Appendix D
Analysis of Impacts to Groundwater Levels South of Morelos Dam due to Operation of Drop 2 Reservoir

June 2007

Numerical modeling analysis of impacts to groundwater levels in riparian zone south of Morelos Dam due to operation of proposed reservoir near Drop 2 of All-American Canal

Objective

The purpose of this analysis is to predict the effect on riparian zone groundwater levels along the Colorado River between Morelos Dam and the Southerly International Boundary (SIB) due to the operation of the proposed reservoir near Drop 2 of the All-American Canal.

Operation of the proposed reservoir is projected to reduce non-storable flows of Colorado River water to Mexico at the Northerly International Boundary, which, in turn, is predicted to reduce flows released from Morelos Dam. Reduced releases from Morelos Dam could affect riparian zone groundwater levels between the dam and the SIB. In this study a numerical groundwater flow model is used to quantify this potential impact.

Groundwater model

The study was performed using a transient groundwater-flow model of the Yuma area, developed by the Arizona Department of Water Resources (ADWR) and published in 1993 (Hill, 1993). The model uses the groundwater-flow code MODFLOW, developed by the U.S. Geological Survey (McDonald and Harbaugh, 1988). It simulates surface-water/groundwater interaction using the Streamflow-Routing Package of MODFLOW (Prudic, 1989). Input for this package includes the flow at the upstream end of rivers and canals. The model is constructed such that the Colorado River flow just below Morelos Dam is specified, as are the flows entering the Colorado River at the 11-Mile and 21-Mile wasteways, the Mexican diversion, and the flow entering Mexico's Alamo Canal. Other input for the groundwater model includes aquifer properties and pumping, irrigation recharge and phreatophyte evapotranspiration data. The basic output of the model is the hydraulic head (i.e. the elevation to which water would rise in a vertical standpipe whose lower end is open at the center of a model cell and whose upper end is open to the atmosphere) in each cell of the model's flow domain at the end of each time step.

The model uses two stress periods per year. (A stress period is a time period in which all aquifer stresses, such as pumping, recharge rates, and headwater flows in rivers and canals are assumed constant.) Each stress period has six equal-length time steps and lasts six months: a summer stress period from April through September, and a winter stress period from October through March of the following year. The model was calibrated using data from October 1978 through March 1989.

In this analysis, simulations were made for a 29 ½ - year period (59 stress periods) from April 1, 1974 through September 30, 2003 (Table 1). For these simulations, mean daily flows of the Colorado River passing Morelos Dam both with and without the reservoir were obtained from the Brown & Caldwell surface water analysis (Appendix C). It was assumed that on flood-flow days (as designated in the Brown & Caldwell analysis), the reservoir was not operational. Therefore, on such days, the flow passing Morelos Dam with the reservoir was assumed equal to the flow passing the dam without the reservoir. Historical mean daily flows for the Mexican diversion, the 11-Mile and 21-Mile wasteways and the discharge from the Wellton-Mohawk Bypass Drain to the river below Morelos Dam were obtained from the International Boundary and Water Commission's web site (www.ibwc.state.gov/wad/histflo2.htm). From these daily flows, average flows for each stress period were computed (Table 2). The flow in the Alamo Canal was taken to be one-half of the Mexican diversion. The flow in the Colorado River below Morelos dam was taken as the sum of the flow passing the dam (either with or without the reservoir operating) and the discharge, if any, to the river from the Wellton-Mohawk Bypass Drain.

To simulate all other aquifer stresses (i.e. other surface flows, pumping, irrigation recharge, and phreatophyte evapotranspiration), the calibration data for the April 1988- September 1988 summer stress period and October 1988 – March 1989 winter stress period were used over and over to fill out the 59 stress periods.

Model simulations

Two simulation runs were made with the model: a run without the Drop 2 reservoir and a run with the reservoir. The only difference between the runs was the flow in the Colorado River just below Morelos Dam. As indicated above, this flow was taken as the sum of the flow passing the dam and the discharge to the river from the Bypass Drain.

