WATER RESOURCES AND CLIMATE CHANGE IN GARDEN PARK, COLORADO

BY

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IN GARDEN PARK, COLORADO

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CHAPTER 1

INTRODUCTION

“When drought returns to
Colorado, as it surely will, it will
be challenging to see just how
far we can stretch our water.”
Quote from:
“*A History of Drought in Colorado: Lessons Learned and What Lies Ahead”*
McKee, et al., 2000

One of the most compelling issues facing Colorado, both now and in the foreseeable future, is the availability of an adequate water supply. Drought is an ever-present danger, and, with an annual statewide precipitation rate of 12 to 17 inches, the quote above is a grim reminder that water is as precious as gold in Colorado. Combine that fact with an accelerated growth in population, and further drying projections (IPCC, 2007), and it is obvious that Colorado faces a growing crisis in water supply management.

The state’s population grew from 3.3 to 4.3 million people between 1990 and 2000 representing an increase of 30 percent in ten years (Topper, 2003). According to recent census statistics, Colorado is the third fastest growing state, by percent, trailing only Nevada and Arizona. Eight of the nation's eighteen fastest growing counties are located in Colorado; Douglas County, Colorado, is the fastest growing county in the country (Nichols, et al. 2001). State population projections indicate an additional 1.7 million residents within the next two decades. Most of this increase is expected to occur along the Front Range. (The Front Range is defined in terms of the following counties: Adams, Arapahoe, Boulder, Denver, Douglas, El Paso, Jefferson, Larimer, Pueblo, and Weld). Colorado state demographics show a 1990 population of 2,694,141 in the Front Range with a projected population of 5,023,086 by the year 2025 (Nichols, et al., 2001).

In the past, human settlement was tied to the availability of water resources and the ability to develop water systems (Worster, 1985). However, this ability is no longer seen as an impediment to development in the West in general and Colorado specifically. University of Colorado geographer William Travis's research in land use trends believes that "water availability is rarely a focus of municipal and industrial land use decisions" (Riebsame, et al., 1997). Further, Daniel Luecke of Environmental Defense, states that water availability is "neither a bottleneck to growth in arid and semi-arid areas, nor a stimulus in regions where it is abundant" (Luecke, 2002).

Facing the current state of affairs, how are water managers coping with land use changes in Colorado and water supply management? Trans-boundary supplies, surface water resources, storage capacity, and groundwater play paramount roles in Colorado's water supply management schemes. This paper examines how climate change can impact the water needs and supplies associated with increasing land use changes and development in the Front Range of Colorado. A climatic water budget model is used to determine the amount of water need (potential evapotranspiration), and estimate the adequacies of water supplies from rainfall and ground water in this context in Garden Park, Colorado. This is done by using a numerical model to determine a baseline amount of available water during the years 1975 through 2000. The model is also used to simulate conditions during the drought period of the Dust Bowl years to provide a historical perspective of past water supplies in Garden Park. Finally, the model is used to project water supply conditions in Garden Park in the future. This projection is accomplished by using the Intergovernmental Panel on Climate Change (IPCC, 2007) A1B (mid- range) Special Report Emissions Scenario (SRES) projections of temperature and precipitation change for the period of 2080 through 2099 and applying these projected changes to the current precipitation and temperature conditions in Garden Park (Nakicenovic et al 2000). The future predictions for Garden Park are presented using the mean as well as best-case and worse-case conditions associated with multi-model A1B model ensembles used in the IPCCs fourth assessment report (IPCC, 2007). The water budget model used for assessing the impacts of climate change on Garden Park water resources was developed by Dr. Johannes Feddema of the University of Kansas. The model uses Microsoft Excel as the platform for all calculations. Garden Park was selected as the study site because it serves as a microcosm for the changes that are taking place, and will take place, in the entire Front Range area. On a practical level, the University of Kansas maintains a geology/geography field camp in Garden Park which provided a base of operations from which to carry out this research.

CHAPTER 2

BACKGROUND

2.1 Drought in Colorado

Colorado is no stranger to drought. Past droughts in Colorado have impacted, among other things, water supplies which caused major disruptions in Coloradoans daily lives. These droughts have affected major segments of the Colorado economy such as agriculture, industry, tourism, forestry, and municipal governments. As in the past, drought will play an increasing role in water management as Colorado's population grows and water supplies dwindle. Water managers will need to factor in the effects of climate change in their future planning strategies. In the future drought mitigation will be a major concern for the State as well as local water managers.

This study focused on the period of 1975 to 2000. During this period several droughts occurred, of which, the severest began in 1999 and ended in 2002 with recovery beginning during the winter season of 2003. This section discusses past droughts and mitigation measures as well as what may occur in future droughts in Garden Park.

The definition of drought varies among the sectors affected by water shortages. Because of this a specific definition of drought is elusive but, in general, drought can be categorized into four areas; meteorological, agricultural, hydrological, and socioeconomic (NMCC, 2003).

Meteorological drought is defined as an interval of time (months to years) during which the water supply falls below that expected on the basis of prevailing climate or the climatic average.

Agricultural drought occurs when soil moisture is inadequate to meet the needs of a particular plant group. Because agricultural systems vary, drought is usually related to specific crops and/or livestock. In this case, drought may be related to either shallow or deep-rooted crops or to a specific livestock species. Agricultural drought usually occurs after or during meteorological drought but prior to hydrologic drought (Hidore and Oliver, 1993).

Hydrologic drought refers to deficiencies in surface and/or subsurface water supplies. Hydrologic droughts are measured as snowpack, streamflow, lake and reservoir levels, and groundwater availability. Hydrologic drought usually lags other drought indicators.

Socioeconomic drought occurs when physical water shortages affect the health, well-being, quality of life, and economy of the affected population.

Each of the above definitions has occurred in Colorado. During the drought of 1999 – 2003, Colorado experienced the affects of meteorological, agricultural, hydrologic, and socioeconomic drought simultaneously. These same conditions will occur in the future, as they have in the past and, possibly, more intense and/or severe due to the effects of climate change.

Colorado’s average annual precipitation is approximately seventeen inches per year but varies from seven inches per year in the San Luis Valley to more than fifty inches in some mountainous areas in the southern and northern parts of the state. However, it is rare for the entire state to experience a moisture deficiency at the same time due to the geographical and climatic variations in the state (McKee, Doesken and Kleist, 2000).

The National Climate Data Center has summarized the extent and severity of drought in the United States since 1900. The drought of the 1930s, or the Dust Bowl years, has been characterized as the most severe drought in the country. Because of the severity of this drought, all other droughts since then have typically been compared to the Dust Bowl years.

Colorado experienced its most dramatic drought during the 1930s. The agricultural sector was severely affected by the lack of moisture, poor farming techniques, and low market prices during the Great Depression (McKee, Doesken and Kleist, 2000). Table 2.1 details dry and wet periods in Colorado.

Table 2.1

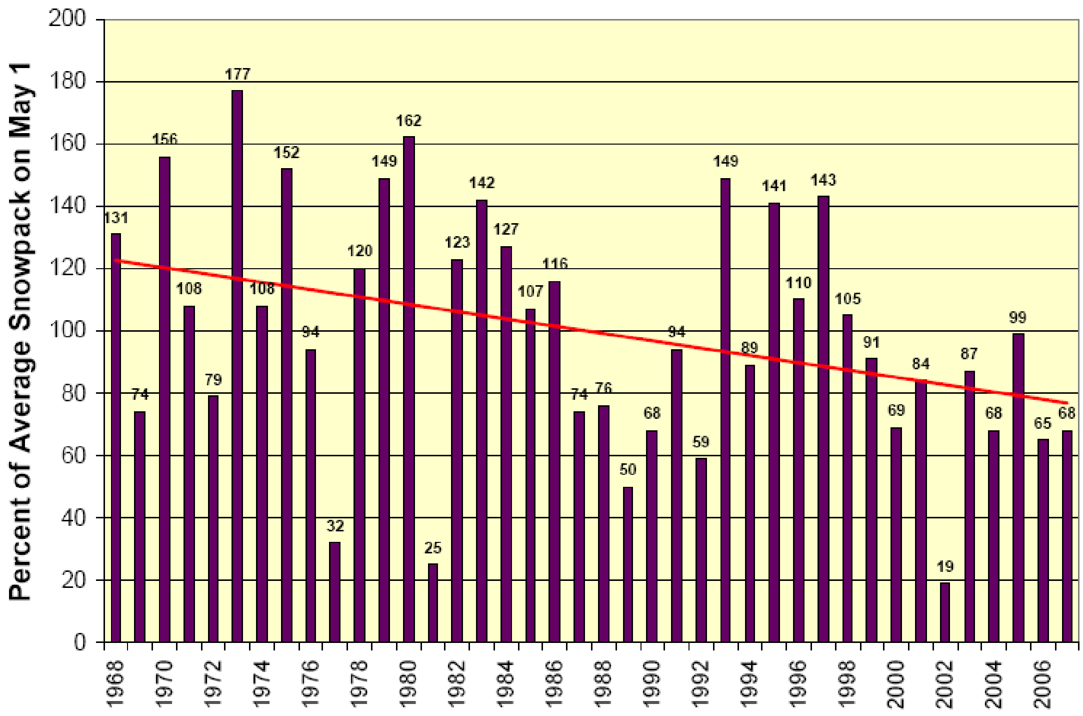
Wet and Dry Periods in Colorado

DATE	DRY	WET	DURATION (years)
1893 - 1905	X		12
1905 - 1931		X	26
1931 - 1941	X		10
1941 - 1951		X	10
1951 - 1957	X		6
1957 - 1959		X	2
1963 - 1965	X		2
1965 - 1975		X	10
1975 - 1978	X		3
1979 - 1996		X	17

Source: McKee, Doesken and Kleist, 2000

The droughts of 1976 – 1977 and 1980 – 1981 were primarily a winter event. Colorado saw an extended period of wet conditions from 1981 until the winter of 2000 (Pielke, et al., 2005). Beginning in the winter of 2000 and lasting until 2003, many regions of the state experienced the driest conditions in instrumented history (Mayer and Wytinck, 2007). Natural Resources Conservation Service's Allen Green described the drought of 2000 – 2003 as more severe than the Dust Bowl of the 1930s (National Climatic Data Center, 2003).

Winter snowpack accounts for most of Colorado’s annual water supply. However, the snowpack level in Colorado as a whole has not exceeded the climatic average since 1998 with 2002 being the single worst year (Mayer and Wytinck, 2007). Figure 2.2 shows the percent of average snowpack level in Colorado on May 1 over the period of 1968 – 2007.



Source: USDA Natural Resources Conservation Service data

Figure 2.1

Percent of Average Snowpack

The trend-line in Figure 2.2 indicates that the period of 1992 through 2007 has been drier than previous years. As indicated, 2002 was the driest year during the period. From 1968 through 1987 there were fourteen years that exceeded the May 1 average. The period from 1988 through 2007 indicates there were only five years that exceeded the May 1 average.

A combination of warmer than normal temperatures in late winter and early spring produced increased streamflow runoff earlier in the season. This condition enhanced the socioeconomic impacts of the drought due to the imbalance of the timing of water supplies versus water demand.

The United States Drought Monitor identifies the beginning of the drought in 1999 and its drop below severe levels in 2003. The Drought Monitor is prepared by the United States Department of Agriculture and is based on the interpretation of water deficit by researches at the National Drought Mitigation Center at the University of Nebraska at Lincoln. The following figures were prepared by the U.S. Drought Monitor and indicate the timing and severity of the drought during the period of 2002 – 2003.

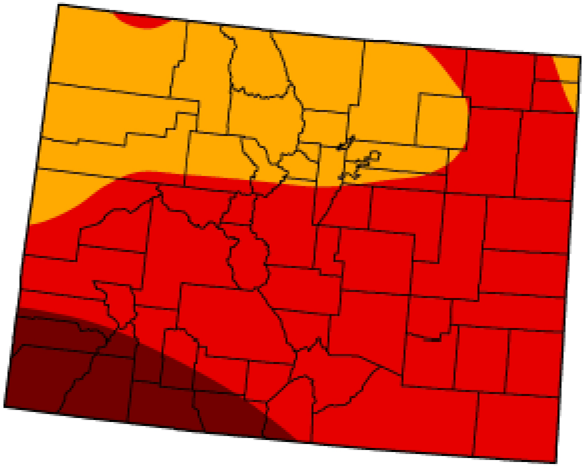
U.S. Drought Monitor

Colorado

June 4, 2002
Valid 7 a.m. EST

Drought Conditions (Percent Area)

	None	D0-D4	D1-D4	D2-D4	D3-D4	D4
Current	0.0	100.0	100.0	100.0	70.4	9.0
Last Week (05/28/2002 map)	0.0	100.0	100.0	100.0	78.0	9.2
3 Months Ago (03/12/2002 map)	0.0	100.0	77.9	35.8	0.0	0.0
Start of Calendar Year (01/01/2002 map)	44.2	55.8	14.7	0.0	0.0	0.0
Start of Water Year (10/02/2001 map)	62.7	37.3	0.0	0.0	0.0	0.0
One Year Ago (06/05/2001 map)	99.9	0.1	0.0	0.0	0.0	0.0



Intensity:

- 🟨 D0 Abnormally Dry
- 🟧 D1 Drought - Moderate
- 🟧 D2 Drought - Severe
- 🟥 D3 Drought - Extreme
- 🟫 D4 Drought - Exceptional

Figure 2.2

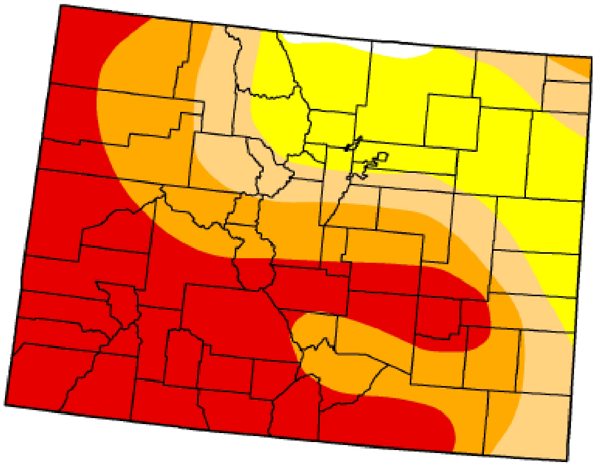
U.S. Drought Monitor

Colorado

June 3, 2003
Valid 7 a.m. EST

Drought Conditions (Percent Area)

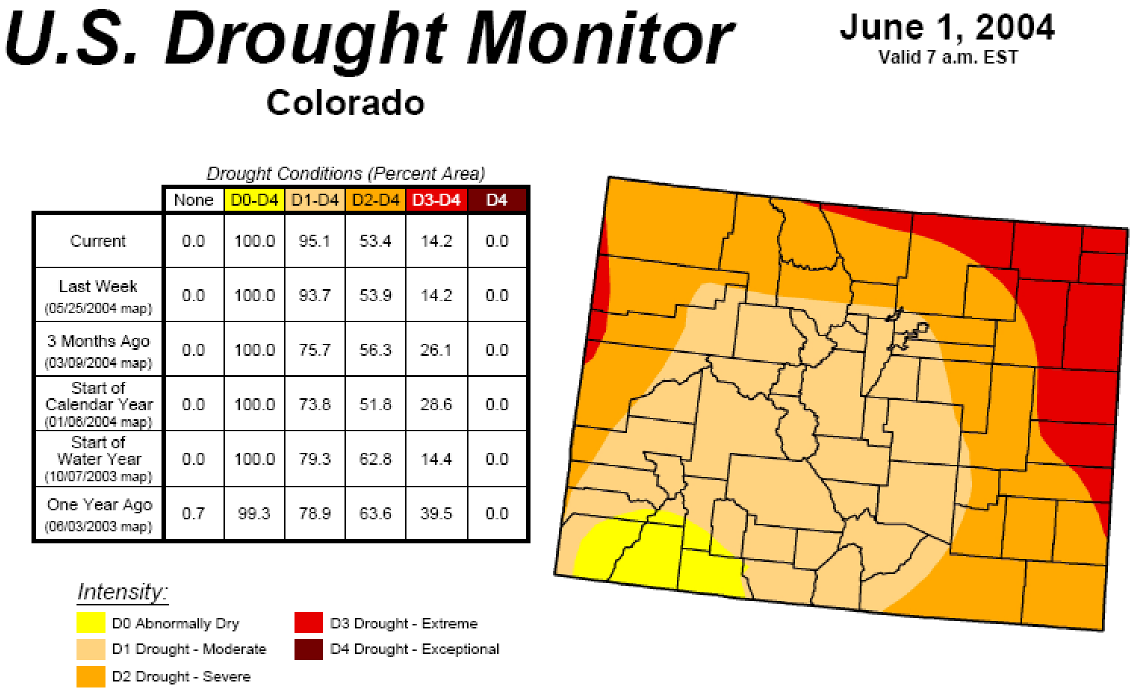
	None	D0-D4	D1-D4	D2-D4	D3-D4	D4
Current	0.7	99.3	78.9	63.6	39.5	0.0
Last Week (05/27/2003 map)	0.0	100.0	82.3	65.8	45.1	0.0
3 Months Ago (03/11/2003 map)	0.0	100.0	99.6	98.7	69.3	7.3
Start of Calendar Year (01/07/2003 map)	0.0	100.0	99.7	99.3	73.4	6.6
Start of Water Year (10/01/2002 map)	0.0	100.0	100.0	99.9	80.3	25.1
One Year Ago (06/04/2002 map)	0.0	100.0	100.0	100.0	70.4	9.0



Intensity:

- 🟨 D0 Abnormally Dry
- 🟧 D1 Drought - Moderate
- 🟧 D2 Drought - Severe
- 🟥 D3 Drought - Extreme
- 🟫 D4 Drought - Exceptional

Figure 2.3



U.S. Drought Monitor

Colorado

June 1, 2004
Valid 7 a.m. EST

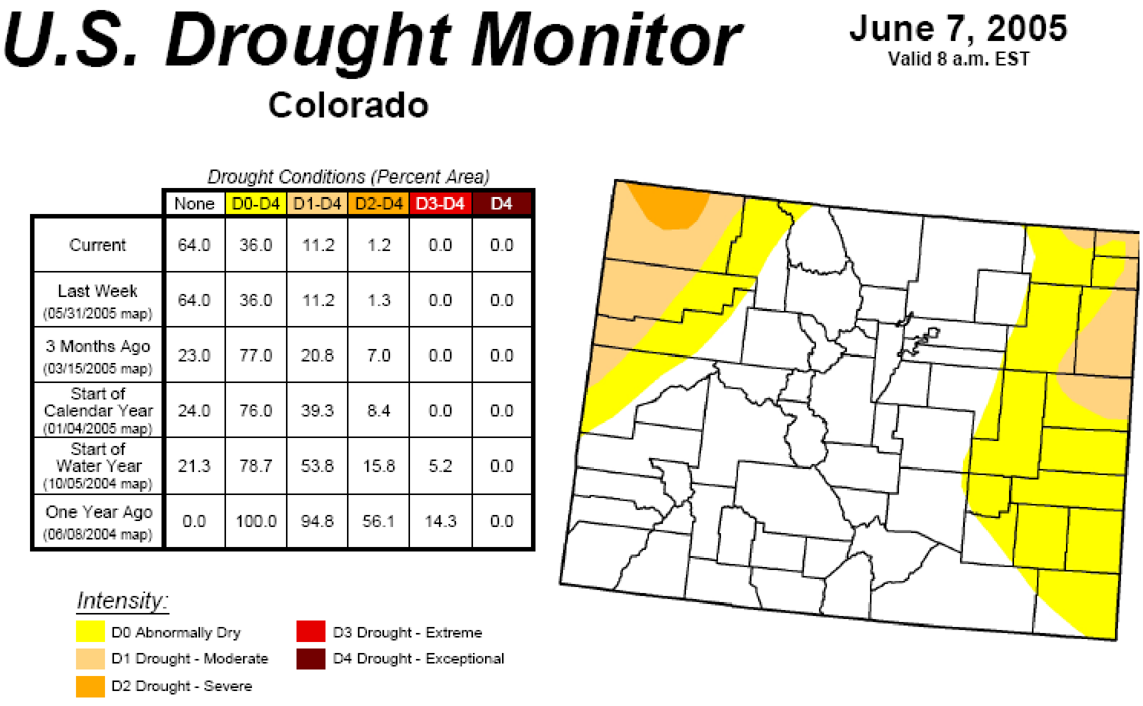
Drought Conditions (Percent Area)

	None	D0-D4	D1-D4	D2-D4	D3-D4	D4
Current	0.0	100.0	95.1	53.4	14.2	0.0
Last Week (05/25/2004 map)	0.0	100.0	93.7	53.9	14.2	0.0
3 Months Ago (03/09/2004 map)	0.0	100.0	75.7	56.3	26.1	0.0
Start of Calendar Year (01/06/2004 map)	0.0	100.0	73.8	51.8	28.6	0.0
Start of Water Year (10/07/2003 map)	0.0	100.0	79.3	62.8	14.4	0.0
One Year Ago (06/03/2003 map)	0.7	99.3	78.9	63.6	39.5	0.0

Intensity:

- 🟨 D0 Abnormally Dry
- 🟧 D1 Drought - Moderate
- 🟧 D2 Drought - Severe
- 🟥 D3 Drought - Extreme
- 🟫 D4 Drought - Exceptional

Figure 2.4



U.S. Drought Monitor

Colorado

June 7, 2005
Valid 8 a.m. EST

Drought Conditions (Percent Area)

	None	D0-D4	D1-D4	D2-D4	D3-D4	D4
Current	64.0	36.0	11.2	1.2	0.0	0.0
Last Week (05/31/2005 map)	64.0	36.0	11.2	1.3	0.0	0.0
3 Months Ago (03/15/2005 map)	23.0	77.0	20.8	7.0	0.0	0.0
Start of Calendar Year (01/04/2005 map)	24.0	76.0	39.3	8.4	0.0	0.0
Start of Water Year (10/05/2004 map)	21.3	78.7	53.8	15.8	5.2	0.0
One Year Ago (06/08/2004 map)	0.0	100.0	94.8	56.1	14.3	0.0

Intensity:

- 🟨 D0 Abnormally Dry
- 🟧 D1 Drought - Moderate
- 🟧 D2 Drought - Severe
- 🟥 D3 Drought - Extreme
- 🟫 D4 Drought - Exceptional

Drought Monitor Source: http://drought.unl.edu/dm

Figure 2.5

During the spring and summer of 2001 precipitation was relatively normal but temperatures were warmer than normal. The warmer summer temperatures created above average evapotranspiration rates which depleted soil moisture and surface water supplies. This scenario set the stage for the severe drought conditions of 2002 (Pielke, et al., 2005).

Figure 2.3 clearly shows the severity of drought conditions (exceptional to extreme) by June, 2002. The winter snowpack had dropped by 52% of average. The spring rains did not materialize and temperatures set record highs. This setup led to the devastating wildfires and water shortages of 2002 (Pielke, et al., 2005).

Figure 2.4 shows little relief from the extreme drought conditions for much of the state in June of 2003. However, there were some exceptions in the eastern portions of the state. Figure 2.5 shows continuing relief from extreme drought conditions in June, 2004. Extreme conditions were found in the northeastern section of the state while the remainder experienced moderate to severe conditions. By June of 2005, (Figure 2.6) most of Colorado was recovering from the worst of the drought conditions. Only the far western and eastern sections of the state were experiencing abnormally dry to moderate drought conditions with the remainder of the state showing no drought conditions.

