**Title:** Economics of Groundwater Interaction and Competing Crops

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**Students:**

| Student Status | Number | Disciplines |
|---|---|---|
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| M.S. | | |
| Ph.D. | 1 | Agricultural Economics |
| Post Doc | | |
| Total | 1 | |

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**Publications:**

Ramaswamy K., A. Stoecker, J. Warren, R. Jones, S. Taghvaeian. 2017. "Choice of Irrigated Corn or Sorghum and Center Pivot or Sub Surface Drip in Oklahoma Panhandle" AAEA conference proceedings, Chicago, IL

Ramaswamy K., A. Stoecker, J. Warren, R. Jones, S. Taghvaeian. 2017. "Irrigation System Choice in Oklahoma Panhandle: Center Pivot versus Subsurface Drip" Oklahoma Governor's Water Conference, Norman, OK

Ramaswamy K., A. Stoecker, J. Warren, R. Jones, S. Taghvaeian. 2018. "Economics of a Potential Groundwater Management Area in Oklahoma Panhandle" Oklahoma Clean Lakes and Watershed Association, Stillwater, OK

**Problem and Research Objectives:**
The major irrigated crops in Oklahoma Panhandle area (OPA) are corn, sorghum, and winter wheat. Irrigated corn gives greater net returns than sorghum when well capacities are above 5 GPM per acre, but irrigated sorghum gives greater net returns than corn if well capacities decline below 5 GPM per acre. Completed studies show that it is more profitable to follow a long-term profit maximizing strategy by replacing irrigated corn with grain sorghum (uses less water) and conventional pivot irrigation with subsurface drip (SDI) when well capacity declines below 5 GPM per acre. Past conservation efforts to slow down the aquifer decline and establish the economic viability of the region have been mostly unsuccessful (Golden, 2017).

Economic valuation of irrigation research shows that producers gain the highest discounted benefits from limited groundwater by following a long-term profit maximizing (LPM) strategy (Ramaswamy, 2016). In this strategy, an LPM producer would use less water than the annual profit maximizing (APM) but irrigate for more years if the discounted net profit from using the saved water is higher in the future. However, it is argued that producers will not adopt the more profitable LPM strategy because they fear that any water saved for the future use will migrate toward and be used by an adjoining APM neighbor. However, it is expected the proportion of lateral groundwater loss from a contiguous group of LPM producers would be less than from a single LPM producer.

The project will determine the recommended optimal contiguous size of the land area that must be controlled or agreed upon to form a cooperative irrigation district (CID) to follow LPM strategies. Increasingly larger CIDs will be evaluated until a size is found where CID producers can utilize at least 90% of their expected groundwater.

Objectives
The overall objective of this research is to determine groundwater migration and observe the benefits of constructing a CID for planning periods of 30 or more years.

Specific objectives test hypothesis
1. To estimate well interference through lateral flows for different sized groups (1, 4, 9, 16, etc., 640-acre sections) of LPM in a CID surrounded by APM producers.

2. To quantify the effect of different hydraulic conductivities on the lateral movement of groundwater from each size of CID defined above surrounded by APM producers.

3. Determine the optimal contiguous size of land area that must be controlled or agreed upon by the producers to follow LPM strategies.

**Methodology:**
In this study, two groups of producers are assumed to compete for a common pool of groundwater. The APM group chooses crops (grain sorghum or corn) and irrigation levels that give maximum annual profits. The LPM group chooses crops and irrigation levels that maximize the net present value (NPV) from the remaining groundwater for 30 or more years. This is determined by a mathematical programming model assuming a

single cell aquifer. Each individual producer is assumed to have a 640-acre field with four wells. Initially, the producer could irrigate up to four 120-acre pivot circles. A representative section of land is shown below in Figure 1.

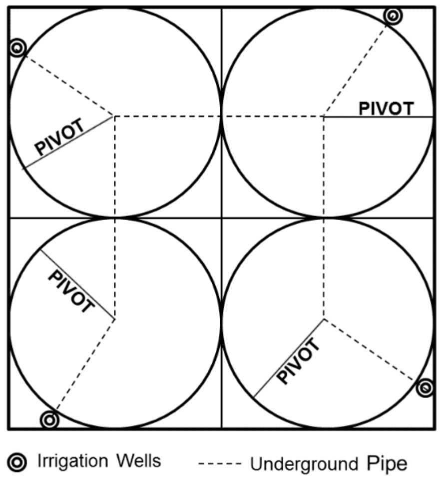


**Figure 1. Representative farm with a discharge wells of 600 GPM that are interconnected using underground pipe.**

The annual pumping rates for all producers are entered into a MODFLOW model which is used to simulate the combined pumping on aquifer levels over the planning period. The LPM water-level declines at a slower rate than APM level because the LPM uses less water annually. Therefore, LPM water table is expected to be at a higher level than that of an adjoining APM producer as shown in Table 1.

**Table 1. Expected Annual Water Use of LPM and APM producers with four wells on a 640 acre for 30 years**

| | Acre-feet per year | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Group | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17-30 |
| LPM | 461 | 461 | 321 | 185 | 185 | 185 | 185 | 185 | 217 | 238 | 238 | 213 | 209 | 209 | 209 | 230 | 104 |
| APM | 462 | 462 | 462 | 462 | 457 | 431 | 405 | 352 | 352 | 284 | 206 | 206 | 206 | 206 | 206 | 104 | 104 |

Various sizes of contiguous CID areas are tested for the LPM group. These are a single 640-acre irrigated section surrounded by eight APM sections, four 640-acre LPM producers surrounded by 12 APM sections, and a block of nine 640-acre LPM producers surrounded by 40 sections of APM producers. This continues until the block of LPM producers can retain at least 90 percent net benefits they would gain if all producers followed the LPM strategy. Representative CIDs surrounded by APM producers are shown in Figure 2a, 2b and 2c.

