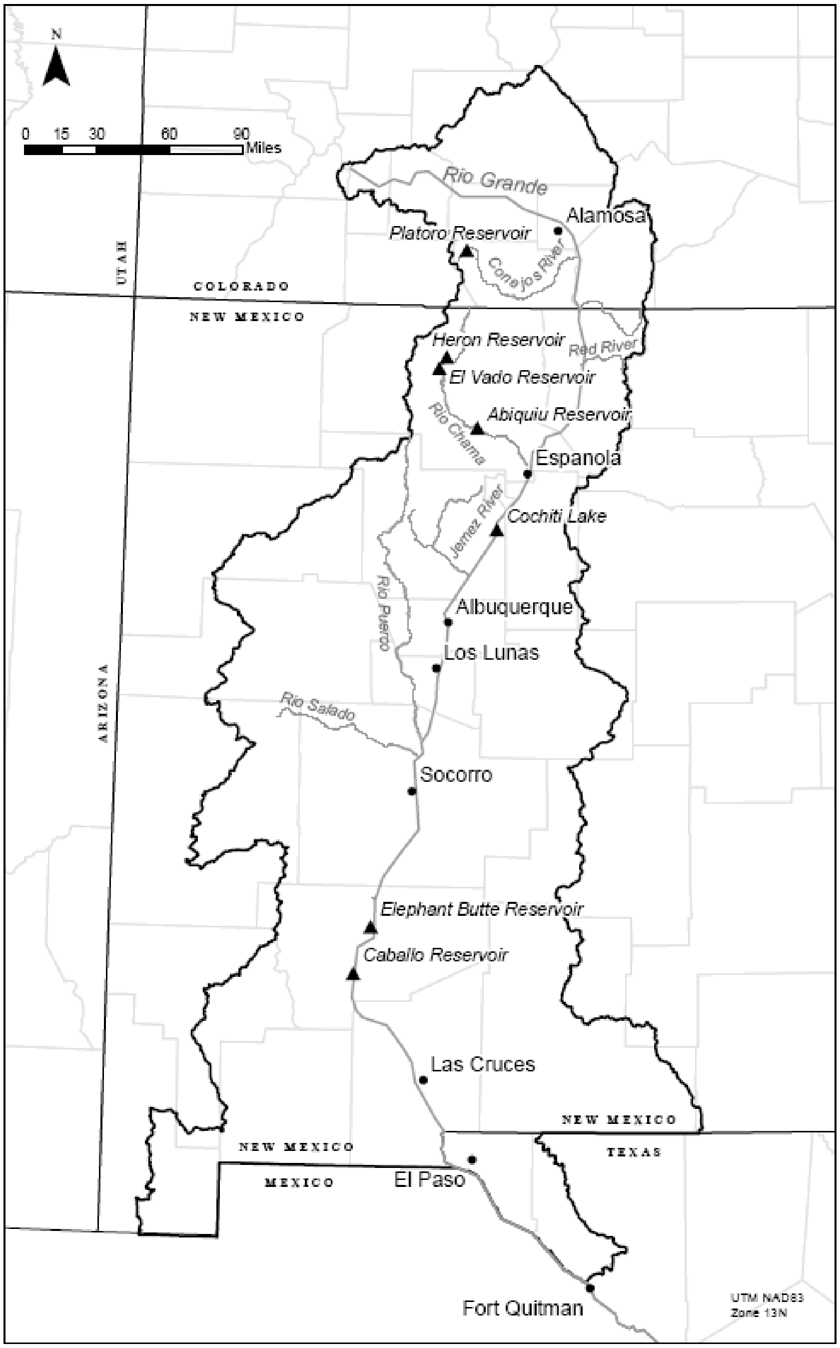

Figure 1. Map of the Rio Grande Basin (Thomson, 2012).

Although averaged data for weather and hydrologic conditions are used in everything from the weather page in the newspaper to technical hydrologic reports, it is apparent from data such as that in Figure 3 and Figure 2 that there is no such thing as an average year. Weather, stream flows, reservoir operations, as well as water diversions change on daily, monthly, annual, and decadal scales. Although water budgets are necessarily constructed using averaged data, selection of the period over which data is to be averaged will influence the results.

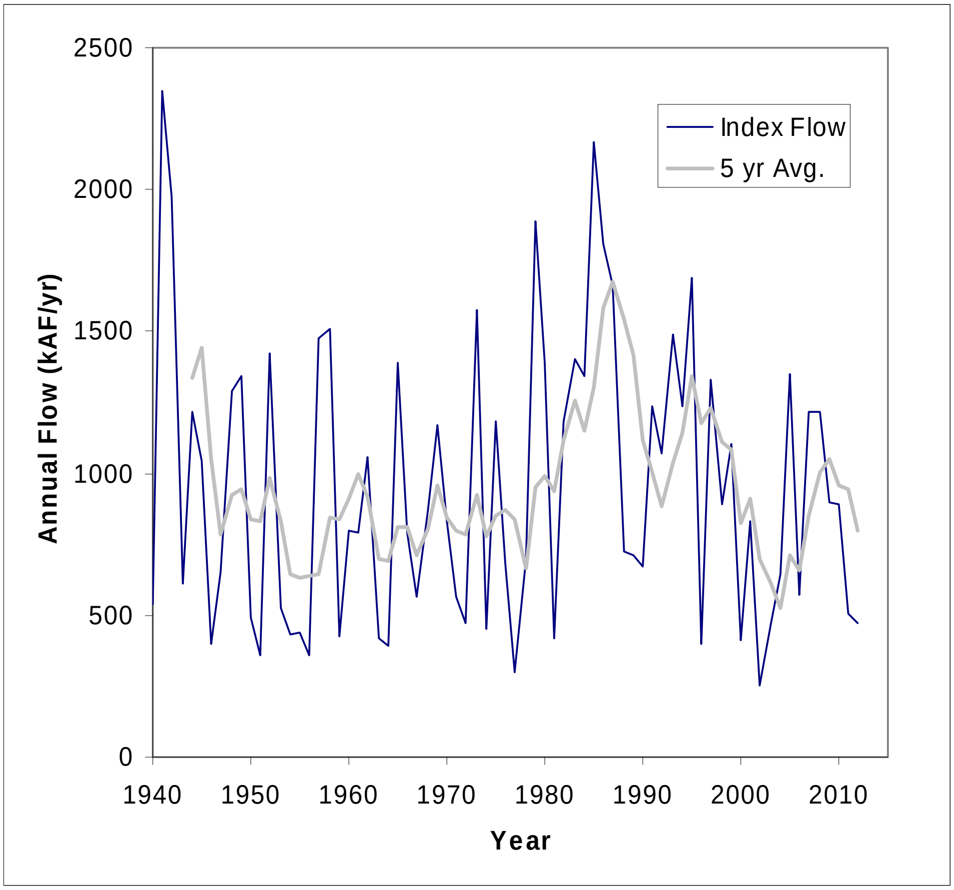

Figure 2. Annual index flows at Otowi gage together with the 5 year moving average (NM Interstate Stream Commission).

The flow data in Table 1, Table 2 and Figure 2 and the precipitation data in Figure 3 illustrate two important points. The first point and most obvious is the high degree of variability in the flows. It is not uncommon for annual flows at Otowi Gage to vary by a factor of three over a period of one or two years, from less than 500 KAF/yr to greater than 1,500 KAF/yr. This variability makes management of surface water resources very difficult since there are no large storage reservoirs on the main stem of the Rio Grande. The flow variability at Otowi also illustrates the conceptual difficulty of developing a water budget for the MRG basin as there is no such phenomenon as an "average year." Thus, a water budget prepared for a single year or even a series of years will vary widely which introduces complexity and limits its utility as an educational tool. Previous budgets are based on average conditions and though inflows and outflows can be averaged to filter out annual variability, the process of averaging makes it difficult to identify long term trends. For example, human uses of water, both M&I use as well as irrigated agricultural use, are constantly changing with trends in population, economy, and demographics. The climate also changes over periods of time with periods of drought or wet weather influenced by oceanic and other cycles that are only now beginning to be understood.

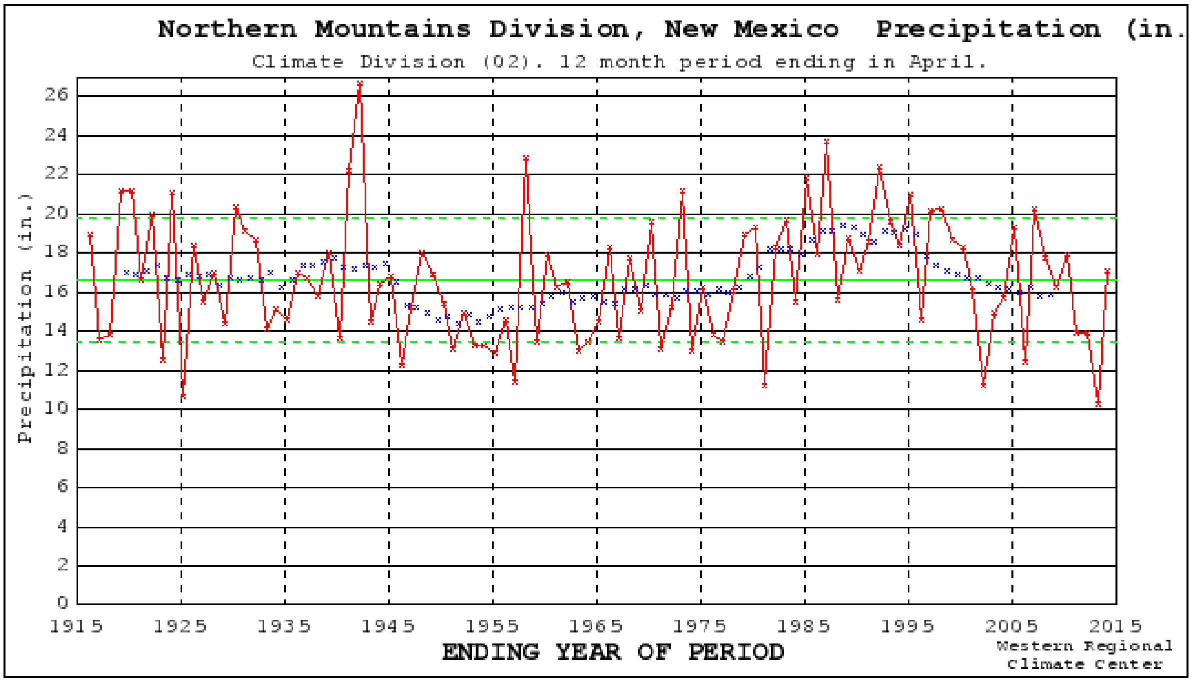

Figure 3. Historic precipitation in northern NM climate region 5. Annual precipitation is represented by the red line, the 5 year moving average is represented by the blue dots, the green line represents average precipitation and the dashed green lines represent 1 standard deviation of the data (WRCC, 2014) (http://www.wrcc.dri.edu/spi/divplot1map.html).