The effects of this drought were devastating to Colorado’s economy as well as the general population. Wildfires ravaged sections of Colorado, ranchers and farmers sold their holdings, tourism and recreation saw a major downturn, and municipalities scrambled to secure water supplies.

Wildfires in 2002 were voted the top news story of the year by the Pueblo Chieftan (Pueblo Chieftan, 2003). Wildfires erupted near Denver, Durango, and Glenwood Springs. By far the most devastating fire was the Hayman fire north of Lake George. This fire destroyed 140,000 acres in Douglas, Jefferson, Park, and Teller counties before it was contained. The end result of this fire, attributed to dry and hot conditions, was the largest fire in Colorado’s history causing $40 million in damages (Sweeney, 2002). In total, the wildfires claimed the lives of nine firefighters, 235 homes were destroyed, and a total of 915,000 acres were consumed (National Climate Data Center, 2003).

At its 2005 annual meeting in Denver, the Geological Society of America reported on the aftereffects of the 2003 wildfires and drought. The drought caused contractive deformations from shrinking clay soils. Municipal lawn-watering restrictions in Denver and its suburbs were responsible for shrinking-related foundation settlement. In one new subdivision, shrinking clay soils were responsible for pulling underground utilities away from homes which resulted in several house fires.

The Geological Society of America also reported massive debris flows during the 1999 – 2003 drought. The largest and most destructive were post-fire mudflows from thunderstorms. The mudflows were the result of dry shrinking soil and die-off of vegetation causing surface soils to become unstable.

The Denver Business Journal reported in December of 2002 that the hardest hit industries by the drought conditions were tourism and landscaping. Lodging, restaurant, and retail businesses suffered from the lack of tourism, partly due to the massive wildfire outbreaks which resulted in tourists canceling plans to vacation in Colorado. The winter skiing industry was also affected due to the lack of snowfall. Due to state and municipal water restrictions, the landscaping industry was hard-hit as most homeowners and commercial businesses cancelled landscaping maintenance (Sweeney, 2002). Fishing and whitewater rafting industries were also affected due to lower streamflow during the drought

The State of Colorado developed the Colorado Drought Mitigation and Response Plan to provide a systematic response to impacts created by drought and water shortages. The Plan outlines methods for drought monitoring, impact assessment, response to emergency drought problems, and mitigation of long term drought impacts (Colorado Drought Mitigation Plan, 2000). The plan was originally developed in 1981 and was revised in 1986, 1990, and 2000.

In addition to the Drought Mitigation and Response Plan, the Colorado Water Conservation Board acts to develop long-term water supplies for the state as well as issuing the Colorado Drought and Water Supply Update. The purpose of the Water Supply Update is to track measures implemented by municipal and urban water providers and their drought mitigation plans (Mayer and Wytinck, 2007).

In May of 2002 the Colorado Water Conservation Board reported that only 22 percent of municipalities had a drought response plan (Klein and Kenny, 2004). Most of the municipal plans focused on restricting outdoor water use such as lawn watering, washing down drive and walkways, limits on filling swimming pools, and car washing. During the 2002 drought, municipalities first implement restrictions on a voluntary basis. These restrictions eventually became mandatory due to the severity of the drought. New pricing structures were implemented in several cities to penalize excessive water use. The American Water Resources Association reported that the most effective measures to save water were those that were the most stringent regulations along with regressive pricing structures.

Most agricultural water users suffered under the effects of the drought. Only senior priority water rights holder could receive water, and usually not their total allotment. Groundwater pumping was limited as the effects of the drought lowered water tables. The winter wheat harvest was the smallest since 1968 and agricultural experts predicted that 20-50 percent of farms and ranches would have no product for the year, a prediction that became reality. In response to the worsening agricultural problem, Governor Bill Owens signed a drought bill that provided $1 million emergency response funds for farmers and ranchers to buy water if they did not have adequate supplies through their own water rights. Additionally, the U.S. Department of Agriculture allowed ranchers to use 2.2 million acres of federal land for grazing (Larimer County Compass, 2004).

Through the efforts of the Colorado Water Conservation Board, Colorado is in a much better position to mitigate the impacts from future droughts. The Board's major emphasis is to ensure adequate water supplies. To accomplish this, the Board has focused on the following strategies:

1) Coordinate acquisition and transfer of agricultural water rights
2) Long-term agricultural land fallowing
3) Water banks
4) Reduce consumptive use through efficiency or cropping while maintaining return flows to streams
5) New supply development through diversion of streams

Although these measures may prove to be successful in facing the next drought, very little consideration has been given to the effects of global warming and its impacts on water resources. The CWCB found only 29 percent of municipal water providers had even considered the impact of climate change on water resources and long term planning (Mayer and Wytinck, 2007).

In its Fourth Assessment Report, the Intergovernmental Panel on Climate Change (IPCC, 2007) found that climate change will constrain North America's already overtaxed water supplies. The IPCC states it is very likely (defined as >90% probability) that competition for water resources among agricultural, municipal, industrial, and ecological uses will increase. The IPCC's Working Group II, responsible for examining the impacts, adaptations, and vulnerabilities to climate change, found that that most important societal and ecological impacts will stem from surface and groundwater supplies (WGII 14.ES, 2008). Working Group II states the following will occur in Western North America including the Rocky Mountain region of Colorado:

1) Annual mean precipitation will decrease in the Central Rockies
2) Extent and duration of snow cover will decrease
3) Mountain snow water equivalent will decrease
4) Stream runoff will decrease
5) Periods of drought will increase

If the above findings materialize, Colorado will face serious water supply shortages in the future. Garden Park, with its reliance on groundwater as its primary water source, may not be able to meet the needs of the future community.

CHAPTER 3

STUDY AREA

3.1 Geographic Setting

Garden Park, Colorado is located in the Upper Arkansas River Basin in the southern portion of the Front Range in central Fremont County. The study area focuses on approximately eight square miles in Garden Park Valley, 10 miles north of Cañon City (T 17S, R 70 W, Sec. 3, 4, 9, 10, 15, 16, 21, 22, elevation 5800-6200 ft.). Four Mile Creek transects the valley on an approximate north-south trend. The area is bounded on the south by Cañon City and the Wet Mountains, Cooper Mountain to the east, Red Canyon Park and Rice Mountain on the west and Pikes Peak to the far north. The headwaters of Four Mile Creek are located on the southwestern side of Pikes Peak in an area known as "*The Crags*" due to the cracked and weathered nature of the Pikes Peak Batholith (Hopkins, et al., 2000). Mean annual temperature (30 year average) is 10º Celsius. Mean annual precipitation (30 year average) is 330 mm. Vegetation ranges from natural and introduced grasses at the lower elevations to pinyon-juniper woodland at higher elevations.

3.2 General Climate Conditions in Garden Park

Climate, working through the geographic framework of space and time, ultimately controls the occurrence of groundwater. Solar radiation, as the driving force of climate, controls such factors as precipitation, evapotranspiration, weathering of geologic formations (and the soils created from them), and vegetation. In the end, groundwater recharge is the result of the interplay among these factors.

The general climate is markedly influenced by distance from major sources of moisture (the Pacific Ocean and the Gulf of Mexico). As a result, precipitation amounts are generally low except during severe thunderstorms. Prevailing air currents reach Colorado from westerly directions during winter. Eastward-moving storms originating in the Pacific Ocean generally carry little moisture due to orographic lifting over the Sierra Nevada, Wasatch, and Western Rockies wringing most of the moisture out of these storm systems. Systems moving from the north, which occur during the fall and winter months, rapidly decrease in spring, are fairly rare, and carry little moisture. A "Southwest Monsoon" season occurs when warm moist air from the south moves into Colorado bringing moisture from the Gulf of Mexico. This monsoon season occurs in spring, summer, and early fall but most often occurs from July into September. As this air is carried northward and westward, frequent showers and thunderstorms occur. These patterns create two periods of precipitation in eastern Colorado; December and January and from July until September.

The local climate in Garden Park is highly variable but can be described as semi-arid. Temperature ranges from 32ºC to 38ºC in summer and winter minimums can fall below -18º Celsius. The most significant climatic factors are generally low annual precipitation and relatively large year-to-year variation in annual precipitation amounts.

3.3 Morphology of Four Mile Creek

The headwaters of Four Mile Creek are located on the southwest side of Pikes Peak in *The Crags National Monument*. West Four Mile Creek, tributary to Four Mile Creek, begins approximately five miles north of Guffey, Colorado, on the southern slope of Thirtynine Mile Mountain. The confluence of West Four Mile Creek with the main stream is at a location approximately one-and-one-half miles south of Wright's Reservoir. This reservoir is a privately held waterworks which supplies water for irrigation purposes. There are no data available relative to flow or releases from this reservoir. However, it does not appear to have much impact on streamflow because water is only diverted during the irrigation season and water levels in the reservoir are maintained by snowmelt from Pikes Peak. Below the reservoir, Four Mile Creek flows south past the west side of Cripple Creek, Colorado, through Garden Park to its confluence with the Arkansas River approximately three miles east of Canõn City.

The headwaters of Four Mile Creek begin at an elevation of approximately 10,630 feet. The environment is a typical subalpine system of spruce, fir, and pine in a gently sloping rocky area. The river flows in a generally west-southwest direction for approximately six miles. At this point the river turns abruptly south at Dome Rock into a narrow valley at an elevation of 8,450 feet. This valley is high pastureland grasses and less than two miles wide. The river follows this course for three miles until emptying into Wright's Reservoir. From this point southward, after joining West Four Mile Creek, the river flows through rugged canyons until entering Garden Park at an elevation of slightly less than 7,000 feet.

The headwaters elevation of West Four Mile Creek is slightly less than 10,000 feet. This branch of Four Mile Creek runs in an east-southeast direction through a valley of high pastureland grasses bordered by pine and spruce. The valley is approximately two-and-one-half miles wide. Approximately two miles south of the confluence of West Four Mile and Four Mile Creek, both the terrain and vegetation change dramatically. The river runs through a narrow, twisting canyon and descends into the relatively flat valley of Garden Park. The south end of the valley lies at an elevation of approximately 5,700 feet. From this point southward the river runs through a semi-populated area to the populated area of Cañon City, finally joining the Arkansas River at an elevation of approximately 5, 300 feet. Total fall of the river is approximately 5,330 feet.

3.4 Geologic Properties of Garden Park

The role of geology, geomorphology, and soils in relation to groundwater cannot be overemphasized. Colorado's Ground Water Atlas puts it succinctly: “geology guides ground water (Topper, 2003)”. To understand ground water recharge one must understand the geomorphology/soils relationships of the area under study. Rock layers form aquifers in which water is stored. Geologic units consist of either consolidated sediments or consolidated rock. Groundwater forms when water fills the pore spaces between rock grains in sedimentary type rocks or cracks and crevices in igneous and metamorphic type rocks. The amount of water in an aquifer is dependent upon a geologic unit's ability to store water in these cracks, crevices, and pore spaces and the interconnectivity between rock units. The most productive aquifers in Colorado are composed of unconsolidated sand and gravel deposits (Topper, 2003). The amount of water storage is dependent upon the rate of interception and infiltration or runoff of precipitation in specific soils within a watershed and the rate of percolation of water into the recharge area of an aquifer. The relationship between landscapes and soils must be considered together and not independently to reach an accurate conclusion on groundwater recharge.

Groundwater inevitably occurs in geologic formations (Topper, 2003). The types of soils that are created from the weathering of geologic formations control the rate and amount, if any, of infiltration and eventually groundwater recharge. Therefore, the study of the geology, geomorphology, and soils of the area is paramount to understanding the process of ground water recharge.

Scott (Scott, 1975) categorized the present-day geomorphic features of the Front Range into six events: 1) Laramide uplift, erosion, and deposition (75Ma); 2) cutting of an Eocene surface (55Ma); 3) Oligocene deposition of sediments and volcanics

(30Ma); 4) early Miocene through Pliocene uplift, erosion, and deposition along with major faulting (25Ma); 5) Pliocene canyon cutting (4Ma); and, 6) Quaternary glaciation and cutting of pediments and terraces (2Ma) (Scott, 1975).

To further describe these events we can logically begin by grouping them according to age and type (Soil Survey, 1986). Colorado's geologic history begins at least 2.5 billion years ago (Chronic and Williams, 2002).

Alternating events of inland sea presence, volcanic activity, orogeny, and weathering and erosion of the mountains tell the story of the area's geologic history. These events led to the Precambrian and Proterozoic granitic and metamorphic complexes of gneiss, quartzite, and granite created from granitic intrusions and events of extensive faulting and folding. The earliest Paleozoic rocks are Cambrian Ignacio and Sawatch quartzites, well-washed beach sands from a receding sea (550Ma). The Ordovician Era was characterized by mudflats which solidified into the Manitou limestone and Fremont dolomites. The Harding sandstone (oldest of the group), sandwiched between the Manitou and Fremont formations, represents a brief time period when enough land was above sea-level to allow wave-erosion to rework older rocks along the shore (480Ma). During Devonian time shallow seas covered the area up to a long island which was roughly where the Front Range and Wet Mountains are located today. This island provided aeolian deposits of silt and sand that were layered between limestone and dolomite know as Williams Canyon limestone formed 340Ma.

Pennsylvanian times were characterized by the Frontrangia and Uncompahgria orogeny (Ancestral Rockies). Sediments which accumulated along the flanks of these mountains formed the Fountain formation (270Ma). During this period coarse, poorly sorted gravels were deposited. Permian time is marked by continuous erosion and reworking of the Uncompahgria and Frontrangia mountains. These materials eventually were worked into silt and other sediments as the mountains weathered and eroded to a flat plain. This time-period also marks the end of the Paleozoic time period due to some catastrophic event either of volcanic origin or by meteorite impact. (Chronic and Williams, 2002).

After the catastrophic events during Permian time, dark red shales and red eolian sandstones accumulated and desert sand dunes formed. The sea again receded and varicolored shales and sands of the Morrison, Ralston Creek, and Bell Ranch formations developed (155Ma). Cretaceous time saw many activities with the sea rising quickly and then falling rapidly. As the sea receded, waves, in conjunction with rivers draining new mountains in Utah, laid down sand and pebble layers of the Dakota formation (130Ma). Once again the land subsided and the sea returned depositing thick layers of fine gray shale of the Pierre formation. Limestone layers (such as the Niobrara formation) formed between shale layers (80Ma). It was at this point that the land began to rise at the start of the Laramide Orogeny during Cenozoic time. At this time the landscape also experienced major tectonic activity; folding and faulting rocks that would become the modern-day Rockies.

The Laramide Orogeny ceased during Eocene time (beginning 55 Ma). Following the period of mountain building, during Oligocene and Miocene times, major volcanic activity occurred covering much of Colorado with ash-flows. Major faulting allowed lava to spread basalt and rhyolite over a wide area. During this same period, regional uplift raised Colorado to its present elevation. Pliocene times were characterized by increased weathering and erosion. The uplift that occurred during the Pliocene allowed streams to entrench and erode sedimentary and crystalline rocks spreading these deposits down-stream. The Pleistocene carried on this erosional period through glacial activity. Melt water carried glacially scoured rock fragments down slope. Finally, continuing erosional events created what has been called the Tertiary pediment. This was an area that was once at the same elevation as the Great Plains and was a remnant of the gently inclined pediment carved into the base of the mountains in Eocene time. As regional uplift occurred during Tertiary time, stream erosion along the edge of the pediment separated this surface from the surface of the Great Plains. This region is generally known as the Colorado Piedmont (Chronic and Williams, 2002).

3.5 Groundwater Resources Related to Geologic Formations

The rocks which might yield groundwater in the Garden Park valley are Quaternary, Pennsylvanian, Devonian, Ordovician, and Precambrian in age.

The Quaternary rocks consist of alluvial deposits along Four Mile Creek. The Pennsylvanian, Devonian, and Ordovician rocks underlie a large portion of the Garden Park valley (O'Connor, 1963). The descriptions of the structure, stratigraphy, and thicknesses that follow are adapted from Boos & Boos (1957) and Sachett (1957).

There are twelve major sedimentary formations in the Garden Park Valley study area. They are, in order of age from oldest to youngest: 1) Manitou Limestone; 2) Harding Sandstone; 3) Fremont formation; 4) Williams Canyon Limestone; 5) Fountain and Lykins formations; 6) Ralston Creek and Morrison formations; 7) Dakota Group; 8) Upper Cretaceous formations (Graneros Shale, Greenhorn Limestone, and Carlile Shale); 9) Niobrara formation; 10) Pierre formation; 11) Trinidad Sandstone and Vermejo formations; and, 12) Wall Mountain Tuff and Mesa Gravel. The most important factor is that these formations are composed of sandstone, shale, limestone, quartzite, and gneiss. The weathering products of these rock types provide the materials for the soils found within the study area. The interception, infiltration, and percolation of water for ground water recharge are totally dependent on the makeup and characteristics of these formations and soils.

Precambrian Rocks:

Precambrian rocks are exposed along the Shelf Road at the north end of the valley. The rocks north and east of the field camp are described by Boos & Boos (1957) as Pikes Peak Granite. Exposures of this formation show it to be well jointed and fractured as well as some locations where weathering has produced soft and friable rock. These well jointed and faulted structures provide for penetration of water into lower depths and may provide low-yield groundwater supplies.

Ordovician System

The Ordovician rocks, in upward order, comprise about 106 feet of Manitou Limestone, 163 feet of Harding Sandstone, and 132 feet of Fremont Limestone as reported by Sackett (1961).

The Manitou Limestone is comprised of three lithologic units: 1) the lower unit about 30 feet thick is medium-bedded dolomite with some chert and sandy shale; 2) the middle unit, about 40 feet thick, is massive dolomitic limestone with abundant layers of chert; 3) the top layer, about 36 feet thick, is dolomitic limestone which is massive-bedded and jointed. The Manitou Limestone is probably not a good aquifer due to the fine-grain structure of the limestone. However, upper layers may yield small amounts of groundwater from the sandy zones and/or fractures in the limestone and dolomites (O'Connor, 1963).

The next younger formation is the Harding Sandstone (Fredericson, 1967). This sandstone consists of fine-grained, poorly consolidated light gray and pink sandstone interbedded with red and gray partly sandy shale. O'Connor believes that this formation contains enough sandstone to yield moderate supplies of groundwater in some parts of the valley (O'Connor, 1963). An artesian well, located near the south end of Garden Park Valley, produces about 1,000 gallons per minute from the Harding formation. This well provides a significant water resource for Canõn City. The well was originally drilled as a test hole for oil production in 1923, and is approximately 3,200 feet deep.

Pennsylvanian System:

Pennsylvanian rocks of the Fountain Formation are the surface rocks seen in the vicinity of the north-end of the valley. The Fountain Formation consists of four units (from the base upwards) as follows: 1) approximately 250 feet of gray to red interbedded sandstone and conglomerate; 2) about 650 feet of massive, crossbedded, red conglomerate; 3) about 150 feet of red sandstone and a minor amount of conglomerate; and 4) about 200 feet of red conglomerate with several very thin beds of dark red and green shale (O'Connor, 1963). The dark red conglomerate and sandstone "pedestals" found in Red Canyon Park are erosional remnants of this formation. The deep red to purple color of the pedestals is a result of deep weathering resulting in iron oxide. Most of the formation can be called an arkose due to its coarse, potassium/feldspar-rich sandstone. It is anywhere from 200 feet to 2,000 feet thick and lies tilted from regional uplift. The formation is not well cemented (crumbly) due to the quartz coarse grain size. The degree of cementation of the sandstone and conglomerate ranges from poorly cemented to well-cemented. Some locations in the Garden Park area units are poorly cemented and well sorted and should have fair permeability and water yield. Other locations are poorly sorted or well cemented resulting in little or no permeability. All play a major role in soil development as well as groundwater recharge.

(The following groups are listed from oldest to youngest.)

The Dakota Group:

The Dakota Group or Dakota Sandstone is divided into two members; the Lytle sandstone and the Glencaire shale. Closely related to the Group but older, is the Purgatorie formation. The Purgatorie formation and Dakota Group were deposited in a mixed marine and non-marine environment. The Group is composed of limestone, thin bedded shale, and fine-grained resistant sandstone. Ripple marks and animal tracks in the Dakota sediments are evidence of the marine environment at the time. The Purgatorie formation is approximately 200 feet thick and the Dakota Group is 100 feet thick. The most visible feature of the Dakota Group is a prominent hogback at the edge of the Cañon City Embayment (Skyline Drive). The tilted beds reveal the bottoms of dinosaur tracks and ripple-marks from the encroaching inland sea. This is Colorado’s most prolific aquifer, including the Denver Basin Aquifer.

Upper Cretaceous Formations – Graneros Shale, Greenhorn Limestone, and Carlile Shale:

Graneros shale is a hard, dark gray silty shale about 100 feet thick superadjacent to brown limestone. This formation is not a producer of groundwater. The Greenhorn limestone is a gray, dense limestone in medium beds separated by shales. The formation is about 130 feet thick. Carlile shale includes the Codell sandstone member. It consists of 130 feet thick beds of light gray calcareous shale with an upper sandstone section. Mollusks' shells and sharks' teeth can be found in the upper sandstone section. This member does not produce groundwater.

Niobrara Formation:

The Niobrara formation includes the Fort Hays member. The beds consist of yellow-brown calcareous shale interbedded with gray limestone layers. The formation is approximately 500 feet thick and contains abundant remains of marine life. These beds formed from limy muds that accumulated on the inland sea floor. The Colorado Geological Survey (Topper, 2003) lists these upper cretaceous formations as ground water producers.

Quaternary System:

The pediment surfaces in the area have veneers of unsaturated gravels but are not a source of groundwater (O'Connor, 1963). *Alluvial deposits along Four Mile Creek are probably thick enough to contain a permanent saturated zone that would yield small water supplies* (O'Connor emphasis). Several ranchers in the valley have shallow alluvial groundwater supplies (O'Connor, 1963).

3.6 Surficial Geology and Soils of Garden Park

The Quaternary Period is characterized by three major episodes of glaciation and several periods of erosion, ushering in the beginning of the modern surficial geology of the region. Generally, surficial geology is characterized as belonging in one of two main groups; pediment or terraced alluvium. Rocky Flats, Verdos, Slocum, and Louviers are pediment deposits found in the study area. Two types of valley fill alluvium are found in the study area; Piney Creek and Post-Piney Creek.

Rocky Flats:

Rocky Flats is the oldest exposed piedmont alluvium in the study area. It ranges from 600,000 years to near one million years old. Rocky Flats is usually found about 300 feet above modern stream channels. Due to its age it has gone through several cycles of erosion and deposition.

Verdos:

Verdos alluvium is approximately 600,000 years old and from 15 to 35 feet in depth. Verdos consists of fairly well stratified sand and gravel in a clayey matrix.

Slocum alluvium is generally 150,000 to 260,000 years old and is between 80 and 130 feet above present streams. It is less than 30 feet thick and has a texture that is finer than Verdos.

Louviers:

The Louviers alluvium is about 140,000 years old and is found along existing streams. It is stratified sand, pebbles, and cobbles in a clayey silt matrix.

Piney Creek Alluvium:

Piney Creek alluvium is roughly 2,800 years old and consists of small boulders, silt, sand, and clay. It is usually found about 4 to 20 feet above present-day streams and may be as thick as 20 feet.

Post-Piney Creek Alluvium:

Post-Piney Creek alluvium is derived from Piney Creek alluvium and consists of gray-brown fine sand and silts with loosely consolidated pebble and cobble. These deposits range from 1.5 to 20 feet deep and cover the entire floodplain of present-day streams.

