THE BENEFITS OF GROUNDWATER OVERDRAFT REDUCTION IN THE PHOENIX ACTIVE MANAGEMENT AREA

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Groundwater overdraft and the resulting decline in groundwater levels are generally believed to impose certain costs on society. These costs include increased groundwater pumping cost, land subsidence damage, and aggravated groundwater quality problems. Hence, any efforts that reduce these overdraft costs would thereby benefit society. The purpose of this paper is to investigate these costs in order to develop a framework for the estimation of overdraft reduction benefits. As an example, the benefits of overdraft reduction by irrigation conservation in the Phoenix Active Management Area (AMA) are estimated.

Increased Groundwater Pumping Cost

Bush and Martin (1986) describe the increases in groundwater pumping cost as the most significant effect of groundwater overdraft in Arizona. As more groundwater is withdrawn from an aquifer than is recharged, the resulting decline in groundwater levels forces users to pump groundwater from increasing depths. Schumann and Genualdi (1986) report cumulative groundwater level declines exceeding 300 feet within the Phoenix AMA.

Variable pumping cost has two components: energy and maintenance. A pump operating at 100 percent efficiency requires 1.024 kilowatt hours of electricity to lift one acre foot of water one foot (Bush and Martin 1986). Evans (1990) notes that typical pump efficiencies in the Phoenix AMA are around 72.5 percent. This efficiency implies an electricity requirement equal to 1.4124 kilowatt hours (1.024 divided by 0.725). In 1985 the average real price of electricity in Arizona was $0.067 per kilowatt hour (Energy Information Administration 1989). All values in this study were indexed by the 1982 GNP implicit price deflator (Council of Economic Advisers 1991). The 72.5 percent average pump efficiency then implies an average real energy cost to pump groundwater equal to $0.0946 per acre foot of water per foot of lift ($/AF/Ft). This cost is assumed to remain constant through time.

The second component of variable pumping cost, maintenance, has been estimated by Hathorn and Farr (1985) as $0.01201/AF/Ft in 1985. In constant 1982 dollars, this cost equals \$0.0108/AF/Ft. This cost is also assumed to remain constant through time. Combining the energy and maintenance costs together, the real variable cost to pump groundwater is estimated as \$0.1054/AF/Ft.

Bush and Martin (1986) estimate the increased fixed pumping cost resulting from overdraft as \$0.016/AF/Ft in 1984. In constant 1982 dollars, the real increased fixed pumping cost equals \$0.0149/AF/Ft. This cost accounts for the additional piping, tubing, and bowls that must be installed on the well as the groundwater level declines.

The increased total cost incurred when the groundwater level declines then equals the sum of the increased variable and fixed costs, or \$0.1203/AF/Ft. This is the unit marginal pumping cost of overdraft. The marginal pumping cost of overdraft is obtained by multiplying the unit marginal pumping cost by the groundwater decline. It is important to note that groundwater declines are cumulative over time. Consider the following discrete time representation of a changing groundwater level. Suppose that withdrawals occur at the beginning of each time period; then, the resulting change in the groundwater level during the period determines the groundwater level at the end of the period. Hence, withdrawals at the beginning of a time period are pumped from the groundwater level existing at the end of the previous period. For notational convenience, summation indices are indicated as subscripts on the summation signs.

Let W_t = groundwater withdrawn at the beginning of period t

dL_t = groundwater level change during period t

L_t = groundwater level at the end of period t

Then

$$L_{t+1} = L_t + dL_{t+1}$$

$$L_{t+2} = L_{t+1} + dL_{t+2}$$

$$= L_t + dL_{t+1} + dL_{t+2}$$

$$L_{t+j} = L_t + \Sigma_k dL_{t+k}, \text{ for } k = 1 \text{ to } j$$

With an infinite time horizon, the effects of a change in the groundwater level will be felt at each future point in time. Thus, overdraft generates a perpetual flow of costs. One implication of this dynamic process is that the marginal pumping cost due to overdraft is also cumulative over time.

Let c^P = unit marginal pumping cost of overdraft

Then $c^P \Sigma_k dL_{t+k}$, for k=1 to j-1, is the marginal pumping cost of overdraft in period t+j

The total pumping cost due to overdraft is obtained by multiplying the marginal pumping cost by the amount of groundwater withdrawn.

