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

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 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

A transient groundwater-flow model of the Yuma area, developed by the Arizona Department of Water Resources (Hill, 1993), was used. The model uses the groundwater-flow code MODFLOW developed by the U.S. Geological Survey (McDonald and Harbaugh, 1988). The model simulates surface-water/groundwater interaction using the Streamflow-Routing Package of MODFLOW (Prudic, 1989). The model is constructed such that the Colorado River flow just below Morelos Dam is specified for each time period. Also specified for each time period are the flows entering the Colorado River at the 11-Mile and 21-Mile Wasteways, the Mexican diversion, and flow entering the Alamo Canal. 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 – time periods in which all aquifer stresses such as pumping, recharge rates, and headwater flows in rivers and canals are assumed constant - per year. 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.

Model calibration used data from October 1978 through March 1989. For this study, data for the last two stress periods, April 1988 - September 1988 and October 1988 - March 1989, were repeated over-and-over to complete a 13 ½-year simulation period (27 stress periods), except as specified otherwise.

Surface flows

The flows used in the analysis were annual flows taken from the period 1974 through 2003. The data are shown in Table 1. The flows passing Morelos Dam with and without the reservoir in operation were obtained from Mr. Ruben Zubia of Brown and Caldwell Engineers and Consultants. From the data set of Table 1, the flows for years in which Colorado River flow arriving at the NIB exceeded 2 million acre-feet were eliminated. These years were 1979, 1980, 1983-1988, 1993, and 1997-1999. Flows downstream of Morelos Dam for these high-flow years were judged to result in higher groundwater levels in the riparian habitat between Morelos Dam and the SIB (both with and without the reservoir), and therefore were not utilized. Flows from the remaining years were utilized to construct the string of 27 summer-winter-summer-winter stress periods shown in Table 2.

The actual surface flows for each stress period used in the model simulations are shown in Table 3. Flows for other river/stream segments not included in Table 3 were kept at their 1988-1989 levels. Surface flows adjusted from their 1988-1989 values were the Colorado River below Morelos Dam, the flow diverted at Morelos Dam, the flow diverted into the Alamo Canal (assumed to be one-half of the flow diverted at Morelos Dam), and the inflows to the Colorado River at the 11-Mile Wasteway and 21-Mile Wasteway. The flow below Morelos Dam was made equal to the flow released from the dam plus the inflow, if any, from the Wellton-Mohawk Bypass Drain.

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. For both cases, as noted above, the flow just below the dam was assumed to consist of the flow released from the dam plus the inflow to the river, if any, from the Wellton-Mohawk Bypass Drain (refer to Table 3).

Results of model simulations and analysis
The results of the two simulation runs consist of the hydraulic head in each active cell of the model at the end of each stress period. For 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 and for each stress period. The result is the drop in water table due to the reduction in river flows 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 layer at a given river cell location. The results are shown in Table 4. The table presents the maximum and mean drops for each reach. The mean drop for each reach was obtained by averaging the computed drops for all cell locations in the reach for all stress periods. The maximum drop for a reach was the maximum drop computed for all cell locations in the reach for all stress periods.

Sensitivity analyses, performed using arbitrary flow reductions to all stress periods, indicate that changes in the drop of the water table are relatively insensitive to large reductions in the flow passing Morelos Dam.

Conclusion
This study modeled the impacts of operating a proposed reservoir, located near Drop 2 of the All-American Canal, to reduce non-storable flows of Colorado River water at the Northerly International Boundary, resulting in reduced flows being released from Morelos Dam to riparian

zones downstream of the dam. The study predicts that this operation will produce a small drop in groundwater levels along the Colorado River between Morelos Dam and the SIB during a succession of non-high-flow years. The predicted drop is on the order of the values shown in Table 4 for the three reaches. Sensitivity analyses indicate that changes to the water table drop are not highly sensitive to larger reductions in the flows passing Morelos Dam.