The second, and more subtle point illustrated by Figure 2 is that there may be a long term decline in Rio Grande flows over the last 2 decades. It will not bet possible for years to determine whether this is simply due to natural climate variability or a trend that is a result of climate warming. But as with changes in water use by population growth and changes in human use it is difficult to detect or quantify changes in the hydrologic cycle using a water budget based on long term averages.

Table 1. Annual average flows and Q_{10} at important locations on the Middle Rio Grande (Thomson, 2012).

Location	Period of Record[1]	Average Annual Flow (kAF/yr)	Q_{10}[2] (kAF/yr)	Q_{10}/Q_{avg}
Rio Grande near Cerro, NM	1949-2011	325.4	106	0.33
Rio Chama near Chamita, NM	1971-2011	413.2	214	0.52
Rio Grande at Otowi Bridge, NM[3]	1940-2012	951.0	410.8	0.43
Rio Grande at Albuquerque, NM	1974-2011	944.9	436.5	0.46
Rio Grande below Elephant Butte Dam, NM	1917-2011	718.5	422	0.59

[1]Period of record used in this analysis.

[2]Q_{10} is annual low flow that has a 10% chance of non-exceedance.

[3]Flows at Otowi Bridge are the Rio Grande Compact Index Flows (i.e. don't include SJC water)

Table 2. Average flows for major tributaries to the Rio Grande (Thomson, 2012).

Tributary	Drainage Area (mi^2)	$Q_{average}$ (kAF/yr)	Q_{10} (kAF/yr)[1]	Period of Record
Conejos River, CO	821	66.7	48	1953-2011[2]
Costillo Creek, CO	200	11.2	0.4	1966-2011
Red River, NM	185	56.7	33.7	1979-2011
Embudo Cr, NM	305	59.5	19.6	1924-2011
Rio Chama, NM	3,159	413.2	214	1971-2011
Galisteo Creek, NM	670	7.4	2	1942-1970
Jemez River, NM	1,038	43.1	13.9	1944-2011
SWRP - Albuq., NM[3]		59.6		2002-2011
Rio Puerco, NM	6,057	28.9	8.5	1941-2011
Rio Salado, NM[1]	1,394	10	0.9	1948-1984

[1]Q_{10} is annual low flow that has a 10% chance of non-exceedance

[2]Data from CO Dept. of Water Resources CONPLACO gage

[3]Southside Water Reclamation Plant, Albuquerque, NM

Previous Water Budgets

In an effort to better understand and explain the hydrologic cycle in the MRG, the Middle Rio Grande Water Assembly (MRGWA) undertook the task of developing a water budget for this watershed from Cochiti Dam to Elephant Butte Dam. The budget was prepared by a volunteer committee under the leadership of Frank Titus and was the first comprehensive quantitative estimation of water supplies, sinks and flows within the MRG basin. The group, known as El Grupo Tecnico, analyzed the data available for the 25 year period from 1972 to 1997 and released its report in 1999 (MRGWA, 1999). The results are summarized in Table 3 and presented as a wiring diagram in Figure 4. The fractional distribution of water depletions in the MRG basin are displayed graphically in Figure 5. Note that they are listed as depletions in the report rather than consumptive uses.

Table 3. Middle Rio Grande Water Budget: Annual Surface-Water & Groundwater Averages (rounded) for 1972-1997 (MRGWA, 1999).

Amount Annual		Amount (KAF/yr)	Annual Variability (KAF/yr)
Annual Surface-Water Inflow (Native Water) Variability			
Rio Grande native water at Otowi Gage ("Otowi Index")		1,100	297-2,170
San Juan-Chama Project imported water reaching Otowi Gage		55	2-150
Tributary inflow (the rios Santa Fe, Galisteo, Jemez, Tijeras, Puerco, Salado)		95	
Ungaged tributaries unknown			
Storm-drain inflow from Albuquerque		5	
Municipal Wastewater inflow (pumped from groundwater)		70	
Discharge from shallow aquifer to surface system Otowi to San Acacia		220	
Total Surface Water Flows		1,545	
Annual Surface-Water Outflow			
Recharge to shallow aquifer Otowi to San Acacia		295	
Open-water evaporation (incl.from farm fields) Otowi to San Acacia		60	30-90
Irrigated agriculture and valley-floor turf Otowi to San Acacia		100	70-130
Riparian ET, irrig. agric. & open-water evap. Combined below San Acacia		100	80-180
Elephant Butte evaporation		140	41-228
Surface-water outflow from Elephant Butte Dam to downstream users*		850	300-1435
Total Surface Water Outflows		1545	
Groundwater Recharge(+) & Discharge(-)			
SHALLOW AQUIFER (underlying Rio Grande flood plain)			
Recharge {from surface wtr & percolation from irrig) Otowi to San Acacia		295	
Septic-tank return flow (from pumping) Otowi to San Acacia		10	
Inflow from deep aquifer Otowi to San Acacia		50	
Riparian evapotranspiration (all non-crop ET) Otowi to San Acacia		-135	
Discharge to surface-system drainage ditches Otowi to San Acacia		-220	
Total Groundwater Recharge(+) & Discharge(-)		0	
Deep Aquifer Recharge(+) & Discharge(-)			
Deep groundwater inflow (from north & west)		40	
Mountain-front & tributary recharge Otowi to San Acacia		110	
Groundwater pumped (all wells) Otowi to San Acacia		-170	
Consumed (that is, evaporated)	90		
Municipal wastewater to river	70		
Septic-tank return flow to shallow aquifer	10		
Outflow to shallow aquifer		-50	
Total Groundwater mined from aquifer Otowi to San Acacia		-70	

Footnote:

*Calculated outflow (rounded) based on the data in this table. The average of wet-water actual flow past the dam is 729,000 ac-ft. 1972-97 Otowi Index supply is 786,000 ac-ft. The average of the Elephant Butte Effective Supply (actual deliveries plus changes in Elephant Butte lake storage) is 799,000 ac-ft. (See Summary, Note 8.)

A more detailed water budget for the MRG watershed was prepared by SS Papodopulos & Associates for the NM Interstate Stream Commission (SSPA, 2004) and was the product of several years of investigation and analysis. This study area considered the Rio Grande from

Otowi gage to Elephant Butte Dam which included Cochiti Reservoir and was a slightly larger study area than analyzed by the Assembly.

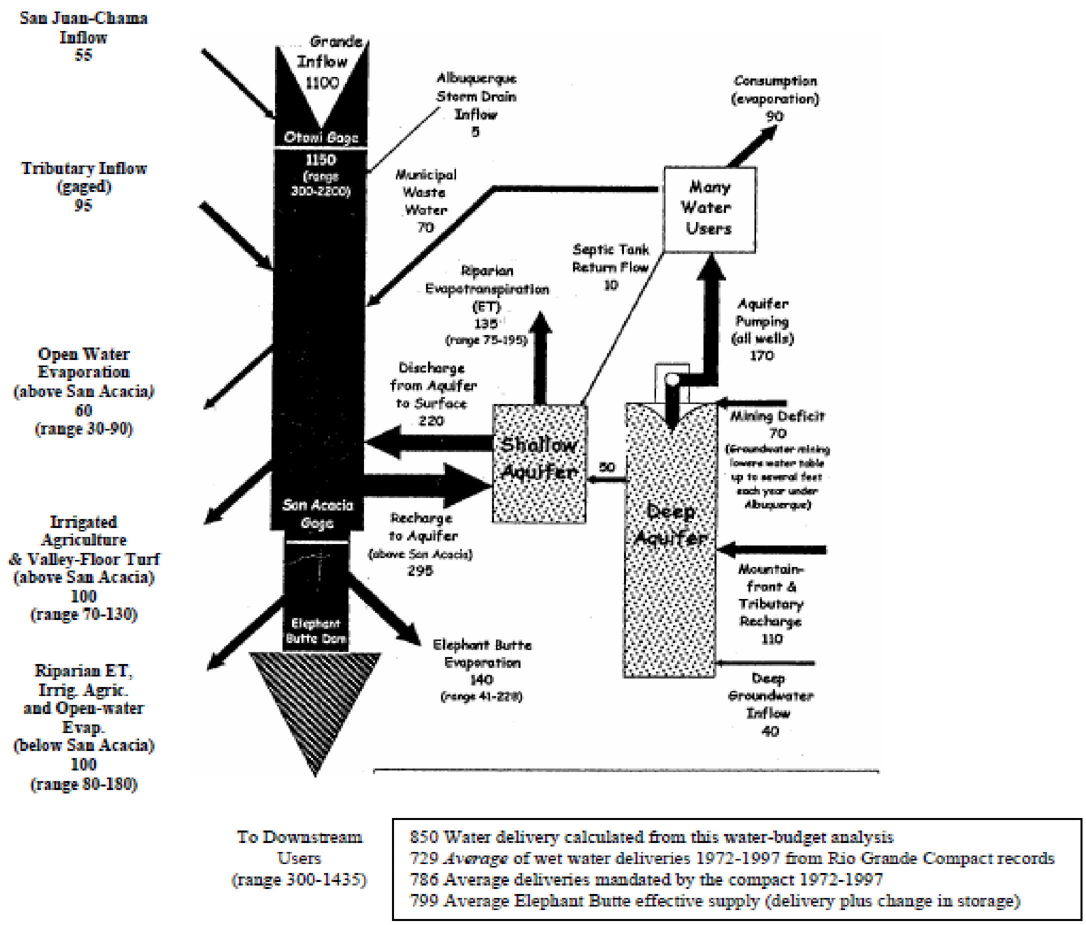

Figure 4. Middle Rio Grande Water Budget. Annual values typical for period 1972-1997 (MRGWA, 1999).