3.7 Correlation of Landforms to Soil Genesis

The above discussion outlines the many geomorphic features of the study area. Alluvial fans, pediments, terraces, and basins are the main features. The geologic formations range in age from Precambrian to Quaternary and consist of igneous and metamorphic rock including gneiss, quartzite, and granites. Sedimentary rocks include sandy siltstones, shales, sandstones, dolomite, and limestone. All these features and materials, combined with the local topography interact to control, in large part, soil genesis in the study area. Birkeland states that “topography or local relief controls much of the distribution of soils in the landscape” (Birkeland, 1999). Johnson, McMaster, and Sorenson, in their study of the changing rangeland usage in Garden Park state that, “a close relationship has been established between soils and the local geomorphology” (Johnson, McMaster, and Sorenson, 1981). Garden Park Valley occupies a broad graben-like depression bounded by a series of reverse faults that follow the margins of the valley. Four Mile Creek transects this relatively flat-floored structural feature from north to south. After major faulting occurred, a series of alluvial fans formed in the basin. These fans head in canyons along fault margins and join alluvial terrace deposits in the valley bottom. Dissected pediments, formed from the Fountain formation, create high benches along the margins of the valley (Johnson, McMaster, and Sorenson, 1981).

Johnson, McMaster, and Sorenson note that in Garden Park, on pediment surfaces, the soils tend to thicken upslope as the pediment surfaces become less dissected and broader. These soils vary from very coarse-textured colluvium to medium-textured soils with heavy concentrations of calcium carbonate. The low-lying fluvial terraces have thick soils with loamy textures and poorly developed profiles. Between the terraces and the pediments, the alluvial fan soils are often thick with well developed horizons and textures that range from silty sands to very coarse gravels (Johnson, McMaster, and Sorenson, 1981).

3.8 Soils

Fremont County consists of two major physiographic regions. About 75 percent of the area is located in the Southern Rocky Mountains province while the southeastern portion falls within the Great Plains province. A narrow zone between the two provinces is characterized by prominent hogbacks of sharply folded and thrust-faulted strata. The plains occur as a narrow protrusion that extends along the Arkansas River and is bounded on the west by the Wet Mountains and the southern foothills on the north. Skyline Ridge on the western edge of Cañon City marks the edge of the plains by what is known as the Florence-Cañon City Embayment. Elevation ranges from 5,000 feet on the plains to 5,000 to 8,000 feet in the foothills, to near 8,500 feet in the mountainous areas (United States Department of Agriculture, 1986; hereinafter Soil Survey, 1986).

Soil map units within the study area include the Limon-Midway-Shanta and Kim soils which are located on the upland plains, Ustic Torriorthents and Kim-Nunn-Fort Collins found on rocky outcrops and lower pediments, and the Travessella-Ustic Torriorthents located adjacent to flood plains. Within these map units are specific soils of importance found within the study area. They are: Bronell Variant, Cascajo, Cerillos, Fort Collins, Neville, Rizozo, Sedillo, Shanta, Ustic Torriorthents, Wages, and Wesix (Soil Survey, 1986). Each of these soils has their own characteristics that are of importance in the process of water infiltration. The important hydrologic properties of these soils include texture, structure, permeability, runoff, and available water capacity (or water holding capacity). Analyses of the hydrologic properties of the soils in Garden Park describe mixed results relative to groundwater recharge. Ten of eleven soils have moderate permeability and one has rapid permeability. Available water capacity is low for seven soils, one moderate, and two high. Runoff is moderate to rapid in seven soils and three are slow to moderate. The majority of the soils exhibit good permeability characteristics; however, they also exhibit moderate or rapid runoff and low available water capacity (Soil Survey, 1986).

The upland soils in Garden Park include Cerillos, Ustic Torriorthents, Sedillo, and Rizozo. The Cerillos is found on terraces and pediments (summit and shoulder) and has a gravelly sandy loam texture. The soil is thick, having a depth to 72 inches. These soils formed from alluvium derived from red sandstone, most probably from the Fountain formation. Although these soils originally formed from alluvium, the modern surface is probably formed from colluvial deposits by erosion of upland formations. Permeability is moderate, runoff is slow to medium, and available water capacity is moderate.

The Ustic Torriorthents soils differ markedly from the Cerillos. Whereas the Cerillos is thick (72 inches), gravelly sandy loam, Ustic Torriorthents ranges from thin to thick (14 to 60 inches) with a very gravelly loam surface. These soils were formed from residuum and colluvium and were derived from shale, siltstone, gneiss, granodiorite, granite, and sandstone. They are found on terrace edges, hills and mountain sides. The Ustic Torriorthents found in Garden Park may have formed from the Ralston Creek-Morrison formations; the only formation in the area that includes all the geologic parent materials found in this soil. Ustic Torriorthents soils have a moderate to slow permeability, low to very low available water capacity, and runoff is rapid (Soil Survey, 1986).

Sedillo soils in Garden Park are found in conjunction with Ustic Torriorthents. However, the Sedillo series has more in common with the Cerillo soils than Ustic Torriorthents soils. Sedillo soils are also found on fan terraces, fan edges, and hills. They formed in calcareous gravelly and cobbly alluvium, much like the Cerillo soils. These soils are likely derived from the Fountain formation as it underwent a fluvial erosional period. Permeability is moderate, available water capacity is low, and runoff is rapid (Soil Survey, 1986).

The Rizozo soils are the least developed of the upland soils. These soils are found on mountainsides, pediments, and fan terraces. The soils formed in residuum derived from red sandstone, probably from the Fountain formation. The Rizozo soils are relatively thin, undeveloped, with a depth of only 20 inches to red sandstone bedrock. Permeability is moderate, available water capacity is very low, and runoff is rapid (Soil Survey, 1986).

Fan and fluvial terrace soils (footslope soils) include Cascajo, Fort Collins, and Neville soils. The Cascajo series consists of deep soils found on the edges of Four Mile Creek terraces that are deeply dissected. These soils have a gravelly sandy loam texture derived from calcareous alluvium. These soils have likely formed from erosion of the Williams Canyon Limestone. Permeability is rapid, runoff is medium to rapid, and available water capacity is low to very low (Soil Survey, 1986).

The Fort Collins soil is found on the west side of Four Mile Creek on fans. The Fort Collins series are deep, well drained soils formed from alluvium. Texture ranges from grayish brown loam near the surface to loam in the substratum. Specific parent materials for this series are not listed in the Soil Survey; however, several assumptions may be made in relation to how these soils were formed. The properties of this series are marked by clay and carbonates. Their positional location is on fans and the soils formed from alluvium. Gerrard (1992) states that one of the main elements of the catena concept is the integration from slope top to base created by the movement of soil and water. Overland flow of water is the major agent in water redistribution while soil creep and erosion are the major factors in soil movement. Based on the position of the Fort Collins series in relation to topography, it is likely that these soils formed from the erosion, transport, and deposition of parent materials from the Morrison formation. These formations are upland from the Fort Collins soils and are composed of siltstone, sandstone, limestone, and conglomerates. It is possible that residual materials were transported downslope and deposited as fans, later becoming interbedded with better sorted sediments (Ruhe, 1975). The movement of water downslope into the well-drained Fort Collins series may account for the clay skins. Permeability is moderate, available water capacity is high, and runoff is slow to rapid (Soil Survey, 1986).

The Neville series is found on the low-lying fluvial terraces adjacent to Four Mile Creek. They are thick, poorly developed soils with A and C horizons only. These soils formed in alluvium derived from red sandstone and siltstone. The Neville soils have textures ranging from fine loam to sandy loam. Any combination of parent materials may have contributed to their genesis due to the alluvial deposition. Likely candidates are the Fountain and Harding formations. It may be possible that the Manitou formation has contributed to the alluvial (fluvial) deposits because of its upstream location. Permeability is moderate, available water capacity is high, and runoff is medium to rapid (Soil Survey, 1986).

The Shanta soils are found on toeslopes, stream terraces, and floodplains adjacent to Four Mile Creek. The Soil Survey states that these soils are located along Four Mile Creek in the southern section of the study area (Soil Survey, 1986). These are deep, well drained, but undeveloped soils formed in alluvium. Permeability is moderate, available water capacity is high, and runoff is slow (Soil Survey, 1986). The Bronell Variant-Wesix-Rock outcrop complex and the Wesix series are found on steep canyon-sides and mountain-sides in the northeast portion of the study area. The

Bronell complex and Wesix series formed in residuum derived from limestone. The slopes range from 30 to 50 percent. The Bronell complex has a very stony loam texture with a content of rock fragments up to 70 percent. The Wesix series has a channery loam texture and the content of rock fragments range from 35 to 55 percent in the A horizon and up to 90 percent in the C horizon. Depth to bedrock in this series is 7 to 20 inches. The residuum of these soils is likely derived from the Manitou formation. It is likely that mass wasting has played a key role in forming these soils. Permeability is moderate, runoff is rapid, and available water capacity is low (Soil Survey, 1986).

Table 3.1 summarizes the hydrologic and soil water holding capacities of the above soils.

Table 3.1

Soil Permeability, Water Holding Capacity, and Hydrologic Soil Group

Soil Type	WHC in/in	Permeability	Hydrologic Group
Bronell	2.07	low	B
Cascajo	2.05	low	B
Cerrillos	2.14	moderate	B
Fort Collins	0.18	high	B
Neville	0.15	high	B
Rizozo	0.13	low	D
Sedillo	0.08	low	B
Shants	0.14	high	B
Ustic Torr.	0.12	low	B
Wages	0.16	high	B
Wesix	0.08	low	D

3.9 Vegetation Impacts on the Hydrology of Garden Park

Outside of its role in soil genesis, vegetation has a major role in regulating the water cycle of Garden Valley. Canopy cover of trees (both deciduous and evergreen) and grasses reduce soil temperature, and therefore, evaporation of moisture from soils (Birkeland, 1999). Vegetation is also a factor in precipitation interception and infiltration of precipitation water. Some amount of precipitation is intercepted by needles, leaves, and grasses allowing that moisture to evaporate rather than infiltrate the soil (Bonan, 2002). Evapotranspiration is also controlled by vegetation through the leaf area and rooting systems of the vegetation.

The general character of the native vegetation within the study area is determined by local climate, elevation, and topography. An association of pinyon pine (*Pinus edulis*) and juniper (*Juniperus scopulorum*) in a park-like density is distributed throughout the area along with a large variety of native and introduced grasses occupying areas among the trees. These grasses include blue grama, sideoats grama, little bluestem, and several noxious weed species. Johnson et al. (1981) show that the greater the stress at a site the more likely juniper would be dominant. Riparian vegetation along Four Mile Creek includes White Willow (*Salix alba*), Sandbar Willow (*Salix exigua*), Cottonwood (Populus *deltoids*). Interspersed with the trees and greases and rocks are a variety of cacti, including prickly pear, cholla and barrel cactus.

3.10 Historical Land Use in Garden Park

The modern history of Garden Park begins in 1859 with the discovery of gold near what would later become Denver. The new gold rush created an influx of settlers to the region and soon the agricultural potential of Garden Park, with its adequate water supply afforded by Four Mile Creek, was quickly realized. By 1860, the first claims for water rights were filed in Garden Park. However, the valley remained relatively untouched until 1891when gold was discovered in nearby Cripple Creek. At this point, the mining town of Cripple Creek needed an adequate food supply. Local families in Garden Park began to capitalize on this new opportunity by supplying fruit and vegetables to the mining community in Cripple Creek. As the gold rush faded by 1910, the valley took on its major role of small cattle ranching operations which continued until the end of the twentieth century.

3.11 Current Land Use in Garden Park

The role of the small rancher in Garden Park is quickly changing. Low prices for cattle, a limited amount of water, and generally rising prices for feed and ranch equipment has placed the small rancher in jeopardy. The current trend has been for ranchers to sell their land for development purposes. One of first such land use changes occurred in 1999 when the Dilley Ranch sold its property to Red Canyon Real Estate. Red Canyon subsequently divided the land into 35 acre “ranchettes”, the smallest acreage that qualifies for well digging rights under current Colorado law while avoiding zoning regulations for smaller parcel sizes. This trend continues today and all indications are that the Garden Park Valley will become a haven for retiring urbanites or for those looking for a quieter lifestyle.

This land use change begs the question, once again, if there is an adequate water supply to provide for the new 35 acre ranchettes. The only water supply for the area is through water wells tapping into groundwater resources. The adequacy of this supply is investigated through the use of a climatic water budget.

3.12 Land Use Change and Impacts on Water Resources

Alteration of the natural landscape changes the hydrologic properties of that landscape. If land is altered from ranching to urbanization, as in the case of Garden Park, decreased interception of rainfall by vegetation, increased runoff due to impervious surfaces (pavement and rooftops), loss of natural depressions which temporarily store surface water, man-made drainage systems (culverts, etc.), as well as other factors, alter the characteristics and rates of runoff and ground water recharge. Leopold (1968) and Mather (1979) have done extensive research between the linkages of land use change and the resultant changes in an area's hydrologic characteristics. Leopold (1968) notes that land use changes alter streamflow characteristics, rates of recharge to water tables, overland runoff, and other hydrologic characteristics. Mather (1979) conducted extensive research in Delaware to quantify the effects of urbanization in a formerly agricultural area and its impacts on streamflow and ground water recharge.

The impacts from urbanization and the associated hydrologic changes have been recognized for over 60 years (Soil Survey, 1986). The pertinent question for this study is what is the best method of determining and quantifying these impacts as related to ground water recharge? Mather (1979) states that “if we are concerned with a factor such as recharge to the water table which cannot be easily measured, we have to develop indirect methods which will provide estimates based on evaluation of other, better understood hydrologic aspects. The climatic water budget accounts for daily, weekly, monthly, and yearly inflows and losses in a particular water shed (Mather, 1979). The climatic water budget, if properly used, allows us to resolve this question by providing a way to determine recharge by means of a bookkeeping procedure that accounts for precipitation, evapotranspiration, and water storage in the root zone of the soil.

3.13 Water Usage in Garden Park

Current water usage in Garden Park must be determined to serve as a benchmark against which projections of future water quantity can be made for future development. This includes both stream and groundwater use and withdrawals. In addition, the interaction between groundwater and surface water must be taken into consideration. This interaction occurs at the streambed surface and any underlying aquifer. In the case of an unconfined aquifer, a “losing stream” allows water to flow from the stream to the underlying unconfined aquifer. A stream gains water if the underlying unconfined aquifer flows into the streambed. Results of the water budget model will provide the data on how much water might be available for groundwater recharge and this will be compared with current water usage as well as future demands for water as development occurs in the Garden Park area.

3.14 Surface Water Rights

In 1876 the state of Colorado passed the Doctrine of Prior Appropriation for managing surface waters within the state. This doctrine is commonly referred to as “first in time, first in right”. An appropriation of water is made when an individual physically takes water from a stream and puts that water to a beneficial use. Beneficial use has been defined as the highest, best, use takes priority; domestic use is the highest use and agriculture is the next most beneficial use. Mining and other economic activities are among the higher uses of water. More recently, the beneficial use of water has been successfully argued to include recreational uses such as fishing and boating as well as other non-consumptive uses (Topper, 2003). The first person who diverts water from a stream for a beneficial use is the “senior” appropriator. In Colorado water law, a senior appropriator is the first applicant to be titled as a senior water-right holder after receiving a court decree verifying their priority status. All other approved applicants to receive court approval for a requested appropriation are “junior” appropriators. Water appropriations requested by appropriators are accommodated according to this priority system. If a stream does not have enough flow, as in the case of a drought, the senior appropriator receives water before any others. The most junior appropriators may not receive any water.

The first water appropriation in Garden Park occurred in 1860 by the O'Brien Ditch Company. Subsequent appropriations took place throughout the valley until 1893. In 1893 the District Court of Fremont County, Colorado, ordered all claimed water rights to be adjudicated, or proved, based on the first date of use and the amount of water historically used for beneficial use by the claimant. Jas L. Cooper was appointed by the court judge to gather information on claims and act as referee in the adjudication process from 1893 through 1894. Judge M.S. Baily adjudicated all water rights in Freemont County in 1894. In 1894 there were 84 appropriations listed for Four Mile Creek dating between 1861 and 1894 (Decree of the District Court of Fremont County, Colorado, 1894). Over time, water rights to Four Mile Creek in Garden Park have been consolidated, transferred, or changed ownership. All flow from Four Mile Creek has been fully appropriated. There are currently only four ranchers that hold water rights in the Garden Park area. All other rights have been transferred to downstream users; some as far away as Lamar, Colorado. When the first ranch (Dilley Ranch) was subdivided into 35-acre parcels, the water rights went with the lots that were abutting the creek. The Garden Park Homeowners association is responsible for administering those rights and providing for the distribution of the water allowed by those water rights. There are four water rights holders in Garden Park today.

3.15 Groundwater Rights

The State of Colorado did not begin to manage and administer groundwater until 1957 when Colorado enacted The Colorado Ground Water Law of 1957. This law required obtaining a permit from the State Engineer prior to construction of a new large capacity well (larger than 50 gallons per minute) in addition to the registration of existing wells. Small capacity wells (less than 50 gallons per minute) remained exempt until 1971 when they became regulated by the State. Thus, the State of Colorado, since 1997, regulates all wells (Topper, 2003).

The advent of the sale of ranch land to developers and subsequent subdivision of the land into 35-acre parcels in the Garden Park area has created the need for groundwater wells as a source of water for domestic, vegetation, fire, and hobby animal uses. These wells fall under the State of Colorado groundwater regulations and are subject to the regulations pertaining to permitting and use of such wells. The regulations require homeowners to apply for a well permit before drilling a new well. The regulations also restrict groundwater wells on 35-acre parcels to no more than 15 gallons per minute flow rates for domestic use and irrigation water for no more than one acre. The regulations further require well drillers to report the depth and flow rates for new well construction (Topper, 2003).

3.16 Stream and Groundwater Usage in Garden Park

The Garden Park area of Four Mile Creek was fully appropriated in 1894. The stream's flow was estimated to be 80 cubic feet per second (cfs), of which all was appropriated. When the original appropriations were adjudicated precipitation rates were much higher than current rates. This fact was confirmed during personal interviews with Water Commissioner Charles Judge and rancher Roy Canterbury (2002). The allocation process is further complicated because the water flow in Four Mile creek is highly variable depending upon the winter snow pack. For example, during the drought of 2000 – 2002, Commissioner Judge stated that no shareholders in the Garden Park area received water during that period (Judge, Canterbury Interview, 2002). The only shareholders receiving water were those holding rights older than 1874. Regardless of the flow in Four Mile Creek in Garden Park, the most important fact is that no water from that source is available for new development.

As of 2003 there were 78 applications for groundwater wells within Garden Park; twenty-seven of those had not been drilled and constructed (Colorado Division of Water Resources, 2002). In 2003 there were 60 groundwater wells within Garden Park and this number is expected to grow as the development of 35-acre ranchettes continues.

Data from The Colorado Division of Water Resources lists well depths ranging from ten feet to 3,000 feet in the Four Mile watershed. Yields range from a low of one gallon per minute to 50 gallons per minutes.

There are a few wells that provide a special case at the south end of the Garden Park valley located one-half mile north of Millsap Creek's junction with Four Mile Creek. The stream flows south from this junction, through a narrow canyon after which Four Mile Creek enters the broad, relatively flat Cañon City valley. The Colorado Division of Water Resources lists six wells with high yields and shallow depths within this area. One such well is owned by the Park Center Water District. This well is approximately 3,200 feet deep and yields between 700 and 1,000 gallons per minute under artesian head. The other high yield wells are located in the same area but draw water from the alluvial sands adjacent to Four Mile Creek. The Park Center well is located within the Harding Sandstone and supplies water for Park City and a portion of Cañon City.

The Park Center well was drilled in 1923 as a test well for oil exploration. Some oil was found but its current major benefit is for water users in Park Center. There are no hydrologic records for this well so it is difficult to determine why this well is such a prolific water producer. The Harding Formation may yield significant sources of groundwater. When the Harding Formation was originally deposited it was sandwiched between the Manitou and Fremont formations from reworked deposits of silt and sand. The Harding Formation is also evident at the north end of Garden Park near the Shelf Road. I believe that the Harding Formation is a semi-confined aquifer which is recharged from waters located near the Pike's Peak Batholith. There is no geologic basis for this belief outside of the observation that this formation produces a consistent artesian flow of water which indicates the flow is under a high hydraulic head. A logical conclusion would indicate that this high flow and hydraulic head would originate from a source of water that is consistent and from an elevation much higher than the Garden Park area. Because the Harding Formation probably lies conformably on the Pike's Peak batholith, this source of water would have a direct path to the lower end of Garden Park valley.

The headwaters of Four Mile Creek originate in *The Crags* area which is characterized by extensive faulting and fissures which allows water to penetrate into deep geologic formations which eventually flow into the aquifer from which the Park Center well draws its supply. The only empirical evidence for this is the fact that the high yields of the Park Center well have remained the same since the wells construction whereas other wells within Garden Park are affected by precipitation events; either from excessive or continuing high precipitation rates or prolonged droughts. If the Park Center well's source was the same as the other wells in Garden Park, its yields would be considerably more variable.

3.17 Water Supply Acquisition at the University of Kansas Geology/Geography Field Camp in Garden Park

A scarcity of information exists relative to groundwater in the Garden Park area. There has been no organized geologic or hydrologic research conducted in the area which would yield information on areas of aquifers or possible groundwater sources. The only information that exists is either anecdotal, especially from well-drillers and ranchers, or test wells dug by oil companies. One primary study conducted by the University of Kansas does provide some information on locations and availability of groundwater.

The University of Kansas has operated a geology field camp in Garden Park, Colorado, since 1922. The camp is located in the northern section of the valley approximately 13 miles north of Cañon City.

In 1939, under the direction of K. K. Landes of the Department of Geology at the University of Kansas, a well site was selected and a well was constructed in the alluvial deposits north of the camp. The alluvial deposits were thinner than expected and little water was developed from this well (O'Connor, 1963).

Still in search of water for the field camp, three test holes were drilled by the Kansas Geological Survey in 1940 near the field camp site. These test bores were approximately 80 feet deep. In addition to these test bores, a drill rig was set up over a former oil test well and drilled to 127 feet. None of the test bores yielded adequate water supplies for the field camp. Unfortunately, none of the well logs or information on these investigations is available. A subsequent flood and water damage destroyed all the records.

One more attempt was made in 1945. W. W. Hambleton, Daniel F. Merriam, and others from the Kansas Geological Survey conducted electrical resistivity profiles. A site was located approximately 500 feet north and 50 feet east of the staff quarters at the field camp. A 125 feet deep hole was drilled but this hole also did not yield enough water for a well.

Up until 1963, before the field camp could locate a suitable well site, water was taken from a diversion ditch along Four Mile Creek. This surface water source was adequate for field camp needs. However, The University of Kansas Field Camp did not have a right to divert water from Four Mile Creek. All water in the Creek had already been adjudicated and no other water rights were available. This situation had not been a problem until the drought of 1963. Because of below normal precipitation and runoff, the district Water Master prevented the field camp from using Four Mile Creek surface water for its needs (O'Connor, 1963).

In 1963, the Kansas Geological Survey recommended a well site near the entrance to the field camp. The Survey believed that a well in this location should be drilled to a depth of at least 300 feet. At this depth, the well should penetrate one or more permeable and saturated zones which would yield an adequate water supply for the field camp. The University approved the recommendations found in the report and drilled a well before the start of the field camp session of 1964. This well now yields approximately three-gallons per minute which is adequate for the needs of the field camp.