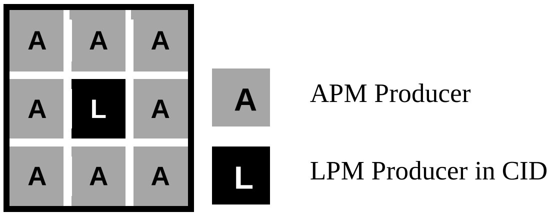


**Figure 2a. One LPM section surrounded by Eight APM sections**

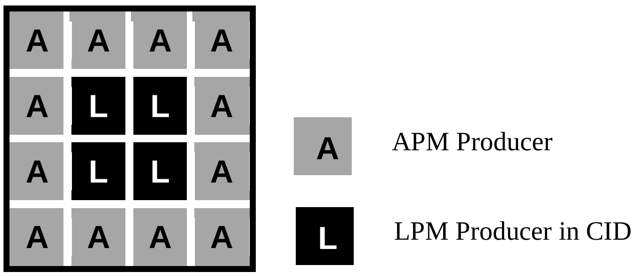


**Figure 2b. Four LPM sections surrounded by 12 APM sections**

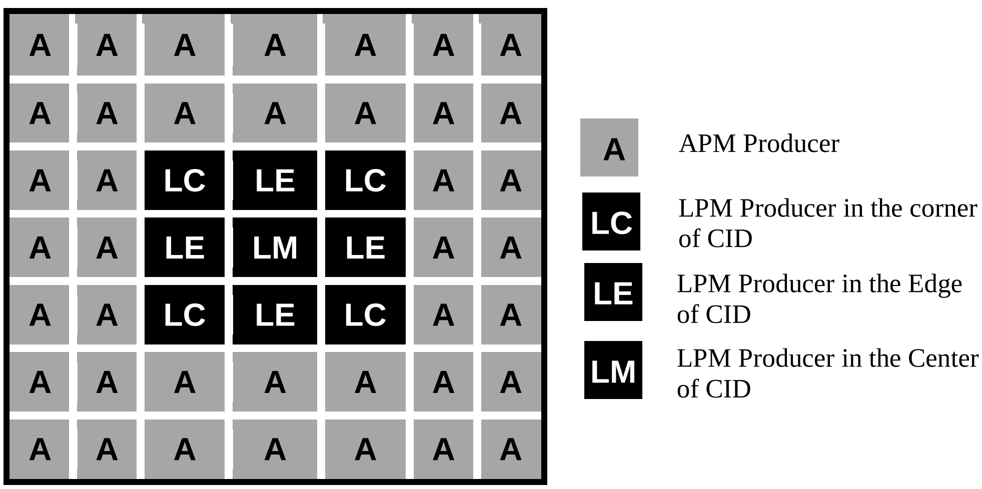


**Figure 2c. Nine LPM sections surrounded by 40 APM sections**

For each size of LPM group and surrounding APM, the hydrology parameters from United States Geological Survey (USGS) and Oklahoma Water Resources Board (OWRB) were collected and entered into the MODLOW model. The hydraulic conductivity in OPA ranges between 25 and 100 feet per day, and specific yield ranges between 0.12 and 0.24.

The optimal water use strategy (crop choice and water use given the current groundwater level) is determined by a multi-period mixed integer programming (MIP) model and the APM optimal water use strategy is determined by Recursive Linear Programming. Following each year the amount of groundwater flow from the CID producers to the surrounding APM producers is calculated. Groundwater interaction analysis are done in MODFLOW for contiguous land sizes and well locations. Drawdown effects on well interference and dewatering for a given saturated thickness are noted. The results for each size of CIDs lateral flow to the surrounding APM producers is compared to potential returns if all producers adopted the LPM strategy.

**Principal Findings and Significance:**

Preliminary results presented in this sections assume that the LPM producers in CID maximize the value of groundwater over a period of 30 years. The annual pumping rates are less than or equal to those in Table 1. The hydraulic conductivity for the current results is 25 feet per day. The specific yield is 0.175.

In the principal findings, three CID sizes were assessed using MODFLOW. In all the three scenarios, LPM producers in CID and surrounding APM producers start with 48 feet of saturated thickness. The maximum well capacity for LPM and APM producers is 600 GPM.

*Scenario 1: One LPM producer surrounded by Eight APM Producers*
In this scenario, the LPM producer's water table declined from 48 to 25.1 in year 10 as shown in Figure 3a. The water table in the CID declined to 13.7 in the year 20 as shown in Figure 3b. Figure 3c shows that the water table of LPM producer declined to 7.1 feet by year 30.

The annual groundwater migration from the LPM producer in CID is shown in Figure 3d. Expected total groundwater migration from the LPM producer in CID to the surrounding APM producers over 30 years is 852 acre-feet. Results show that LPM producer in the CID can retain up to 77% of potential groundwater saved. The water table and levels and lateral flow rates one LPM producer CID are compared to results of all producers following LPM. Summary of the scenario one results are provided in Table 2.

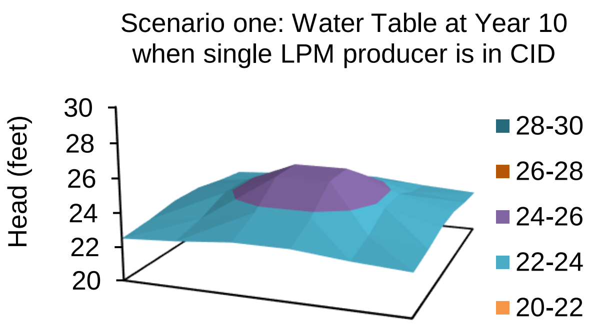


**Figure 3a. Water table level of one single LPM producer in CID surrounded by 8 APM producers at year 10**

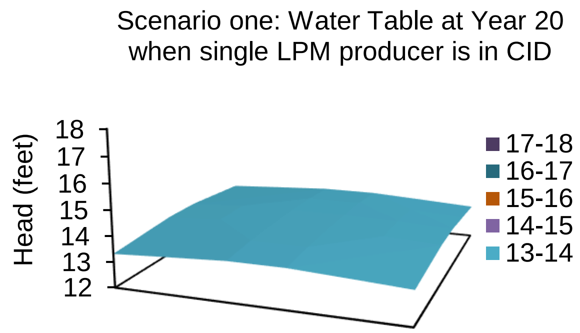


**Figure 3b. Water table level of one single LPM producer in CID surrounded by 8 APM producers at year 20**

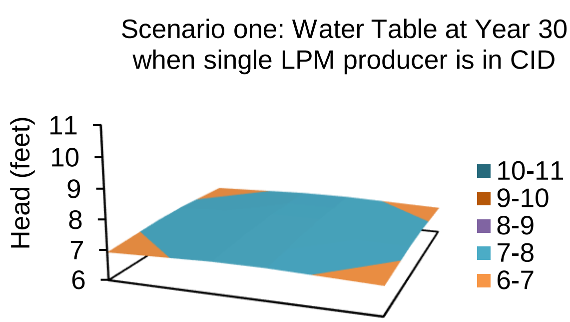


**Figure 3c. Water table level of one single LPM producer in CID surrounded by 8 APM producers at year 30**

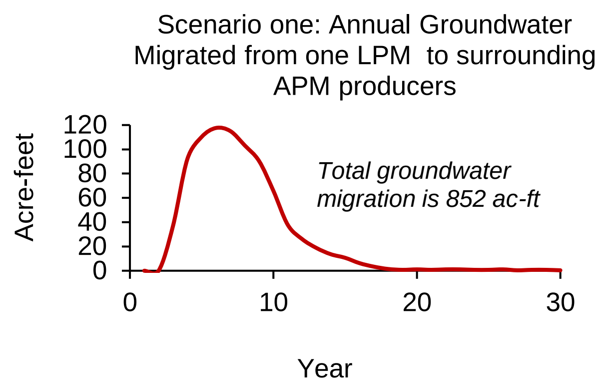


**Figure 3d. Annual groudwater migrated from the LPM producer in CID to surrounding APM producers**

*<u>Scenario two</u>: Four LPM producers surrounded by 12 APM Producers*

In the case of four LPM producers in CID are surrounded by 12 APM producers, the results of groundwater levels are shown in Figure 4a, 4b, and 4c. The water table of the CID producers declined to 27.4 in year 10 as shown in Figure 4a. In year 20, the water table declined to 15.4 feet as shown in Figure 4b. As shown in Figure 4c, the water table reached 8.6 feet in year 30.