Results of model simulations and analysis

The results of the two simulation runs used in the analysis were the hydraulic head in each active cell of the model at the end of each stress period. For the analysis, the Colorado River between Morelos Dam and the SIB was divided into three reaches: Reach 1 from Morelos Dam (river mile (RM) 22) to RM 16.8; Reach 2 from RM 16.8 to RM 5.8; and Reach 3 from RM 5.8 to the SIB (RM 0).

To determine the drop in groundwater levels due to operation of the reservoir, the water-table elevation from the run with the reservoir was subtracted from the water table elevation from the run without the reservoir for each river cell location at the end of each stress period. The result is the drop in water table due to the reduction in river flow below Morelos Dam from operation of the Drop 2 reservoir. For each run, the water table was determined as the hydraulic head in the uppermost active model layer at a given river cell location. The results are shown in Table 3. The table presents the overall maximum drop, the overall mean drop, and the maximum mean drop for each reach. The overall maximum drop for a reach was the maximum drop computed for all cell locations in the reach for all 59 stress periods. The overall mean drop for each reach was obtained by averaging the computed drops for all cell locations in the reach and all stress periods. To obtain the maximum mean drop for a reach, a mean drop was computed for the cells of the reach for each of the 59 stress periods. The largest of the 59 mean drops for a reach was taken as the maximum mean drop.

Sensitivity analysis

Assuming the flows passing the dam with and without the reservoir are valid, the accuracy of the computed drops in water table depends on how well the groundwater model simulates the interaction between groundwater and the river between Morelos Dam and the SIB. This interaction depends on a number of factors, including the hydraulic conductance of the river-bed material and the hydraulic properties of the aquifer. A special series of simulations were performed to investigate the sensitivity of the computed drops in water table to the following parameters: the river-bed conductance, the horizontal hydraulic conductivity in the upper three model layers, the vertical hydraulic conductance between model layers, the transmissivity of the bottom layer, the specific yield of the uppermost active layer and the storage coefficient of lower layers. The results are presented in Table 4. From the table, the parameters may be ranked from most to least sensitive as follows: River-bed conductance, transmissivity of layer 4, vertical conductance, horizontal hydraulic conductivity, specific yield, and storage coefficient. These results suggest that if the values of river-bed conductance used in the model underestimate actual values by 10 to 50%, the computed mean drop may underestimate the actual mean drop which would occur by 7 to about 50%. Similarly, if the values of layer 4 transmissivity or vertical conductance used in the model overestimate actual values by 10 to 50%, the computed mean drops may underestimate the actual mean drops which would occur by 0 to about 40% or 0 to about 20%, respectively.

Calibration of model for river/groundwater interaction

The calibration analysis presented in the documenting report for the model (Hill, 1993) gives mixed indications of how well the model simulates river/groundwater interaction in the riparian zone between Morelos Dam and the SIB (riparian zone). On the one hand, the model simulates groundwater levels in about 35% of the riparian zone quite accurately (to within an average of less than one foot of measured values) (Hill, 1993, p.88). In the rest of the riparian zone, the model computes groundwater levels with reasonable accuracy (within an average of 3 to 4 feet or less of measured values) (Hill, 1993, p. 88). Since groundwater levels near the river are in part due to river/groundwater interaction, this generally accurate simulation is consistent with generally accurate simulation of river/groundwater interaction.

On the other hand, in the calibration analysis the model appeared to greatly underestimate river losses to the groundwater system in the riparian zone. The model computed river losses in this zone at 48,000 acre-feet/year compared to estimated losses of 174,000 acre-feet/year (Hill, 1993, p. 84). This would indicate that the model may poorly simulate river/groundwater interaction in this area. However, the estimated losses were highly uncertain (Hill, 1993, pp. 67-68 and Table 10 on p. 33), making it impossible to draw a firm conclusion based on this comparison.