CHAPTER 4

METHODOLOGY

4.1. Introduction

The goal of this study is to determine the overall water supply available for development in Garden Park, Colorado. The Feddema model will be used to determine the baseline supply of groundwater for the period 1975 through 2000. The drought period of the "Dust Bowl" years (1930 – 1939) will be used to determine what drought conditions were like in Garden Park. To determine what effect future climate change will have on Garden Park's water supply, the model is run using select IPCC's (2007) temperature and precipitation projections for the period 2080 through 2099. This project selected the the median, worst-case, and best-case water supply conditions from the A1B SRES scenarios IPCC multi-model ensemble for Garden Park. The model runs are contained on a compact disc (CD) and attached to this thesis.

The Thornthwaite-Mather climate water budget model has been used successfully in determining groundwater recharge (Mather, 1978). Many models exist that test for groundwater recharge, however, the Thornthwaite-Mather method is relatively simple and requires minimal input information, making it useful for application like this one where relatively little data is available. Fetter (2001) states that "a water budget for the recharge area of an aquifer is a very useful means of determining groundwater recharge.” Fetter notes that the advantage to this approach, rather than more complicated methods requiring extensive knowledge of the aquifer in question, is that the aquifer does not have to be in dynamic equilibrium (meaning that the aquifer or groundwater recharge area is known to be in a constant state) to use it. Most of the parameters used in water budget models (as in the case of this study) are measured directly. Precipitation, streamflow, well usage, and evapotranspiration rates are used rather than direct measurement of the aquifer through some type of potentiometric process or direct measurement of the aquifer.

4.2 Water Budget Parameters

Mather (1979) states that the water budget is a daily or monthly accounting of moisture inflows, outflows, and storages at a particular place or over a geographic area. Evaluation of a water budget provides quantitative values of various moisture factors that are important in understanding the water resources of a place or an area (Mather, 1978). In this study, the water budget method is used to calculate the amount of moisture available for groundwater recharge.

Groundwater recharge is ultimately controlled by climatic conditions because the source of recharge is the infiltration of precipitation. Colorado’s climatic conditions can be expressed as a mass balance in a water budget where inflows minus outflows produce a change in storage. Inputs include: 1) precipitation, 2) surface water inflow, and, 3) groundwater inflow. The hydrologic outputs include; 1) evaporation from land areas and surface water; 2) transpiration from plants; 3) runoff of surface water; 4) groundwater withdrawals; and, 5) groundwater outflow (Fetter, 2002). The terms "evaporation" and "transpiration" can be combined into a new term: "Evapotranspiration".

This hydrologic model can be stated mathematically by:

$$\Delta S = P + G_{in} - (ET + Q + G_{out})$$

where ΔS is the change in water storage, P is precipitation, G_{in} is groundwater flowing into the watershed, ET is water loss from evapotranspiration, Q is streamflow, and G_{out} is groundwater flowing out of the watershed ($Q + G_{out}$ is also total runoff – R). In addition, groundwater balance, or storage, may be stated as:

$$\Delta S_{gw} = R_p + R_{sw} – (C + Q_{gw} + G_{out}) – E$$

where ΔS_{gw} is groundwater storage, R_p is percolation, R_{sw} is recharge, C is capillary rise, Q_{gw} is return flow, G_{out} is groundwater outflow, and E is total extraction (evapotranspiration and or extraction) (Bonan, 2002).

The above mathematical expressions can be broken down into the most important terms affecting water budget use. Besides precipitation, the terms potential and actual evapotranspiration need to be understood in order to understand the "wetness or dryness" of a place. Groundwater recharge can only take place after potential evapotranspiration requirements have been met; therefore, this concept is paramount to the water budget method.

Potential evapotranspiration is the water loss from a large homogeneous, vegetation-covered area that never suffers from a lack of moisture (Mather, 1978). Potential evapotranspiration is a function of solar radiation and not the type of vegetation, soils, soil moisture, or land use. Actual evapotranspiration does depend on all these factors.

When precipitation exceeds the climatic demand for water (potential evapotranspiration), soil moisture will increase, and if there is enough available moisture, ground water recharge may occur. Surplus can only occur if soil moisture has reached the water holding capacity of the soil, even if precipitation is greater than potential evapotranspiration. Once the water holding capacity of the soil has been met, any excess precipitation will runoff as overland flow or infiltrate the soil as storage. The National Resources Conservation Service has prepared runoff curve numbers (SCS curve numbers) to determine overland runoff. These computations are based on the moisture condition of the soil (antecedent moisture condition), vegetation, and the hydrologic condition of the soil (as explained in the next section). Lastly, groundwater recharge is a computed value based on the water retained in the soil over time. Groundwater recharge, as used in this study, is 50 percent of storage based on the hydrologic soil group and the SCS runoff curve number.

The importance of the water budget method is that a quantitative measure of this excess moisture is possible. The result of calculating all the factors will yield: 1) the amounts of water stored in the soil; 2) water surplus or excess water above the climatic demands; 3) water runoff that will ultimately find its way back to the ocean in surface streams; and 4) water deficit or climatic demands for water not met by available precipitation or stored soil moisture (Mather, 1978).

4.3 Model Types

A model is a representation of a real system. A conceptual model is the beginning step in determining any representation of what occurs in the area of interest. A conceptual model of groundwater recharge could begin with the concept of groundwater being contained in deposits of sand and gravel overlying a bedrock surface. However, the conceptual model is static and only describes what the system is, not what it will do. To predict how a system will respond to varying conditions in the future, a dynamic model must be developed. Dynamic models include physical or scale models (in the case for groundwater flow systems), analog, and mathematical models. Analog models rely on electrical circuits to represent groundwater flow through porous materials. Mathematical models rely on equations to predict flow. A stochastic model is a numerical model based on statistical theories. In general, stochastic models are difficult to apply and to understand when applied to groundwater systems (Fetter, 2001). This study uses a mathematical (numerical) model to predict groundwater recharge. Modal inputs include precipitation, temperature, antecedent moisture conditions, and day-length to predict runoff, infiltration, and water available for groundwater recharge.

4.4 The Water Budget Model

The water budget model used in this study was created by Dr. Johannes Feddema of the University of Kansas and closely follows the formulations used by Willmott (1977) with the added component of a surface runoff parameterization based on the NRCS methodology. The model uses Microsoft Excel as the platform for all calculations. The model is built on parameters developed over time by C. W. Thornthwaite and John R. Mather (1955). Water budget model methods range from the overly simplistic to overly sophisticated. Mather argues that some models are quite complex and involve such detailed observations that they are nearly impossible to evaluate in practice. Others are so simple that they fail to discriminate between different climatic, soil, and vegetation situations (Mather, 1978). The model used in this study is a balance between the two extremes, is easy to use, and yields useful quantitative results that will characterize the hydrologic characteristics of the place under study.

The Feddema model can be used to calculate hydrologic parameters over time periods ranging from daily occurrences to multi-year scenarios. The model requires several inputs including: 1) precipitation; 2) minimum and maximum, or mean temperature; 3) latitude and longitude of the study site; 4) NRCS curve number (CN); 5) antecedent moisture conditions which are calculated by the model; and, 6) selection of the method for calculating potential evapotranspiration (Thornthwaite or Hamon). The Natural Resources Conservation Service (the former Soil Conservation Service) curve numbers are used for predicting the amount of precipitation which becomes runoff and the amount which infiltrates into the soil, if any. The curve numbers are based on soil type and vegetation cover/land use. Curve numbers (CN) can be found in the National Engineering Handbook, Section 4, Hydrology (210-VI-4, 1985). To compute the CN it is necessary to determine: 1) the hydrologic soil group; 2) land cover or usage; and, 3) the antecedent soil moisture conditions. The hydrologic soil group classifies soils into four categories based on soil characteristics (sand, silt, clay) and the permeability of the soils in the study area and found in the Soil Survey. The median soil hydrologic group for Garden Park was determined to be Class B. The water holding capacity, determined from the Soil Survey was estimated to be 182.88 millimeters. However, the water holding capacities are calculated to a depth of 60 inches which in many instances is deeper than the actual soil depths found in Garden Park. Therefore, a water holding capacity of 150 millimeters was chosen to compensate for this fact. The antecedent soil moisture conditions are used to set a baseline for soil moisture. There are three conditions labeled I, II, and III. The conditions are based on the total amount of precipitation in the previous five days prior to the start of a rainfall event (Mather, 1978). From mass balance, runoff is:

$$R = (P - I_a) - F \quad \text{for} \quad P - I_a > F$$

where P is rainfall, F is actual retention after runoff begins (infiltration), and

I_a is the initial water retention before runoff begins. The potential retention after runoff begins (S) is related to a CN that depends on soil type, vegetation, land use and antecedent soil moisture conditions. Runoff is found in this method by:

$$S = (1000/CN - 10)\ 25.4$$

Runoff increases with curve number until the curve number equals 100, when there is a one-to-one relationship between precipitation and runoff. The initial retention of precipitation prior to runoff decreases with the curve number.

The Feddema model calculates daylength from the study site's latitude and the Julian day of a particular day. The model calculates solar declination and daylength which vary with latitude, time of the year, and time of the day. These are necessary for calculating potential evaporation which is dependent on the average daily temperature and daylength (Thornthwaite, 1948)..

There are two requirements for evaporation to occur; an energy input and a mechanism for the transport of water vapor away from a saturated surface. The energy budget approach considers the net radiation available at the surface (shortwave radiation absorbed less longwave radiation emitted) for the energy input needed for evaporation (Reed, et al., 1997). This model provides two methods for determining potential evaporation; Thornthwaite or Hamon. Thornthwaite (1968) states that potential evaporation is an index of thermal efficiency. It possesses the virtue of being an expression of the day length as well as of temperature

(Thornthwaite, 1948). In his method potential evaporation is computed from mean monthly temperatures adjusted for the number of hours of sunlight in the day adjusted for the latitude and longitude of the study site (Mather, 1985).

Thornthwaite's potential evaporation formula is: $Et_p = 16.2\ d_f\ [10T_a / I]^a$

d_f : daylight factor – number of hours of daylight, function of latitude and solar declination

T_a : mean monthly temperature of months above freezing

I : heat index

a : coefficient set by I

$$I = \Sigma\ [T_m / 5]^{1.51}$$

T_m : sum of all months with temperatures above freezing

The model also adjusts for the water equivalent of snowfall by multiplying a factor (usually 10%) times the amount of snowfall in millimeters to convert to millimeters of water. The Hamon method was not used in this study and will not be discussed.

The model output includes overland runoff, effective precipitation (total precipitation minus overland runoff), precipitation minus potential evapotranspiration, actual evapotranspiration, water storage, deficit, surplus, total runoff, and ground water recharge.

4.5 Field Methodology

Historical data were collected over a five-day period. Historical research was conducted at the Cañon City Historical Museum, Cañon City Public Library, Fremont County Administration office, State of Colorado Division of Water Resources in Pueblo, Colorado, and Cañon City City Hall. The Cañon City Historical Museum proved especially useful in providing information documenting the early development of Garden Park as well as material on local geology. Both the Fremont County Administrative Office and Cañon City City Hall provided information on local canal companies and water districts. The State of Colorado Division of Water Resources provided data on wells, well permits and the permitting process, and water rights.

Field data were collected over a three-week period. Field data collection methods included visual surveys of Four Mile and West Four Mile Creeks, photographic documentation of the river's morphology and flow, and interviews with local residents of Garden Park

4.6 Data Collection Methodology

Data collection and verification is unarguably the most difficult task in the process of simulating water resources. The results of any model are dependent on accurate and relevant data. The data collection and verification phase of this study was no different.

Climate data for this study includes daily temperature and precipitation measurements for 25 years (1975 – 2000). The original data search focused on National Climate Data Center records for Cañon City, Colorado, the nearest official weather collection station to Garden Park. However, even though Cañon City is approximately 10 miles south of the study area, the climate conditions are quite different from Garden Park. The elevation at Garden Park is approximately 1,200 feet higher than Cañon City. Changes in elevation not only alter temperature, precipitation, and winds, but also alter the climates of mountains and lower elevation urban location. Additionally, and most importantly, the topography is totally different between Cañon City and Garden Park. Topographic variations of slope and aspect can produce differences in solar radiation equivalent to tens of degrees of latitude (Bonan, 2002). Cañon City lies at the extreme western edge of the Great Plains, also known as the Cañon City Embayment, the western extent of the ancient inland sea. The relief gently slopes upward where the embayment reaches the Gore Hills, the end of the Front Range and the Wet Mountains. In contrast Garden Park is a small valley surrounded by mountains on the west and open to the plains on the east. This setting has a completely separate microclimatology compared to Garden Park and therefore has different temperature and precipitation regimes. Urban climates differ from rural climates in both temperature and precipitation regimes. Albedos in urban areas can be quite different from those of mountainous regions. Important surface properties related to albedo and temperature of urban areas include surface roughness, building and paving materials, and vegetation types which affect the amount and extent of evaporation areas. One well-known aspect of this is the urban heat island (Bonan, 2002). These thermal properties are significantly different between urban and mountainous regions. Due to these factors it is likely that climatic data from Cañon City would not be appropriate for use in Garden Park.

Because no other temperature and precipitation data was available, modeling schemes which estimate temperature and precipitation were investigated to ascertain their appropriateness to the Garden Park area.

Many models were found to be to complex and burdensome relative to the equipment required or the amount of computing power needed to generate appropriate data. The most appropriate of these models that was within the scope of this project was Daymet data from the Daymet United States Data Center. This model only requires latitude and longitude coordinates for the area under study. The Daymet model generates daily surfaces of temperature, precipitation, humidity, and radiation over large areas of complex terrain. The model was developed at the University of Montana, Numerical Terradynamic Simulation Group. The model's original intent was to provide daily meteorological data for input into coupled models for plant growth. The model uses a digital elevation model and daily observations of minimum and maximum temperatures and precipitation from ground-based meteorological stations. One 18 year daily data set (1980 – 1997) for temperature and precipitation was produced yielding a continuous surface at a one-kilometer resolution. This model was used to generate data for the Four Mile Creek watershed. However, it was apparent that the results were unreliable when judged against what little actual data were available. This was probably due to the lack of meteorological reporting stations near the watershed under study. In addition, the terrain is extremely variable within the watershed and the Daymet model could not correct for this with any accuracy. Combined analysis of data sets is difficult, if these data sets are available at all, because different data sources (satellite, remote sensing towers, and streamflow monitoring sites) collect data at different resolutions and spatial scales. A good example is the prediction of vegetation response to precipitation events, a modeling parameter in most water balance models. As determined by Brunsell (Brunsell and Young, 2008), this individual prediction involves the assimilation of NEXRAD (Next Generation Weather Radar) precipitation data with MODIS (Moderate Resolution Imaging Spectroradiometer) vegetation temperature data. The assimilation of data involves both relating these data sources to each other and determining a common scale of analysis that allows for an accurate representation of the landscape. The result of this is often counter-intuitive in that it can be more difficult to accurately account for phenomenon and topography on small-scale projects (such as the watershed within Garden Park) due to data availability at large spatial scales than it is to account for large-scales phenomenon and topography due to the averaging effect of modeling at large scales (independent variables carry less weight).

The only other possible technology was radar-based modeling. These models use radar data from meteorological stations equipped with Doppler radar. Rainfall rates are recorded and tabulated into a database. Once again, this technology could not be used for the Four Mile Creek watershed due to inherent problems of using radar in mountainous regions and a lack of meteorological monitoring stations in the area.

The data collection problem was resolved as a result of an interview with a local rancher (Shoemaker ranch, 2003) in the Garden Park area. This rancher had kept daily precipitation records and entered these measurements into a yearly calendar. The Shoemaker Ranch is located about mid-way between the north and south extremes of the Garden Park valley. These records covered the entire 25 year period and were actually more complete than records for Cañon City. These records were entered into the water balance model used in this study. However, one problem still existed. The records only included precipitation measurements. To determine temperature measurements, daily data from Cañon City were used but were adjusted to take into consideration the difference in elevation. The Cañon City temperatures were adjusted downward by using the environmental lapse rate of 6.5ºC per 1000 meters.

Actual streamflow data was not available. The only reporting gauging station within the Four Mile Creek watershed from the headwaters to Garden Park was located south of Cripple Creek near Victor, Colorado, on Cripple Creek which is tributary to

Four Mile Creek. Subsequent research showed this gauge provides, at best, only intermittent flow data. One other gauge was found east of Cañon City where the river crosses under Highway 50. This gauge was decommissioned in 1997. Data prior to decommissioning would only reflect stream conditions below the area of interest and were therefore not used in this study.

4.7 Intergovernmental Panel on Climate Change (IPCC) Projections

The IPCC has modeled projections for future climate change. These projections are found in the IPCC's Fourth Assessment Report or AR4 (IPCC, 2007). These projections where applied to the baseline model run (1975-2000) for Garden Park to determine how climate may affect water supplies in the future. To understand the process it is helpful to understand the terminology used by the IPCC.

The IPCC bases future climate change on various scenarios. The regional averages for temperature and precipitation projections used by the IPCC are based on the AB1 scenario and are used in this study. This scenario family line describes the future having very rapid economic growth, population that will peak at mid-century but decline thereafter, and advances will be made in more efficient technologies. The families are distinguished by what constitutes technological change in energy systems. The A1B scenario family, which is used for the IPCC regional projections, is based on not relying primarily on one energy source but on a mix of energy sources with similar technological advances (See the IPCC Third Assessment Report for further explanation of the emission scenarios.)

The 2080 through 2099 projections are based on a range of temperature and precipitation responses for models simulating the A1B IPCC climate simulations. The North American projections are broken down by regions based on latitude and longitude (Table 4.1). Garden Park lies between the western and central North American regions. Temperature and precipitation change projections from the two regions were averaged and applied to the Feddema model to determine the effects of climate change on water resources in Garden Park for the 2080 to 2099 time period. The IPCC model results are subdivided for both responses into minimum, maximum, median (50%) and 25th and 75th quartile values by regions (Table 11.1; IPCC, 2007). The values used in this thesis are the median values for the average mean scenario (i.e. averaged for the two regions), the two region average of the minimum temperature/maximum precipitation for the best-case scenario and the two-region average of the maximum temperature/minimum precipitation values for the worst-case scenario.

Table 4.1

Temperature Response (C°)

Region	Season	Min	25%	50%	75%	Max
WNA	DJF	1.6	3.1	**3.6**	4.4	5.8
	MAM	1.5	2.4	**3.1**	3.4	6.0
30N, 50E	JJA	2.3	3.2	**3.8**	4.7	5.7
to	SON	2.0	2.8	**3.1**	4.5	5.3
75N, 100E	Annual	2.1	2.9	**3.4**	4.1	5.7

Region	Season	Min	25%	50%	75%	Max
CAN	DJF	2.0	2.9	**3.5**	4.2	6.1
	MAM	1.9	2.8	**3.3**	3.9	5.7
30N, 103W	JJA	2.4	3.1	**4.1**	5.1	6.4
to	SON	2.4	3.0	**3.5**	4.6	5.8
50N, 85W	Annual	2.3	2.9	**3.5**	4.4	5.8

Precipitation Response (%)

Region	Season	Min	25%	50%	75%	Max
WNA	DJF	-4	2	**7**	11	36
	MAM	-7	2	**5**	8	14
30N, 50E	JJA	-18	-10	**-1**	2	10
to	SON	-3	3	**6**	12	18
75N, 100E	Annual	-3	0	**5**	9	14

Region	Season	Min	25%	50%	75%	Max
CAN	DJF	-18	0	**5**	8	14
	MAM	-17	2	**7**	12	17
30N, 103W	JJA	-31	-15	**-3**	4	20
to	SON	-17	-4	**4**	11	24
50N, 85W	Annual	-16	-3	**3**	7	15

To provide a historical example against which these future projections might be put in perspective, the long term Cañon City precipitation and temperature records were used to estimate similar change values to those provided by the IPCC report for every decade since 1890. From these decadal deviations relative to the current 25 year period, the relative temperature and precipitation anomalies from the 1930s were selected to represent a period that was significantly drier and slightly warmer compared to the 25 year baseline period used in this study (it was also the driest of all the historical decades evaluated).

The relative changes in temperature and precipitation for each scenario (historical and future) were applied to the daily temperature and precipitation values for the 25 year base to determine how these average changes related to the water balance of Garden Park. From the water balance analysis a comparison could be made to a number of water balance outcomes, including impacts on potential and actual evapotranspiration estimates, moisture deficit, moisture surplus and potential water availability for groundwater recharge.

CHAPTER 5

MODEL RESULTS

5.1 Results – 1975 through 2000

The model is contained on a compact disc (CD) attached to this thesis. The CD contains water budgets and all data for the 1930-1939, 1975-2000, and 2080-2099 median, best-case, and worst-case scenarios. Tables 5.1 and 5.2 display the annual and monthly averages for the base line period of 1975 through 2000.

Table 5.1

Annual Averages – Baseline Period

Year	Tmean	Prec	Melt	PE	AE	DEF	SURP	Rec	R/O
1975	10.5	162.8	12.0	646.6	174.3	472.3	0.0	0.0	0.0
1976	10.0	331.5	35.6	617.4	294.0	323.4	16.7	8.3	12.8
1977	10.7	273.3	7.6	651.6	293.3	358.3	0.0	0.0	0.6
1978	8.8	275.6	55.9	584.1	223.9	360.2	5.3	2.7	3.2
1979	10.0	321.2	58.9	649.0	310.6	338.4	19.6	9.8	9.8
1980	11.6	445.7	75.8	712.2	300.4	411.8	177.8	88.9	99.5
1981	12.2	403.2	46.7	708.1	350.3	357.7	0.0	0.0	0.0
1982	10.0	585.8	89.2	619.4	458.7	160.7	122.0	61.0	83.1
1983	9.6	528.8	17.8	617.2	449.1	168.2	52.3	26.1	26.1
1984	10.0	461.2	40.6	634.0	373.6	260.5	90.9	45.5	61.9
1985	8.7	396.9	55.9	580.8	316.8	263.9	62.6	31.3	31.6
1986	10.3	389.9	20.3	612.2	340.3	271.9	47.9	23.9	23.9
1987	9.8	424.3	55.9	602.3	360.4	242.0	89.0	44.5	45.1
1988	9.9	355.9	53.3	627.9	293.6	334.3	59.4	29.7	35.3
1989	9.6	543.3	82.0	605.2	359.3	245.9	134.0	67.0	86.2
1990	9.7	479.5	5.1	597.6	409.5	188.1	64.1	32.1	38.3
1991	9.7	503.7	40.6	608.0	444.5	163.5	60.1	30.1	30.1
1992	9.9	346.4	30.5	593.7	359.1	234.6	3.0	1.5	1.5
1993	9.3	321.8	25.4	590.3	315.8	274.5	0.5	0.3	0.3
1994	10.5	458.2	52.0	645.8	369.4	276.5	105.9	52.9	53.0
1995	9.4	421.7	54.6	583.6	361.9	221.7	82.9	41.5	41.6
1996	10.6	413.7	15.3	656.2	359.7	296.5	2.7	1.4	1.4
1997	10.2	552.1	34.0	632.3	432.7	199.6	106.2	53.1	59.3
1998	10.9	313.0	4.1	651.5	343.1	308.3	12.0	6.0	6.0
1999	11.2	435.5	0.0	642.4	421.2	221.1	0.0	0.0	0.0
2000	10.6	394.1	36.8	664.3	350.6	313.8	62.0	31.0	31.0
AVG.	10.1	405.3	38.7	628.2	348.7	279.5	53.0	26.5	30.1

Table 5.2

Monthly Averages – Baseline Period

	Tmean	Prec	melt	PE	AE	DEF	SURP	Rec	R/O
Jan	-0.42	24.96	10.62	9.69	7.48	2.21	5.64	2.82	2.83
Feb	1.43	13.27	8.94	14.32	11.35	2.97	5.38	2.69	2.69
Mar	4.34	31.32	6.25	26.01	20.56	5.44	11.51	5.76	5.82
Apr	8.67	39.26	1.71	43.94	32.66	11.27	13.35	6.68	6.89
May	13.3	45.49	0.1	71.66	48.11	23.55	6.05	3.03	3.43
Jun	18.66	34.91	0	103.55	52.15	51.4	2.58	1.29	1.3
Jul	22.03	59.84	0	125.47	54.79	70.68	0.14	0.07	0.23
Aug	21.21	67.6	0	104.13	58.25	45.88	1.83	0.92	1.75
Sep	16.97	28.59	0	65.73	32.25	33.49	0.47	0.24	0.25
Oct	10.62	19.63	0	36.68	15.93	20.75	1.04	0.52	0.52
Nov	4.06	22.58	3.87	17.02	9.22	7.81	3.84	1.92	2.17
Dec	0.1	18.07	5.61	10.02	5.95	4.07	2.04	1.02	1.04

The annual estimated average temperature for Garden Park is 10.14° Celsius. It is interesting to note that the years between 1996 and 2000 (the last year for the study) recorded the highest temperatures, all above 10.14°C with the highest in 1999 at 11.21° Celsius. Monthly temperatures range from a low of -0.42°C in January to a high of 22.03°C in July.