The water budget developed by the Assembly (MRGWA, 1999) was based on average conditions over a 25 year time period while the SSPA study evaluated the regional hydrologic cycle over a period of years from 1950 to 2002. The SSPA report gave more full consideration to the stochastic nature of the water supply and included considerable analysis of the statistical likelihood of water sources, sinks, and diversions. The SSPA study placed a strong emphasis on the following (SSPA, 2004):

- An updated quantification of the impacts on flow of the Rio Grande from groundwater pumping under both current and future City of Albuquerque pumping, including possible diversion of surface water from the river (the City began diverting surface water from the river in December, 2008);

- Improved estimates of agricultural and riparian consumptive uses, based on revised acreages and consumptive use rates, scaling to translate potential agricultural consumptive use to actual consumptive use, and limitations placed on agricultural consumptive use in response to available supply;

- Improved estimates of Elephant Butte evaporative losses, taking into account potential open water, wet sediment, and riparian losses from exposed portions of the Elephant Butte delta and northern basin;

- An updated risk evaluation of the water supply, identifying the range of expected water supply conditions under both baseline and drought conditions;

- Evaluation of the probability of achieving deliveries at Elephant Butte dam as required by the Rio Grande Compact under full implementation of the Middle Rio Grande, Socorro Sierra, and Jemez y Sangre Planning Regions proposed water planning alternatives during both historic (1950-2002) and drought conditions.

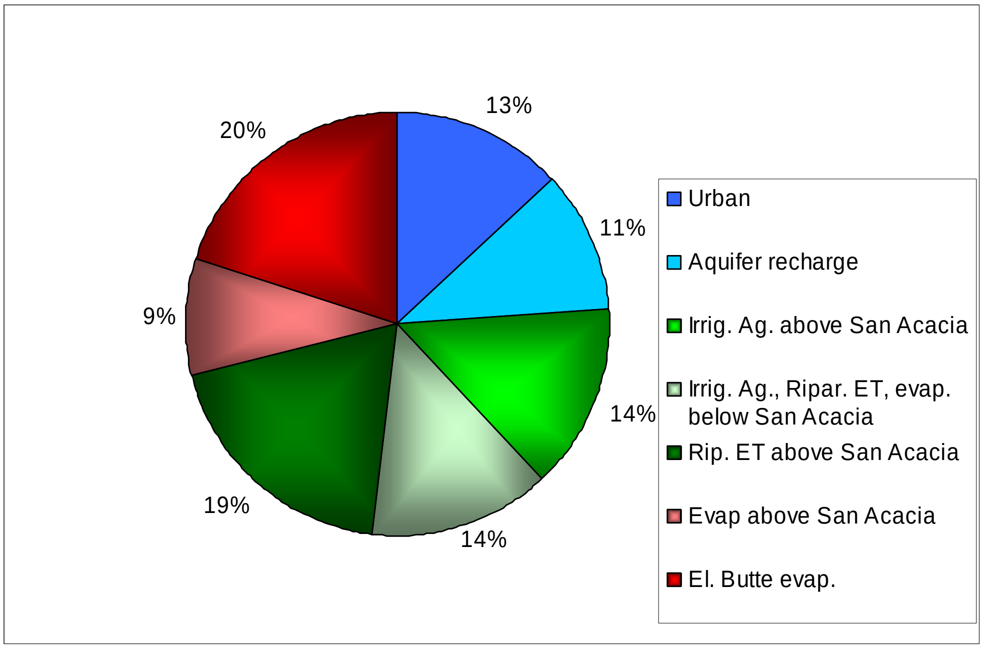

Figure 5. Fractional distributions of Middle Rio Grande water depletions for period 1972-1997 (MRGWA, 1999).

A probabilistic approach was used to estimate the range of key variables in the water cycle including measurement uncertainty, anthropogenic demands (municipal, industrial, and agricultural) and the effects of possible climate change. Figure 6 presents a summary water budget for variable supply based on water availability and use for the year 2000. The study concluded that based on the most likely conditions of water supply and water use, it was most probable that New Mexico would have an average deficit under the compact of about 40,000 AF. SSPA (2004) also prepared a summary of river depletions for year 2000 conditions which is presented in Figure 7. The study found that regional aquifer depletions amounted to approximately 71,000 AF/yr.

The statistical analysis of the SSPA (2004) budget allowed estimation of uncertainties in the source of supply and factors affecting water loss. The study found that the greatest uncertainties are associated with riparian and agricultural evapotranspiration (ET). Small changes in the coefficients used to calculate these losses resulted in large changes in estimated losses. Other terms with significant uncertainties included flows from ungaged tributaries and storm water runoff, open water evaporation from the river and Elephant Butte reservoir, and ground water recharge.

Though it is not formally a water budget, every 5 years the NM Office of the State Engineer compiles a report titled “New Mexico Water Use by Categories” in which water diversions are separated into 9 categories that are summarized according to river basin and county. The most recent report is for the year 2010 (Longworth et al., 2013). The report is titled “water use” however, it actually is a compilation of water diversions. In other words, this report does not include information on consumptive use. The water use data for 2010 for the four MRG counties (Sandoval, Bernalillo, Valencia, and Socorro) is summarized in Table 4. Note that evaporative losses from Elephant Butte reservoir are not fully captured by the summary in Table 4 because most of this reservoir is in Sierra County. Reservoir evaporation losses in Sierra County for 2010 were estimated at 100,620 AF/yr which of course includes losses from both Elephant Butte and Caballo reservoirs.

Although this information in the State Engineer’s report is useful its value in understanding the hydrologic cycle of the MRG is limited for several reasons:

- It only presents data for a single year. The highly variable nature of NM hydrology shows that conditions can change dramatically from one year to the next thus limiting the value of a “snapshot” approach

- This compilation only accounts for diversions or withdrawals and doesn’t include data pertaining to sources of water to the basin (river flows and precipitation) or some flows within the basin such as ground water recharge or urban and agricultural return flows.

- The report does not provide information on water losses from the basin such as outflows or evapotranspiration.

Nevertheless the State Engineer’s report constitutes a valuable collection of data that helps explain the statewide water use. Perhaps its most valuable feature is that these reports provide a 20 year period of record of water use which can be used to identify trends in population, agricultural acreage and irrigation methods, and water uses for nine different categories.

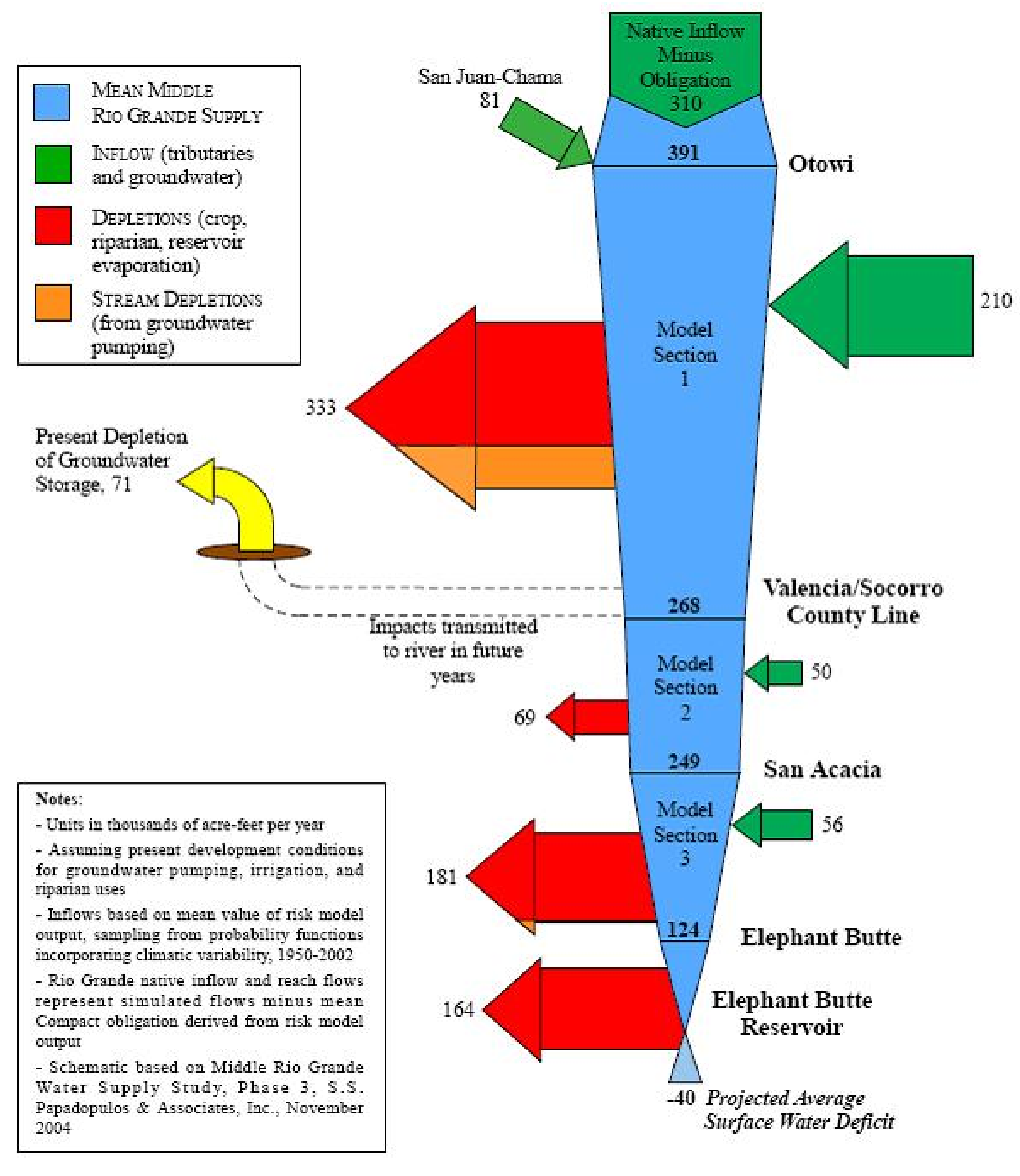

Figure 6. Water budget prepared for NM Interstate Stream Commission by SSPA (2004).