The total groundwater migration from each LPM producer in the CID to the surrounding APM producers over 30 years is 659 acre-feet. Amount of annual groundwater migration from each LPM producers was shown in Figure 6d. Results show that LPM producers in this CID can retain up to 82% of potential groundwater saved. The results of groundwater levels and lateral flow rates are compared with results if all producers were following LPM use in Table 3.

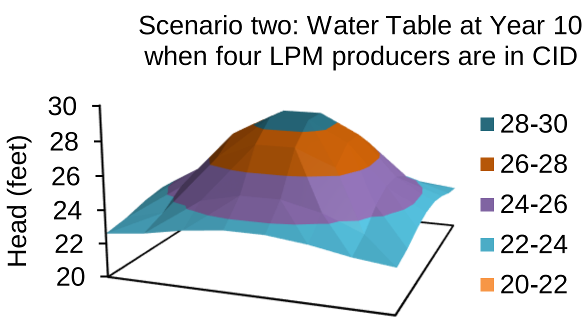


**Figure 4a. Water table level of four LPM producers in CID surrounded by 12 APM producers at year 10**

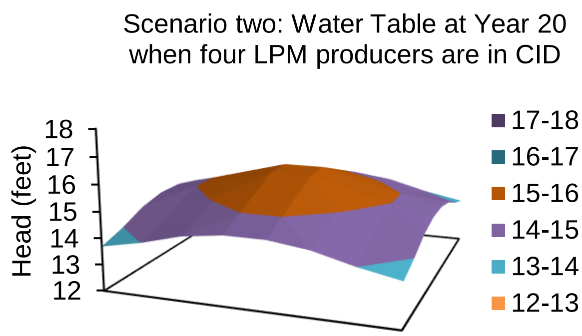


**Figure 4b. Water table level of four LPM producers surrounded by 12 APM producers in CID at year 20**

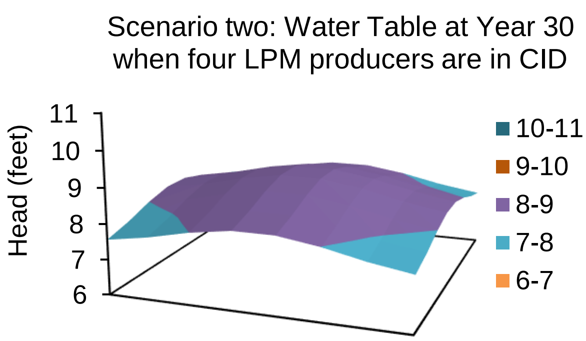


**Figure 4c. Water table level of four LPM producers in CID surrounded by 12 APM producers at year 30**

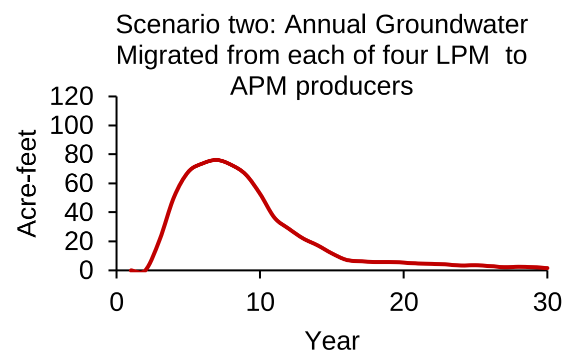


**Figure 4d. Annual groudwater migrated from each of four LPM producers in CID to surrounding APM producers**

*<u>Scenario three</u>: Nine LPM producers surrounded by 40 APM Producers*

If nine LPM producers in a CID are surrounded by 40 APM producers, the LPM producer in the corners and edges will save less water than the LPM producer in the center of CID. The water table for this scenario in year 10, 20, and 30 are shown in Figure 5a, 5b, and 5c respectively.

Groundwater level of the LPM producers on corners of the CID declined to 28.1 feet in year 10, by year 20 the water table declined to 16.2 feet, and by the end of year 30 water table reached to 9.3 feet. Results show that LPM producers in the corners of CID can retain up to 84% of potential groundwater saved. The water table and lateral flow results of this scenario is compared with the results of all producers are following LPM in Table 4.

LPM producers' groundwater level on edges of the CID decline to 29.2 feet in year 10, water table declined to 17.0 feet by year 20, and by end of year 30 the water table reached to 9.9 feet. LPM producers on edges of the CID can retain up to 86% of potential groundwater saved. The results of this scenario results are compared with the results of all producers are following LPM in Table 5.

In this scenario, the water table level of LPM producer in the center of CID declined from 30.6 in year 10, the water table declined to 17.9 in year 20, and by end of year 30 the water table reached to 10.5 feet. LPM producer in the center of CID can retain up to 88% of potential groundwater saved compared to results of all producers are following LPM. A summary of the scenario three results are provided in Table 6.

The corner LPM producers in scenario three are expected to lose 582 acre-feet over 30 years. The amount of groundwater migrated over 30 years from LPM producers on edges CID is 519 acre-feet and from the center LPM producers is 448 acre-feet. Amount of annual groundwater migration from each corner, edge, and center LPM producer are shown in Figure 5d.