The average annual precipitation is 405.34 millimeters, or 15.96 inches. This figure compares favorably with the U.S.G.S isohyetal map which shows Garden Park is within the 16 inch isohyet range (USGS, 1984). During the twenty-five year period, 1975 had the lowest precipitation at 163 millimeters while 1997 recorded the highest precipitation at 552 millimeters. Monthly precipitation rates show two maxima; one occurs in May with an average of 45.49 millimeters and one in August at 67.60 millimeters. In general, the months of April through August record the highest amounts of precipitation. The May maximum results from the last of the winter storm patterns (zonal flow). June is a transition period between the winter patterns and the summer monsoon season. The monsoon season is evident in July and August, which record the highest average amounts of monthly precipitation.

Average annual potential evapotranspiration (PE) for the period is 628.22 millimeters, approximately 223 mm higher than average annual precipitation. The highest PE occurs in July (125.47 mm) while the lowest (9.69 mm) occurs in January. The only period where precipitation exceeds potential evapotranspiration is November through mid – February.

Average annual actual evapotranspiration (AE) for the period is 348.69 mm, or approximately 280 mm less than potential evapotranspiration. The comparison of annual average precipitation and AE explains the semi-arid climate of Garden Park. As with PE, the highest amounts of AE occur from May through August. The highest month is August (58.25 mm) with July slightly lower (54.79 mm). December has the lowest AE at 5.95 millimeters.

Mather states that “effective precipitation” is defined as that precipitation that will infiltrate the soil for use as evapotranspiration, soil moisture recharge, or be lost from the soil as percolation to the water table (Mather, 1979). Effective precipitation is found by subtracting the value of total monthly overland runoff from the monthly value of precipitation. Effective precipitation, basically, is the amount of water, after climatic demands such as PE have been satisfied, and what is left over for groundwater recharge.

Deficit is the difference between PE and AE and shows the absolute water shortage of a location. The model shows every month in Garden Park has a deficit of moisture. However, during December and January precipitation is greater than potential evapotranspiration which may indicate a combination of runoff to streamflow and storage. The average annual deficit is 279.53 millimeters. Again, the monthly period between May and August are the driest months with deficits ranging from 23.56 mm in May to 45.88 mm in August. On average July is the highest at 70.68 millimeters. The monthly figures show a dramatic change in deficit from May to June. May has a deficit of 23.56 mm which jumps to 51.40 mm in June. This change is the result of what little storage of water has occurred during the year is used by the end of June.

Runoff is a measure of the amount of water that does not infiltrate as soil moisture for later use. Runoff water occurs when the infiltration capacity of the soil is exceeded and/or rain intensity exceeds the ability of the soil to hold water. This water runs off as overland flow and on into river systems.

Average annual runoff is 30.06 millimeters. This relatively low amount is evidence of the low precipitation amounts and that the infiltration capacity of the soils in Garden Park is moderate to good. Monthly averages range from a high of 7.37 mm in April to a low of 0.25 mm in September. Highest runoff occurs from January to April. This amount is in part the result of snowmelt due to warming temperatures that begin in February (snow minus snowmelt). Analysis of the model's daily data shows that runoff only occurs when the water holding capacity of the soil is exceeded. There is no lag time between storm events and when runoff occurs. Streamflow "peakiness" should be observed when these conditions are met. Due to the lack of stream gauging stations this can only be an intuitive supposition and not something verified by actual streamflow data. However, during the period of field studies, increased streamflow was observed shortly after storm events occurred which further verifies the model's prediction of when runoff occurs.

The average annual surplus for Garden Park is 52.96 millimeters. The highest surplus occurs in April (snowmelt) with 12.43 mm while July is the lowest with virtually no surplus (0.14mm). Almost all surplus water occurs between November and May.

Average annual recharge, or the amount of water that is actually available for groundwater recharge after all climatic demands have been satisfied, is 26.48 millimeters. The monthly recharge for Garden Park presents an interesting picture. The highest monthly recharge (6.22 mm) occurs in April as the result of snowmelt.

This is also the month when irrigation demand begins; if water from Four Mile Creek is available for irrigation after all downstream priority water rights have been satisfied. There is a minimum of recharge in the month of July (0.07 mm), August increases to 0.92 mm (from monsoon rains) followed by only 0.0.24 mm in September; water is infiltrating soil to its water holding capacity. The majority of recharge occurs between January and June. What little recharge occurs between June and September is the result of the summer monsoon season. However, potential evaporation is also very high during this same period which reduces the amount of water available for groundwater recharge. As in the case of runoff, recharge does occur after storm events and shortly after snowmelt occurs but only if the maximum water holding capacity has been reached.

5.2 Results – 1930 through 1983 Drought Period

Tables 5.3 and 5.4 are annual and monthly averages by applying the average temperature and precipitation change values from the 1930s to the 25 year daily records.

Table 5.3

Annual Averages – 1930s Drought Period

T mean	Prec	Melt	PE	AE	DEF	SURP	Recharge	Runoff
11.40	323.25	23.81	689.06	307.90	381.15	14.45	7.23	8.43

Table 5.4

Monthly Averages – 1930s Drought Period

Month	Tmean	Prec	Melt	PE	AE	ST	Def	Sur	Rec	R/O
Jan	0.80	18.76	6.51	11.69	7.75	52.50	3.94	0.80	0.40	0.40
Feb	2.71	9.85	5.19	16.84	11.28	52.26	5.55	1.55	0.77	0.77
Mar	5.77	22.89	3.63	29.16	20.00	52.40	9.17	2.10	1.05	1.05
Apr	9.84	28.70	0.93	47.82	30.98	45.91	16.84	4.69	2.34	2.73
May	14.46	33.25	0.07	77.15	42.72	34.09	34.43	2.41	1.21	1.21
Jun	20.02	28.21	0.00	112.65	43.79	18.51	68.86	0.00	0.00	0.00
Jul	23.38	48.35	0.00	136.50	46.59	20.26	89.91	0.00	0.00	0.00
Aug	22.51	54.61	0.00	113.28	49.58	24.74	63.70	0.00	0.00	0.55
Sep	18.41	26.27	0.00	71.87	26.41	24.60	45.46	0.00	0.00	0.00
Oct	12.06	18.03	0.00	40.40	13.66	27.83	26.74	0.63	0.31	0.38
Nov	5.50	20.75	3.22	19.62	8.93	37.88	10.69	1.64	0.82	1.02
Dec	1.31	13.59	4.27	12.07	6.21	43.45	5.86	0.64	0.32	0.32

The Dust Bowl period of the 1930s was the most serious drought in recent history as discussed in Chapter 2, section 2.8. This period saw higher temperatures and less precipitation than Colorado’s drought period of the early 2000s.

The annual average temperature was 11.40°C compared to 10.14°C for the baseline period of 1975 through 2000. The warmest average monthly temperatures in July were 23.38°C compared to 22.03°C in July for the baseline years. The average winter temperatures were above freezing. The coldest months occurred in January with an average temperature of 0.80°C compared to January average temperatures of -0.42°C for the baseline period.

The average annual precipitation was 323.25 mm for the drought period compared to 405.34 for the baseline period. The highest monthly precipitation occurred in August for both the drought period and baseline period: 54.61 mm of precipitation for the drought period and 67.60 mm for the baseline period. Also, the least amount of precipitation occurs in February for both periods: 9.85 mm for the drought period and 13.10 mm for the baseline period. Each month during the baseline period saw more precipitation than the respective months during the drought period.

Average annual PE for the drought period was 689.06 mm compared to 628.22 mm for the baseline years; a clear indication of the warmer temperatures during the drought period. The highest monthly average for PE occurred in July (136.50 mm). The highest PE also occurs in July for the baseline period (125.47 mm). The lowest monthly PE during the drought period occurred in January (11.69 mm). As expected, the January average PE for the baseline period is 9.69 mm.

Average annual AE was 307.90 during the drought period. The highest monthly AE occurred in August (49.58 mm). The highest monthly average AE for the baseline years is 58.25 mm due to the higher precipitation amounts compared to the drought years. The lowest monthly average AE for the drought years occurred in December (6.21 mm) compared to 5.95 mm during December of the baseline years. This would be expected due to the lower temperatures during the baseline years.

The average annual deficit for the drought period was 381.15 mm compared to 279.53 mm for the baseline period. The months of August for both periods have the highest average deficit amounts; 89.91 mm for the drought period compared to 45.8 mm for the baseline period.

An extreme difference in surplus between the two time periods is obvious when the data are examined. During the drought period, the annual surplus was 14.45 mm compared to 52.96 mm during the baseline period. This difference is not surprising given the higher temperatures and lower precipitation amounts (comparison of precipitation to potential evapotranspiration) during the drought years. The highest amount of surplus for both periods occurs in April (snow melt). There is no surplus during the months of June through September for the drought period. There are no months during the baseline period where there is no surplus.

As would be expected from the lack of surplus during the Dust Bowl years, very little recharge occurs during this same period. The average annual recharge was 7.23 mm compared to 26.48 mm for the baseline years. The highest amount of recharge occurs in April (2.34 mm) due to the marginal higher amounts of precipitation. The average monthly recharge for the baseline period also occurs during April with almost three times the amount (6.22 mm) compared to the drought period.

Because of the lack of precipitation, runoff amounts are very low during the drought period. Average annual runoff was 8.34 mm with the highest amount (2.73 mm) occurring in April.

The model confirms the extreme conditions of the Dust Bowl period in Garden Park. Annual temperatures were higher by 1.26°C during the drought period. Average annual precipitation was 82.09 mm less during this period and average annual potential evapotranspiration was higher by 61 mm compared to the baseline years. As a result drought was intensified as demonstrated by a doubling of moisture deficit; directly affecting plant productivity and reduction in moisture surplus conditions, reducing streamflow and soil moisture recharge

5.3 Results – 2080 through 2099 Future Climate Scenarios

This section discusses the A1B climate scenario for Garden Park using the median values from the IPCC projections. Table 5.5 displays the average annual values and table 5.5 displays average monthly values.

Table 5.5

Annual Median Averages – 2080 through 2099

T mean	Prec	Melt	PE	AE	DEF	SURP	Recharge	Runoff
13.45	415.97	21.75	792.68	376.00	416.69	36.63	18.31	21.84

Table 5.6

Monthly Median Averages – 2080 through 2099

Month	T mean	Prec	Melt	PE	AE	DEF	SURP	Recharge	Runoff
Jan	2.95	26.46	6.41	14.97	10.53	4.44	3.80	1.90	1.92
Feb	4.87	13.88	5.05	20.75	15.01	5.74	4.17	2.09	2.09
Mar	7.80	33.20	2.59	34.48	24.82	9.66	7.79	3.89	4.00
Apr	11.87	41.62	0.62	54.67	37.28	17.39	9.76	4.88	6.22
May	16.50	48.22	0.00	87.55	52.57	34.98	5.07	2.54	3.02
Jun	22.23	34.21	0.00	129.24	53.90	75.34	0.71	0.36	0.36
Jul	25.60	58.64	0.00	156.61	55.17	101.44	0.00	0.00	0.15
Aug	24.73	66.24	0.00	129.97	60.40	69.57	0.25	0.12	1.02
Sep	20.22	30.02	0.00	80.41	31.18	49.23	0.19	0.09	0.11
Oct	13.87	20.61	0.00	45.39	15.95	29.45	0.86	0.43	0.66
Nov	7.31	23.71	2.91	23.09	10.77	12.32	2.60	1.30	1.58
Dec	3.47	19.16	4.17	15.55	8.41	7.14	1.42	0.71	0.71

Average annual temperature for the period is 13.45°C or 3.31° C warmer than the average annual temperatures during the baseline period. The warmest average monthly temperature occurs in July (25.60° C) while the lowest average monthly temperature occurs in January (2.95° C). Average winter temperatures are above freezing.

Average annual precipitation is 415. 97 mm compared to 405.34 mm for the baseline period. The highest average monthly value occurs in August (66.24 mm) compared to the highest average monthly value for the baseline period also occurring in August (67.60 mm). The lowest average monthly value occurs in February (13.88 mm) with only 4.55 mm falling as snow. This is a critical factor as Colorado depends on winter snowpack for its water supplies during the summer season. Additionally, less snowpack during wintertime affects winter sports and tourism which impacts Colorado’s economic stability.

Due to higher average temperatures, average annual potential evapotranspiration is 792.68 mm compared to 628.22 mm for the baseline period. Average annual actual evapotranspiration was 376.00 mm compared to 348.69 mm for the baseline period. The higher amounts of AE for the future scenario are due to the higher temperatures and precipitation for that time period. Again, the highest monthly averages occur from May (52.57 mm) through August (60.40 mm) for a total amount during that period of 222.04 mm or 60 percent of the total annual actual evapotranspiration.

Average annual deficit is 416.69 mm compared to 279.53 mm for the baseline period. Again, this occurs due to the temperature increases which increase potential evapotranspiration. The highest monthly average occurs in July (101.44 mm) compared to 70.68 mm for July in the baseline period. This deficit, combined with lower winter snowpack, would have serious consequences for summertime water needs.

Average annual surplus is 36.63 mm compared to 52.96 mm during the baseline period; again, a consequence of higher temperatures during the future period. The highest average monthly surplus occurs in May (5.07 mm) while the highest average monthly surplus for the baseline period occurs in April (12.43 mm). This is an indication of earlier snowmelt due to warmer temperatures during the future period.

Average annual recharge is 18.31 mm with the highest average monthly value occurring in April (4.88 mm). Average annual recharge for the baseline period is 26.48 mm with the highest monthly average occurring in April (6.22 mm). Average annual runoff is 21.84 mm with most of that occurring in April (6.22 mm) as would be expected.

5.4 Comparison of All Periods

For the purpose of comparison between the baseline period, drought period, median future scenario, and best and worst case scenarios, the periods will be based on seasons. Table 5.7 displays the baseline period, table 5.8 displays the drought period, table 5.9 displays the median value future scenario, table 5.10 displays the best-case scenario, and table 5.11 displays the worst-case scenario. Figures 5.12 through 5.30 are graphical displays of the below tables and are presented for ease of comparison.

Table 5.7

Baseline Period Seasonal Averages – 1975 through 2000

	T mean	Prec	Melt	PE	AE	DEF	SURP	Recharge	Runoff
DJF	0.39	18.71	8.94	11.34	8.26	3.08	4.33	2.17	2.20
MAM	8.86	38.69	2.67	47.20	33.78	13.42	10.01	5.00	5.54
JJA	20.61	54.12	0.00	111.05	55.06	55.99	1.52	0.76	1.24
SON	10.55	23.60	1.29	39.81	19.13	20.68	1.79	0.90	1.05

Table 5.8

Drought Period Seasonal Averages – 1930 through 1939

	T mean	Prec	Melt	PE	AE	DEF	SURP	Recharge	Runoff
DJF	1.76	28.61	11.70	28.53	19.03	9.50	2.35	1.17	1.17
MAM	10.02	32.74	8.82	46.00	31.28	14.72	3.65	1.82	1.82
JJA	21.97	51.59	4.56	76.98	50.97	26.01	6.79	3.39	3.78
SON	11.99	61.95	1.00	124.96	73.70	51.27	7.10	3.55	3.94

Table 5.9

Future Scenario Seasonal Median Averages – 2080 through 2099

	T mean	Prec	Melt	PE	AE	DEF	SURP	Recharge	Runoff
DJF	3.91	40.34	11.46	35.72	25.54	10.18	7.97	3.99	4.00
MAM	12.06	47.08	7.64	55.24	39.83	15.40	11.96	5.98	6.09
JJA	24.19	74.82	3.21	89.15	62.10	27.05	17.55	8.77	10.22
SON	13.80	89.83	0.62	142.21	89.85	52.37	14.84	7.42	9.24

Table 5.10

Future Scenario Seasonal Best-Case Averages – 2080 through 2099

	T mean	Prec	Melt	PE	AE	DEF	SURP	Recharge	Runoff
DJF	2.28	47.57	17.61	30.40	24.19	6.21	18.82	9.41	9.72
MAM	10.56	52.54	10.68	48.32	38.11	10.21	21.16	10.58	10.87
JJA	22.64	81.52	4.86	80.10	60.47	19.63	25.98	12.99	14.93
SON	12.50	97.89	1.22	129.25	89.63	39.62	21.59	10.80	13.08

Table 5.11

Future Scenario Seasonal Worst-Case Averages – 2088 through 2099

	T mean	Prec	Melt	PE	AE	DEF	SURP	Recharge	Runoff
DJF	6.43	33.87	5.48	44.75	25.93	18.82	1.67	0.84	0.84
MAM	14.71	39.22	2.87	67.11	39.56	27.55	2.57	1.28	1.28
JJA	26.56	62.11	0.17	106.55	61.70	44.85	4.91	2.46	3.14
SON	16.25	74.58	0.00	167.95	86.19	81.75	5.87	2.94	3.78