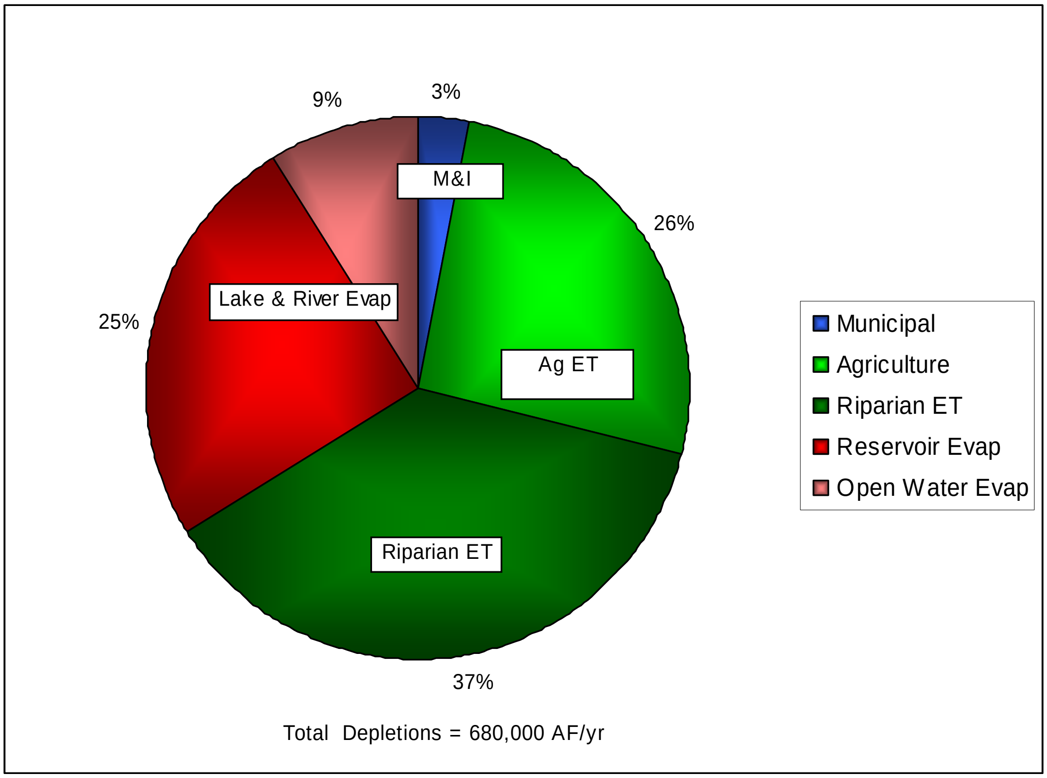

Figure 7. Mean depletions to Rio Grande system for year 2000 conditions. Total depletions were 680,000 AF/yr. Not included is an additional 71,000 AF/yr pumped from basin aquifers (Figure 4.22, SSPA, 2004).

Table 4. Water use for the four Middle Rio Grande Counties (Sandoval, Bernalillo, Valencia and Socorro) for 2010 (Longworth et al., 2013).

Category	Surface Water (AF/yr)	Ground Water (AF/yr)	Total (AF/yr)
Commercial (self-supplied)	17	13,449	13,466
Domestic (self-supplied)	0	9,781	9,781
Industrial (self-supplied)	0	4,520	4,520
Irrigated Agriculture	362,682	45,020	407,702
Livestock (self-supplied)	176	2,160	2,337
Mining (self-supplied)	0	566	566
Power (self-supplied)	0	472	472
Public Water Supply	45,371	89,535	134,906
Reservoir Evaporation	12,740	0	12,740
Totals	**420,986**	**165,503**	**586,490**

Updated Water Budget

Both of the previous water budgets are based on data through 1997 (MRGWA, 1999) and 2002 (SSPA, 2004). One of the limitations of previous water budgets is that they are based on long term average conditions. This approach does not capture trends in water use, weather patterns, or climate. The statistical approach used in the SSPA study analyzed the inherent variability of these parameters but the study itself is limited to data up through 2002; recent changes in the hydrologic cycle and water use are not captured. Several new developments and initiatives have occurred since publication of the MRGWA (1999) and SSPA (2004) reports including:

- Completion of the San Juan Chama surface water diversion structure and treatment plant by the City of Albuquerque which subsequently became the ABCWUA.

- Installation of continuous flow measurement in major canals and drains by the Middle Rio Grande Conservancy District.

- Implementation of aggressive water conservation measures by both municipal & industrial (M&I) users as well agricultural users.

- Continued population growth in the basin.

- Several years of extraordinary drought conditions.

These changes suggest a need for an update of the MRG water budget.

The update described in this report is based on values calculated using URGSiM, a system dynamics model developed at Sandia National Labs (USBOR, Appendix E, 2013). Development of the model was supported by Sandia National Laboratories, the Department of Energy, the US Army Corps of Engineers, and the US Bureau of Reclamation. URGSiM is similar to the Upper Rio Grande Water Operations Model (URGWOM) but its simulations are based on a monthly time step instead of a daily time step (USACE, 2014). It is used by federal water managers to understand and quantify water resources and flows in the Rio Grande above Caballo Reservoir and was extensively used on the Bureau of Reclamation's climate risk assessment for the upper Rio Grande (Llewellyn et al., 2013).

In its simplest form, URGSiM is a mass balance model that computes downstream flows based on given inflows, diversions, and consumptions on a monthly time step in the Rio Grande, its tributaries and ground water basins extending from the headwaters of the river in southern CO to the river below the dam at Caballo Reservoir. The model divides the river up into 20 reaches, 9 reservoirs, and 3 ground water basins. Each of the ground water basins were subsequently divided into sub-basins to provide improved model resolution; the Albuquerque ground water basin was divided into 51 spatial zones and the Socorro basin was divided into 12 spatial zones.

URGSiM was developed to allow estimation of water availability under future conditions of water supply, water demand, climate, and management strategies. However, for this study it was simply used as an accounting tool. Historic data for inflows and outflows, surface and ground water diversions, rainfall, weather observations, reservoir volume, agricultural and riparian acreage, and other information were compiled and entered into the model which then used a mass balance approach to determine how water moved through the basin and was used for three study periods; 1975-1997, 2000-2012, and 2008-2012.

Perhaps the greatest advantage of using URGSiM to calculate a water budget is that allows calculation of water flows and losses within the basin that cannot be measured directly including

ET from agricultural fields and the riparian zone, ground water recharge, seepage flows to ditches and drains, and evaporation from the river and reservoir. The mass balance approach also allows estimation of flows that are not measured such as those from ungaged tributaries, stormwater runoff, and M&I consumptive use.

In an arid environment the greatest loss of water, generally referred to as depletion, from the basin is plant ET which cannot be measured basin-wide and instead must be calculated. A variety of methods have been used to calculate ET. URGSiM uses the Hargreaves method to calculate ET for a reference crop then multiplies this by a crop coefficient that is specific for the actual crop being grown (USBOR, 2013). Though widely used, this and all other methods have considerable uncertainty. In addition to the reference ET and crop coefficient, ET losses by riparian vegetation also depends on the to the ground water as these plants, primarily cottonwoods and salt cedar, have root systems that extend into the shallow water table. Average annual riparian ET rates can exceed 5 ft/yr if ground water is sufficiently shallow.

ET calculations are based on weather data and crop coefficients. Although crop coefficients are published in the ag literature, they vary significantly with location and farming practice. Selection of the proper crop coefficient requires some judgment and represents perhaps the biggest source of uncertainty in the water budget calculations described here. The crop coefficients used in URGSiM for ag lands are based on values published by the United Nations (Allen, 1998). Crop coefficients for riparian ET depletions in URGSiM were selected to be consistent with previous ground water models in the Socorro and Albuquerque basins (USBOR, 2013).

The water budgets described in this report are for three time periods: 1975-1997, 2000-2012, and 2008-2012. The first period, 1975-1997, is similar to the period used in the MRGWA (1999) study and provides data of higher quality and improved spatial resolution that can be used for comparison to previous water budgets. The period of 2000-2012 was selected because it represents precipitation patterns that more closely resemble those of the long term average (Figure 3) as well as more recent usage of surface and ground water. The period 2008-2012 was selected because it covers the period during which the City of Albuquerque (and subsequently the ABCWUA) has been diverting surface water from the river to more directly capture its share of San Juan Chama water.

The water balance for the period 1975-1997 generated by URGSIM is shown in detail in Figure 8. It shows 1,279 KAF/yr entering the basin at Cochiti Reservoir and 766 KAF/yr being delivered to the lower Rio Grande and TX at Elephant Butte. These values are slightly greater than the 1,100 KAF/yr inflow and 850 KAF/yr deliveries at Elephant Butte Dam reported by the MRGWA (1999) budget. Note that over this period of time Elephant Butte Reservoir increased in volume by 68 KAF/yr. Over the 22 year study period this constitutes a total increase of 1,500 KAF which is in good agreement with the actual increase in reservoir volume over this time as shown in Figure 9.

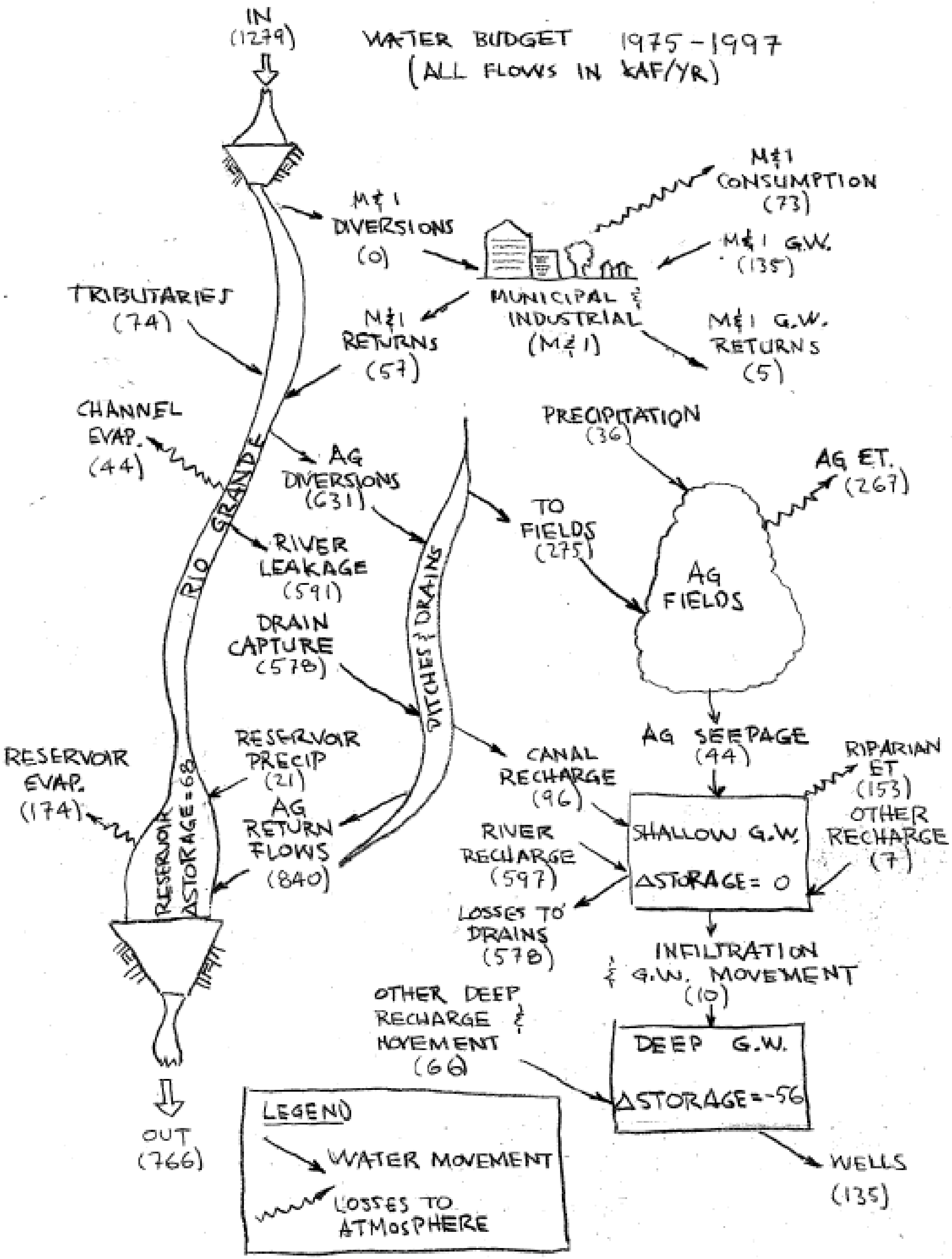

Figure 8. Diagram of sources, sinks and flows of water in the Middle Rio Grande basin for the period 1975-1997.

