Title: Economics of Groundwater Interaction and Competing Crops

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

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Publications:

Ramaswamy, K & A.L. Stoecker. 2018. "Economics of Cooperative Irrigation District in Oklahoma Panhandle" Paper Presented at Oklahoma Governor's Water Conference & Research Symposium, Midwest City, OK, Dec. 5-6.

Ramaswamy, K., A.L. Stoecker, R. D. Jones, J. G. Warren, S. Taghvaeian. 2018. “Economics of Groundwater Interaction and Competing Producers” Paper Presented at Agricultural & Applied Economics Association Annual Meeting, Washington, D.C., Aug 5-7.

Ramaswamy, K., A. L. Stoecker, J. G. Warren, S. Taghvaeian, R. D. Jones. 2018. “Economics of Potential Groundwater Management Area in Oklahoma Panhandle” Poster Presented at Oklahoma Clean Lakes and Watershed Association, Stillwater, OK, Apr 4-5.

Introduction

Irrigated in Oklahoma Panhandle began at the beginning of the last century and steadily increased until the 1950s. Advancement in drill techniques, crop genetics, and groundwater laws during the second half of the century have rapidly increased irrigation wells and irrigated acres in the Oklahoma Panhandle counties (OPC). The OPC consists of Beaver, Cimarron, and Texas counties. The total area of OPC is 14,784 square kilometers, and almost 90 percent of the OPC area overlies Ogallala aquifer. Since 1934, OPC had about 36 irrigation wells and irrigated land was less than 2,057 hectares (OWRB, 2018 and NASS, 2012). In 1954, the irrigated area in OPA were 5,601 with 184 wells. By 1974, the total irrigation wells in OPC reached 1,566 and irrigated area increased to 102,653 hectares. This peak increase of irrigated land in OPC is mainly due to the development of drilling techniques and groundwater law imposed in 1949 under appropriation doctrine. Unfortunately, development of irrigation has resulted in severe groundwater declined in OPC. United States Geological Survey (USGS) groundwater monitoring program shows that the groundwater level in some parts of OPA has declined up to 100 feet (McGuire, 2017).

The major irrigated crops in the Oklahoma Panhandle area (OPA) are corn, sorghum, and winter wheat. Previous Oklahoma Water Resource Center (OKWRC) reports have shown that irrigated corn gives greater net returns than grain sorghum when well capacities are above 39.1 lit min^{-1} ha^{-1}. But, irrigated sorghum gives greater net returns than corn when well capacities decline below 39.1 lit min^{-1} ha^{-1} (Warren et al., 2016). Completed economic valuation of irrigation study (Ramaswamy, 2016) shows that it is more profitable to follow a long-term profit maximizing (LPM) strategy by replacing irrigated corn with grain sorghum when the well capacity declines below 39.1 lit min^{-1} ha^{-1}.

LPM producer uses less water than the annual profit maximizing (APM) but irrigates 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. 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. Thus, forming an irrigating district and following LPM could be a better choice than past efforts made by the producers. Because, past conservation efforts to slow down the aquifer decline and establish the economic viability of the region have been mostly unsuccessful (Golden, 2017).

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, and 9, 259-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

Drawdown calculation

The Ogallala aquifer underlying OPC has heterogeneous characteristics. The major aquifer properties that influence the pumping behavior is hydraulic conductivity (K) and specific yield (S). The varying K in OPC is shown in Figure 1. The first step of this project was to determine the maximum drawdown possible for 90 days of pumping at K = 7.62, 15.24, and 30.48 m/day and S = 0.125, 0.175, and 0.225 for well capacities (WC) 380, 760, ..., 2,280 lit min^{-1}. Throughout this study, it is assumed that the maximum WC available to pump is 2,280 lit min^{-1}.

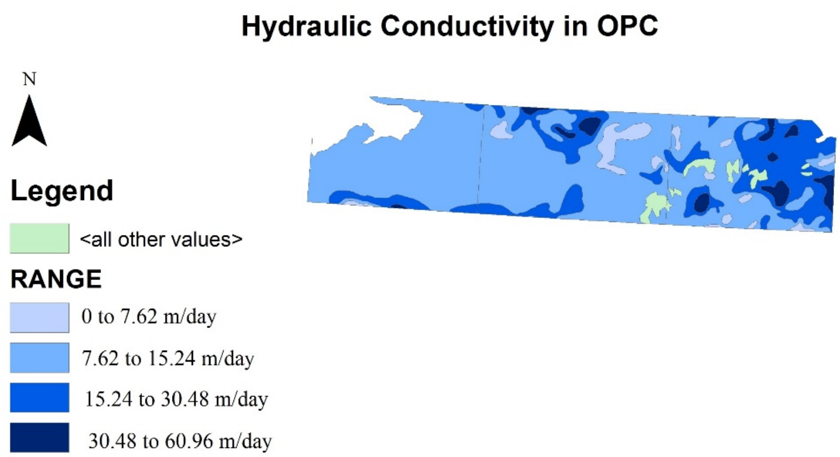

Figure 1. Range of Hydraulic Conductivity of Ogallala Aquifer underlying OPC (OWRB)

The following notation from Cooper-Jacob, 1946 was used to determine the drawdown at various *K* and *S*.

$$D_{ijk} = \frac{Q_i}{4\pi T_j}\left[-0.577216 - \ln\left(\frac{r^2 S_k}{4T_j t}\right)\right]$$

where,

D_{ijk} is the drawdown for well capacity i, hydraulic conductivity j and specific yield k,
Q_i is the discharge rate (well capacity) $i = 380, 760, \ldots 2{,}280\ lit\ min^{-1}$
T_j is the transmissivity with the hydraulic conductivity (K) $j = 7.62, 15.24, and\ 30.48\ m/day$; $T = K \times H$, where H is the required saturated thickness to pump Q,
r is the distance from the well; here $r = 0.3\ m$,
S_k is the specific yield (S) $k = 0.125, 0.175, and\ 0.225$,
t is the duration of pumping Q; here $t = 90\ days$.