Conclusion

The study predicts that reservoir operation will produce a small drop in groundwater levels along the Colorado River between Morelos Dam and the SIB. The estimated magnitude of the drop is on the order of the values shown in Table 3 for the three reaches. **This estimated impact is based on the assumption that the predicted reductions in flows passing the dam from the surface-water analysis (Appendix C) are representative of actual future reductions due to reservoir operation.**

This analysis was performed in an appropriate manner using the best available model. Nevertheless, as with almost any prediction made with a groundwater model, there is significant uncertainty in the magnitude of the predicted water-table drop. Contributing to this uncertainty are the mixed results in the calibration of the model near the river below Morelos Dam and the relatively high sensitivity of the drop calculations to certain parameters governing river/groundwater interaction.

The predicted drop in water table is due only to the predicted reduction in flows passing the dam from operation of the reservoir. Other factors, such as variations in irrigation recharge rates and pumping, can also cause groundwater levels to rise or fall and are not included in this analysis.

References

Hill, B.M., 1993, “Hydrogeology, Numerical Model and Scenario Simulations of the Yuma Area Groundwater Flow Model Arizona, California, and Mexico”, Modeling Report No. 7, Arizona Department of Water Resources.

McDonald, M.G. and A.W. Harbaugh, 1988, “A modular three-dimensional finite-difference ground-water flow model,” Techniques of Water-Resources Investigations of the United States Geological Survey, Book 6, Chapter A1.

Prudic, D.E., 1989, “Documentation of a computer program to simulate stream-aquifer relations using a modular, finite-difference, ground-water flow model,” U.S. Geological Survey Open-File Report 88-729.

Table 1
Beginning and end dates of summer and winter stress periods

Stress period	Season	Beginning of stress period		End of stress period	
		Date	Days after 12/31/1973	Date	Days after 12/31/1973
1	summer	4/1/1974	91	9/30/1974	273
2	winter	10/1/1974	274	3/31/1975	455
3	summer	4/1/1975	456	9/30/1975	638
4	winter	10/1/1975	639	3/31/1976	821
5	summer	4/1/1976	822	9/30/1976	1004
6	winter	10/1/1976	1005	3/31/1977	1186
7	summer	4/1/1977	1187	9/30/1977	1369
8	winter	10/1/1977	1370	3/31/1978	1551
9	summer	4/1/1978	1552	9/30/1978	1734
10	winter	10/1/1978	1735	3/31/1979	1916
11	summer	4/1/1979	1917	9/30/1979	2099
12	winter	10/1/1979	2100	3/31/1980	2282
13	summer	4/1/1980	2283	9/30/1980	2465
14	winter	10/1/1980	2466	3/31/1981	2647
15	summer	4/1/1981	2648	9/30/1981	2830
16	winter	10/1/1981	2831	3/31/1982	3012
17	summer	4/1/1982	3013	9/30/1982	3195
18	winter	10/1/1982	3196	3/31/1983	3377
19	summer	4/1/1983	3378	9/30/1983	3560
20	winter	10/1/1983	3561	3/31/1984	3743
21	summer	4/1/1984	3744	9/30/1984	3926
22	winter	10/1/1984	3927	3/31/1985	4108
23	summer	4/1/1985	4109	9/30/1985	4291
24	winter	10/1/1985	4292	3/31/1986	4473
25	summer	4/1/1986	4474	9/30/1986	4656
26	winter	10/1/1986	4657	3/31/1987	4838
27	summer	4/1/1987	4839	9/30/1987	5021
28	winter	10/1/1987	5022	3/31/1988	5204
29	summer	4/1/1988	5205	9/30/1988	5387
30	winter	10/1/1988	5388	3/31/1989	5569
31	summer	4/1/1989	5570	9/30/1989	5752
32	winter	10/1/1989	5753	3/31/1990	5934
33	summer	4/1/1990	5935	9/30/1990	6117
34	winter	10/1/1990	6118	3/31/1991	6299
35	summer	4/1/1991	6300	9/30/1991	6482
36	winter	10/1/1991	6483	3/31/1992	6665
37	summer	4/1/1992	6666	9/30/1992	6848
38	winter	10/1/1992	6849	3/31/1993	7030
39	summer	4/1/1993	7031	9/30/1993	7213
40	winter	10/1/1993	7214	3/31/1994	7395
41	summer	4/1/1994	7396	9/30/1994	7578
42	winter	10/1/1994	7579	3/31/1995	7760
43	summer	4/1/1995	7761	9/30/1995	7943
44	winter	10/1/1995	7944	3/31/1996	8126
45	summer	4/1/1996	8127	9/30/1996	8309
46	winter	10/1/1996	8310	3/31/1997	8491
47	summer	4/1/1997	8492	9/30/1997	8674
48	winter	10/1/1997	8675	3/31/1998	8856
49	summer	4/1/1998	8857	9/30/1998	9039
50	winter	10/1/1998	9040	3/31/1999	9221
51	summer	4/1/1999	9222	9/30/1999	9404
52	winter	10/1/1999	9405	3/31/2000	9587
53	summer	4/1/2000	9588	9/30/2000	9770
54	winter	10/1/2000	9771	3/31/2001	9952
55	summer	4/1/2001	9953	9/30/2001	10135
56	winter	10/1/2001	10136	3/31/2002	10317
57	summer	4/1/2002	10318	9/30/2002	10500
58	winter	10/1/2002	10501	3/31/2003	10682
59	summer	4/1/2003	10683	9/30/2003	10865