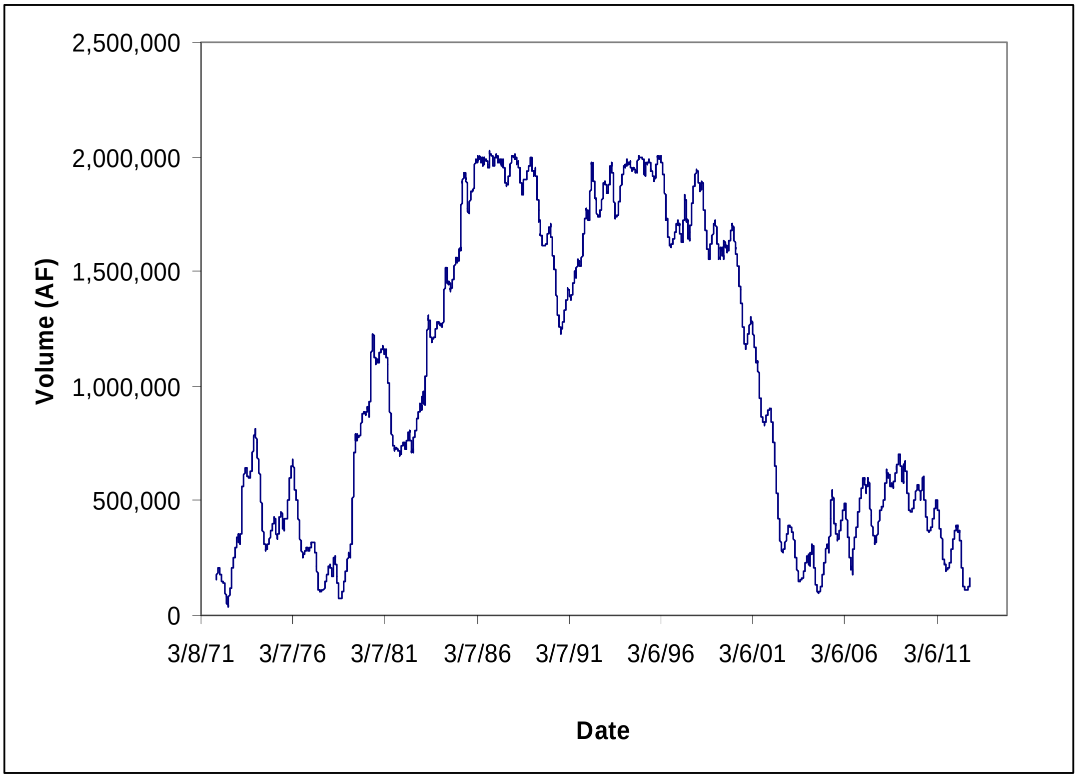

Figure 9. Volume of Elephant Butte Reservoir over the period 1972 to 2012.

The sources of water supply for the basin are summarized in Figure 10. The data show that water in the main stem of the river at Cochiti Reservoir constitutes greater than 90% of the water supply for the basin. This emphasizes the importance of spring runoff from winter snowpack; precipitation and storm runoff within the basin both contribute a very small fraction of the supply. The results for the 2000-2012 and 2008-2012 periods are also summarized in Figure 10 and show a decrease in flow into the basin of approximately 30%, virtually all of which is due to decreased river flow entering the basin at Cochiti dam. This is due to decreased precipitation in the headwaters (Figure 3) which results in decreased flows at Otowi gage (Figure 2).

Water leaves the basin in the form of releases from Elephant Butte Reservoir, evaporation from Elephant Butte Reservoir and the river, evapotranspiration (ET)from irrigated agricultural fields, ET from riparian vegetation, and consumptive use from urban areas (evaporation and evapotranspiration). These depletions and outflow are summarized in Figure 11 and Table 6. Open water evaporation and ETfrom urban, ag, and riparian depletions are nearly equal to the water deliveries at Elephant Butte (709 KAF/yr compared to 766 KAF/yr) for the period 1975-1997. The depletions and outflow for this period are, in order of decreasing magnitude; ET from irrigated agricultural activities (267 KAF/yr), reservoir evaporation (174 KAF/yr), ET from the riparian vegetation (i.e. the bosque) (152 KAF/yr), M&I consumptive us (73 KAF/yr), and river evaporation (43 KAF/yr).

The water budget shows that agricultural ET constitutes the largest depletion of water from the MRG basin. URGSiM calculated total ET values of 267 KAF/yr and 305 KAF/yr for the 1975-1997 and 2008-2012 periods respectively. The net ET is the difference between total ET and the water supplied by precipitation which is 231 KAF/yr and 245 KAF/yr for the two time periods. This is the amount of water that must be provided to the fields by the irrigation system. The 1975-1997 value of 231 KAF/yr is higher than the 177 KAF/yr reported by SSPA (2004) for year 2000 conditions. The Water Assembly's previous budget reported ag ET depletions of 200 KAF/yr, however this value includes both ag and riparian ET between the San Acacia diversion dam and Elephant Butte Reservoir so is not directly comparable. The difference between ag ET estimates for the three water budgets highlights one of the major uncertainties in this type of analysis. Evapotranspiration must be determined by calculation because it cannot be measured. The calculation requires both a lot of data as well as professional judgment in selecting appropriate crop coefficients. Reducing this uncertainty requires further study.

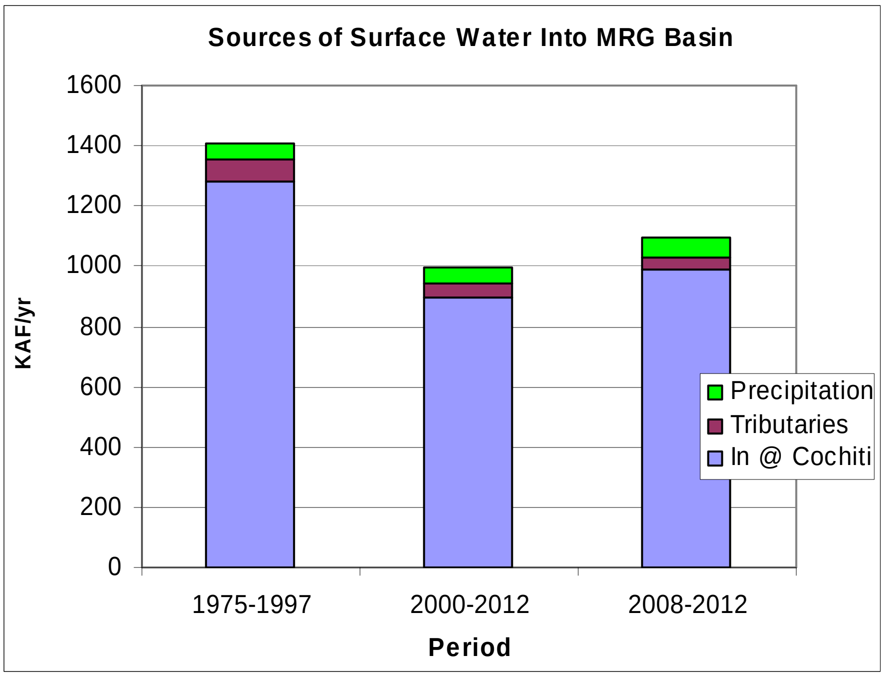

Figure 10. Sources of water flowing into the Middle Rio Grande basin.

Table 5. Summary of the sources of water flowing into the Middle Rio Grande basin.

Sources to Basin	1975-1997	2000-2012	2008-2012
In @ Cochiti	1279	894	987
Tributaries	75	50	43
Precipitation	55	52	68
Totals	1408	996	1098

Water depletions and outflow from the MRG basin for the 2000-2012 and 2008-2012 periods decrease by almost 20% which is primarily due to decreased outflow from Elephant Butte Reservoir, decreased M&I consumption and decreased reservoir evaporation; there was little change in depletions due to agricultural or riparian ET (Figure 11 and Table 6). Decreased releases from Elephant Butte Reservoir are due to decreased native river flows measured at the Otowi gage. Under the Rio Grande Compact deliveries to the lower Rio Grande and TX at

Elephant Butte dam depend on the flows at the Otowi gage so that as flows decrease in the north, compact deliveries to the south drop accordingly.

Reduced M&I depletions reflect the remarkable success of urban water conservation programs. Even though the population in the basin has increased since 1975 consumptive water use has decreased in excess of 10,000 AF/yr between 1995 and 2012. Finally, reservoir evaporation losses have decreased due to a decrease in the lake's surface area. The dry period from 2000 to 2012 has caused a dramatic decrease in the volume of water stored in Elephant Butte reservoir (Figure 9). The data show a slight increase in ET depletions from irrigated agriculture in recent years while all other water depletions have not changed within the uncertainty of the calculations.