Table 1. Drawdown sustaining for pumping 90 days at various hydraulic conductivity (*K*) and specific yield (*S*)

Well capacity			Drawdown (m) $K = 7.62\ m\ day^{-1}$			$K = 15.24\ m\ day^{-1}$			$K = 30.48\ m\ day^{-1}$		
gal min^{-1}	*lit min*$^{-1}$	*m*^{3} *day*$^{-1}$	$S = 0.125$	$S = 0.175$	$S = 0.225$	$S = 0.125$	$S = 0.175$	$S = 0.225$	$S = 0.125$	$S = 0.175$	$S = 0.225$
600	2,280	3,270	17.98	17.68	17.68	11.89	11.58	11.58	7.62	7.32	7.32
500	1,900	2,725	16.15	15.85	15.54	10.36	10.36	10.36	6.71	6.4	6.4
400	1,520	2,180	14.02	13.72	13.41	8.84	8.84	8.84	5.79	5.49	5.49
300	1,140	1,635	11.58	11.28	11.28	7.32	7.32	7.01	4.57	4.57	4.27
200	760	1,090	8.84	8.53	8.53	5.49	5.49	5.18	3.35	3.35	3.05
100	380	545	5.49	5.18	5.18	3.05	3.05	3.05	1.83	1.83	1.83

A 10.7 m of saturated sand was assumed as safety zone. Adding the safety zone to the drawdown is the required saturated thickness for pumping 90 days at above well capacities.

To estimate the pumping cost for the crop activities, the drawdown was calculated depending on the amount of the irrigation applied and number of days required to complete the irrigation.

Representative farm

LPM and APM individual producers assumed to have a 259-ha field with four wells. Initially, the producer could irrigate up to four 48.6-ha using center pivot (CP). A representative section of land is shown below in Figure 2.

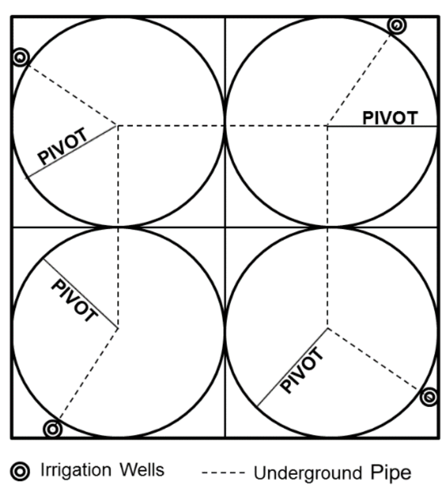

Figure 2. Representative farm with a discharge wells of 600 GPM that are interconnected using underground pipe.

Water Supply Calculation

The required saturated thickness was split into six layers. The size of the layer is the minimum thickness required to sustain 90 days of pumping the WC 380, 760, ..., 2,280 lit min^{-1}. The available water supply for each producer is the groundwater beneath the 259-ha land. Size of the each layer for various K and S is shown in Table 2. Total water supply available for each WC to pump is listed in the Table 3. Total supply of groundwater available for each producer is calculated as,

$$W_{ijkt} = A \times C_{ijk} \times S_k$$

where,

WS_{ijk} is the water supply available to pump at WC i from aquifer with hydraulic conductivity j and specific yield k,

A is the area of land owned by each producer; here 259 hectares,

C_{ijk} is the size of the aquifer layer with WC i, hydraulic conductivity j, and specific yield k,

S_k is the specific yield k.

Table 2. Aquifer layer size at various hydraulic conductivity (*K*) and specific yield (*S*)

Well capacity			Aquifer layer size (m)								
			K = 7.62 *m day*$^{-1}$			*K* = 15.24 *m day*$^{-1}$			*K* = 30.48 *m day-*^{1}		
gal min^{-1}	lit min^{-1}	m^3 day^{-1}	*S* = 0.125	*S* = 0.175	*S* = 0.225	*S* = 0.125	*S* = 0.175	*S* = 0.225	*S* = 0.125	*S* = 0.175	*S* = 0.225
600	2,280	3,270	3.35	3.35	3.35	2.44	2.44	2.13	1.52	1.52	1.22
500	1,900	2,725	2.74	2.74	2.74	1.83	1.83	1.83	1.22	1.22	1.22
400	1,520	2,180	2.44	2.44	2.13	1.52	1.52	1.83	1.22	0.91	1.22
300	1,140	1,635	2.13	2.13	2.13	1.52	1.52	1.52	0.91	0.91	0.91
200	760	1,090	1.83	1.83	2.13	1.52	1.22	1.22	0.91	0.91	0.91
100	380	545	1.83	1.83	1.83	1.22	1.22	1.22	0.91	0.91	0.91
Total			14.33	14.33	14.33	10.06	9.75	9.75	6.71	6.40	6.40

Table 3. Water Supply available to pump at various hydraulic conductivity (*K*) and specific yield (*S*)

Well capacity	Water supply (ha-cm)								
	K = 7.62 *m day*$^{-1}$			*K* = 15.24 *m day*$^{-1}$			*K* = 30.48 *m day*$^{-1}$		
m^3 day^{-1}	*S* = 0.125	*S* = 0.175	*S* = 0.225	*S* = 0.125	*S* = 0.175	*S* = 0.225	*S* = 0.125	*S* = 0.175	*S* = 0.225
3,270	10,855	15,197	19,538	7,894	11,052	12,434	4,934	6,908	7,105
2,725	8,881	12,434	15,986	5,921	8,289	10,657	3,947	5,526	7,105
2,180	7,894	11,052	12,434	4,934	6,908	10,657	3,947	4,145	7,105
1,635	6,908	9,671	12,434	4,934	6,908	8,881	2,960	4,145	5,329
1,090	5,921	8,289	12,434	4,934	5,526	7,105	2,960	4,145	5,329
545	5,921	8,289	10,657	3,947	5,526	7,105	2,960	4,145	5,329
Total	46,379	64,931	83,482	32,564	44,208	56,839	21,709	29,012	37,301

Crop Choice models

Nine crop choice models were developed for LPM and APM producers with hydraulic conductivity 7.62, 15.48, and 30.48 and specific yield 0.125, 0.175, and 0.225. The optimal water use for LPM strategy was determined by a multi-period mixed integer programming (MIP) model. APM optimal water use was determined by a recursive linear programming (RLP) model. The MIP and RLP followed the analysis performed in Ramaswamy, 2016. Optimal discharge rates for all producers are shown in Table 4, Table 5 and Table 6.