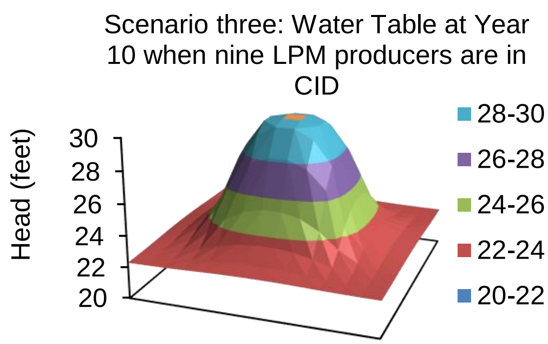


**Figure 5a. Water table level of nine LPM producers in CID surrounded by 40 APM producers at year 10**

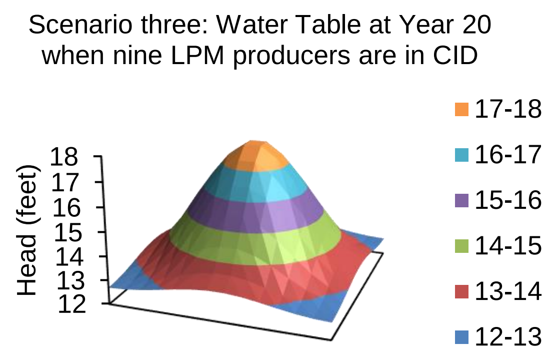


**Figure 5b. Water table level of nine LPM producers in CID surrounded by 40 APM producers at year 20**

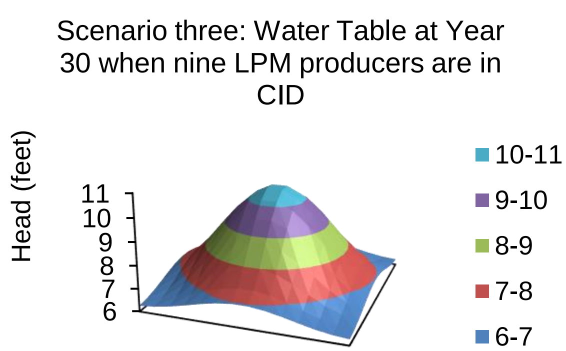


**Figure 5c. Water table level of nine LPM producers in CID surrounded by 40 APM producers at year 30**

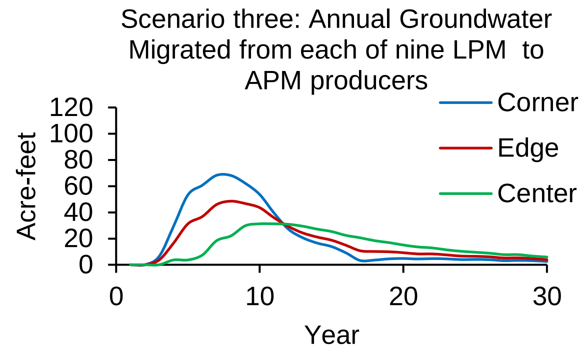


**Figure 5d. Annual groudwater migrated from each of nine LPM producers in CID to surrounding APM producers**

The water table decline rates for cases where all producers in the area were LTM and when all producers were APM producers are shown by the upper and lower lines in Figure 6. When there are 4 LPM or 9 LPM producers in a CID, the water table will be between the upper and lower levels in Figure 6. The LPM producers in nine section CID will retain between 84 and 88 % of the water supply they would have in all producers were LPM.

Results show that LPM can reduce the water migration to APM if the CID size is increased from one LPM section to four LPM sections. This research will continue until a size of CID is reached where 90% of the potential groundwater is saved (or only 10 % is lost by lateral flow) to surrounding APM producers. The research will be repeated with 50 feet per day hydraulic conductivity.

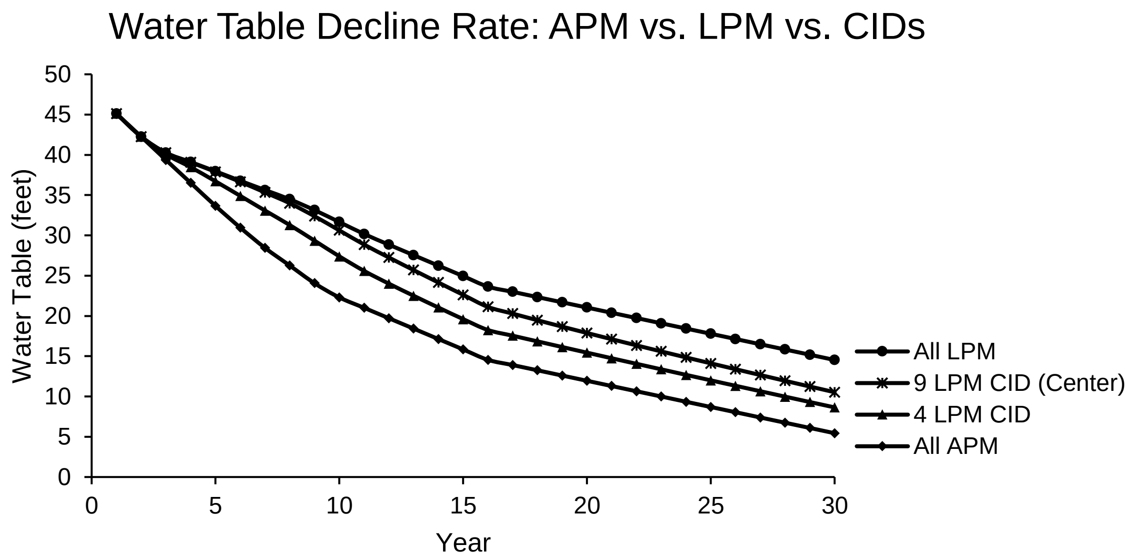


**Figure 6. Water table decline rate for a group of four and nine LPM producers in CID as compared to decline rates if all irrigators were LPM producers, and if all irrigators were APM producers.**

**Table 2. MODFLOW results for Scenario one – One LPM producer surrounded by Eight APM producers compared with results of all producers following LPM**