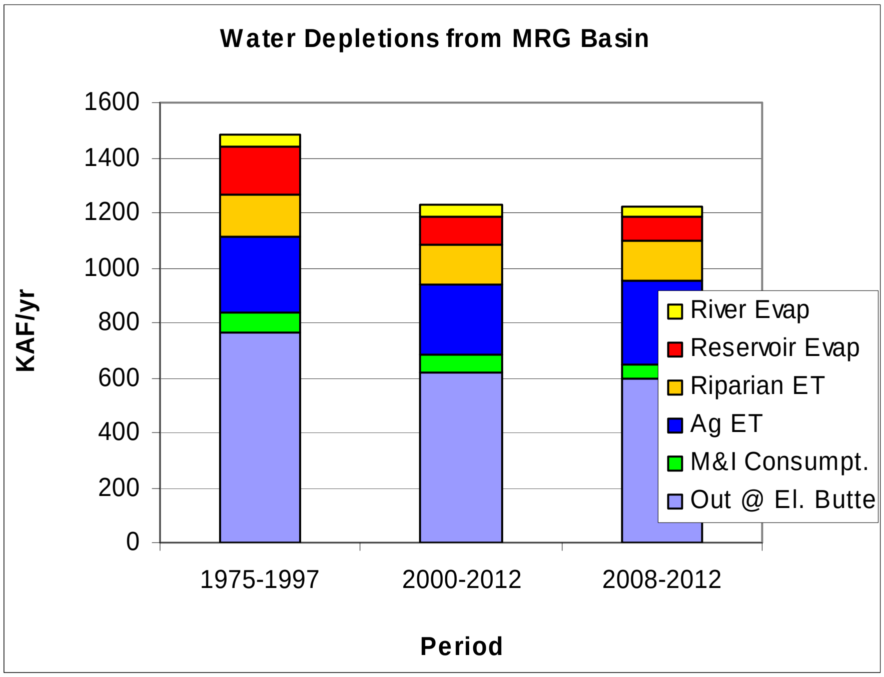

Figure 11. Water depletions from the Middle Rio Grande basin.

Table 6. Summary of the water depletions from the Middle Rio Grande basin.

Losses from Basin	1975-1997	2000-2012	2008-2012
Out @ El. Butte	766	622	594
M&I Consumpt.	73	59	53
Ag ET	271	261	305
Riparian ET	153	145	145
Reservoir Evap	174	101	84
River Evap	44	39	40
Totals	1480	1227	1222

Surface water diversions are shown in Figure 12 and show that diversions for irrigated agriculture (633 KAF/yr) are similar to leakage from the river channel (591 KAF/yr) for the period of 1975-1997. Much of this water, both ag and river leakage, is captured by the drains in the valley and is subsequently returned to the river in the form of return flows. The amount of water that actually recharges the deep regional aquifer over the period of 1975 to 1997 was calculated to be 77 KAF/yr.

Until 1997 few of the MRGCD canals and drains were metered which introduced uncertainty to estimates of agricultural diversions and return flows. A comprehensive program to install flow measurement devices on river diversions, main canals, and main drains began in the late 1990's that took nearly 10 years to complete. Thus, the amount of return flows over the period of 1975 to 1997 reported by previous water balances and calculated by URGSiMis an estimate. Annual return flow volumes from the agricultural drains depends largely on the difference between surface water diversions, agricultural and riparian ET, river leakage, and ground water recharge. Together ag and riparian ET constitute the largest depletion of water from the basin but also introduce the greatest source of uncertainty in the water budget calculations. Better measurement of return flows will reduce the uncertainty of these calculations.

While leakage of water from the river to the drains remained essentially constant for the three time periods, the average annual surface diversions decreased over the 2000-2012 and 2008-2012 periods. This was primarily due to reduced diversions for irrigated agriculture as a result improved water management practices by the Middle Rio Grande Conservancy District. Beginning in late 2008 the ABCWUA began diverting water from the river to take full advantage of its share of SJC water. The Authority is permitted to divert almost 100 KAF/yr from the river but only diverted an average of 30 KAF/yr over the period of 2008-2012. This was due to a slow and cautious ramping up of the diversion over several years to avoid problems that might occur with a new system and also to limited allowable withdrawals from the river during drought conditions in order to minimize the Authority's impact on the river. The ABCWUA plans to increase surface water diversions in the future to reduce its dependence on ground water.

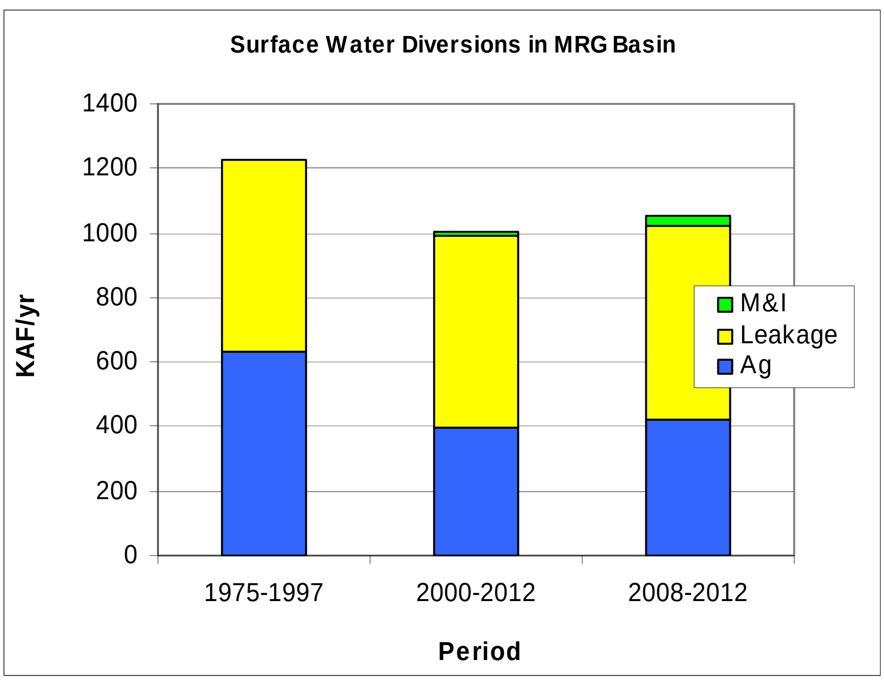

Figure 12. Surface water diversions in the Middle Rio Grande basin.

There are three significant ground water flows in the MRG basin: 1) pumping from deep wells, mostly for M&I use; 2) flow of shallow ground water to agricultural drains, and 3) depletion of shallow ground water to the atmosphere as a result of riparian ET (Figure 13). Together they constitute a total diversion of 866 KAF/yr over the period of 1975-1997. Pumping from the deep aquifer was calculated to be 133 KAF/yr. Recharge of the deep aquifer was estimated at 77 KAF/yr. The difference between aquifer recharge and pumping, flow to drains and riparian ET resulted in a net depletion of 56 KAF/yr. This can be compared to a net depletion of 71 KAF/yr estimated by SSPA (2004).

Table 7. Summary of surface water diversion in the Middle Rio Grande basin.

Surface Water Diver	1975-1997	2000-2012	2008-2012
Ag	633	396	423
Leakage	591	595	599
M&I	0	12	30
Totals	1224	1002	1052

The flow of shallow ground water to drains and ET losses by riparian vegetation remained essentially constant over the periods of 2000-2012 and 2008-2012 which is consistent with the observations that: 1) much of the shallow ground water flow is seepage from the river (Figure 14 and Table 9) and 2) shallow ground water elevation in the riparian zone is established by river elevation which varies by only a few feet during the year. Ground water pumping in the MRG basin decreased from an estimated 135 KAF/yr in the 1975-1997 period to 98 KAF/yr in the 2008-2012 as a result of M&I conservation and increased reliance on surface water as a source of supply. Reduced ground water pumping in Albuquerque has reduced in an approximate 10 ft rise in the water table underneath much of the city.

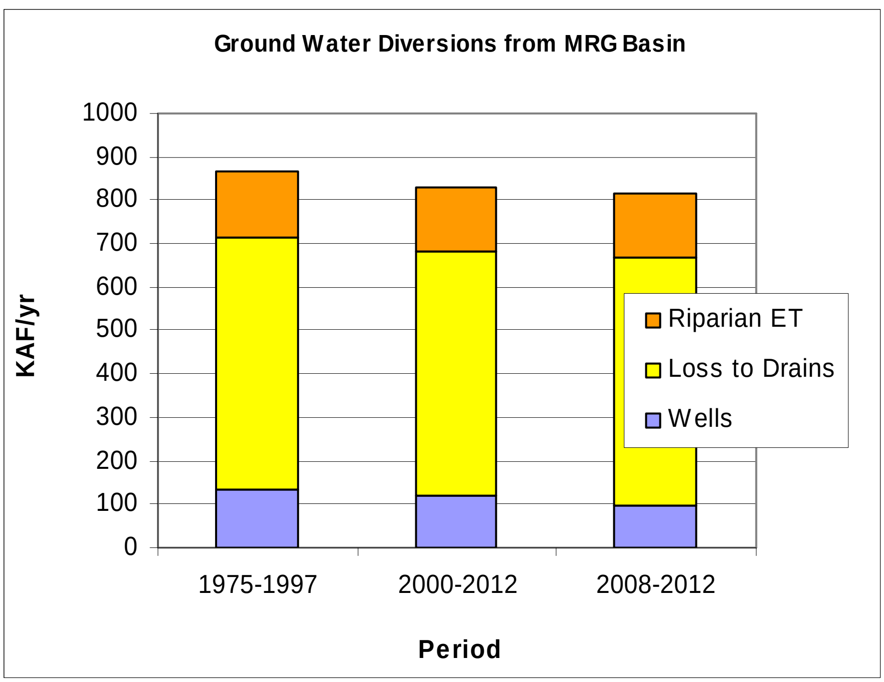

Figure 13. Ground water diversions in the MRG basin.

Table 8. Summary of ground water diversions from the Middle Rio Grande basin.

Ground Water Diver	1975-1997	2000-2012	2008-2012
Wells	135	120	98
Loss to Drains	578	564	572
Riparian ET	153	145	145
Totals	866	829	815

Ground water recharge is summarized in Figure 14. The total calculated recharge over the period 1975-1997 was 810 KAF/yr, of which 74% was from the river. Seepage from irrigated agriculture was found to be 44 KAF/yr which primarily goes to shallow ground water. Most of the water in the shallow aquifer eventually flows back to the river through the drain system (579 KAF/yr). There was virtually no change in ground water recharge over the three time periods considered which is consistent with the observations that changes in water surface in the river, irrigation canals and drains were very small. These water levels are the main factors that establish the hydraulic gradient that affects recharge rates. Further, there was little change in seepage from irrigated fields which is consistent with little change in the total number of irrigated acres.