Table 4. Optimal annual water use of LPM and APM producers overlying aquifer with hydraulic conductivity, K = 7.62 m/day and three levels of specific yield

	Discharging rates (m^3/day)					
	K = 7.62 m/day					
Year	APM S = 0.125	LPM S = 0.125	APM S = 0.175	LPM S = 0.175	APM S = 0.225	LPM S = 0.225
1	783	783	1,566	1,566	1,566	1,566
2	783	783	1,566	1,566	1,566	1,566
3	783	783	1,566	1,566	1,566	1,566
4	783	783	1,566	1,454	1,566	1,566
5	783	783	1,525	1,060	1,566	1,566
6	783	783	1,463	855	1,566	1,566
7	783	783	1,221	855	1,487	1,020
8	783	783	705	855	1,463	855
9	783	783	705	788	1,135	855
10	783	530	705	705	705	855
11	783	530	705	705	705	739
12	783	530	501	705	705	705
13	553	530	276	705	705	705
14	352	530	276	447	705	705
15	352	374	276	276	618	705
16	352	352	352	352	352	783
17	352	352	352	352	352	488
18	352	352	352	352	352	352
19	352	352	352	352	352	352
20	352	352	352	352	352	352
21	326	352	352	352	352	352
22			352	352	352	352
23			352	352	352	352
24			352	352	352	352
25			45	352	352	352
26				209	352	352
27					352	352
28					352	352
29					352	352
30					352	352

Table 5. Optimal annual water use of LPM and APM producers overlying aquifer with hydraulic conductivity, K = 15.24 m/day and three levels of specific yield

	Discharging rates (m^3/day)					
	K = 15.24 m/day					
Year	APM S = 0.125	LPM S = 0.125	APM S = 0.175	LPM S = 0.175	APM S = 0.225	LPM S = 0.225
1	783	783	783	783	1,566	1,566
2	783	783	783	783	1,566	1,566
3	783	783	783	783	1,566	1,566
4	783	783	783	783	1,566	1,060
5	783	783	783	783	1,469	968
6	783	783	783	783	1,463	855
7	783	783	783	783	744	855
8	783	783	783	783	705	837
9	635	568	783	726	705	705
10	352	352	783	530	705	705
11	352	352	783	530	364	705
12	352	352	626	530	276	705
13	352	352	352	530	276	333
14	352	352	352	352	276	276
15	285	352	352	352	276	276
16			352	352	352	352
17			352	352	352	352
18			352	352	352	352
19			352	352	352	352
20			352	352	352	352
21			87	352	332	352
22				216		352
23						158
24						
25						
26						
27						
28						
29						
30						

Table 6. Optimal annual water use of LPM and APM producers overlying aquifer with hydraulic conductivity, K = 30.48 m/day and three levels of specific yield

	Discharging rates (m^3/day)					
	K = 30.48 m/day					
Year	APM S = 0.125	LPM S = 0.125	APM S = 0.175	LPM S = 0.175	APM S = 0.225	LPM S = 0.225
1	783	783	783	783	783	783
2	783	530	783	783	783	783
3	783	530	783	783	783	783
4	783	530	783	749	783	783
5	783	530	783	530	783	783
6	734	530	783	530	783	783
7	352	530	783	530	783	783
8	352	438	678	530	783	783
9	352	392	352	530	783	783
10	258	352	352	462	783	783
11		352	352	352	609	609
12		352	352	352	352	352
13		23	352	352	352	352
14			49	352	352	352
15				352	352	352
16						
17						
18						
19						
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MODFLOW

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 water-level because the LPM uses less water annually. Thus, LPM water table is expected to be at a higher level than that of an adjoining APM producer. Three sizes of contiguous CID areas were tested for the LPM group. These CID are a single 259-ha LPM irrigated section surrounded by eight 259-ha APM sections, four 259-ha LPM producers surrounded by 12 259-ha APM sections, and a block of nine 259-ha LPM producers surrounded by 40 259-ha sections of APM producers. Representative CIDs surrounded by APM producers are shown in Figure 3a, 3b and 3c.