| | If all producers follow LPM | | | | | One LPM producer in CID surrounded by Eight APM producers | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | Beg Head (ft) | End Head (ft) | Change in Head (ft) | Water Used (ac-ft/Q.sec) | Water Used (ac-ft/sec) | Beg Head (ft) | End Head (ft) | Change in Head (ft) | Water Used (ac-ft/Q.sec) | Water Used (ac-ft/sec) | Water Lost by LPM to APM (ac-ft) |
| 1 | 48.0 | 45.1 | 2.9 | 80.8 | 323.4 | 48.00 | 45.11 | 2.9 | 80.8 | 323.4 | 0.0 |
| 2 | 45.1 | 42.3 | 2.9 | 79.9 | 319.7 | 45.11 | 42.26 | 2.9 | 79.9 | 319.7 | 0.0 |
| 3 | 42.3 | 40.3 | 2.0 | 56.0 | 224.1 | 42.26 | 39.93 | 2.3 | 65.2 | 260.9 | 36.7 |
| 4 | 40.3 | 39.1 | 1.1 | 32.2 | 128.6 | 39.93 | 37.96 | 2.0 | 55.1 | 220.5 | 91.9 |
| 5 | 39.1 | 38.0 | 1.1 | 32.2 | 128.6 | 37.96 | 35.83 | 2.1 | 59.7 | 238.8 | 110.2 |
| 6 | 38.0 | 36.8 | 1.2 | 33.1 | 132.3 | 35.83 | 33.60 | 2.2 | 62.5 | 249.9 | 117.6 |
| 7 | 36.8 | 35.6 | 1.1 | 32.2 | 128.6 | 33.60 | 31.42 | 2.2 | 60.9 | 243.6 | 115.0 |
| 8 | 35.6 | 34.5 | 1.1 | 32.2 | 128.6 | 31.42 | 29.35 | 2.1 | 58.0 | 231.9 | 103.3 |
| 9 | 34.5 | 33.1 | 1.3 | 37.7 | 150.7 | 29.35 | 27.20 | 2.2 | 60.3 | 241.0 | 90.4 |
| 10 | 33.1 | 31.7 | 1.5 | 41.3 | 165.4 | 27.20 | 25.13 | 2.1 | 57.8 | 231.1 | 65.8 |
| 11 | 31.7 | 30.2 | 1.5 | 41.5 | 166.1 | 25.13 | 23.31 | 1.8 | 51.0 | 203.9 | 37.8 |
| 12 | 30.2 | 28.8 | 1.3 | 37.2 | 148.8 | 23.31 | 21.75 | 1.6 | 43.7 | 174.9 | 26.1 |
| 13 | 28.8 | 27.5 | 1.3 | 36.5 | 145.9 | 21.75 | 20.28 | 1.5 | 41.2 | 164.6 | 18.7 |
| 14 | 27.5 | 26.2 | 1.3 | 36.5 | 145.9 | 20.28 | 18.86 | 1.4 | 39.9 | 159.5 | 13.6 |
| 15 | 26.2 | 24.9 | 1.3 | 36.4 | 145.5 | 18.86 | 17.46 | 1.4 | 39.0 | 156.2 | 10.7 |
| 16 | 24.9 | 23.6 | 1.3 | 36.5 | 139.6 | 17.46 | 16.22 | 1.2 | 34.9 | 145.9 | 6.3 |
| 17 | 23.6 | 23.0 | 0.6 | 18.2 | 72.8 | 16.22 | 15.66 | 0.6 | 15.6 | 73.7 | 0.9 |
| 18 | 23.0 | 22.3 | 0.7 | 18.3 | 73.1 | 15.66 | 15.02 | 0.6 | 17.9 | 73.7 | 0.6 |
| 19 | 22.3 | 21.7 | 0.6 | 18.2 | 72.8 | 15.02 | 14.36 | 0.7 | 18.4 | 73.5 | 0.7 |
| 20 | 21.7 | 21.0 | 0.6 | 18.2 | 72.8 | 14.36 | 13.70 | 0.7 | 18.5 | 73.4 | 0.6 |
| 21 | 21.0 | 20.4 | 0.7 | 18.3 | 73.1 | 13.70 | 13.04 | 0.7 | 18.5 | 73.9 | 0.7 |
| 22 | 20.4 | 19.7 | 0.6 | 18.2 | 72.8 | 13.04 | 12.39 | 0.7 | 18.5 | 73.1 | 0.3 |
| 23 | 19.7 | 19.1 | 0.6 | 18.2 | 72.8 | 12.39 | 11.73 | 0.7 | 18.5 | 73.9 | 1.1 |
| 24 | 19.1 | 18.4 | 0.7 | 18.3 | 73.1 | 11.73 | 11.07 | 0.7 | 18.5 | 73.9 | 0.7 |
| 25 | 18.4 | 17.8 | 0.6 | 18.2 | 72.8 | 11.07 | 10.41 | 0.7 | 18.4 | 73.5 | 0.7 |
| 26 | 17.8 | 17.1 | 0.6 | 18.2 | 72.8 | 10.41 | 9.75 | 0.7 | 18.5 | 73.9 | 1.1 |
| 27 | 17.1 | 16.5 | 0.7 | 18.3 | 73.1 | 9.75 | 9.09 | 0.7 | 18.4 | 73.5 | 0.4 |
| 28 | 16.5 | 15.8 | 0.6 | 18.2 | 72.8 | 9.09 | 8.44 | 0.7 | 18.4 | 73.5 | 0.7 |
| 29 | 15.8 | 15.2 | 0.6 | 18.2 | 72.8 | 8.44 | 7.78 | 0.7 | 18.4 | 73.5 | 0.7 |
| 30 | 15.2 | 14.5 | 0.7 | 18.3 | 73.1 | 7.78 | 7.13 | 0.7 | 18.4 | 73.5 | 0.4 |

**Table 3. MODFLOW results for Scenario Two – Four LPM producers surrounded by 12 APM producers compared with results of all producers following LPM**

| | If all producers follow LPM | | | | | Four LPM producers in CID surrounded by 12 APM producers | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | Beg Head (ft) | End Head (ft) | Change in Head (ft) | Water Used (ac-ft/Q.sec) | Water Used (ac-ft/sec) | Beg Head (ft) | End Head (ft) | Change in Head (ft) | Water Used (ac-ft/Q.sec) | Water Used (ac-ft/sec) | Water Lost by LPM to APM (ac-ft) |
| 1 | 48.0 | 45.1 | 2.9 | 80.8 | 323.4 | 48.0 | 45.1 | 2.9 | 80.8 | 323.4 | 0.0 |
| 2 | 45.1 | 42.3 | 2.9 | 79.9 | 319.7 | 45.1 | 42.3 | 2.9 | 79.9 | 319.7 | 0.0 |
| 3 | 42.3 | 40.3 | 2.0 | 56.0 | 224.1 | 42.3 | 40.1 | 2.2 | 61.3 | 245.3 | 21.1 |
| 4 | 40.3 | 39.1 | 1.1 | 32.2 | 128.6 | 40.1 | 38.5 | 1.6 | 44.8 | 179.1 | 50.5 |
| 5 | 39.1 | 38.0 | 1.1 | 32.2 | 128.6 | 38.5 | 36.7 | 1.8 | 49.1 | 196.6 | 68.0 |
| 6 | 38.0 | 36.8 | 1.2 | 33.1 | 132.3 | 36.7 | 34.9 | 1.8 | 50.5 | 202.1 | 69.8 |
| 7 | 36.8 | 35.6 | 1.1 | 32.2 | 128.6 | 34.9 | 33.1 | 1.8 | 51.2 | 204.8 | 76.2 |
| 8 | 35.6 | 34.5 | 1.1 | 32.2 | 128.6 | 33.1 | 31.3 | 1.8 | 50.3 | 201.4 | 72.8 |
| 9 | 34.5 | 33.1 | 1.3 | 37.7 | 150.7 | 31.3 | 29.3 | 1.9 | 54.2 | 216.8 | 66.1 |
| 10 | 33.1 | 31.7 | 1.5 | 41.3 | 165.4 | 29.3 | 27.4 | 1.9 | 54.5 | 218.1 | 52.7 |
| 11 | 31.7 | 30.2 | 1.5 | 41.5 | 166.1 | 27.4 | 25.6 | 1.8 | 50.6 | 202.5 | 36.4 |
| 12 | 30.2 | 28.8 | 1.3 | 37.2 | 148.8 | 25.6 | 24.0 | 1.6 | 44.4 | 177.6 | 28.8 |
| 13 | 28.8 | 27.5 | 1.3 | 36.5 | 145.9 | 24.0 | 22.5 | 1.5 | 42.0 | 167.9 | 22.0 |
| 14 | 27.5 | 26.2 | 1.3 | 36.5 | 145.9 | 22.5 | 21.0 | 1.5 | 41.0 | 164.1 | 18.2 |
| 15 | 26.2 | 24.9 | 1.3 | 36.4 | 145.5 | 21.0 | 19.6 | 1.4 | 40.2 | 160.8 | 15.2 |
| 16 | 24.9 | 23.6 | 1.3 | 36.5 | 139.6 | 19.6 | 18.3 | 1.4 | 37.9 | 151.6 | 5.7 |
| 17 | 23.6 | 23.0 | 0.6 | 18.2 | 72.8 | 18.3 | 17.5 | 0.7 | 19.8 | 79.1 | 6.3 |
| 18 | 23.0 | 22.3 | 0.7 | 18.3 | 73.1 | 17.5 | 16.8 | 0.7 | 19.8 | 79.0 | 5.9 |
| 19 | 22.3 | 21.7 | 0.6 | 18.2 | 72.8 | 16.8 | 16.1 | 0.7 | 19.7 | 78.6 | 5.9 |
| 20 | 21.7 | 21.0 | 0.6 | 18.2 | 72.8 | 16.1 | 15.4 | 0.7 | 19.5 | 78.2 | 5.4 |
| 21 | 21.0 | 20.4 | 0.7 | 18.3 | 73.1 | 15.4 | 14.7 | 0.7 | 19.5 | 77.9 | 4.8 |
| 22 | 20.4 | 19.7 | 0.6 | 18.2 | 72.8 | 14.7 | 14.1 | 0.7 | 19.3 | 77.3 | 4.6 |
| 23 | 19.7 | 19.1 | 0.6 | 18.2 | 72.8 | 14.1 | 13.4 | 0.7 | 19.2 | 76.9 | 4.1 |
| 24 | 19.1 | 18.4 | 0.7 | 18.3 | 73.1 | 13.4 | 12.7 | 0.7 | 19.1 | 76.5 | 3.4 |
| 25 | 18.4 | 17.8 | 0.6 | 18.2 | 72.8 | 12.7 | 12.0 | 0.7 | 19.1 | 76.3 | 3.6 |
| 26 | 17.8 | 17.1 | 0.6 | 18.2 | 72.8 | 12.0 | 11.3 | 0.7 | 18.9 | 75.8 | 3.0 |
| 27 | 17.1 | 16.5 | 0.7 | 18.3 | 73.1 | 11.3 | 10.7 | 0.7 | 18.9 | 75.4 | 2.3 |
| 28 | 16.5 | 15.8 | 0.6 | 18.2 | 72.8 | 10.7 | 10.0 | 0.7 | 18.8 | 75.3 | 2.6 |
| 29 | 15.8 | 15.2 | 0.6 | 18.2 | 72.8 | 10.0 | 9.3 | 0.7 | 18.8 | 75.1 | 2.3 |
| 30 | 15.2 | 14.5 | 0.7 | 18.3 | 73.1 | 9.3 | 8.6 | 0.7 | 18.7 | 74.8 | 1.7 |