$W_{t+j} c^P \Sigma_k dL_{t+k}$, for k=1 to j-1, is the total pumping cost of overdraft in period t+j

The present value of this component of overdraft cost equals the discounted sum of the increased pumping costs in each time period from the time of the overdraft into perpetuity, given an infinite time horizon.

Land Subsidence Damage

Little information is available concerning the cost of land subsidence damage in Arizona. The only economic analysis available on the subject is McCauley (1973). McCauley's study area is western Pinal County, adjacent to the Phoenix AMA. This area has experienced some of the most severe groundwater overdraft conditions in Arizona and is noted for the severity of its subsidence problems (Bush and Martin 1986). McCauley inventoried all subsidence damage to agricultural fields and facilities, transportation facilities, and domestic and urban structures. The estimated annual cost of subsidence damage in western Pinal County is presented in table 1.

The only other study to estimate the cost of land subsidence damage in Arizona is Pewe and Larson (1982). Pewe and Larson report the occurrence of a fissure 400 feet long with hairline cracks, small holes, and a linear opening 15 feet long, 8 feet deep, and 15 inches wide in Phoenix near 40th Street and Lupine Avenue on January 19, 1980. This was the first known occurrence of a fissure in a densely populated, urban area within Arizona. This fissure occurred on a property that was currently being developed. The temporary halting of construction, modification of building plans, hiring of consultants, and other expenses were estimated to cost $500,000. The authors report that a reopening of the fissure is probable. However, since the local aquifer had been essentially de-watered, compaction and fissuring could cease at some point in the future.

These two studies were used to form a combined land subsidence damage cost estimate, which is presented in table 2. In constant 1982 dollars, land subsidence damage is estimated to cost $0.2664/AF/Ft. The estimate is expressed in terms of AF of groundwater withdrawn for comparability between different areas, as in Bush and Martin (1986). This is the unit marginal subsidence cost of overdraft. The marginal subsidence cost of overdraft is obtained by multiplying the unit marginal subsidence cost by the groundwater decline. It is assumed that this subsidence damage occurs at the beginning of the time period following the groundwater level decline. There is no evidence to suggest that this marginal cost is cumulative over time.

Let c^S = unit marginal subsidence cost of overdraft

Then $c^S dL_{t-1}$ is the marginal subsidence cost of overdraft in period t

$W_t c^S dL_{t-1}$ is the total subsidence cost of overdraft in period t

Therefore, subsidence damage resulting from overdraft is treated in this study as a one-time cost.

Aggravated Groundwater Quality Problems

The concentration of total dissolved solids (TDS) is a general indicator of water quality (Arizona Department of Water Resources 1988). Components of TDS include inorganic compounds such as calcium, magnesium, sodium, sulfate, bicarbonate, chloride, and silica. Concentrations of TDS within the Phoenix AMA rise as high as 3,500 milligrams per liter (mg/l) (ibid.). The U.S. Public Health Service recommends a maximum of 500 mg/l for domestic water supplies (Arizona Water Commission 1975). For irrigation use, TDS concentrations greater than 1,500 mg/l are acceptable if special management practices are used or salt resistant crops are grown; however, concentrations over 3,000 mg/l are generally unsuitable (Arizona Department of Water Resources 1988). For livestock use, TDS concentrations less than 2,500 mg/l are considered satisfactory (ibid.).

The Arizona Water Commission (1975) reports the average TDS concentration for the Salt River basin equal to 1,138 mg/l in 1946 and 1,120 mg/l in 1965. The Salt River basin has contributed 97 percent of all groundwater withdrawals in the Phoenix AMA from 1915 to 1984 (Arizona Department of Water Resources 1988). Therefore, the decline in average TDS concentration within the Salt River basin indicates an improvement in groundwater quality for the Phoenix AMA as a whole.

To confirm this indication, groundwater quality data for all wells monitored by the U.S. Geological Survey in the Salt River basin during the years 1960 through 1980 were obtained (U.S. Geological Survey 1990). These data consist of the measured specific conductance of groundwater for each monitored well in units of micromhos per centimeter. Specific conductance measures the ability of water to conduct an electrical current and is used to estimate TDS concentration (U.S. Geological Survey 1982). The estimated rate of change in TDS concentration was then calculated for each well with two or more years of data. Out of 199 such wells, 89 had positive rates of change while

110 had negative rates of change. The average rate of change for all 199 wells was -36.05 mg/l per year. Once again, an improvement in groundwater quality was indicated for the Phoenix AMA. The Arizona Department of Water Resources (1988) suggests two possible explanations. First, the urbanization of agricultural land has reduced the movement of salts within the aquifer by reducing irrigation. Second, newer wells perforate the aquifer at greater depths, where groundwater may have lower TDS concentrations.