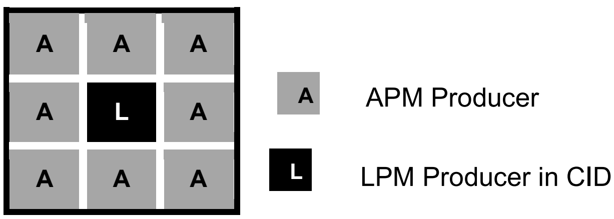

Figure 3a. One LPM section surrounded by eight APM sections

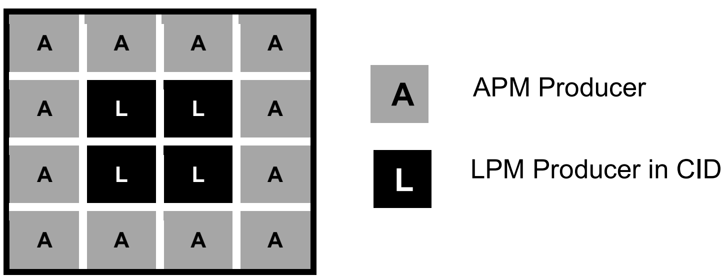

Figure 3b. Four LPM sections surrounded by 12 APM sections

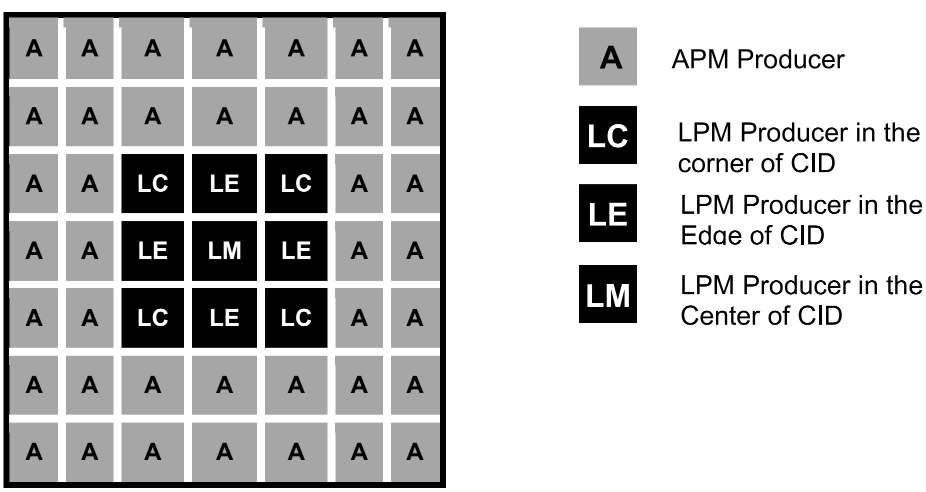

Figure 3c. Nine LPM sections surrounded by 40 APM sections

For each size of LPM group and surrounding APM, the hydrology parameters were hydraulic conductivities 7.62, 15.24, and 30.48 m/day and specific yield 0.125, 0.175. and 0.225 (USGS and OWRB). 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.

Results

The results presented in this section assumes that the LPM producers in CID maximize the value of groundwater over a period of 30 years and APM producers choose the crop choice and are that gives greatest annual net returns. The annual pumping rates are less than or equal to those in Table 4-6.