**Table 4. MODFLOW results for Scenario Three (Corner Wells)- Nine LPM sections surrounded by 40 APM sections compared with results of all producers following LPM**

| | If all producers follow LPM | | | | | Four LPM producers in CID surrounded by 40 APM producers | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | Beg Head (ft) | End Head (ft) | Change in Head (ft) | Water Used (ac-ft/Q.sec) | Water Used (ac-ft/sec) | Beg Head (ft) | End Head (ft) | Change in Head (ft) | Water Used (ac-ft/Q.sec) | Water Used (ac-ft/sec) | Water Lost by LPM to APM (ac-ft) |
| 1 | 48.0 | 45.1 | 2.9 | 80.8 | 323.4 | 48.0 | 45.1 | 2.9 | 80.8 | 323.4 | 0.0 |
| 2 | 45.1 | 42.3 | 2.9 | 79.9 | 319.7 | 45.1 | 42.3 | 2.9 | 79.9 | 319.7 | 0.0 |
| 3 | 42.3 | 40.3 | 2.0 | 56.0 | 224.1 | 42.3 | 40.2 | 2.1 | 57.6 | 230.6 | 6.4 |
| 4 | 40.3 | 39.1 | 1.1 | 32.2 | 128.6 | 40.2 | 38.8 | 1.4 | 39.5 | 158.0 | 29.4 |
| 5 | 39.1 | 38.0 | 1.1 | 32.2 | 128.6 | 38.8 | 37.2 | 1.6 | 45.5 | 181.9 | 53.3 |
| 6 | 38.0 | 36.8 | 1.2 | 33.1 | 132.3 | 37.2 | 35.4 | 1.7 | 48.2 | 192.9 | 60.6 |
| 7 | 36.8 | 35.6 | 1.1 | 32.2 | 128.6 | 35.4 | 33.7 | 1.8 | 49.2 | 196.9 | 68.3 |
| 8 | 35.6 | 34.5 | 1.1 | 32.2 | 128.6 | 33.7 | 31.9 | 1.8 | 49.2 | 196.7 | 68.1 |
| 9 | 34.5 | 33.1 | 1.3 | 37.7 | 150.7 | 31.9 | 30.0 | 1.9 | 53.2 | 212.8 | 62.1 |
| 10 | 33.1 | 31.7 | 1.5 | 41.3 | 165.4 | 30.0 | 28.1 | 2.0 | 54.7 | 218.9 | 53.6 |
| 11 | 31.7 | 30.2 | 1.5 | 41.5 | 166.1 | 28.1 | 26.2 | 1.8 | 51.4 | 205.5 | 39.4 |
| 12 | 30.2 | 28.8 | 1.3 | 37.2 | 148.8 | 26.2 | 24.7 | 1.6 | 44.0 | 175.9 | 27.1 |
| 13 | 28.8 | 27.5 | 1.3 | 36.5 | 145.9 | 24.7 | 23.2 | 1.5 | 41.6 | 166.5 | 20.6 |
| 14 | 27.5 | 26.2 | 1.3 | 36.5 | 145.9 | 23.2 | 21.7 | 1.5 | 40.6 | 162.4 | 16.5 |
| 15 | 26.2 | 24.9 | 1.3 | 36.4 | 145.5 | 21.7 | 20.3 | 1.4 | 39.8 | 159.4 | 13.9 |
| 16 | 24.9 | 23.6 | 1.3 | 36.5 | 139.6 | 20.3 | 18.9 | 1.4 | 38.7 | 155.0 | 9.1 |
| 17 | 23.6 | 23.0 | 0.6 | 18.2 | 72.8 | 18.9 | 18.2 | 0.7 | 19.0 | 76.0 | 3.2 |
| 18 | 23.0 | 22.3 | 0.7 | 18.3 | 73.1 | 18.2 | 17.6 | 0.7 | 19.2 | 76.7 | 3.6 |
| 19 | 22.3 | 21.7 | 0.6 | 18.2 | 72.8 | 17.6 | 16.9 | 0.7 | 19.3 | 77.3 | 4.5 |
| 20 | 21.7 | 21.0 | 0.6 | 18.2 | 72.8 | 16.9 | 16.2 | 0.7 | 19.4 | 77.5 | 4.8 |
| 21 | 21.0 | 20.4 | 0.7 | 18.3 | 73.1 | 16.2 | 15.5 | 0.7 | 19.4 | 77.5 | 4.4 |
| 22 | 20.4 | 19.7 | 0.6 | 18.2 | 72.8 | 15.5 | 14.8 | 0.7 | 19.4 | 77.4 | 4.7 |
| 23 | 19.7 | 19.1 | 0.6 | 18.2 | 72.8 | 14.8 | 14.1 | 0.7 | 19.3 | 77.3 | 4.5 |
| 24 | 19.1 | 18.4 | 0.7 | 18.3 | 73.1 | 14.1 | 13.4 | 0.7 | 19.3 | 77.1 | 4.0 |
| 25 | 18.4 | 17.8 | 0.6 | 18.2 | 72.8 | 13.4 | 12.7 | 0.7 | 19.2 | 76.8 | 4.0 |
| 26 | 17.8 | 17.1 | 0.6 | 18.2 | 72.8 | 12.7 | 12.0 | 0.7 | 19.2 | 76.6 | 3.9 |
| 27 | 17.1 | 16.5 | 0.7 | 18.3 | 73.1 | 12.0 | 11.4 | 0.7 | 19.1 | 76.2 | 3.1 |
| 28 | 16.5 | 15.8 | 0.6 | 18.2 | 72.8 | 11.4 | 10.7 | 0.7 | 19.0 | 76.1 | 3.3 |
| 29 | 15.8 | 15.2 | 0.6 | 18.2 | 72.8 | 10.7 | 10.0 | 0.7 | 19.0 | 75.9 | 3.1 |
| 30 | 15.2 | 14.5 | 0.7 | 18.3 | 73.1 | 10.0 | 9.3 | 0.7 | 18.9 | 75.6 | 2.5 |