Table 2
Surface flow data for simulations with and without operation of Drop 2 reservoir (page 1 of 2)

Stress period	Diversion to Mexico (ft3/d) (Segment* 30)	Alamo Canal (ft3/d) (Segment 32)	Passing Morelos Dam w/o reservoir (ft3/d)	Passing Morelos Dam w/ reservoir (ft3/d)	Wellton-Mohawk discharge to river below Morelos D. (ft3/d)	Passing Morelos Dam w/o reservoir + W-M discharge (ft3/d) (Segment 38)	Passing Morelos Dam w/ reservoir + W-M discharge (ft3/d) (Segment 38)	11-Mile Wasteway (ft3/d) (Segment 39)	21-Mile Wasteway (ft3/d) (Segment 42)
1	195966528	97983264	379121	253534	24972904	25352025	25226438	75867	165
2	116101664	58050832	196536	196536	25974118	26170654	26170654	182689	166
3	196982080	98491040	1834230	368287	24980460	26814690	25348747	113812	1832
4	145510816	72755408	477797	412643	24203332	24681129	24615975	148476	6827
5	177791840	88895920	14055344	7727446	24733534	38788878	32460980	124732	0
6	149824240	74912120	517925	472826	24467816	24985741	24940642	210075	499
7	194086032	97043016	15817338	12101715	12601652	28418990	24703367	129015	0
8	126318696	63159348	19333186	11345984	408264	19741450	11754248	224782	0
9	200426752	100213376	385259	385259	7554	392813	392813	101924	1501
10	129873440	64936720	12826127	10798576	0	12826127	10798576	161497	0
11	311689184	155844592	142856496	142856496	472	142856968	142856968	144883	0
12	229131376	114565688	234161936	234161936	0	234161936	234161936	187214	0
13	381970624	190985312	547053632	547053632	0	547053632	547053632	139656	0
14	239432432	119716216	368838752	366280000	0	368838752	366280000	198644	0
15	255264784	127632392	805928	516984	0	805928	516984	135332	8834
16	148099088	74049544	1734646	1550453	0	1734646	1550453	224953	102094
17	183568368	91784184	1996643	570807	0	1996643	570807	118439	20675
18	182521904	91260952	152949360	151287376	0	152949360	151287376	181763	39568
19	383095232	191547616	1508860290	1508860290	906492	1509766782	1509766782	145025	8645
20	316925600	158462800	1863962880	1863962880	1368708	1865331588	1865331588	186246	0
21	371574752	185787376	1397740930	1397740930	87344	1397828274	1397828274	163367	2823
22	232040496	116020248	1585267710	1585267710	0	1585267710	1585267710	235635	11379
23	367811872	183905936	925224064	925224064	44380	925268444	925268444	140261	6610
24	289563904	144781952	952017408	952017408	23262	952040670	952040670	237187	274443
25	353848128	176924064	977182592	977182592	12748	977195340	977195340	197370	198153
26	231986368	115993184	894863808	894863808	0	894863808	894863808	467908	451630
27	274085824	137042912	65401968	65401968	22190	65424158	65424158	204570	73275
28	224467680	112233840	164688320	164389920	267226	164955546	164657146	423492	335610
29	245460512	122730256	8286846	2071239	1813456	10100302	3884695	216222	74191
30	154354544	77177272	4060325	1567568	0	4060325	1567568	533601	249682
31	204586704	102293352	3313889	284695	8026	3321915	292721	298793	36515
32	139634272	69817136	0	0	13292	13292	13292	313342	9390
33	190267904	95133952	1944708	114753	10387	1955095	125140	115044	0
34	142633104	71316552	1669134	109187	4747	1673881	113934	197139	1676