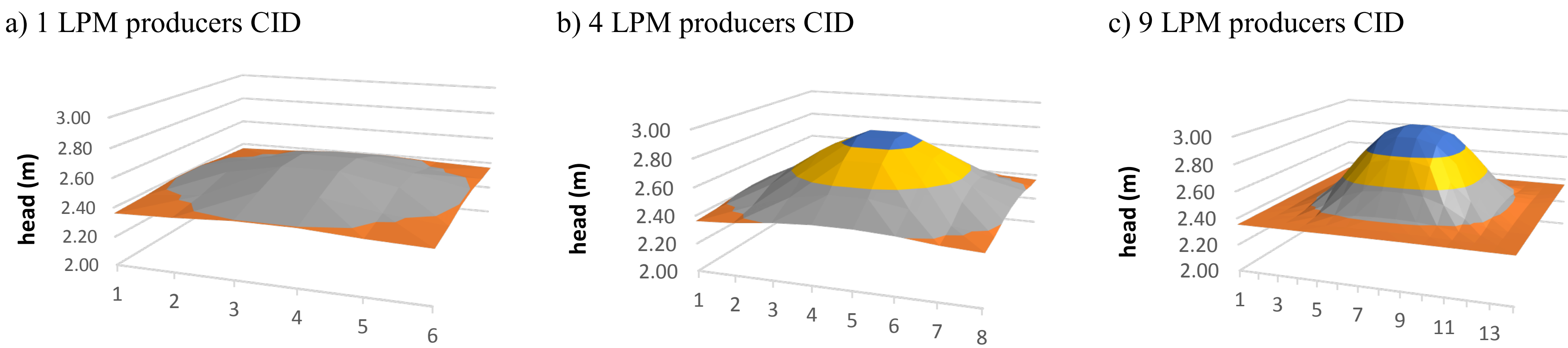

Figure 4. K = 7.62 m/day and S = 0.125, Year 15

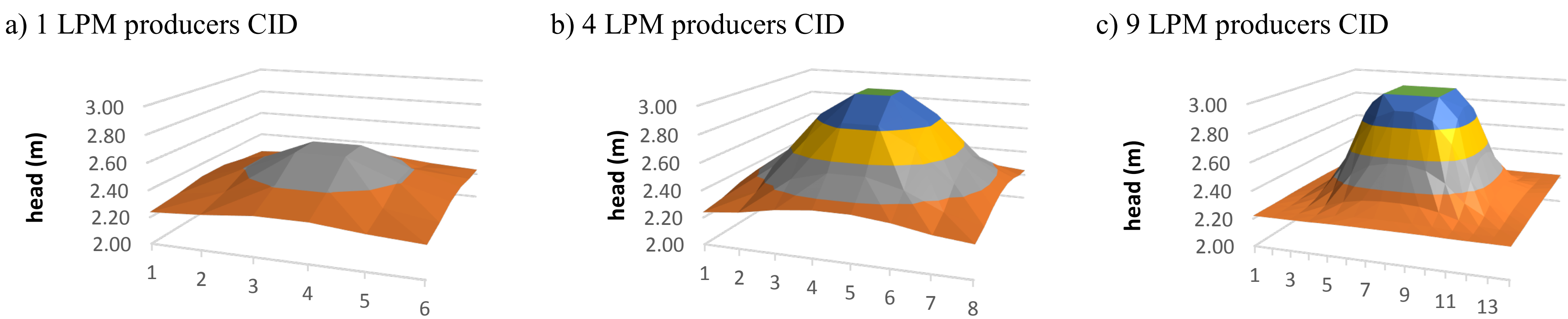

Figure 5. K = 7.62 m/day and S = 0.175, Year 15

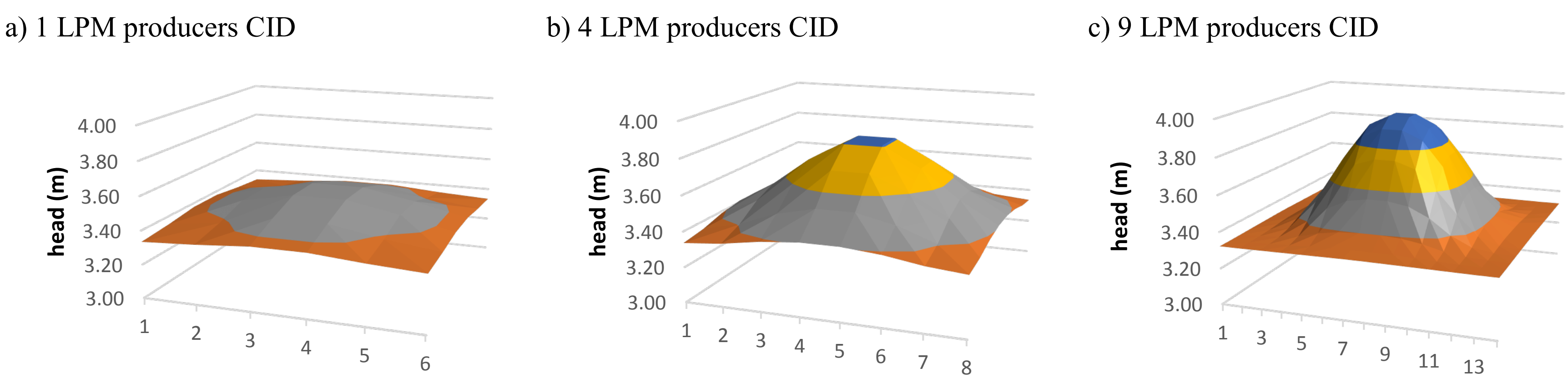

Figure 6. K = 7.62 m/day and S = 0.225, Year 15

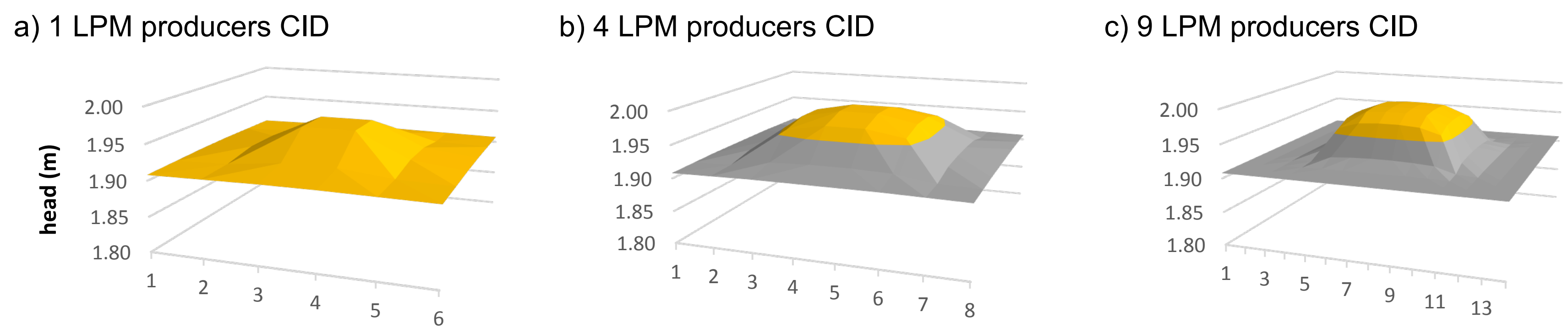

Figure 7. K = 15.24 m/day and S = 0.125, Year 10

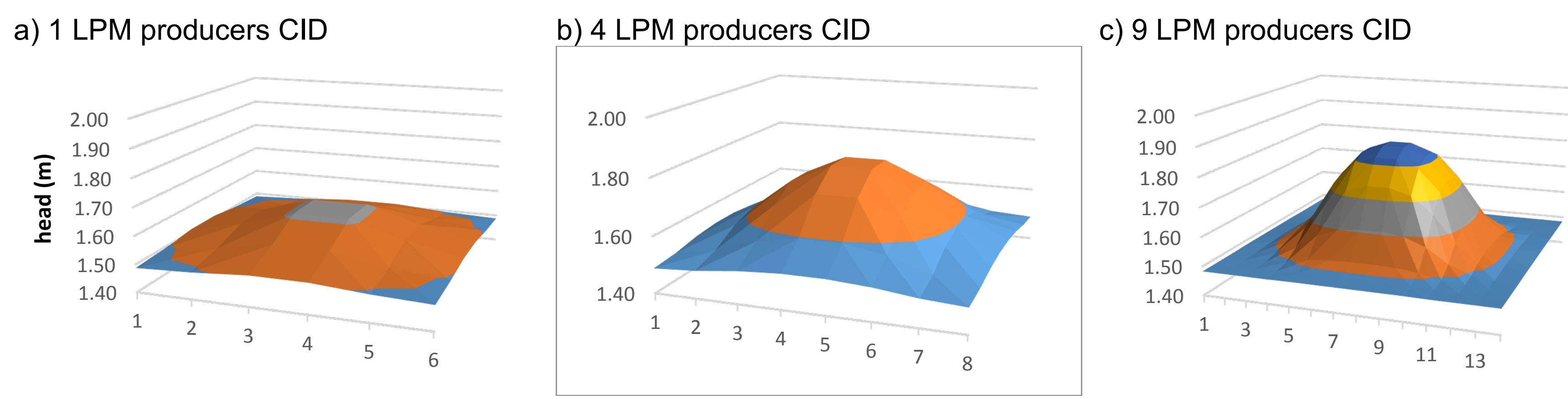