**Table 5. MODFLOW results for Scenario Three (Edge Wells)- Nine LPM sections surrounded by 40 APM sections**

| | Independent LPM section | | | | | Four LPM sections in CID | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | Beg Head (ft) | End Head (ft) | Change in Head (ft) | Water Used (ac-ft/Q.sec) | Water Used (ac-ft/sec) | Beg Head (ft) | End Head (ft) | Change in Head (ft) | Water Used (ac-ft/Q.sec) | Water Used (ac-ft/sec) | Water Lost by LPM to APM (ac-ft) |
| 1 | 48.0 | 45.1 | 2.9 | 80.8 | 323.4 | 48.0 | 45.1 | 2.9 | 80.8 | 323.4 | 0.0 |
| 2 | 45.1 | 42.3 | 2.9 | 79.9 | 319.7 | 45.1 | 42.3 | 2.9 | 79.9 | 319.7 | 0.0 |
| 3 | 42.3 | 40.3 | 2.0 | 56.0 | 224.1 | 42.3 | 40.2 | 2.0 | 57.0 | 227.8 | 3.7 |
| 4 | 40.3 | 39.1 | 1.1 | 32.2 | 128.6 | 40.2 | 38.9 | 1.3 | 36.3 | 145.1 | 16.5 |
| 5 | 39.1 | 38.0 | 1.1 | 32.2 | 128.6 | 38.9 | 37.5 | 1.4 | 40.0 | 159.8 | 31.2 |
| 6 | 38.0 | 36.8 | 1.2 | 33.1 | 132.3 | 37.5 | 36.0 | 1.5 | 42.3 | 169.0 | 36.7 |
| 7 | 36.8 | 35.6 | 1.1 | 32.2 | 128.6 | 36.0 | 34.4 | 1.6 | 43.6 | 174.5 | 45.9 |
| 8 | 35.6 | 34.5 | 1.1 | 32.2 | 128.6 | 34.4 | 32.9 | 1.6 | 44.3 | 177.1 | 48.5 |
| 9 | 34.5 | 33.1 | 1.3 | 37.7 | 150.7 | 32.9 | 31.1 | 1.8 | 49.3 | 197.3 | 46.7 |
| 10 | 33.1 | 31.7 | 1.5 | 41.3 | 165.4 | 31.1 | 29.2 | 1.9 | 52.2 | 208.9 | 43.5 |
| 11 | 31.7 | 30.2 | 1.5 | 41.5 | 166.1 | 29.2 | 27.4 | 1.8 | 50.5 | 201.9 | 35.8 |
| 12 | 30.2 | 28.8 | 1.3 | 37.2 | 148.8 | 27.4 | 25.8 | 1.6 | 44.5 | 178.0 | 29.2 |
| 13 | 28.8 | 27.5 | 1.3 | 36.5 | 145.9 | 25.8 | 24.3 | 1.5 | 42.5 | 170.1 | 24.3 |
| 14 | 27.5 | 26.2 | 1.3 | 36.5 | 145.9 | 24.3 | 22.8 | 1.5 | 41.8 | 167.0 | 21.1 |
| 15 | 26.2 | 24.9 | 1.3 | 36.4 | 145.5 | 22.8 | 21.4 | 1.5 | 41.1 | 164.3 | 18.7 |
| 16 | 24.9 | 23.6 | 1.3 | 36.5 | 139.6 | 21.4 | 19.9 | 1.4 | 40.2 | 160.8 | 14.9 |
| 17 | 23.6 | 23.0 | 0.6 | 18.2 | 72.8 | 19.9 | 19.2 | 0.7 | 20.9 | 83.4 | 10.7 |
| 18 | 23.0 | 22.3 | 0.7 | 18.3 | 73.1 | 19.2 | 18.4 | 0.7 | 20.8 | 83.2 | 10.1 |
| 19 | 22.3 | 21.7 | 0.6 | 18.2 | 72.8 | 18.4 | 17.7 | 0.7 | 20.7 | 82.7 | 9.9 |
| 20 | 21.7 | 21.0 | 0.6 | 18.2 | 72.8 | 17.7 | 17.0 | 0.7 | 20.5 | 81.9 | 9.2 |
| 21 | 21.0 | 20.4 | 0.7 | 18.3 | 73.1 | 17.0 | 16.2 | 0.7 | 20.3 | 81.4 | 8.3 |
| 22 | 20.4 | 19.7 | 0.6 | 18.2 | 72.8 | 16.2 | 15.5 | 0.7 | 20.3 | 81.0 | 8.3 |
| 23 | 19.7 | 19.1 | 0.6 | 18.2 | 72.8 | 15.5 | 14.8 | 0.7 | 20.1 | 80.3 | 7.5 |
| 24 | 19.1 | 18.4 | 0.7 | 18.3 | 73.1 | 14.8 | 14.1 | 0.7 | 19.9 | 79.7 | 6.6 |
| 25 | 18.4 | 17.8 | 0.6 | 18.2 | 72.8 | 14.1 | 13.4 | 0.7 | 19.8 | 79.2 | 6.4 |
| 26 | 17.8 | 17.1 | 0.6 | 18.2 | 72.8 | 13.4 | 12.7 | 0.7 | 19.7 | 78.8 | 6.1 |
| 27 | 17.1 | 16.5 | 0.7 | 18.3 | 73.1 | 12.7 | 12.0 | 0.7 | 19.6 | 78.3 | 5.1 |
| 28 | 16.5 | 15.8 | 0.6 | 18.2 | 72.8 | 12.0 | 11.3 | 0.7 | 19.5 | 78.0 | 5.2 |
| 29 | 15.8 | 15.2 | 0.6 | 18.2 | 72.8 | 11.3 | 10.6 | 0.7 | 19.4 | 77.4 | 4.7 |
| 30 | 15.2 | 14.5 | 0.7 | 18.3 | 73.1 | 10.6 | 9.9 | 0.7 | 19.2 | 77.0 | 3.9 |