While decreasing TDS concentrations generally indicate improving groundwater quality, TDS concentration itself is not a final measure of acceptability for specific water uses (Arizona Department of Water Resources 1988). Individual constituent components of TDS have different implications for different water uses. For example, sulfate concentrations above 250 mg/l degrade residential water use due to taste considerations and a laxative effect on people not accustomed to the water, while concentrations below 600 mg/l do not limit irrigation water use and concentrations below 500 mg/l do not limit livestock water use (ibid.). Due to the complexity of these groundwater quality issues as well as the indications of decreasing TDS concentrations in the presence of a continuing groundwater overdraft, no overdraft cost with respect to groundwater quality is included in this study.

Overdraft Reduction Benefit Estimation

As an example, the overdraft reduction benefit of irrigation conservation enforcement in the Phoenix AMA was estimated. Consider two scenarios. The "maximum-conservation" scenario assumes perfect compliance with all irrigation and non-irrigation conservation measures required by the Arizona Groundwater Management Act. Alternatively, the "no-conservation" scenario assumes perfect compliance with all non-irrigation conservation measures; however, no irrigation conservation measures are enforced. The difference in overdraft costs between these two scenarios provides an estimate of the benefits of irrigation conservation in the Phoenix AMA.

Projections of maximum-conservation overdraft are provided by the Arizona Department of Water Resources (DWR) (Arizona Department of Water Resources 1988). These projections are illustrated in figure 1. No-conservation overdraft equals maximum-conservation overdraft plus the overdraft reduction potential of irrigation conservation. Evans (1990) estimates this potential by simulating the profit maximizing behavior of irrigators in response to irrigation conservation measures and the increasing groundwater pumping costs due to overdraft. These estimates were added to the maximum-conservation overdraft projections to obtain estimates of no-conservation overdraft. Ordinary least squares regression was then used to obtain continuous estimates of the maximum-conservation and no-conservation time paths. These time paths are illustrated in figure 2.

The estimated maximum-conservation and no-conservation time paths of overdraft provide only part of the information required to calculate overdraft costs. Also required are estimates of withdrawal. Projections of maximum-conservation withdrawal are provided by DWR (Arizona Department of Water Resources 1988). This projections were then adjusted to obtain estimates of no-conservation withdrawal. The difference in overdraft between the two conservation scenarios is due to the difference in irrigation groundwater withdrawal. DWR estimates the irrigation incidental recharge rate prior to the imposition of conservation measures as 32 percent (ibid.). Hence, the difference in overdraft between the two scenarios equals 68 percent of the difference in withdrawal (100% - 32%). Conversely, the difference in withdrawal between the two scenarios equals the difference in overdraft (i.e. overdraft reduction potential) divided by 68 percent. This calculated difference in withdrawal was added to the maximum-conservation withdrawal projections to obtain estimates of no-conservation withdrawal.

To obtain estimates of overdraft and withdrawal beyond 2025, an assumption had to be made. The Groundwater Management Act established a goal of zero overdraft in the Phoenix AMA by 2025. Since the maximum-conservation scenario assumes perfect compliance with all conservation measures, it suggests that DWR will be unable to achieve this goal by conservation enforcement alone (see figure 1). Hence, DWR must rely on a second policy tool, groundwater rights retirement, to further reduce overdraft below the maximum-conservation time path of overdraft. It is assumed that DWR will retire sufficient groundwater rights to achieve and maintain zero overdraft at 2025 and beyond.

If overdraft equals zero, groundwater withdrawal must equal groundwater recharge. Groundwater recharge is comprised of natural and incidental recharge. Incidental recharge results from the use of groundwater, surface water indigenous to the Phoenix AMA, and augmentation water. Augmentation water includes effluent reuse, Central Arizona Project water, and other water imported into the AMA. Natural recharge and the incidental recharge from surface water indigenous to the Phoenix AMA have been estimated by DWR (Arizona Department of Water Resources 1988). These are expected values and are assumed to continue beyond 2025. However, the incidental recharge from augmentation water is an uncertain quantity beyond 2025. This uncertainty obtains from the continuing evolution of the legal status of effluent, possible reallocations of Colorado River water, and pending legislation affecting water transfers into the Phoenix AMA.