Figure 8. K = 15.24 m/day and S = 0.175, Year 15

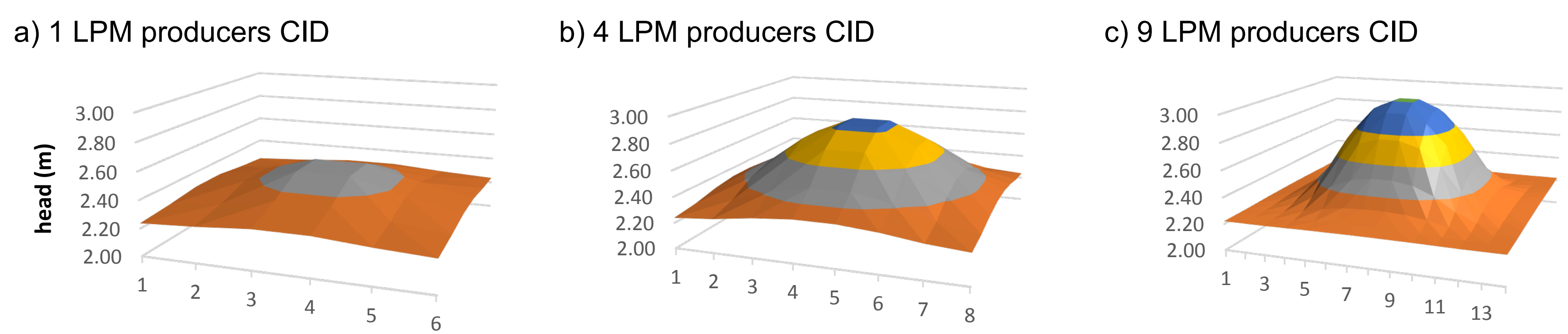

Figure 9. K = 15.24 m/day and S = 0.225, Year 10

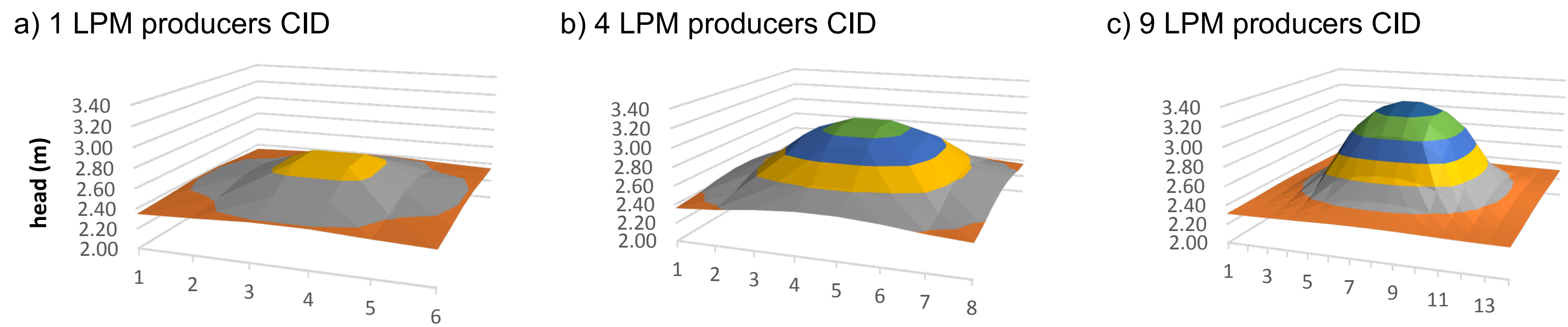

Figure 10. K = 30.48 m/day and S = 0.125, Year 5

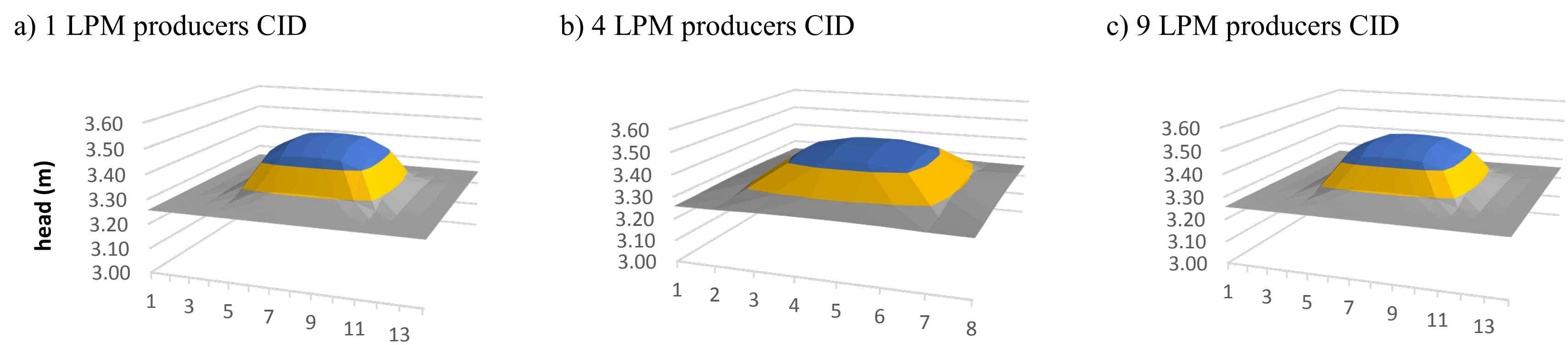

Figure 11. K = 30.48 m/day and S = 0.175, Year 5

Case 1: Rate of groundwater decline for CID with K = 7.62 m/day

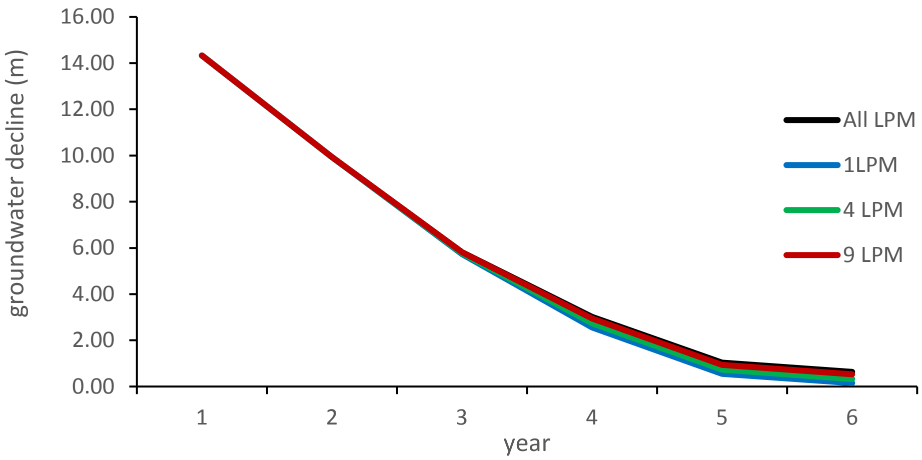

Figure 12. K = 7.62 m/day, S = 0.125