**Table 6. MODFLOW results for Scenario Three (Center Well)- Nine LPM sections surrounded by 40 APM sections**

| | Independent LPM section | | | | | Four LPM sections in CID | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | Beg Head (ft) | End Head (ft) | Change in Head (ft) | Water Used (ac-ft/Q.sec) | Water Used (ac-ft/sec) | Beg Head (ft) | End Head (ft) | Change in Head (ft) | Water Used (ac-ft/Q.sec) | Water Used (ac-ft/sec) | Water Lost by LPM to APM (ac-ft) |
| 1 | 48.0 | 45.1 | 2.9 | 80.8 | 323.4 | 48.0 | 45.1 | 2.9 | 80.8 | 323.4 | 0.0 |
| 2 | 45.1 | 42.3 | 2.9 | 79.9 | 319.7 | 45.1 | 42.3 | 2.9 | 79.9 | 319.7 | 0.0 |
| 3 | 42.3 | 40.3 | 2.0 | 56.0 | 224.1 | 42.3 | 40.3 | 2.0 | 56.0 | 224.1 | 0.0 |
| 4 | 40.3 | 39.1 | 1.1 | 32.2 | 128.6 | 40.3 | 39.1 | 1.2 | 33.1 | 132.3 | 3.7 |
| 5 | 39.1 | 38.0 | 1.1 | 32.2 | 128.6 | 39.1 | 37.9 | 1.2 | 33.1 | 132.3 | 3.7 |
| 6 | 38.0 | 36.8 | 1.2 | 33.1 | 132.3 | 37.9 | 36.6 | 1.2 | 34.9 | 139.6 | 7.3 |
| 7 | 36.8 | 35.6 | 1.1 | 32.2 | 128.6 | 36.6 | 35.3 | 1.3 | 36.7 | 147.0 | 18.4 |
| 8 | 35.6 | 34.5 | 1.1 | 32.2 | 128.6 | 35.3 | 34.0 | 1.3 | 37.7 | 150.7 | 22.0 |
| 9 | 34.5 | 33.1 | 1.3 | 37.7 | 150.7 | 34.0 | 32.4 | 1.6 | 45.1 | 180.4 | 29.8 |
| 10 | 33.1 | 31.7 | 1.5 | 41.3 | 165.4 | 32.4 | 30.6 | 1.8 | 49.1 | 196.6 | 31.2 |
| 11 | 31.7 | 30.2 | 1.5 | 41.5 | 166.1 | 30.6 | 28.9 | 1.8 | 49.3 | 197.3 | 31.2 |
| 12 | 30.2 | 28.8 | 1.3 | 37.2 | 148.8 | 28.9 | 27.3 | 1.6 | 44.9 | 179.7 | 30.9 |
| 13 | 28.8 | 27.5 | 1.3 | 36.5 | 145.9 | 27.3 | 25.7 | 1.6 | 43.8 | 175.3 | 29.4 |
| 14 | 27.5 | 26.2 | 1.3 | 36.5 | 145.9 | 25.7 | 24.1 | 1.5 | 43.3 | 173.1 | 27.2 |
| 15 | 26.2 | 24.9 | 1.3 | 36.4 | 145.5 | 24.1 | 22.6 | 1.5 | 42.7 | 170.9 | 25.4 |
| 16 | 24.9 | 23.6 | 1.3 | 36.5 | 139.6 | 22.6 | 21.1 | 1.5 | 42.1 | 168.3 | 22.4 |
| 17 | 23.6 | 23.0 | 0.6 | 18.2 | 72.8 | 21.1 | 20.3 | 0.8 | 23.3 | 93.3 | 20.6 |
| 18 | 23.0 | 22.3 | 0.7 | 18.3 | 73.1 | 20.3 | 19.5 | 0.8 | 22.9 | 91.5 | 18.4 |
| 19 | 22.3 | 21.7 | 0.6 | 18.2 | 72.8 | 19.5 | 18.7 | 0.8 | 22.4 | 89.7 | 16.9 |
| 20 | 21.7 | 21.0 | 0.6 | 18.2 | 72.8 | 18.7 | 17.9 | 0.8 | 22.0 | 87.8 | 15.1 |
| 21 | 21.0 | 20.4 | 0.7 | 18.3 | 73.1 | 17.9 | 17.1 | 0.8 | 21.7 | 86.7 | 13.6 |
| 22 | 20.4 | 19.7 | 0.6 | 18.2 | 72.8 | 17.1 | 16.3 | 0.8 | 21.4 | 85.6 | 12.9 |
| 23 | 19.7 | 19.1 | 0.6 | 18.2 | 72.8 | 16.3 | 15.6 | 0.8 | 21.0 | 84.1 | 11.4 |
| 24 | 19.1 | 18.4 | 0.7 | 18.3 | 73.1 | 15.6 | 14.8 | 0.7 | 20.9 | 83.4 | 10.3 |
| 25 | 18.4 | 17.8 | 0.6 | 18.2 | 72.8 | 14.8 | 14.1 | 0.7 | 20.6 | 82.3 | 9.6 |
| 26 | 17.8 | 17.1 | 0.6 | 18.2 | 72.8 | 14.1 | 13.4 | 0.7 | 20.4 | 81.6 | 8.8 |
| 27 | 17.1 | 16.5 | 0.7 | 18.3 | 73.1 | 13.4 | 12.7 | 0.7 | 20.2 | 80.8 | 7.7 |
| 28 | 16.5 | 15.8 | 0.6 | 18.2 | 72.8 | 12.7 | 11.9 | 0.7 | 20.1 | 80.5 | 7.7 |
| 29 | 15.8 | 15.2 | 0.6 | 18.2 | 72.8 | 11.9 | 11.2 | 0.7 | 19.8 | 79.4 | 6.6 |
| 30 | 15.2 | 14.5 | 0.7 | 18.3 | 73.1 | 11.2 | 10.5 | 0.7 | 19.8 | 79.0 | 5.9 |

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