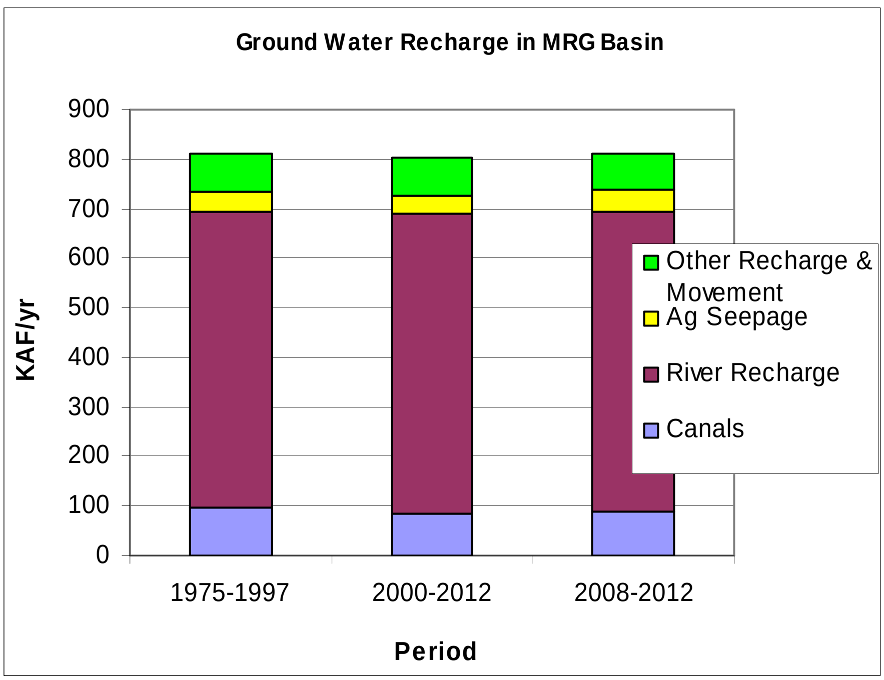

Figure 14. Sources of ground water recharge in the Middle Rio Grande basin.

Table 9. Summary of ground water recharge in the Middle Rio Grande basin.

Ground Water Rech	1975-1997	2000-2012	2008-2012
Canals	96	86	89
River Recharge	597	603	607
Ag Seepage	44	39	43
Other Recharge & M	73	74	73
Totals	810	802	812

The detailed water balance for the period of 2008-2012 is presented in Figure 15. The changes between the conditions for the period of 1975-1997 are summarized in Figure 10 through Figure 14 and the numeric data are presented in Table 5 through Figure 9. This diagram represents the best estimate of the hydrologic cycle in the MRG basin for current conditions.

The water balance for 2008-2012 (Figure 15) shows that the basin continues to be out of balance, most recently by 48 KAF/yr. Water deliveries to meet Rio Grande Compact requirements to the lower Rio Grande and TX has been achieved in part by drawing down Elephant Butte Reservoir by 43 KAF/yr and withdrawing 5 KAF/yr more from the deep aquifers than is replenished by ground water recharge. Figure 9, the plot of the volume of water in Elephant Butte Reservoir, shows a sharp decline in storage of about 200 KAF from 2008 to 2012 which is consistent with URGSiM calculation.

Note that the average water budget deficit of 48 KAF/yr for the period 2008-2012 is close to the 40 KAF/yr deficit estimated for the year 2000 by SSPA (2004). Although significant decreases in M&I consumptive use has been achieved and water diversion for irrigation has been reduced, the overall water supply for the MRG basin remains out of balance with the demand. It is clear that further measures for reducing basin wide consumptive use will be required to bring the basin into balance based on current water uses. Furthermore, even more aggressive measures will be required in the future to meet the conflicting situations of increased demand due to projected growth and decreased future supplies as a result of long term drought and climate change.

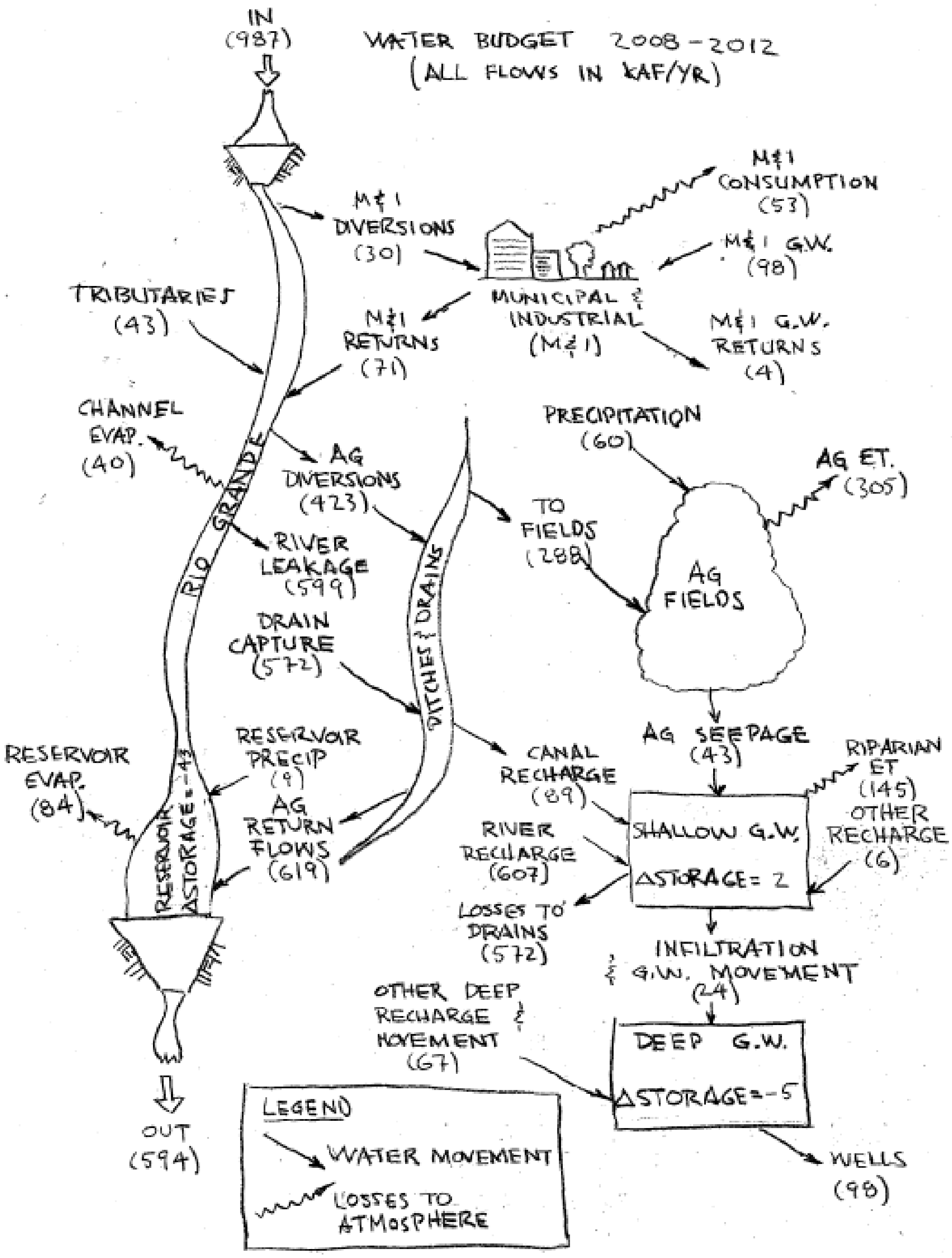

Figure 15. Diagram of sources, sinks and flows of water in the Middle Rio Grande basin for the period 2008-2012.

Summary

The hydrologic data and water budget calculations for the period 2008-2012 show that a total of 1,098 KAF/yr of water entered the basin in the form of flow from the river (987 KAF/yr), tributaries in the MRG (43 KAF/yr) and atmospheric precipitation (68 KAF/yr). Roughly half of this, 598 KAF/yr, was subsequently delivered to the Lower Rio Grande and TX at Elephant Butte Dam. The total losses from the basin of 715 KAF/yr that were calculated by URGSiM for 1975-1997 compare favorably to the depletions of 680 KAF/yr for the year 2000 reported by SSPA (2004). The distribution of the losses is quite different as seen by comparing Figure 7 to Figure 16. While lake and river evaporative losses are roughly the same, URGSiM shows M&I consumption to be 10% of total depletions compared to 3% by SSPA (2004). Furthermore, there are large differences calculated for riparian ET(21% vs 37% by SSPA, 2004) and agricultural ET (39% vs 26% by SSPA, 2004).

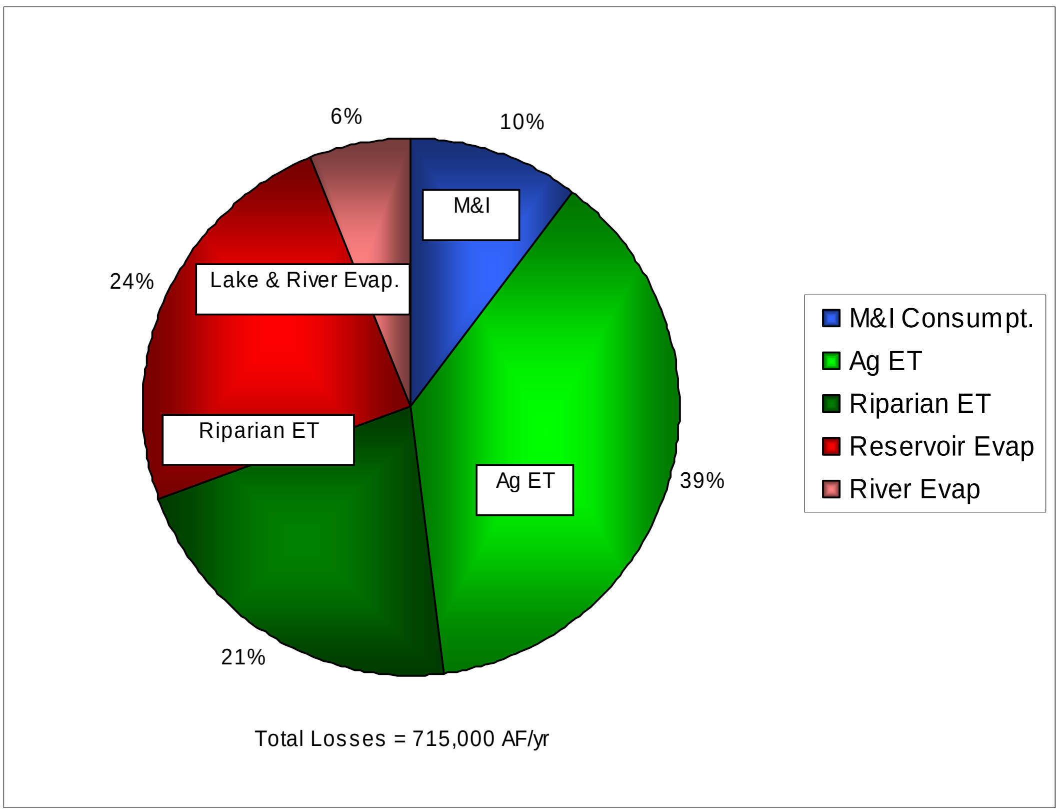

Figure 16. Distribution of the losses of water from the Middle Rio Grande Basin for the period 1975-1997 as calculated by URGSiM.