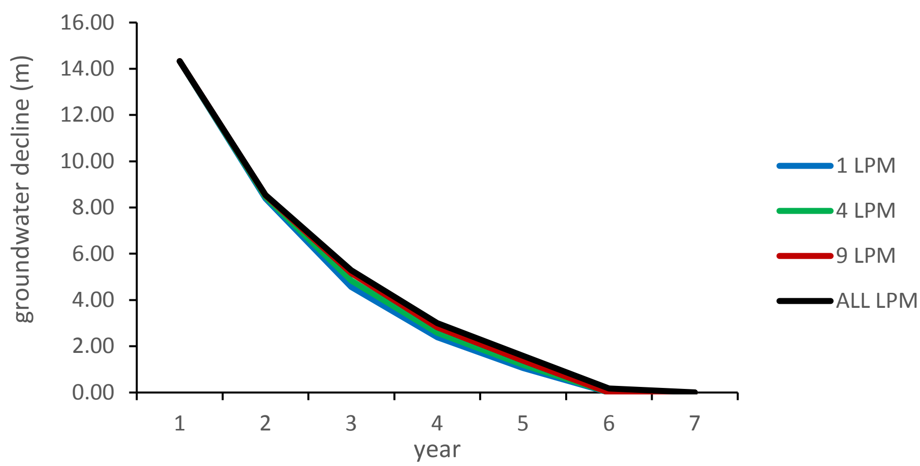

Figure 13. K = 7.62 m/day, S = 0.175

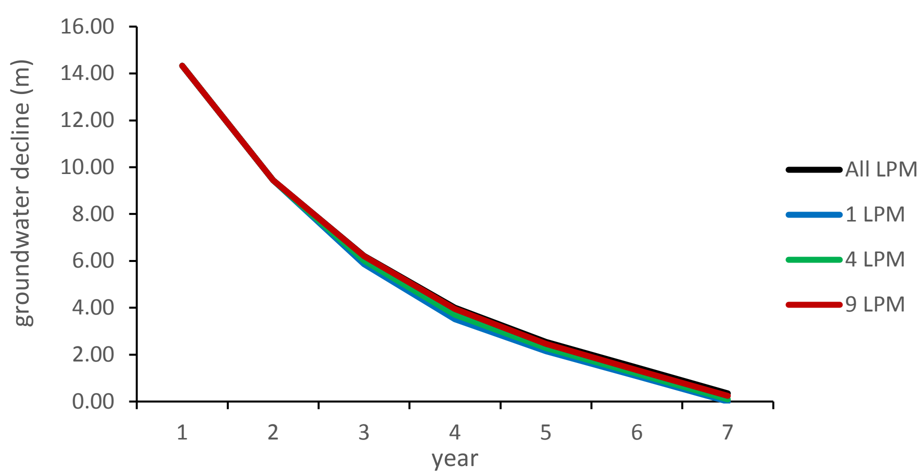

Figure 14. K = 7.62 m/day, S = 0.225

Case 2: Rate of groundwater decline rate for CID with K = 15.24 m/day

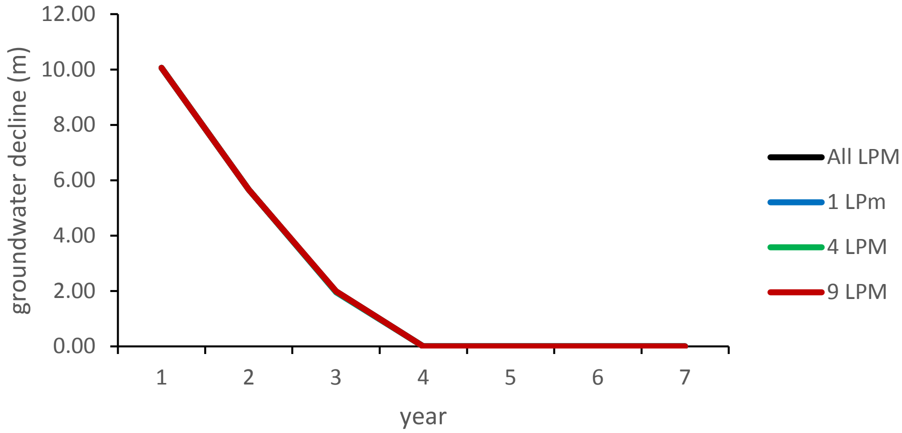

Figure 15. K = 15.24 m/day, S = 0.125

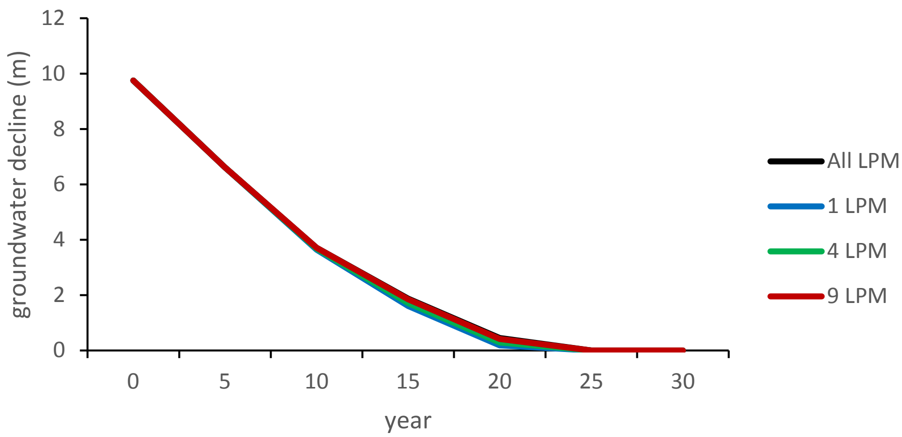

Figure 16. K = 15.24 m/day, S = 0.175