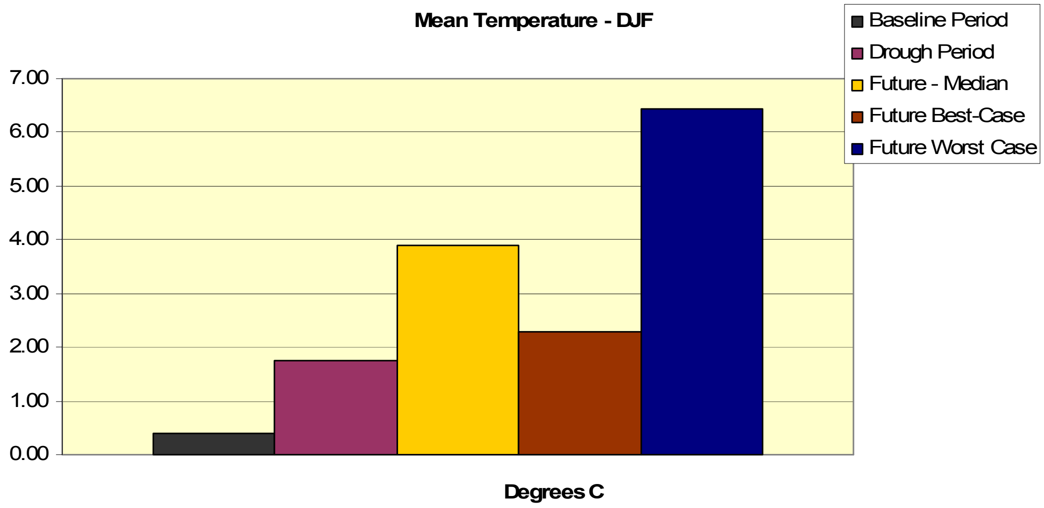


Figure 5.1

Mean Temperatures – December through February

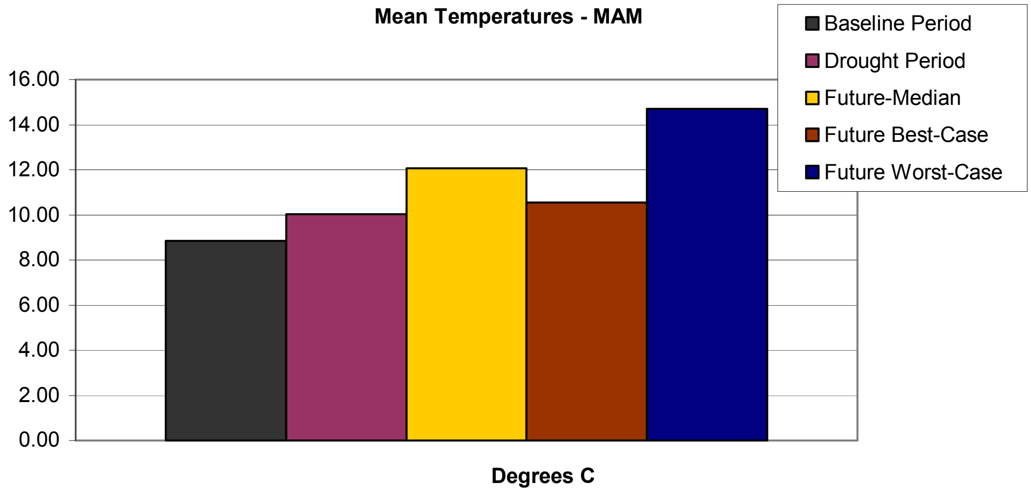


Figure 5.2

Mean Temperatures – March through May

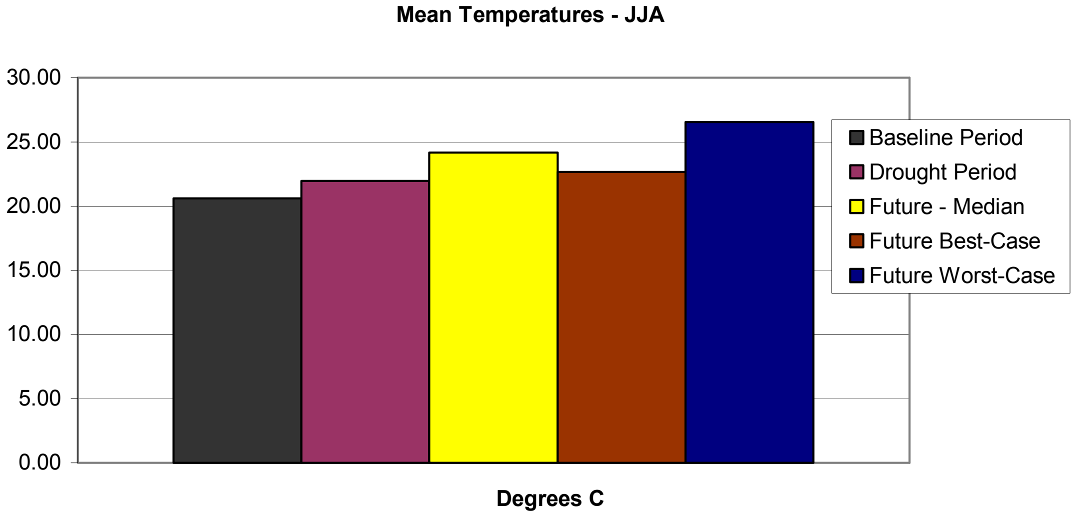


Figure 5.3

Mean Temperatures – June through August

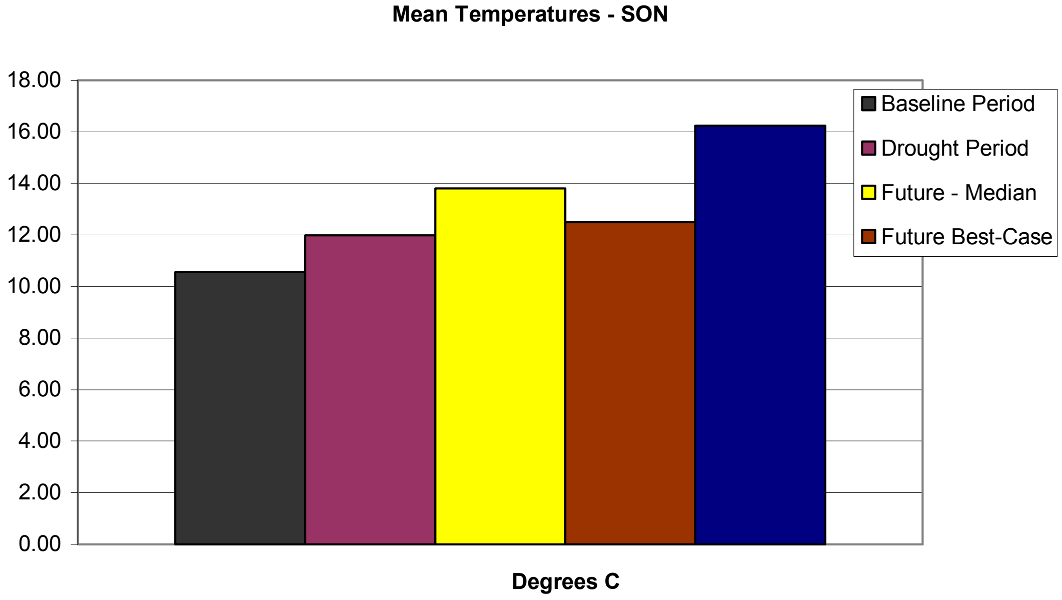


Figure 5.4

Mean Temperatures – September through November

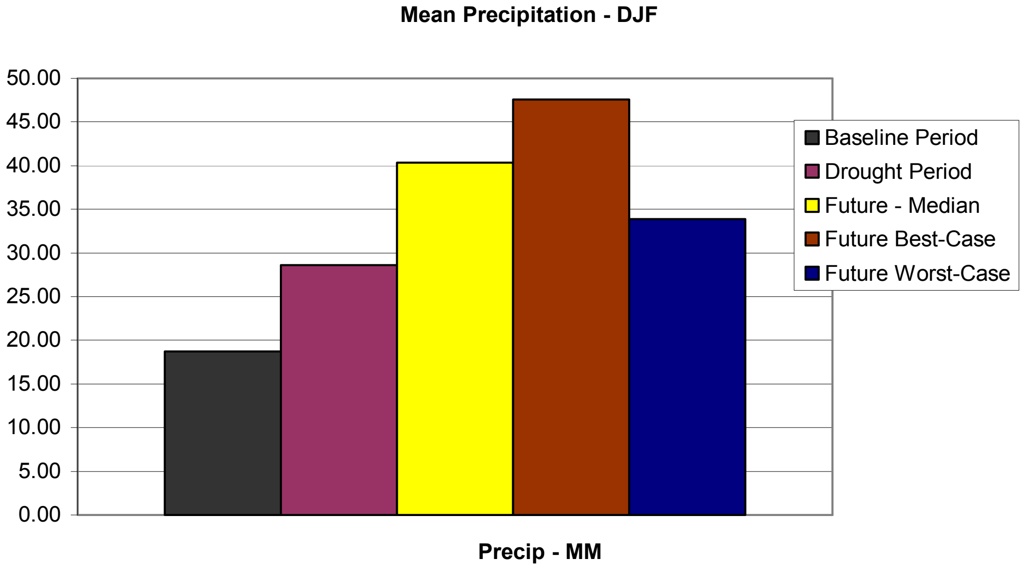


Figure 5.5

Mean Precipitation – December through February

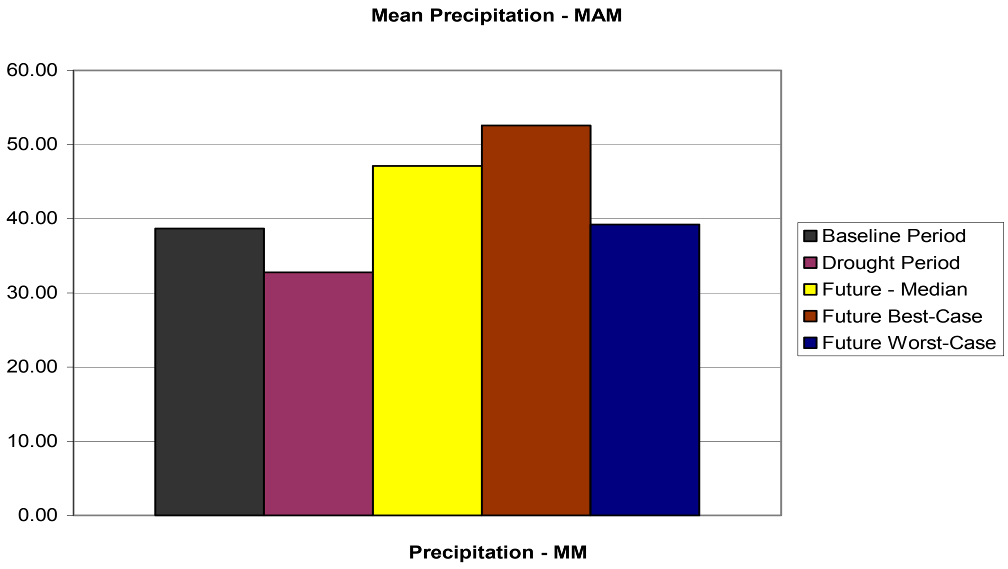


Figure 5.6

Mean Precipitation – March through May

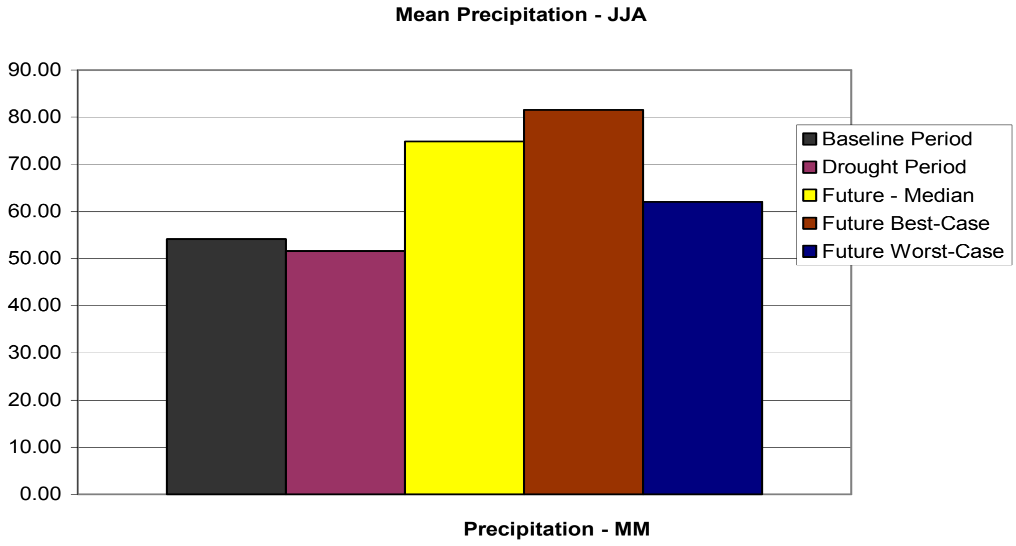


Figure 5.7

Mean Precipitation – June through August

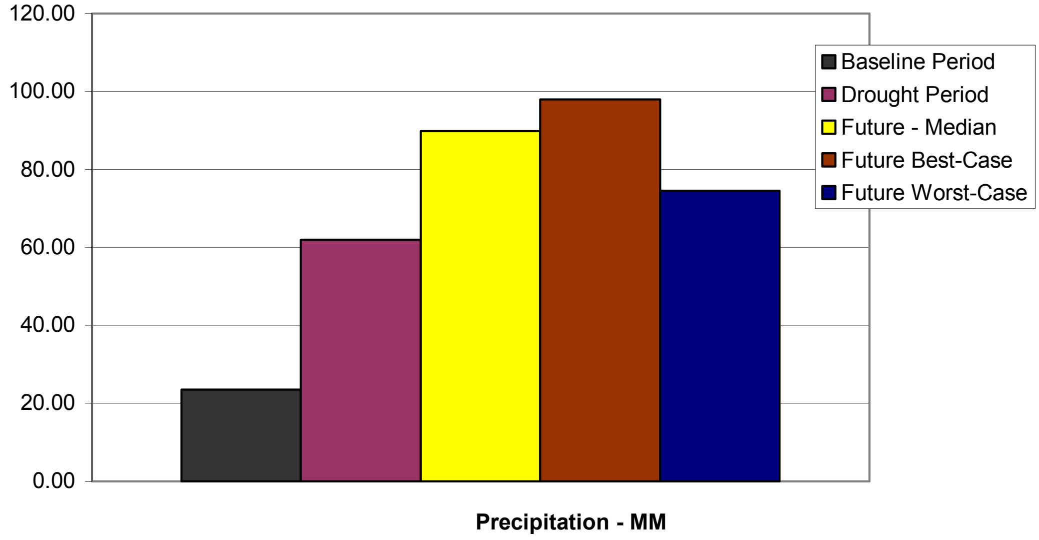


Figure 5.8

Mean Precipitation – September through November

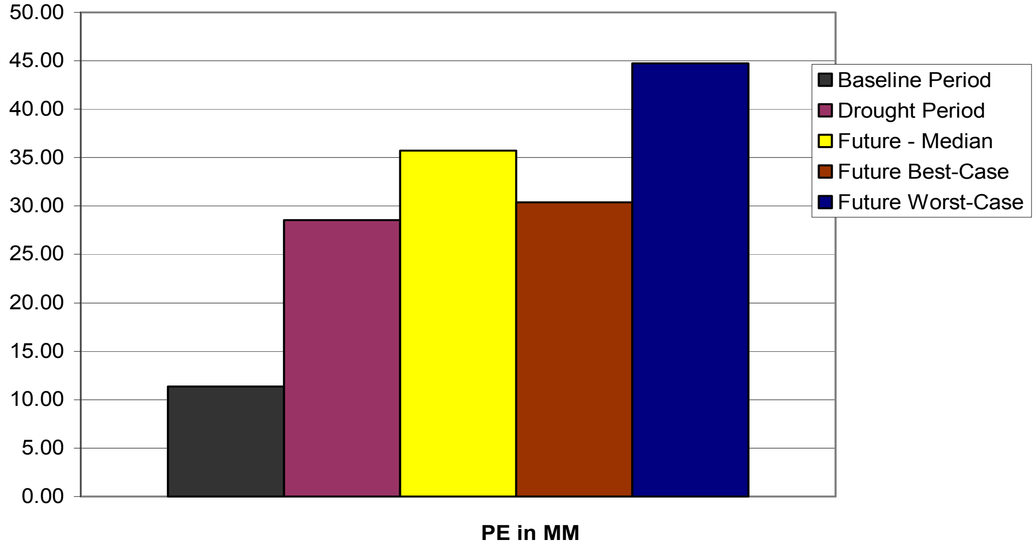


Figure 5.9

Mean PE – December through February

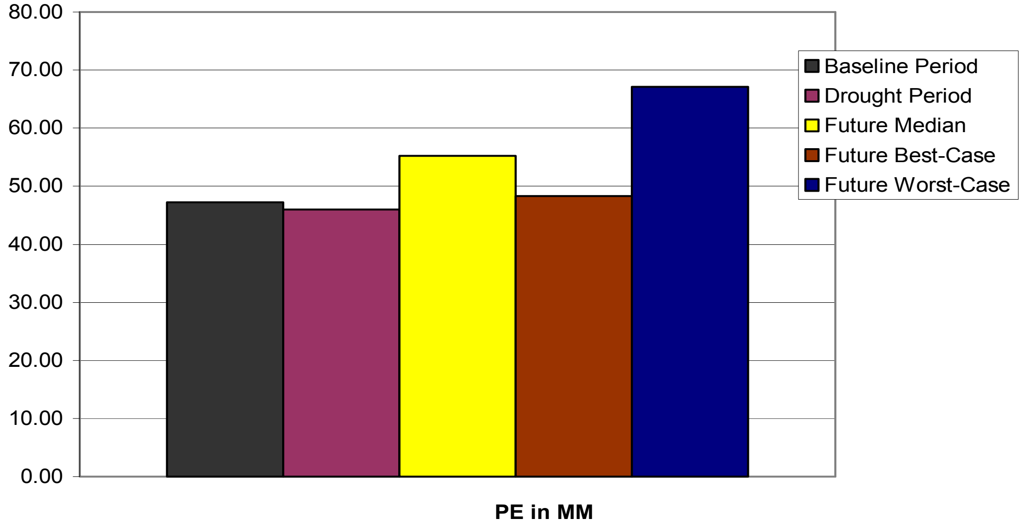


Figure 5.10

Mean PE – March through May

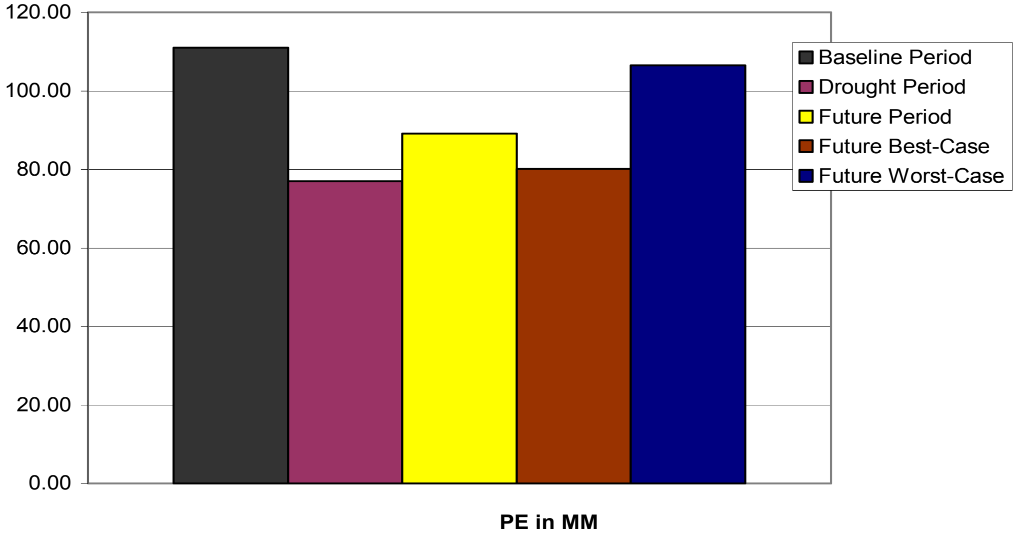


Figure 5.11

Mean PE – June through August

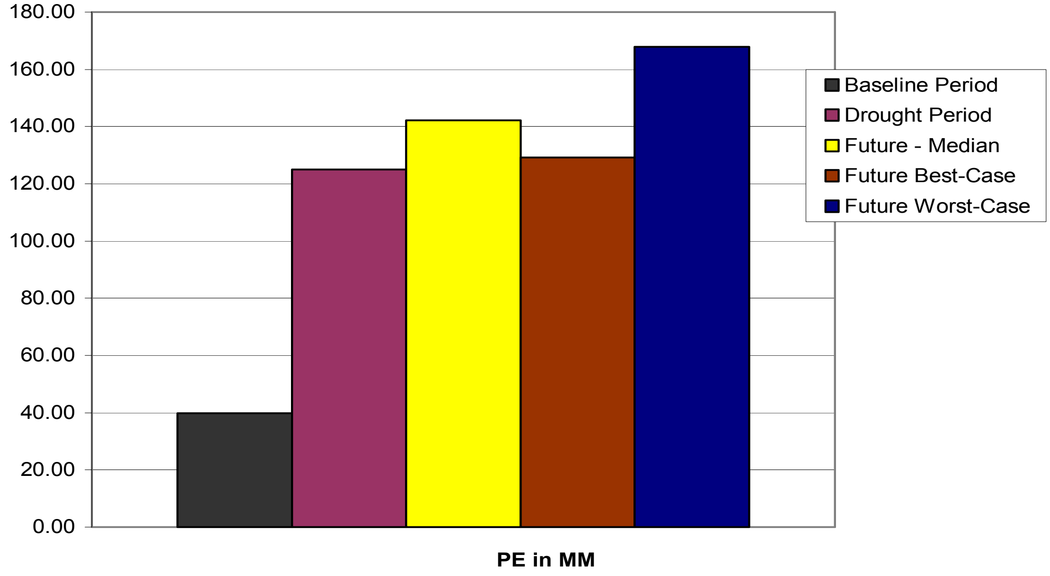


Figure 5.12

Mean PE – September through November

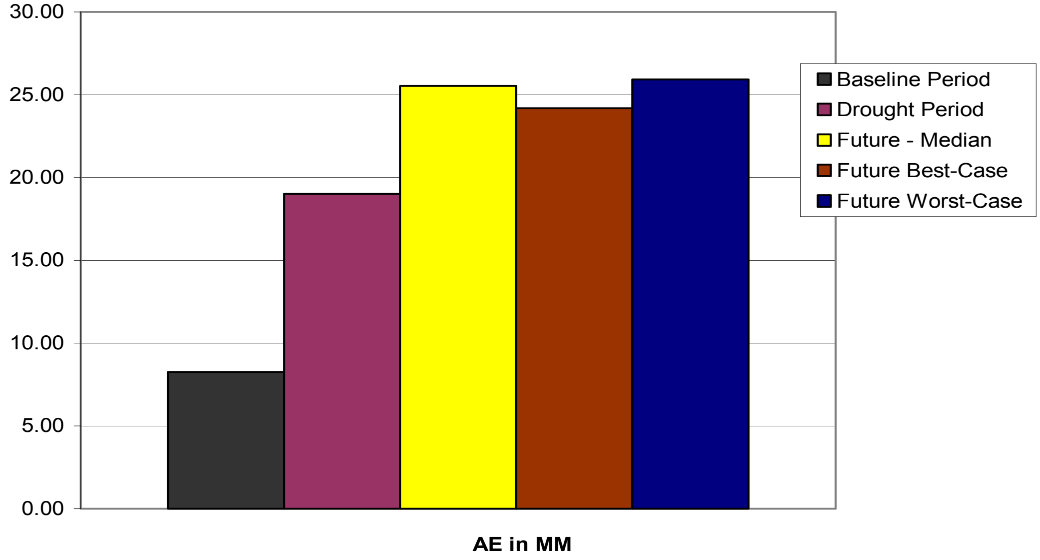


Figure 5.13

Mean AE – December through February

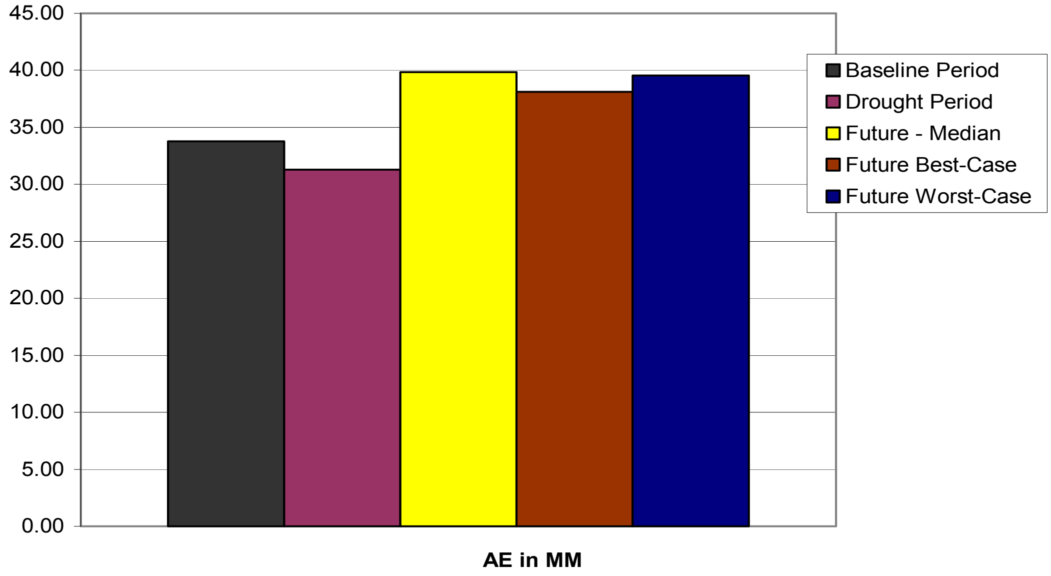


Figure 5.14

Mean AE – March through May

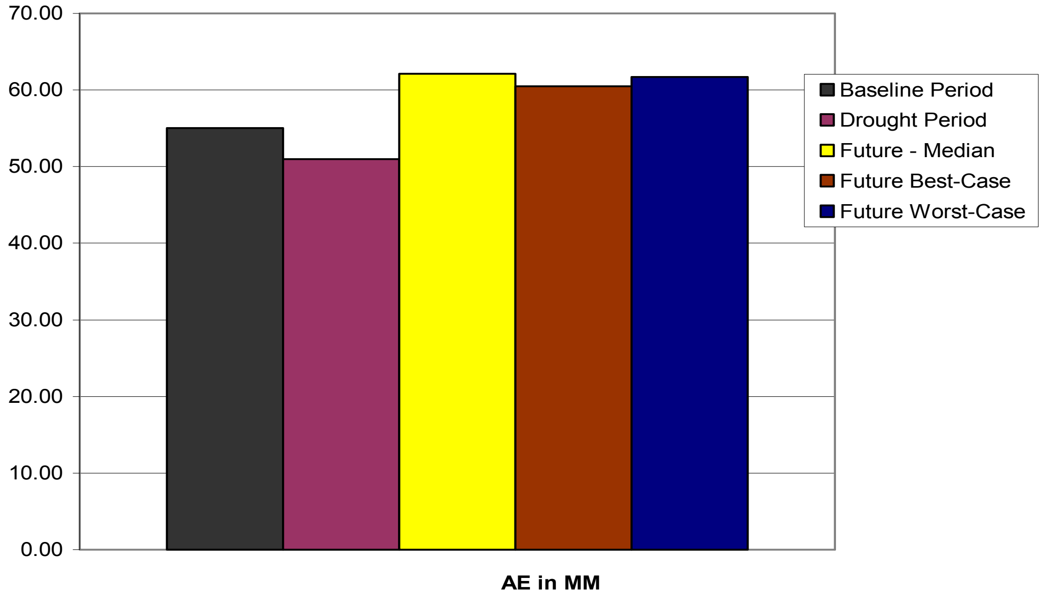


Figure 5.15

Mean AE – June through August

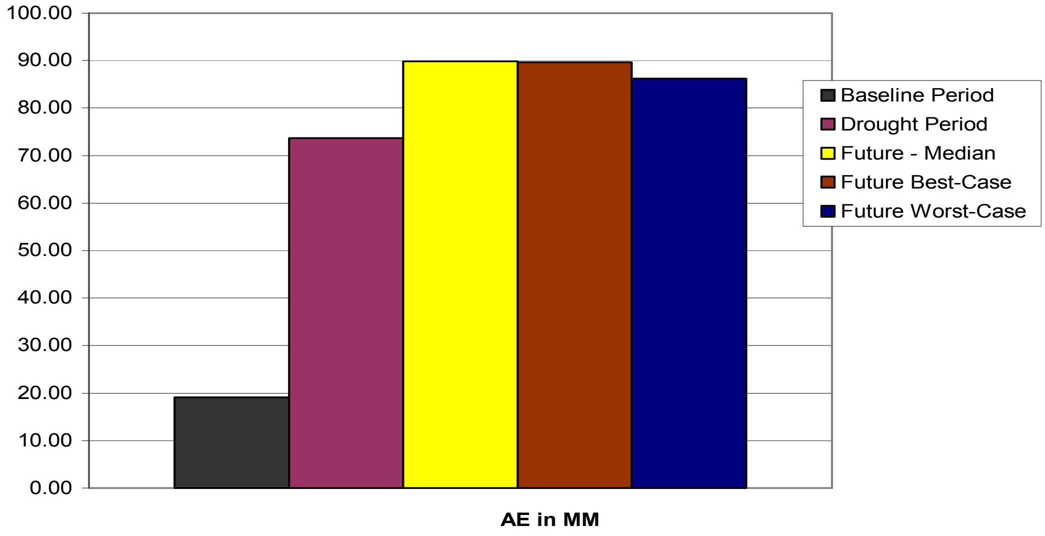


Figure 5.16

Mean AE – September through November

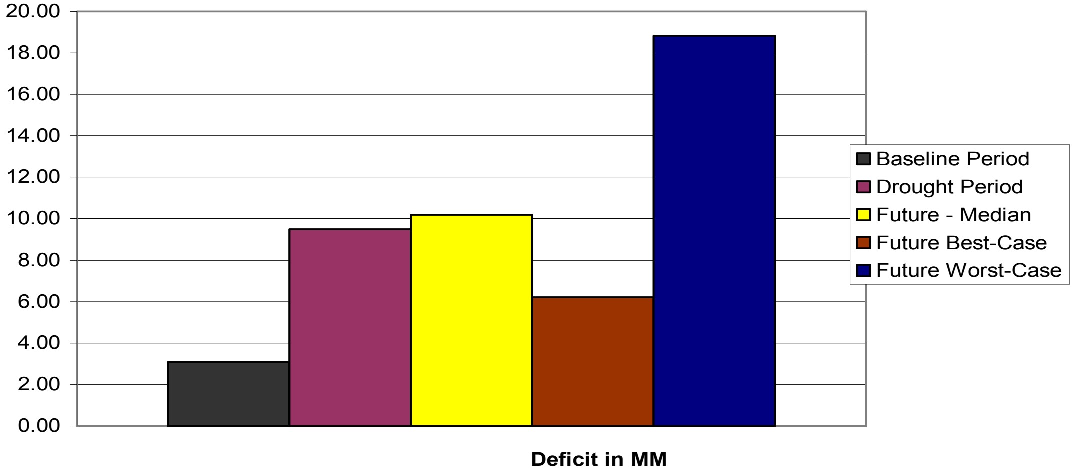


Figure 5.17

Mean Deficit – December through February