Lower and upper bounds on augmentation water were used to account for this uncertainty. The lower bound on augmentation water is assumed to be zero since it is unreasonable to suggest that the Phoenix AMA would be a net exporter of water at any time in the future. The upper bound is assumed to be double the level estimated by DWR for 2025. In 2025 the average incidental recharge rate is projected to be 13 percent (Arizona Department of Water Resources 1988). This rate and the assumed zero overdraft imply a lower and upper bound on annual groundwater withdrawal beyond 2025 equal to 180,722 and 501,238 AF, respectively.

The total costs of the maximum-conservation and no-conservation time paths of overdraft were calculated using the discrete time model presented above. A 3 percent periodic discount rate was used in all calculations. Calculations for the maximum-conservation time path are presented in table 3 and those for the no-conservation time path are presented in table 4. The groundwater level decline listed for each year was calculated by using an average decline to overdraft ratio (Arizona Department of Water Resources 1988). The overdraft cost listed for each year equals the present value of all costs resulting from the overdraft in that year. For example, in the maximum-conservation scenario, overdraft in the year 2000 resulted in a 1.31 foot decline in the groundwater level. As discussed above, this decline results in a one time subsidence cost and a perpetual flow of increased groundwater pumping costs. The present value of all these costs, discounted back to 2000, is bounded between $2,698,246 and $3,503,324. The present value of all costs resulting from the entire time path of overdraft, discounted back to 1985, is given at the bottom of each table.

A comparison of tables 3 and 4 indicates that perfect compliance with irrigation conservation measures would yield a groundwater level 3.37 feet higher than if no irrigation conservation measures were enforced. The benefit of this irrigation conservation, discounted back to 1985, is bounded between $8,226,576 and $9,556,954. This benefit includes the flow of subsidence cost savings from 1985 to 2025 and the perpetual flow of groundwater pumping costs savings from 1985 into the future.

Conclusions

The increased groundwater pumping cost and land subsidence damage associated with groundwater overdraft were estimated for the Phoenix AMA. No evidence was found to suggest that groundwater overdraft has aggravated groundwater quality problems in this area. The benefits of overdraft reduction due to irrigation conservation in the Phoenix AMA were estimated as an example. This analysis indicated a benefit bounded between $8,226,576 and $9,556,954. While the estimated benefits of irrigation conservation are positive, no inference with respect to its desirability can be made without also examining its cost. Using economic efficiency as a criterion, such irrigation conservation should not be employed if its cost exceeds the estimated benefit.

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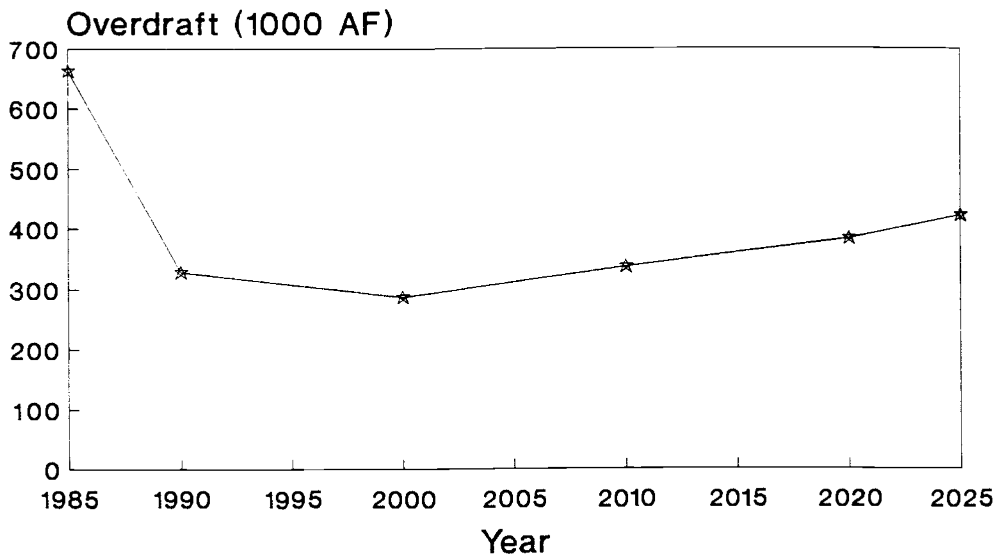