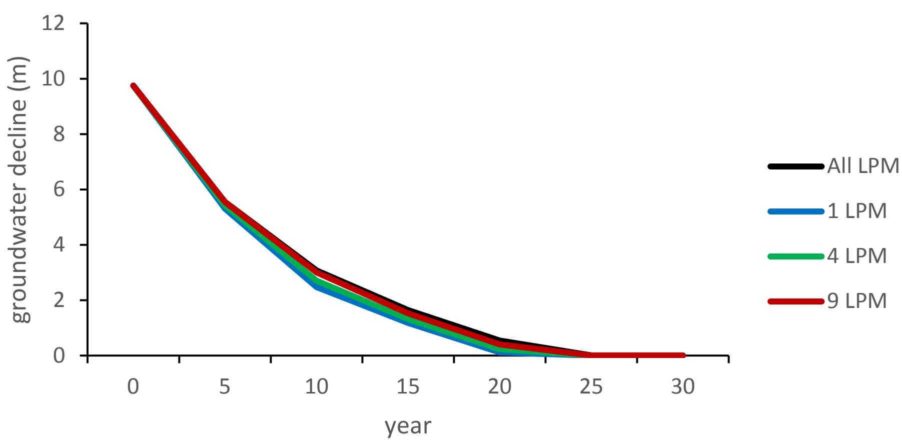

Figure 17. K = 15.24 m/day, S = 0.225

Case 2: Rate of groundwater decline rate for CID with K = 30.48 m/day

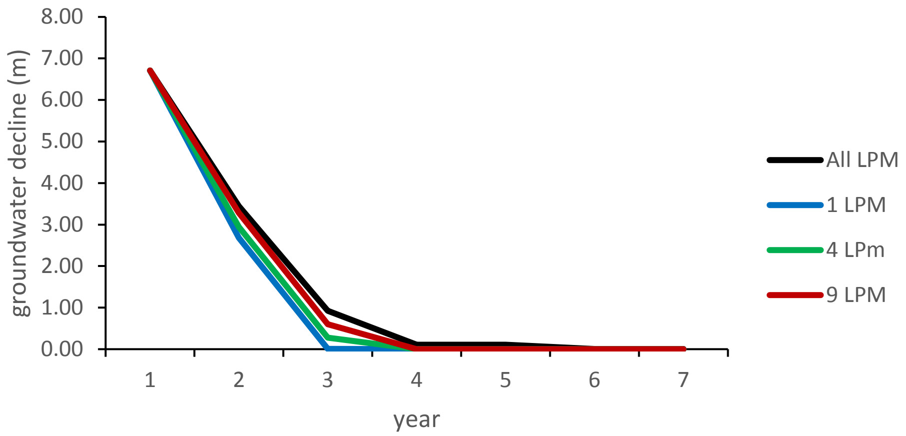

Figure 18. K = 30.48 m/day, S = 0.125

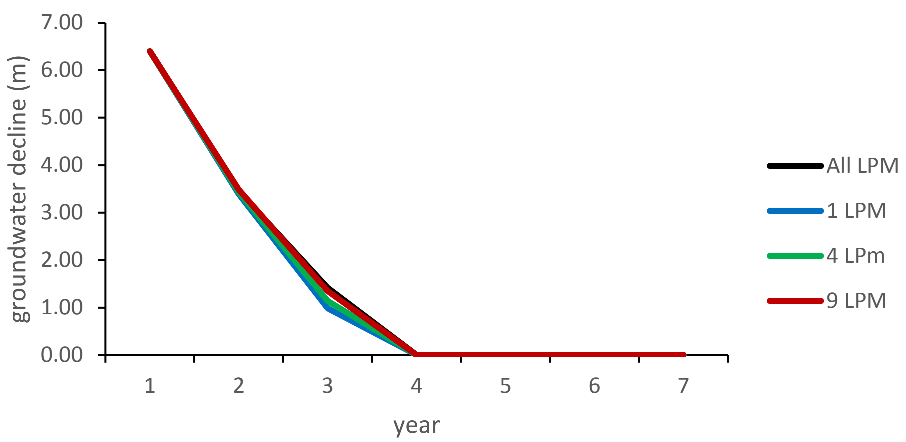

Figure 19. K = 30.48 m/day, S = 0.175

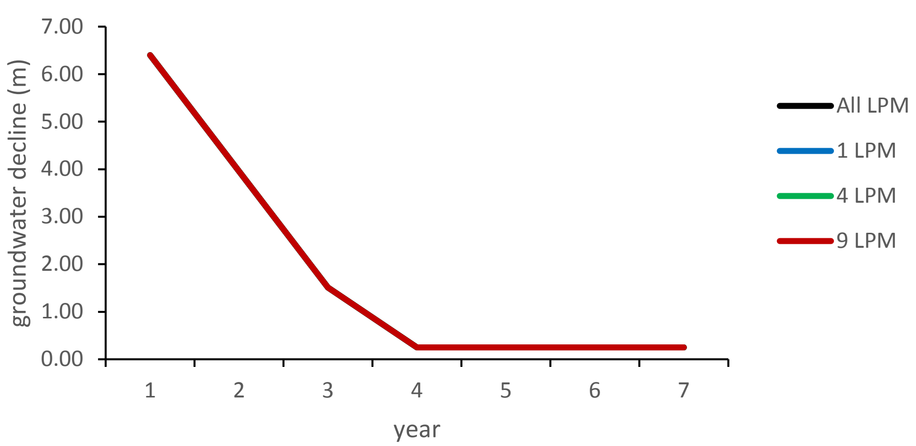

Figure 20. K = 30.48 m/day, S = 0.225

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