A second similarity between the two studies is that whereas SSPA (2004) reported a net deficit of 40 KAF/yr (Figure 6) for 2000, URGSiM reports a decrease in storage in Elephant Butte Reservoir of 43 KAF/yr. In other words, deliveries to the lower Rio Grande and TX are being met in part by draining this lake. Of course one benefit of this strategy is that reservoir evaporation is reduced from 164 KAF/yr to 84 KAF/yr; it is important to remember that the SSPA (2004) study included Caballo Reservoir in its study area.

The results of the URGSiM calculations show that aquifer depletions have been reduced from 56 KAF/yr for the period 1975-1997 to only 5 KAF/yr for the period 2008-2012. This is due to conservation by the M&I sector and to use of surface water by the ABCWUA as part of its source of supply.

The water budget presented in this report illustrates the complexity of the hydrologic cycle in the MRG basin. Use of the URGSiM system dynamics model allows calculation of how much water is available, how it moves through the MRG basin, and how it is lost from the basin with unprecedented resolution. Use of a system dynamics model allows all of the major components of the hydrologic cycle to be included. In addition use of the URGSiM model allows comparative ease of updating the budget as new data become available and improved methods for calculating difficult to measure flows (e.g. evapotranspiration) are developed.

It is informative to compare the distribution of depletions during period of wet years and full reservoirs (Figure 16) with those of the drought years of 2008-2012 (Figure 17). This comparison shows that total depletions decreased from 715 KAF/yr to 628 KAF/yr. It also shows reduced fractional depletions for lake and river evaporation and riparian ET while the fraction of water lost to agricultural ET from 39% to 49%. M&I consumptive losses remained the same.

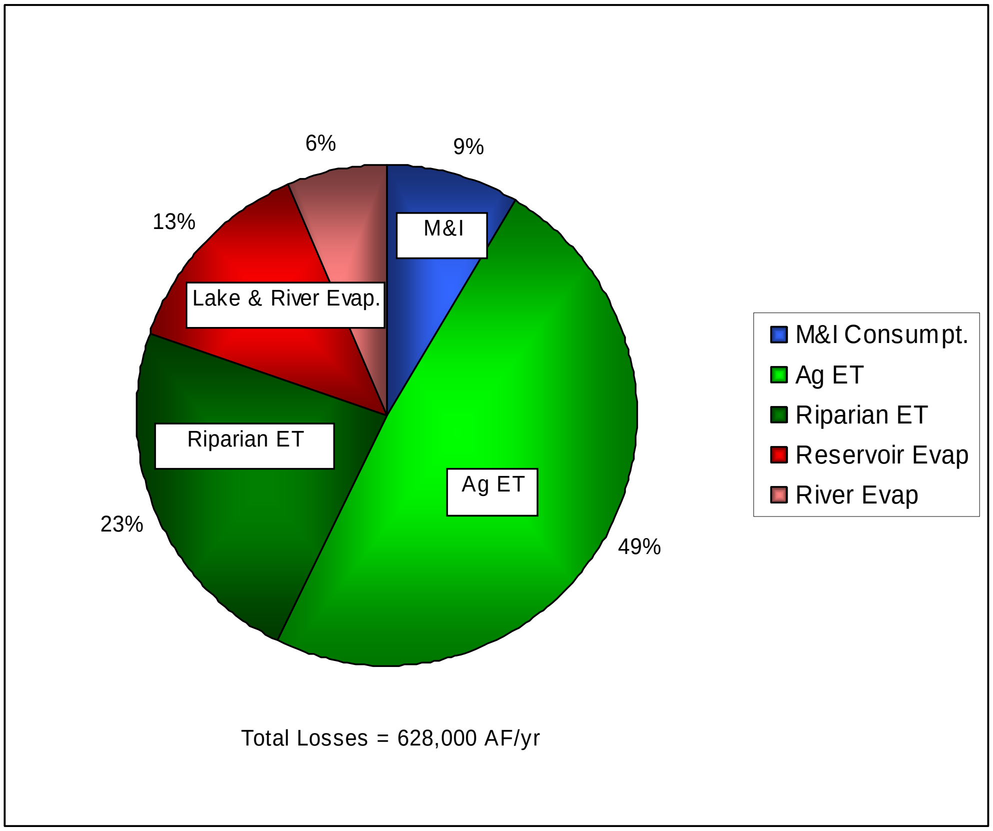

Figure 17. Distribution of the losses of water from the Middle Rio Grande Basin for the period 2008-2012.

The results of this study confirm that of previous investigations; we cannot continue to use water in New Mexico as we have in the past, especially in the MRG basin. The basin has experienced remarkable growth over the past several decades and yet is almost entirely dependent on water from outside the watershed as its source of supply. Although the demand for water has remained relatively flat over the last 15 years through aggressive conservation programs, the deficit of 48 KAF/yr over the period 2008-2012 demonstrate that current efforts are not sufficient to bring the basin's water resources into balance. Recent experience with a prolonged drought as well as the expected impacts of climate change suggest that future water supplies will be substantially reduced, especially in comparison to the last two decades of the 20^{th} century which were inordinately wet.

The water budget presented in this report is intended to show clearly and quantitatively what the sources of water are in the MRG basin, how the water is used, and the natural phenomenon and human uses that account for its losses. It is clear that changes are needed in water management and use in the basin. Although this study focused on and provided an extraordinary level of detail for the MRG basin, summary reports for other basins such as that by Thomson (2012) and regional water plans developed for the NM ISC show that the problems faced in this basin are not unique; all other major river basins in the state face similar problems of excessive water diversions and inadequate water supply. The changes needed to address the water resource challenges in NM will impact all of the state's residents. Implementation of these changes will require an uncommon degree of collaboration and cooperation among all as we meet the challenges of living within the water supply that nature provides.

Different levels of detail are provided in this report. Comprehensive diagrams as shown in Figure 8 and Figure 15 that can assist water managers by providing a quantitative accounting for water sources, water losses and flows of water within the basin that will aid in developing strategies for meeting future needs. At the same time summary charts such as Figure 17 can be used to inform the public and elected officials to achieve a more complete understanding of the challenges we face today and the difficult decisions that must be made so that we can meet the water challenges of the future.

There are two especially valuable features of this water budget. First, it provides a best estimate of the current sources, sinks, and internal flows of water in the MRG basin. Second, and equally important, it allows identification of what the most important uncertainties are and where we need to focus future efforts to understand the hydrologic cycle and to develop strategies for meeting water needs of the future.

Reviewers

John Brown, Carol Kennedy, Lynn Montgomery, Don Rudey, John Stomp, Bob Wessely

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Appendix 1: Glossary

ABCWUA – Albuquerque Bernalillo County Water Utility Authority, also referred to as the Authority

acre-ft (AF) – A volume of water that is 1 acre in area by 1 ft deep. 1 AF =43,560 ft^3 = 325,829 gallons

AMAFCA – Albuquerque Metropolitan Arroyo Flood Control Authority

Aquifer - A geological strata in the subsurface that is saturated with water (i.e., is below the "water table") and is sufficiently permeable to yield usable quantities of water to wells. See also "Deep Aquifer" and "Shallow Aquifer."

Consumptive Use - The difference between water withdrawn from a source of supply and that returned to surface or ground water. Water used consumptively is water lost to the atmosphere through evaporation and evapotranspiration.

Deep Aquifer The saturated, potentially water-yielding part of the older basin-fill sediments that geologists-call the Santa Fe Group. The deep aquifer is the primary water source for most municipal, industrial, and many privatedomestic users. It is in direct hydraulic connection with the Shallow Aquifer, which rests on it along the river floodplain. The water table in the deep aquifer is locally as much as 1,000 feet below land surface.

Depletion - The net reduction in surface-water flow between two specified points in the hydrologic system. Middle Rio Grande basin depletion is calculated as follows; native-water inflow at Otowi, minus outflow at Elephant Butte Dam.

Evapotranspiration - The combined processes of evaporation and plant transpiration through which liquid water is converted to water vapor and lost from the water system.

ET - Evapotranspiration

Ground Water (also Groundwater) – Water present in an aquifer. The term usually does not include moisture in wet soils above the top of the water table.

KAF/yr – Kilo acre-ft per year (1,000 AF/yr)

M&I – Municipal and industrial, refers to urban areas since virtually all industrial water users in the Middle Rio Grande basin are located in the cities.

MRG – Middle Rio Grande

MRGCD – Middle Rio Grande Conservancy District

Native Water - Water that originates in the Rio Grande drainage and is not imported from other basins.

NM ISC – New Mexico Interstate Stream Commission

NM OSE – New Mexico Office of the State Engineer

Paper Water - A term that whimsically identifies water rights owned or claimed within a system. Often it is different from "Wet Water" which is associated with the actual water present within the hydrologic system.

Recharge - The general process of water seeping into an aquifer. The process includes infiltration from surface water, downward migration of water from wet soils, and subsurface flow of ground water from adjacent aquifers.

Riparian - The environment immediately adjacent to streams and rivers where shallow ground water supports vegetative growth.

San Juan-Chama Project - The trans-basin diversion project that began operating in 1972 to transport water from three tributaries of the San Juan River (in the Colorado River system) into the Chama River basin, thence into the Rio Grande at Española. Heron Reservoir, perched dramatically above the Chama River, receives an average of 96,000 acre-feet of water annually through the Azotea Tunnel, which passes under the continental divide.

SJC Project – San Juan-Chama Project.

SSCAFCA – Southern Sandoval County Arroyo Flood Control Authority

Shallow Aquifer - This is the saturated part of the geologically "Recent" alluvium--those river-borne deposits 60-100 feet thick that underlie the ancestral Rio Grande floodplain. It is hydraulically interconnected with the surface water system consisting of the river, irrigation ditches and canals, and agricultural drains. It is also hydraulically connected to the deep aquifer. Water in the shallow aquifer is subject to evapotranspiration by plants that are able to extend their roots to the water table.

USGS – United States Geological Survey

Water Budget - A summary calculation that shows the balance in a hydrologic system between water supplies (inflow) to the system and water losses (outflow) from the system. It is a common reporting tool for water-resource systems.

Water Table - The surface designating the top of the zone of saturated strata in the subsurface. Below the water table all pore spaces among sediment grains, and all fractures in the geological materials are water filled.

Wet Water - The actual water in a water-resource system; as opposed to "paper water", which is a term used for water rights owned or claimed within the system.