Table 3
Predicted maximum, mean and maximum mean drops in water table due to operation of reservoir at Drop 2

Reach	Overall Maximum drop (ft)	Overall mean drop (ft)	Maximum mean drop (ft)
1	0.3	0.03	0.2
2	0.7	0.09	0.5
3	0.7	0.1	0.6

Overall maximum and mean drops are with respect to all of the river cells making up the specified reach and all 59 stress periods. The maximum mean drop for a reach is the maximum of 59 mean drops computed for that reach, one for each stress period.

Table 4
Sensitivity of computed drop in water table to parameters related to river/groundwater interaction

Parameter	% increase in parameter	Reach 1		Reach 2		Reach 3	
		Overall mean drop in WT (ft)	% increase in WT drop	Overall mean drop in WT (ft)	% increase in WT drop	Overall mean drop in WT (ft)	% increase in WT drop
	0	0.030	0	0.092	0	0.117	0
River-bed conductance	-10	0.028	-7	0.083	-10	0.106	-9
	+10	0.032	7	0.101	10	0.127	9
	+30	0.035	17	0.117	27	0.146	25
	+50	0.038	27	0.134	46	0.164	40
Horizontal hydraulic conductivity in layers 2 & 3	+10	0.029	-3	0.091	-1	0.115	-2
	-10	0.030	0	0.092	0	0.118	1
	-30	0.030	0	0.094	2	0.121	3
	-50	0.031	3	0.095	3	0.124	6
Transmissivity of layer 4	+10	0.029	-3	0.088	-4	0.112	-4
	-10	0.030	0	0.096	4	0.122	4
	-30	0.032	7	0.109	18	0.137	17
	-50	0.035	17	0.131	42	0.161	38
Vertical conductance between layers 1 & 2, 2 & 3, and 3 & 4	+10	0.029	-3	0.090	-2	0.114	-3
	-10	0.030	0	0.094	2	0.120	3
	-30	0.032	7	0.102	11	0.128	9
	-50	0.034	13	0.106	15	0.139	19
Specific yield in uppermost active layer	+10	0.029	-3	0.092	0	0.116	-1
	-10	0.030	0	0.092	0	0.117	0
	-30	0.031	3	0.095	3	0.119	2
	-50	0.031	3	0.096	4	0.120	3
Storage coefficient in lower layers	+10	0.029	-3	0.090	-2	0.116	-1
	-10	0.030	0	0.092	0	0.117	0
	-30	0.030	0	0.094	2	0.118	1
	-50	0.031	3	0.096	4	0.120	3