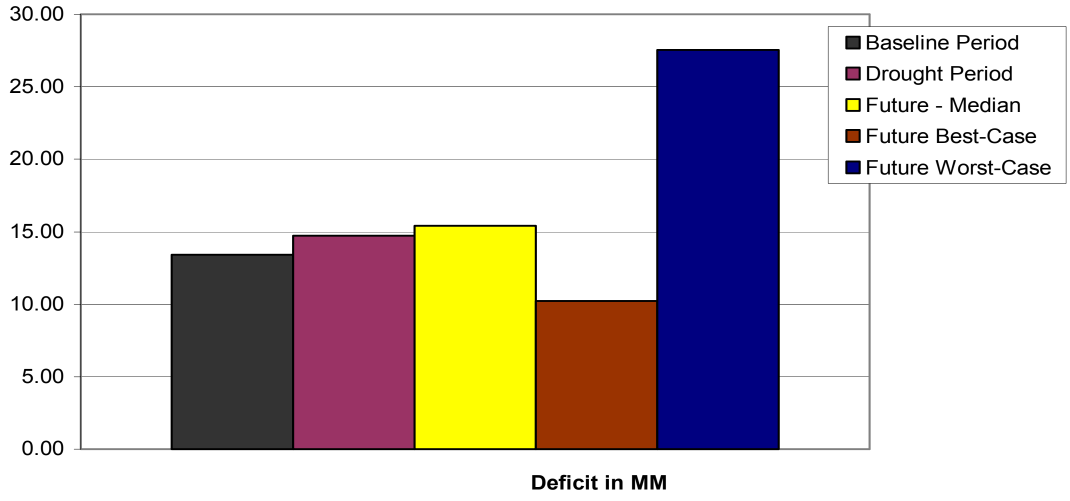


Figure 5.18

Mean Deficit – March through May

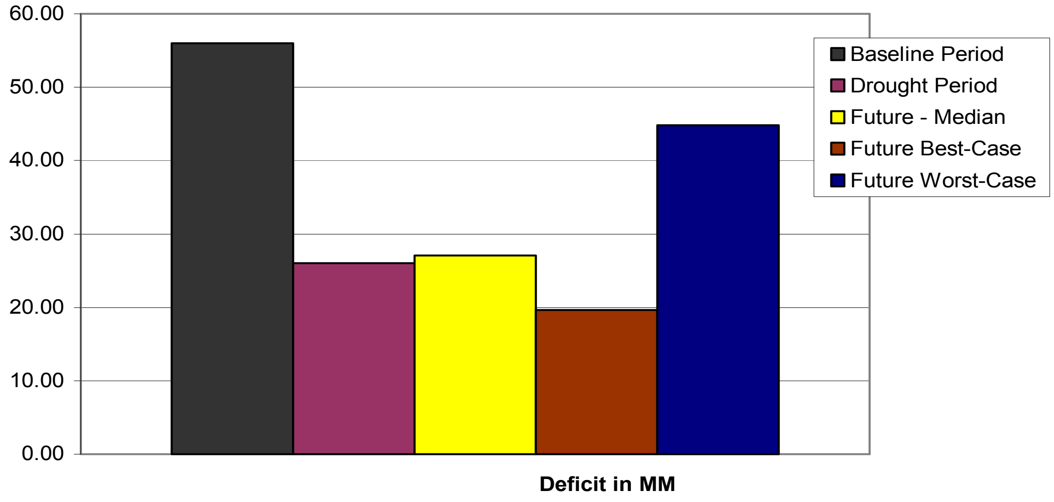


Figure 5.19

Mean Deficit – June through August

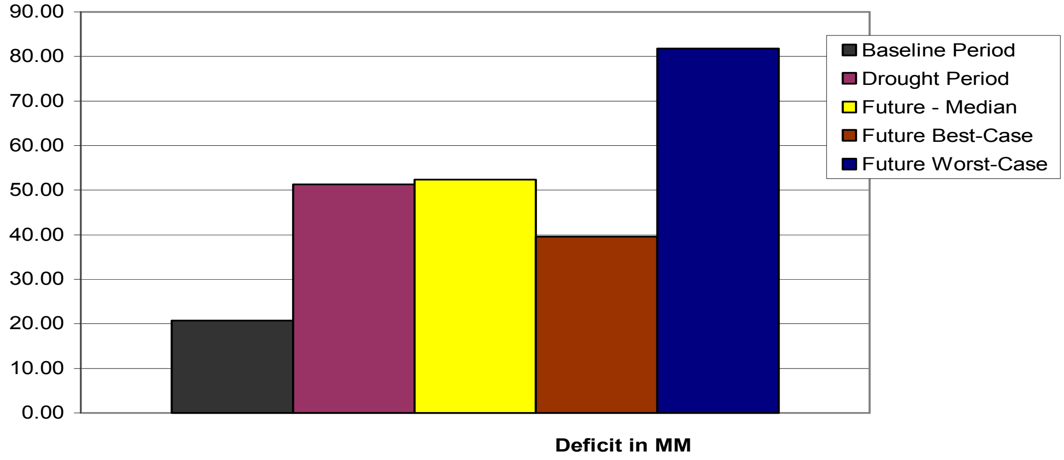


Figure 5.20

Mean Deficit – September through November

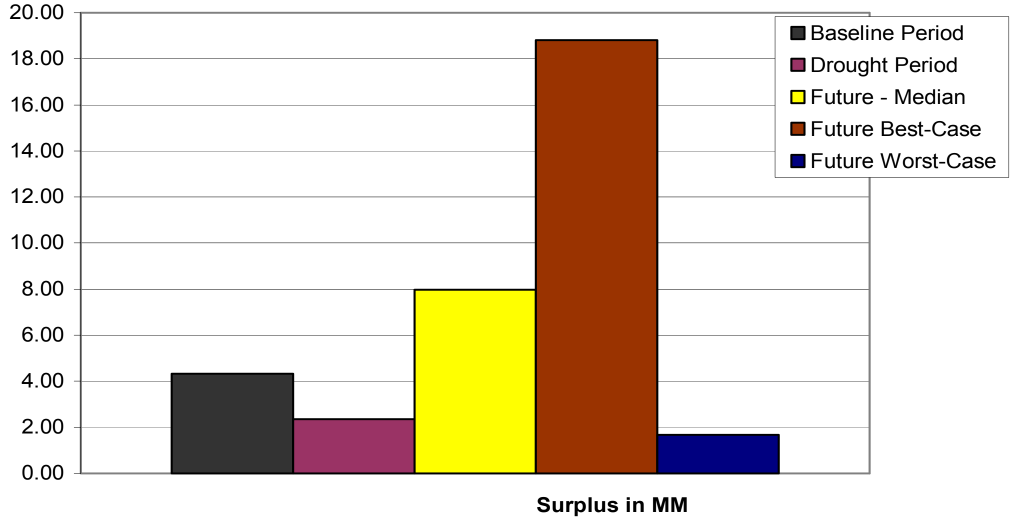


Figure 5.21

Mean Surplus – December through February

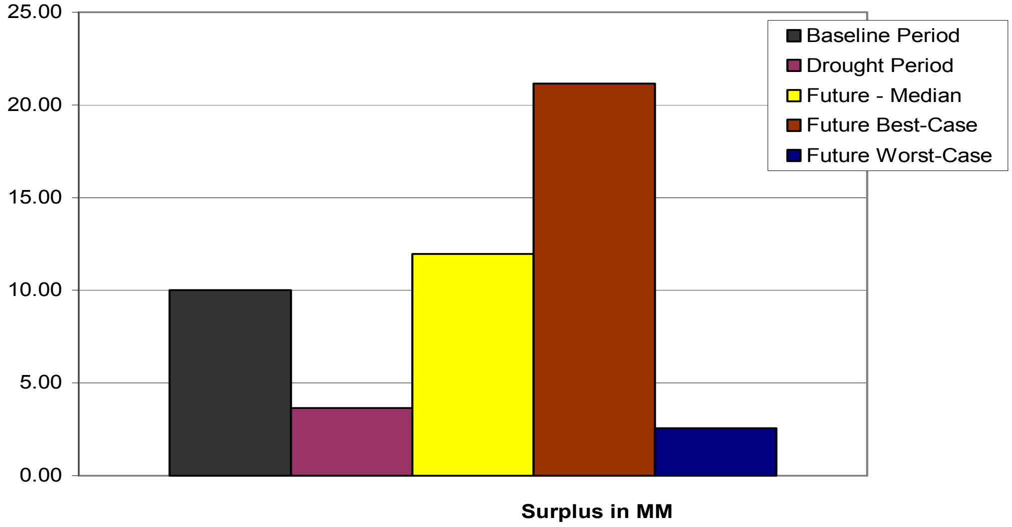


Figure 5.22

Mean Surplus – March through May

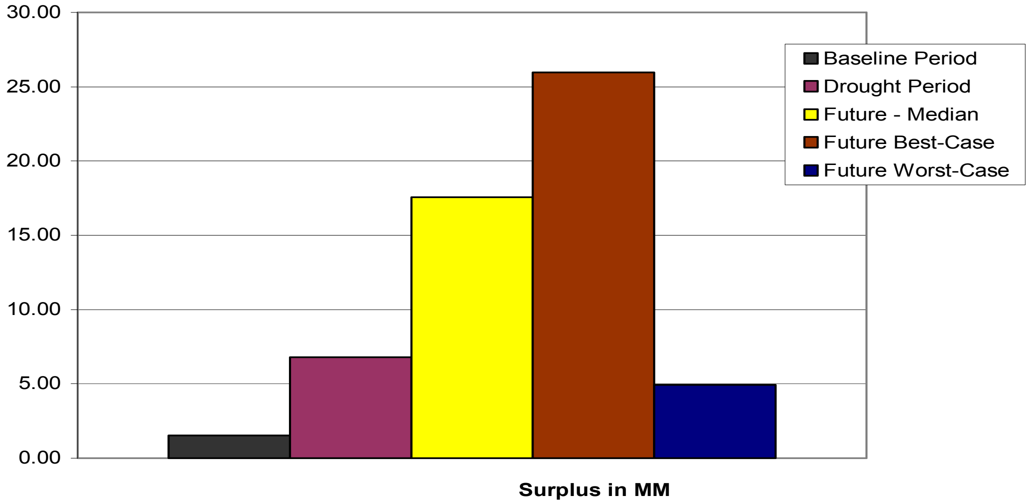


Figure 5.23

Mean Surplus – June through August

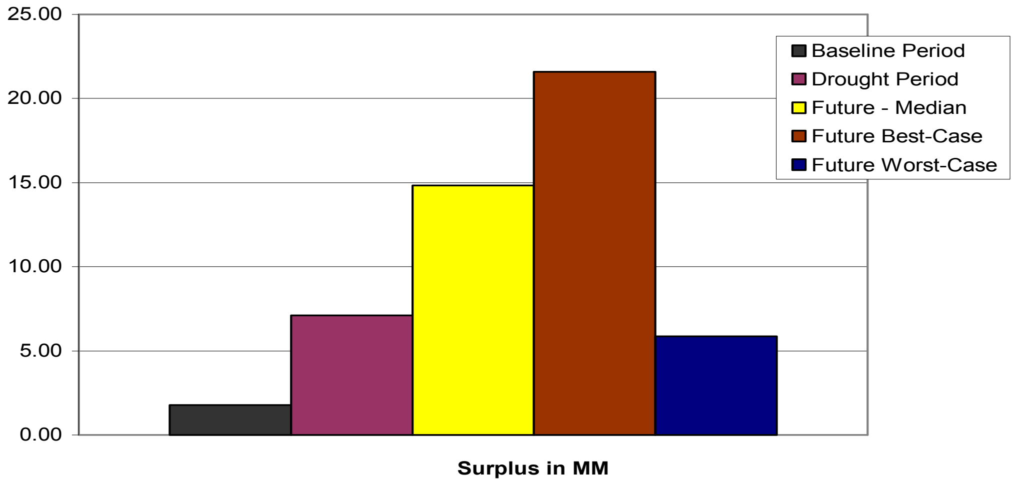


Figure 5.24

Mean Surplus – September through November

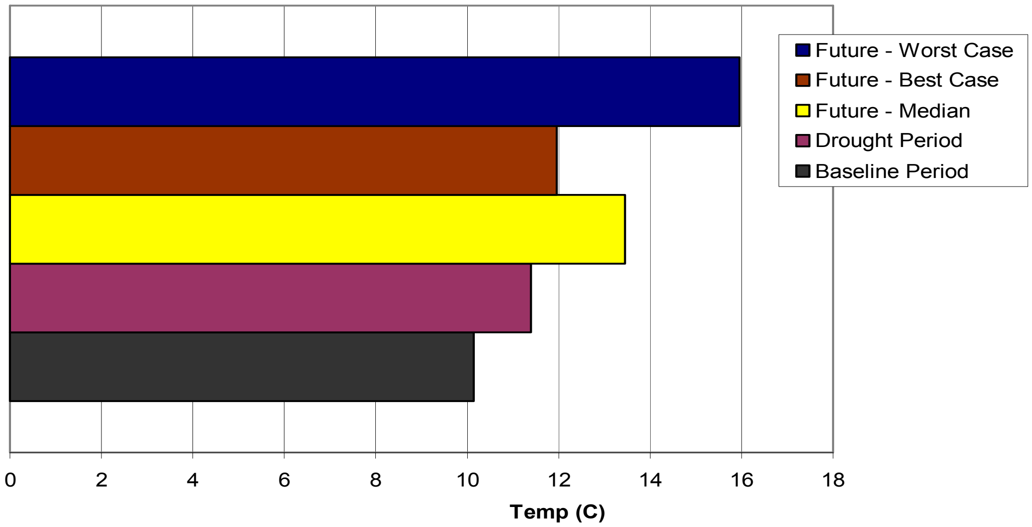


Figure 5.25

Mean Annual Temperatures

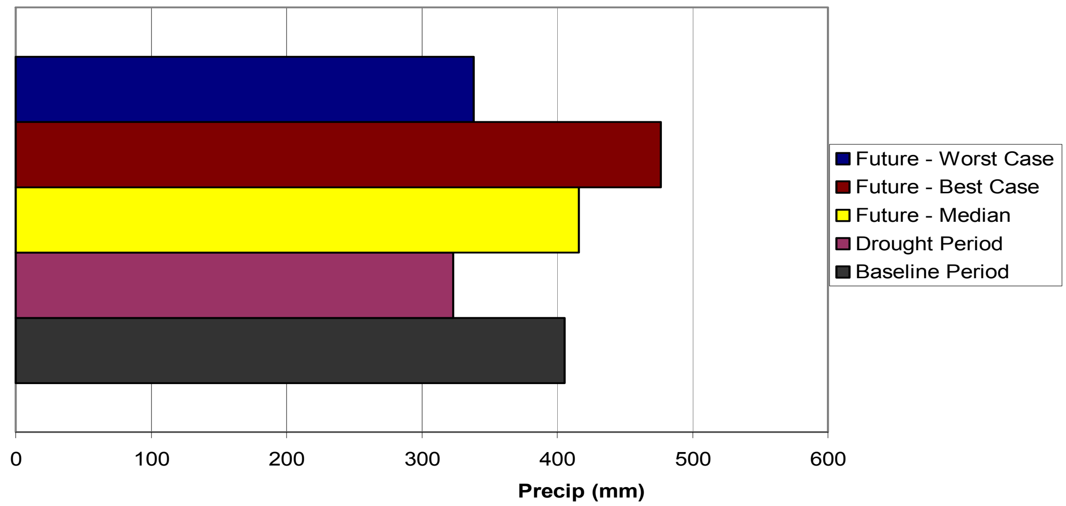


Figure 5.26

Mean Annual Precipitation

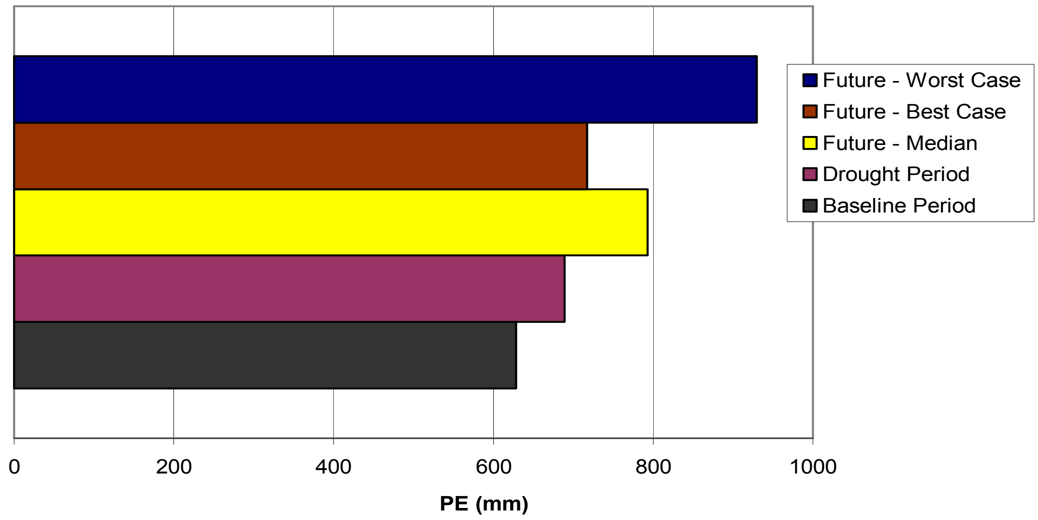


Figure 5.27

Mean Annual Potential Evapotranspiration

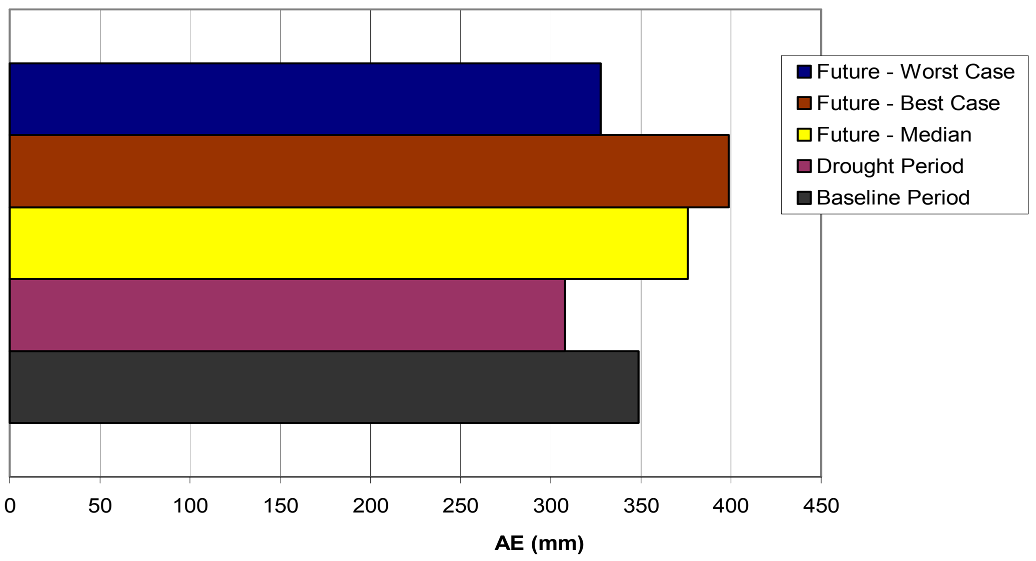


Figure 5.28

Mean Annual Actual Evapotranspiration

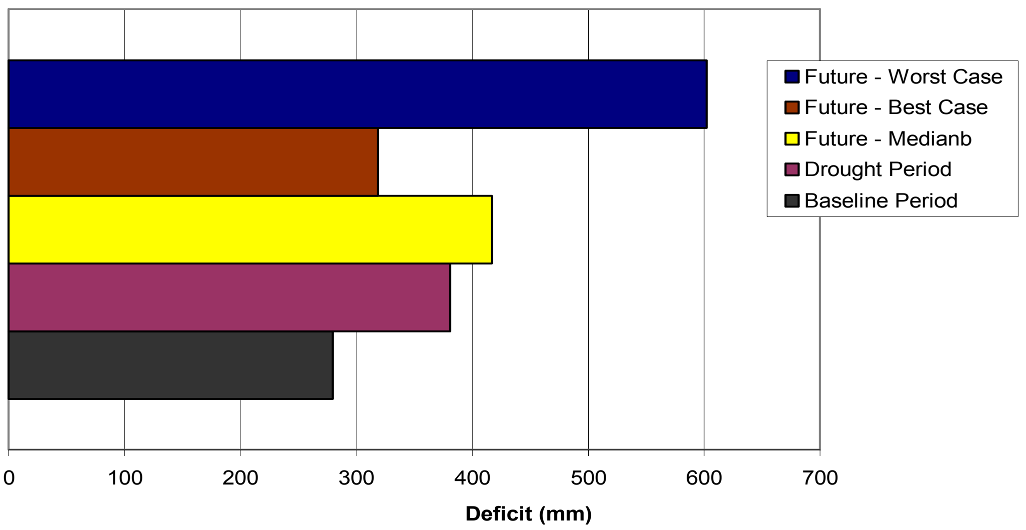


Figure 5.29

Mean Annual Deficit

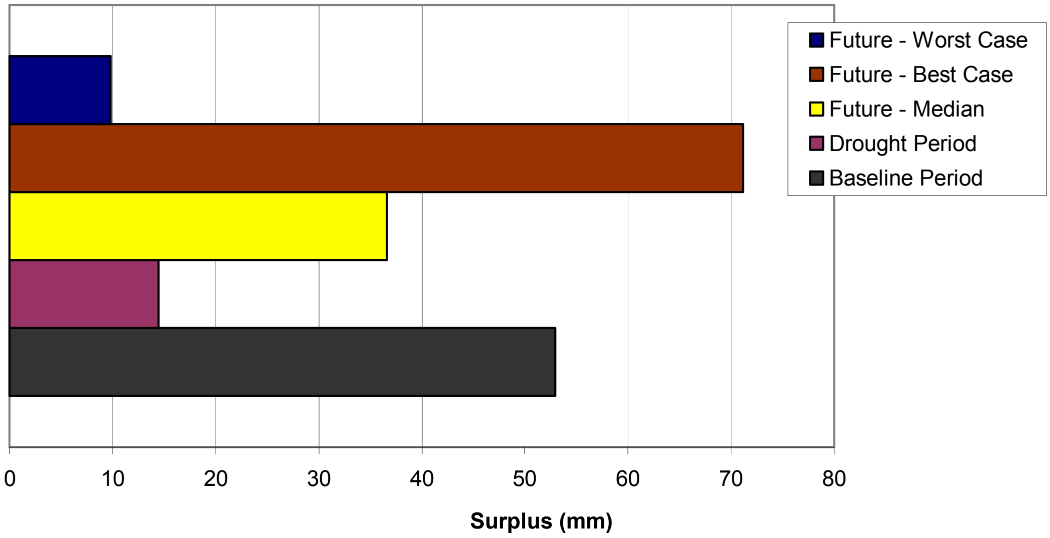


Figure 5.30

Mean Annual Surplus

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The important comparisons of the results in Chapter 5 are among the baseline period, drought period, and future best-case scenarios. This is a conservative approach but it will serve a realistic comparison between these scenarios. The future median (most likely future outcome) and worst-case scenarios, if they occur as a result of global warming, will increase the negative effects of the more conservative approach.