Figure 1
Phoenix AMA Overdraft Projections
Source: Arizona DWR, 1988

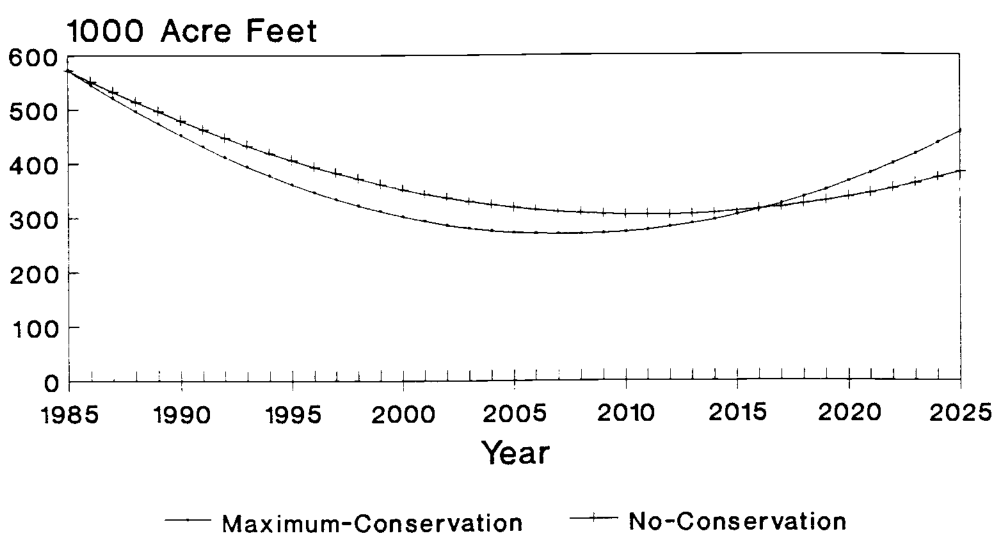

Figure 2
Time Paths of Overdraft
in the Phoenix AMA

Table 1: Estimated Annual Subsidence Costs in Western Pinal County (1970 Dollars)

Agriculture:	Land Leveling	60,000
	Crack Repair	60,000
	Well Repair	57,250
	Ditch Repair	10,000
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	Subtotal	187,250
Transportation:	Highways	15,500
	All Other	4,300
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	Subtotal	19,800
Domestic & Urban Structures:		0
Total:		207,050

Source: McCauley 1973.

Table 2: Combined Land Subsidence Damage Cost Estimate

McCauley (1973):		
Annual total subsidence damage cost	$207,050	
Annual groundwater withdrawal	1,100,000 AF	
Annual groundwater level decline	5 Ft	
Average land subsidence damage cost	$0.0376/AF/Ft	(1970 $)
	$0.0895/AF/Ft	(1982 $)
Pewe and Larson (1982):		
Urban subsidence damage cost in 1980	$500,000	
(Assume similar costs in the future)		
Arizona Department of Water Resources (1988):		
Annual groundwater withdrawal (Phoenix AMA)	1,221,700 AF	
Annual groundwater level decline (Phoenix AMA)	2.7 Ft	
Average urban land subsidence damage cost	$0.1516/AF/Ft	(1980 $)
	$0.1769/AF/Ft	(1982 $)
Combined average subsidence damage cost	$0.2664/AF/Ft	(1982 $)