The baseline period temperatures are lower than either the drought period or the best-case scenario. The drought period temperatures are approximately 1.5°C warmer than the baseline period. The best-case temperatures are 1.9°C warmer than the baseline period and 0.6°C warmer than the drought period. The data reveal that in both the drought period and the best-case scenario warming increases most during the winter season. Winter snowmelt is 2.27 mm higher during the drought period as compared to the baseline period and the best-case snowmelt is 5.91 mm higher than the drought period and 8.67 mm higher than the baseline period. This is a critical factor as water supplies are dependent upon winter snowpack. If snowmelt occurs earlier than normal, than the critical summer period will see an extended period of water shortage.

Precipitation values for the best-case scenario are higher by 60 percent compared to the baseline period for December through February and 40 percent higher than the drought period. However, it must be remembered that this precipitation falls during warmer temperatures without building the winter snowpack. In addition, this can be shown by a comparison of precipitation to potential evapotranspiration. Potential evapotranspiration is higher by 63 percent over the baseline period and 7 percent higher than the drought period. This indicates that, with higher temperatures in the future, PE will be greater than during the drought period.

The highest water deficits occur during the September, October, and November time period in both the drought period and the best-case future scenario period as compared to the baseline period. In the baseline period, the highest deficits occur during the June, July, and August time frame and recover during the December, January, and February time period. Although the future best-case scenario may have slightly higher amounts of precipitation, the majority falls as liquid precipitation and not snow.

The future scenario exhibits higher surplus and recharge amounts than either the drought period or the baseline period. The runoff rates are 80 percent higher than the baseline period and 78 percent higher than the drought period.

6.2 Baseline Water Usage Estimates

The primary objective of this study is to determine the amount of water available for future development in Garden Park. The climatic water balance model used in this study yields results that help determine the climatic conditions that exist in Garden Park and the amount of water that may be available for future development. The final step is to determine the amount of water needed if full development actually occurs in Garden Park and what effects will future droughts and global warming have on the water supply.

The Garden Park watershed is approximately 48.5 square miles or 31,000 acres. This includes the area available for subdivision including roads, and the areas not suited for subdivision due to steep terrain or other obstacles. Red Canyon Park (which is not part of the subdivision) is also included in this acreage because it is part of the overall watershed. As currently configured, there are 90, thirty-five acre ranchettes available for subdivision. Fifty-seven of these are now occupied. This study projects all 90 ranchettes will be built.

Based on the watershed size and the baseline period average annual precipitation, a total of 41,230 acre-feet of precipitation falls within the watershed. This amount converts to over 13.44 billion gallons of water. Runoff for the watershed is 4,340 acre-feet or 1.41 billion gallons of water. Potential evapotranspiration for the watershed is 64,790 acre-feet or 21.11 billion gallons of water. From Mather's definition of effective precipitation (EP = P – R0) the model predicts 36,890 acre-feet of water, or 12 billion gallons of water, which can be used for climatic demands, recharge, and soil moisture storage. Of that amount, it is estimated that 6,510 acre-feet (2.12 billion gallons) become groundwater recharge.

Actual evapotranspiration for the watershed is approximately 40,610 acre-feet or 13.23 billion gallons of water. There is an obvious shortage of water when comparing potential and actual evapotranspiration with total precipitation. The actual deficit is 23,870 acre-feet or 7.78 billion gallons of water.

If future development in Garden Park is realized and all 90 ranchettes are built, based on the U.S. Census figures, population should approximately be 225 persons (2.5 persons per household) (Census, 2002). The United States Geological Survey estimates that each person in a household uses between 80 to 100 gallons per day of water; a conservative number (Kenny, et al. 2009). Extrapolating these figures and using an average of 90 gallons per day per person for all 90 ranchettes, household water use would be approximately 20,250 gallons per day or 7,391,250 gallons of water per year. This equates to 22.68 acre-feet per year.

Lawn and garden water use (for 5,000 sq. ft. of lawn and garden area) is estimated to be 500 gallons per day per ranchette during the spring and summer months (USGS, 2005). This form of irrigation would only occur during the four-month growing season. The total amount of water for this use is slightly more than three acre-feet or 5.4 million gallons or 16.6 acre-feet of water per year.

The majority of people moving to the new Garden Park ranchettes do so to enjoy the rural lifestyle. Many in Garden Park, but certainly not all, enjoy raising specialty crops such as grapes or acquiring hobby animals such as horses for riding. All of these hobbies require water. If one-half of all ranchettes set aside one acre (maximum allowable acreage placed under irrigation from wells) for crops or pasture, the estimated water usage is six acre-feet per acre per ranchette. Total water use for this purpose, during the four-month growing period would be 1,080 acre-feet or approximately 352 million gallons of water per year. If these same ranchettes have one horse, water use would increase by annual average of 227 acre-feet or 73.9 million gallons.

The combined water usage (ranchettes, gardens, pastures, and hobby animals) after Garden Park has been fully developed is 1337.19 acre-feet or 435,791,250 million gallons per year. It is obvious that groundwater recharge lags far behind the actual demand regardless of the recharge scenario, present or future.

Mather states that a “climatic water budget methodology can be reliably used to provide estimates of annual streamflow from a basin” (Mather, 1979). Streamflow response is a complex system and depends on vegetation, topography, watershed size, and soil properties, rainfall intensity and amount, climatic conditions, and subsurface geology. Mather conducted streamflow studies on three small watersheds to determine the usefulness of the water budget method to determine streamflow. His studies of the three basins in Delaware concluded that about 25 percent of runoff became streamflow. However, the computed percentage of runoff adding to streamflow is not a universal percentage applicable to all conditions (Mather, 1979).

Recharge from Four Mile Creek in Garden Park was not estimated in this study for several reasons. The primary reason was the lack of streamflow gauging stations in the watershed to quantitatively determine streamflow into and out of the basin. Additionally, all water in the creek has been appropriated which affects the amount of water available for recharge to groundwater. However, recharge from Four Mile Creek does occur. Observations during field studies show that the lower portion of Four Mile Creek may have streamflow when the upper portion does not. Intuitively, these observations would suggest that the flow in the lower portion of the river is due to return flow from irrigation and storage water. Additionally, observations of data for wells located in close proximity to this section of the creek show these wells to be shallower and have higher flow rates than wells in other parts of the watershed.

An increase in impervious surfaces from development will also affect the hydrologic conditions in the Garden Park watershed. The increase in impervious surface area includes building sites, patios, roads, and a possible change in vegetation type. With less soil exposed due to the increase in impervious surfaces, water holding capacity decreases and water surplus and runoff will increase (Mather, 1978). If the average house size is 1,600 square feet, a total of 3.31 acres will be covered by the footprint of these houses. Considering other factors such as barns and paved driveways, a total of 9.5 acres will be lost for infiltration, potentially increasing runoff by 12.64 acre-feet. However, this water may become overland flow to Four Mile Creek or infiltrate the soil at some point. This may increase soil moisture storage and likely increase the "peakiness" of the streamflow during storm events. The only effective way to calculate these changes is by comparing measured values before the initial land-use changes to changes in values after development has occurred. However, in the case of Garden Park, this effect will probably be minimal as compared to higher density urbanization. In addition, it is assumed that the road networks linking the new ranchettes to the main highway will remain as dirt roads rather than paved surfaces.

One final factor must be recognized. All the new ranchettes will have septic systems rather than formal sewer systems. Depending on the size of the septic tanks and leach fields, some negligible amount of groundwater recharge, and/or soil moisture storage, should be expected.

6.3 Drought and Best-Case Water Usage Estimates

During the drought period of the Dust Bowl years, precipitation amounts dropped to an annual average amount of 323.34 mm compared to the baseline annual average of 405.34 millimeters. Total amount of precipitation was 32,860 acre-feet or 10.7 billion gallons of water. Annual average potential evapotranspiration was 689.06 or 70, 060 acre-feet of water; an obvious deficit of water occurred during this period (EP = -37,200 gallons). The actual annual deficit was 381.15 millimeters or 38,750 acre-feet of water. The Dust Bowl period was an incredible dry period in Garden with an obvious extended shortage of water supplies.

The final comparison is for the best-case scenario for 2080 through 2099. The annual average precipitation is estimated to be 476.58 millimeters. Total amount of precipitation would be 48,360 acre-feet. Effective precipitation is estimated to be 72,850 acre-feet. Again, an obvious shortage of water almost double that of the drought period. Actual evapotranspiration is estimated to be 40,300 acre-feet and an annual deficit of 32,364 acre-feet. Although the deficit is not quite as large as during the drought period, it must be remembered that the bulk of the precipitation which falls during the winter months does not contribute to snowpack for later use during the dry summer period. Also the best case scenario is highly unlikely within the IPCC outcomes.

6.4 Final Conclusions

If the IPCC future projections for temperature and precipitation are realized, even under the best-case scenario, temperatures will rise, potential evapotranspiration will increase, and deficits will seriously affect the water supplies in Garden Park. The slight increase in projected precipitation amounts for the best-case scenario, however, will occur during the critical winter months. With winter temperatures predicted to be above freezing, the accumulation of a snowpack for summer water supplies is minimal at best.

The summer growing season months of May through August for the best-case future scenario depict a deficit far higher than either the baseline period or even the drought period of the 1930s. The baseline growing season deficit is 191.51 mm compared to 256.90 mm for the drought period and 281.33 mm for the best-case future scenario. We can expect agriculture to suffer the same poor economic conditions as the drought period and a significant loss to the agricultural economy.

The summer deficit will also play a role in Colorado's emergency management situation. With the increased dryness and higher temperatures predicted by the model, fires will become a likely possibility. Fire managers will need to be prepared for conditions, and outcomes, comparable to the Colorado fires of the 2000-2003 period. As in the 2000-2003 period, tourism will likely suffer. Lower river flows will affect white-water raftering and vacation travel in general.

The winter snowpack will also be affected. Snowmelt for the baseline period is 27.12 mm compared to 16.26 mm for the drought period and 14.67 mm for the future best-case scenario. It is obvious that winter precipitation for the future scenario will be in the form of rain instead of snow. This condition will also reduce tourism in the skiing industry and winter vacationers in general. The normal "spring" runoff will occur earlier which will affect summer water supplies for irrigation.

As discussed in Chapter two, Colorado water managers are not well prepared for drier conditions due to future climate change. Colorado state authorities will need to educated, and encourage, water managers to prepare for these drier conditions. Water management strategies will need to consider earlier snowmelt and water storage for the summer growing season, fallowing land, and alternative methods for water transfers.

6.5 Recommendations

With very limited data (temperature and precipitation), the model was able to predict the climatic and hydrologic conditions in Garden Park. However, a model is only as good as the data used for input to the model. Based on the findings of this study, there are several recommendations to verify the accuracy of the model:

1. In this model precipitation was assumed to be equal over all parts of the Garden Park watershed, a highly unlikely scenario. Therefore, precipitation and temperature data should be collected throughout the Four Mile Creek watershed including West Four Mile Creek and from the headwaters at *The Crags*. Willing residents in these areas could be contacted and asked to participate in the project and provide these data. In Garden Park, the same process could be followed. Residents located in the Garden Park Valley as well as residents located at higher elevations could provide useful data. Additionally, a recording weather station, including evaporation pans or similar methods to measure evaporation, should be implemented to verify evaporation rates.

2. Stream gauging is of primary importance. A stream gauge should be set up in the north-end of Garden Park as well as the south-end of Four Mile Creek. This system would measure the actual streamflow as well as streamflow changes during storm events or during periods of irrigation. If possible, it would be helpful to implement stream gauges on the West Four Mile Creek branch as well as *The Crags* branch.

3. Particular attention should be given to soil moisture for different types of soils within Garden Park. Soil samples at various locations and soil depths should be collected and tested for soil water content.

4. Well logs from new groundwater wells should be obtained. This will provide accurate information on the location and flow of groundwater to help map where groundwater occurs. Additionally, actual water usage from homeowners should be obtained if possible.

5. A geographical information system should be implemented. Data for the system should be for a database containing climatic, well log data, soil types and soil chemistry results, location of ranchettes, homes and outbuildings including square footage, data on location and types of impervious surfaces, topography, and vegetation types and coverage. This process will enable the researcher to analyze and display data as needed.

6. The refinement of the input variables will help to more precisely predict future climatic events in conjunction with the IPCC projections.

With the implementation of the above recommendations for future study, the conclusions of this study using the climatic water budget model could be verified.

REFERENCES

Birkeland, Peter W. 1999. *Soils and Geomorphology – Third Edition.* New York: Oxford University Press, pp. 131, 232, 237, 261, 265.

Bonan, Gordon. 2002. *Ecological Climatology.* Cambridge: Cambridge University Press, pp. 137, 152-152.

Boos, C. M., and Boos, M. F., 1957. *Tectonics of Eastern Flank and Foothills of the Front Range, Colorado.* American Association of Petroleum Geologists Bulletin, Vol. 41, no. 12, pp. 2603 – 2676.

Brunsell, N. A. and C. B. Young. 2008. *Land Surface Response to Precipitation Events Using MODIS and NEXRAD Data.* International Journal of Remote Sensing, 29, 1965 – 1982.

Census 2002. Census data obtained found at: http://www.census.gov/main/www/Cen2000.html

Chronic, Halka, and Felicie Williams. 2002. *Roadside Geology of Colorado.* Missoula, Montana, Mountain Press Publishing, pp. 4, 9 – 18.

Colorado Division of Water Resources. 2002. *Well Permits.* http://www.dwr.state.co.us/WELLVIEWWEB

Colorado Drought Mitigation Plan. 2000. State of Colorado. Found at: http://www.cwcb.state.co.us/NR/coloradodroughtresponseplan.

Commissioner Charles Judge and Rancher Roy Canterbury, interview by author, Garden Park, Colorado, August 12, 2002.

Decree of the District Court of Fremont County, Colorado. 1894. Jas. L. Cooper, Referee.

Fetter, C. W. 2002. *Applied Hydrology – Fourth Edition.* Upper Saddle River, New Jersey: Prentice Hall, pp. 444-445.

Frederickson, E. A.,1976. *Pre-Pennsylvanian Rocks of the Cañon City Area.* Rocky Mountain Association of Geologists, pp. 133 – 142.

Gerrard, J. 199. *Soil Geomorphology: An Integration of Pedology and Geomorphology.* New York, Chapman and Hall, pp. 29 – 31.

Hidore, John J. and John Oliver. 1993. *Climatology: An Atmospheric Science.* New York: Macmillan Publishing Company, pp. 124 – 125.

Hopkins, R.L., and L.B. Hopkins. 2000. *Hiking Colorado's Geology.* Seattle: The Mountaineers, p. 239.

IPCC. 2007. *Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on
Climate Change. Cambridge University Press. New York. Chapter 11.

Johnson, W. C., R. C. McMaster, and C. J. Sorenson. 1981. *Changing Range Land Usage in Garden Park, Colorado*. The Great Plains-Rocky Mountain Geographical Journal. Vol. 9, pp. 59-71.

Klein, Roberta, and Douglas S. Kenney. 2004. *Use of Climate Information in Municipal Drought Planning in Colorado.* Western Water Works Association, WWA01-06.

Kenny, J. F., N. L. Barber, S. S. Huston, K. S. Linsey, J. K. Lovelace, and M. A. Maupin. 2009. *Estimated Use of Water in the United States in 2005:* U.S. Geological Survey Circular 1344, p. 52.

Larimer County Compass. 2004. *The Drought 2004, A Report,* August, 2004.

Leopold, Luna, Daniel F. M. Gordan Wolman, and John P. Miller. 1968. *Fluvial Processes in Geomorphology.* New York: Dover Publications, pp. 49-50.

Luecke, Daniel F. 2002. *The Role of Markets in Allocation of Water Among Agricultural and Urban Users in the Western United States.* Presented at the Natural Resources Law Center, Boulder, Colorado, June, 2002.

Mather, John R. 1978. *The Climatic Water Budget in Environmental Analysis.* Lexington, Massachusetts: Lexington Books, pp. 1-8, 13.

Mather, John R. 1979. *The Influence of Land-Use Change on Water Resources.* Newark, Delaware: Publications in Climatology, pp. 4-25.

Mather, John R. 1984. *Water Resources: Distribution, Use, and Management.* New York: Wiley, pp. 221-250.

Mayer, Peter, and Sonya Wytinck. 2007. *Colorado Drought and Water Supply Update 2007.* State of Colorado, Colorado Water Conservation Board.

McKee, Thomas B., Nolan J. Doesken, and John Kleist. 2000. *A History of Drought In Colorado: Lessons Learned and What Lies Ahead.* Colorado Water Conservation Board, Denver. No. 9. pp. 4 – 10.

Nakicenovic, N. et al (2000). Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, U.K., 599 pp.

National Climatic Data Center, 2003. Found at: http://www.ncdc.noaa.gov/ oa/climate/research/2002/dec/st005dv00pcp200212.html

Nichols, Peter D., Megan K. Murphy, and Douglas S. Kenney. 2001. *Water and Growth In Colorado: A Review of Legal and Policy Issues.* Boulder, Colorado: Natural Resources Law Center, pp. 3, 18-20.

NMCC, 2003. New Mexico Climate Center. Drought definitions found at http//weather.nmsu.edu.

O'Connor, Howard G., 1963. *Development of a Water Supply at the University of Kansas Geology Field Camp near Cañon City, Colorado.* Report submitted to Dr. William M. Merrill.

Pielke, Roger A., Nolan Doesken, Odilia Bliss, Tara Green, Clara Chaffin, Jose D. Salas, Connie A. Woodhouse, Jeffrey J. Lukas, and Klause Wolter. 2005. *Drought 2002 in Colorado: An Unprecedented Drought or a Routine Drought?* Pure Applied Geophysics, 162, pp. 1455 – 1479.

Pueblo Chieftan. 2002. Wildfires of 2002 Top News Story. December, 2002.

Reed, S.M., D.R. Maidment, and J. Patoux. 1997. *Spatial Water Balance o f Texas.* Online Report 97-1, February, 1997, at http://www.ce.utexas.edu, pp. 44.

Riebsame, W., James Westcoat, and Peter Morriesette. 1997. *Western Land Use Trends and Policies: Implications for Water Resources.* U. S. Bureau of Reclamation. Denver. Report for the Western Water Policy Review Advisory Commission.

Ruhe, R.V. 1975. *Climatic Geomorphology and Fully Developed Slopes.* Catena 2. pp. 309 – 320.

Sackett, D. H., 1961. *Geology of the Garden Park Area, Fremont, County, Colorado:* Unpublished master's thesis, University of Kansas Library, pp. 1-38.

Scott, Glen R. 1973. *The Geologic Setting of the Grand Canyon of the Arkansas.* Article accessed at Cañon City Public Library, Cañon City, Colorado.

Sweeney, Patrick. "Drought, Spate of Wildfires Threatened Key Industries". Denver Business Journal, December 20, 2002.

Thornthwaite, C. W. 1948. *An Approach Toward a Rational Classification of Climate.* Geographical Review, vol.38, pp. 55-94.

Topper, Ralf, Karen L. Spray, William Bellis, Judith L. Hamiliton, Peter Barkman. 2003. *Ground Water Atlas of Colorado.* Department of Natural Resources. Denver.

United States Department of Agriculture. 1986. *Soil Survey of Fremont County Area, Colorado.* Natural Resources Conservation Service, Colorado Agricultural Experiment Station, United States Department of the Interior, Bureau of Land Management, pp. 5, 123, 125, 127, 132, 146, 150, 152, 154, 158, 160.

United States Department of the Interior. 1984. *Water Resources Investigations.* Report 82-4114. U.S. Geological Survey, Lakewood, Colorado.

Willmott, C. J., 1997. *WATBUG: A FORTRAN IV Algorithm for Calculating the Climatic Water Budget.* Publications in Climatology, 30, pp. 1-55.

Worster, Donald. 1985. *Rivers of Empire.* New York: Oxford University Press, pp.20.

Abstract:

This paper examines whether groundwater can provide adequate water supplies for land use change and future development in Garden Park, Colorado. A climatic water budget model was used to determine the amount and adequacy of the groundwater supply for future use in Garden Park, Colorado. The model was used to determine a baseline amount of available water during the years 1975 through 2000. The model was then applied to the drought period of the "Dust Bowl" (1930-1939) years to determine the water supply in Garden Park during that time period. Finally, the model was used to project water supply conditions in Garden Park in the future based on the Intergovernmental Panel on Climate Change temperature and precipitation projections during the period of 2080-2099 and applying the results to Garden Park. Future conditions in Garden Park are projected to be warmer than the baseline period with winter precipitation falling as rain.