Table 3: Overdraft Costs in the Maximum-Conservation Scenario

Year	Groundwater Level Decline (Feet)	Overdraft Costs Lower Bound	Overdraft Costs Upper Bound
1985	2.49	$7,537,307	$8,517,268
1986	2.37	$6,972,448	$7,935,030
1987	2.26	$6,453,439	$7,398,920
1988	2.16	$5,977,172	$6,905,929
1989	2.06	$5,540,723	$6,453,238
1990	1.96	$5,141,347	$6,038,217
1991	1.87	$4,776,473	$5,658,417
1992	1.79	$4,443,696	$5,311,565
1993	1.71	$4,140,772	$4,995,559
1994	1.64	$3,865,613	$4,708,460
1995	1.57	$3,616,275	$4,448,487
1996	1.51	$3,390,955	$4,214,010
1997	1.45	$3,187,983	$4,003,543
1998	1.40	$3,005,811	$3,815,734
1999	1.35	$2,843,007	$3,649,362
2000	1.31	$2,698,246	$3,503,324
2001	1.28	$2,570,298	$3,376,629
2002	1.24	$2,458,023	$3,268,390
2003	1.22	$2,360,357	$3,177,811
2004	1.20	$2,276,304	$3,104,181
2005	1.18	$2,204,921	$3,046,862
2006	1.17	$2,145,313	$3,005,278
2007	1.17	$2,096,612	$2,978,905
2008	1.17	$2,057,973	$2,967,257
2009	1.18	$2,028,556	$2,969,876
2010	1.19	$2,007,511	$2,986,320
2011	1.20	$1,993,969	$3,016,146
2012	1.22	$1,987,022	$3,058,899
2013	1.25	$1,985,706	$3,114,098
2014	1.28	$1,988,992	$3,181,217
2015	1.32	$1,995,760	$3,259,672
2016	1.36	$2,004,787	$3,348,806
2017	1.41	$2,014,725	$3,447,866
2018	1.47	$2,024,083	$3,555,991
2019	1.52	$2,031,206	$3,672,190
2020	1.59	$2,034,253	$3,795,320
2021	1.66	$2,031,176	$3,924,073
2022	1.73	$2,019,695	$4,056,945
2023	1.81	$1,997,275	$4,192,220
2024	1.90	$1,961,100	$4,327,945

Cumulative Groundwater Level Decline: 61.65 Feet
Present Value of Lower Bound Overdraft Costs: $85,151,545
Present Value of Upper Bound Overdraft Costs: $109,440,405

Table 4: Overdraft Costs in the No-Conservation Scenario

Year	Groundwater Level Decline (Feet)	---------Overdraft Costs-------- Lower Bound	Upper Bound
1985	2.49	$7,789,757	$8,769,717
1986	2.40	$7,305,901	$8,279,544
1987	2.31	$6,855,042	$7,822,552
1988	2.23	$6,435,281	$7,396,904
1989	2.16	$6,044,812	$7,000,859
1990	2.08	$5,681,915	$6,632,765
1991	2.01	$5,344,956	$6,291,065
1992	1.94	$5,032,383	$5,974,287
1993	1.88	$4,742,725	$5,681,048
1994	1.82	$4,474,588	$5,410,045
1995	1.76	$4,226,652	$5,160,059
1996	1.71	$3,997,667	$4,929,946
1997	1.66	$3,786,453	$4,718,640
1998	1.61	$3,591,891	$4,525,143
1999	1.57	$3,412,925	$4,348,529
2000	1.53	$3,248,555	$4,187,936
2001	1.49	$3,097,834	$4,042,563
2002	1.46	$2,959,862	$3,911,669
2003	1.43	$2,833,786	$3,794,566
2004	1.41	$2,718,791	$3,690,615
2005	1.38	$2,614,097	$3,599,226
2006	1.37	$2,518,954	$3,519,847
2007	1.35	$2,432,637	$3,451,966
2008	1.34	$2,354,441	$3,395,101
2009	1.33	$2,283,673	$3,348,798
2010	1.32	$2,219,649	$3,312,624
2011	1.32	$2,161,686	$3,286,163
2012	1.33	$2,109,095	$3,269,009
2013	1.33	$2,061,176	$3,260,760
2014	1.34	$2,017,211	$3,261,013
2015	1.35	$1,976,453	$3,269,356
2016	1.37	$1,938,124	$3,285,362
2017	1.39	$1,901,400	$3,308,581
2018	1.41	$1,865,411	$3,338,534
2019	1.44	$1,829,223	$3,374,701
2020	1.47	$1,791,835	$3,416,521
2021	1.50	$1,752,168	$3,463,374
2022	1.54	$1,709,055	$3,514,579
2023	1.58	$1,661,229	$3,569,381
2024	1.62	$1,607,313	$3,626,943

Cumulative Groundwater Level Decline: 65.02 Feet
Present Value of Lower Bound Overdraft Costs: $93,378,121
Present Value of Upper Bound Overdraft Costs: $118,997,359