The predicted drop in water table is due only to the predicted reduction in flows passing Morelos Dam from operation of the Drop 2 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
Flows below Morelos Dam 1974-2003

Year (A)	Diversion into Mexicali Valley at Morelos Dam (af/y) (B)	Diversion into Alamo Canal (af/y) (C)	Flow passing Morelos Dam before reservoir (af/y) (D)	Flow passing Morelos Dam after reservoir (af/y) (E)	W-M inflow below Morelos Dam (af/y) (F)	Inflow from 11-Mile WW (af/y) (G)	Inflow from 21-Mile WW (af/y) (H)
1974	1330482	665241	4737	3473	210733	943	5
1975	1383593	691797	11899	4241	214729	1137	10
1976	1382449	691225	67162	32846	205395	1227	30
1977	1382792	691396	85712	62666	98794	1499	0
1978	1367635	683818	90044	48462	1662	1118	6
1979	2044287	1022144	1035543	328245	3	1364	0
1980	2735390	1367695	4198068	3138823	0	1409	0
1981	1684408	842204	240974	152908	0	1396	226
1982	1410146	705073	30458	12748	0	1339	408
1983	2798192	1399096	11291417	10235828	9556	1356	118
1984	2675671	1337836	12753949	11519833	370	1532	61
1985	2529078	1264539	9169601	7938857	264	1584	1014
1986	2675488	1337744	8012640	6781897	76	2311	2076
1987	2089818	1044909	2445003	1711872	100	2859	2055
1988	1887035	943518	340544	183531	8742	2885	1482
1989	1421311	710656	32807	4588	76	3187	507
1990	1398867	699433	9418	0	89	1253	34
1991	1375590	687795	10580	954	42	1347	3
1992	1395687	697844	57749	20376	2285	2161	2
1993	1976926	988463	3099650	2320969	0	2050	257
1994	1386540	693270	12645	1154	2422	900	84
1995	1519899	759949	74575	41702	120	766	55
1996	1388246	694123	0	0	0	573	388
1997	2065462	1032731	691704	301795	0	1757	968
1998	2180584	1090292	2407946	1689695	0	4720	2084
1999	1897884	948942	862362	459356	0	4778	1781
2000	1763947	881973	135586	5905	0	6474	1367
2001	1456207	728104	110733	34913	0	13614	2590
2002	1451759	725880	34657	1381	67	11532	7887
2003	1400772	700386	17621	0	0	6535	3130

Notes:

Data for columns D and E are "unadjusted flows" from Ruben Zubia of Brown and Caldwell Engineers and Consultants. These data are the flows passing Morelos Dam in the Colorado River without (column D) and with (column E) the Drop 2 reservoir in operation.

Data from other columns are from International Boundary and Water Commission's Western Water Bulletin "Flow of the Colorado River and other Western Boundary Streams and Related Data" for years 1970 through 2003

Groundwater model assumes 1/2 of water diverted by Mexico at Morelos Dam is diverted into Alamo Canal.

Column F gives the flows in the Wellton-Mohawk Bypass Drain which were diverted into the Colorado River just below Morelos Dam.

Table 2
Calculation of flows for 27 summer and winter stress periods using data from 1974 through 2003

Stress period	Season	Data years used to calculate	Calculation of flow Q in cubic feet per day
1	summer	1974	Q=(AF/Y for 1974) x 43560/365.25
2	winter	1974 & 1975	Q=(AF/Y for 1974 + AF/Y for 1975) x 43560/(2 x 365.25)
3	summer	1975	Q=(AF/Y for 1975) x 43560/365.25
4	winter	1975 & 1976	Q=(AF/Y for 1975 + AF/Y for 1976) x 43560/(2 x 365.25)
5	summer	1976	Q=(AF/Y for 1976) x 43560/365.25
6	winter	1976 & 1977	Q=(AF/Y for 1976 + AF/Y for 1977) x 43560/(2 x 365.25)
7	summer	1977	Q=(AF/Y for 1977) x 43560/365.25
8	winter	1977 & 1978	Q=(AF/Y for 1977 + AF/Y for 1978) x 43560/(2 x 365.25)
9	summer	1978	Q=(AF/Y for 1978) x 43560/365.25
10	winter	1981 & 1982	Q=(AF/Y for 1981 + AF/Y for 1982) x 43560/(2 x 365.25)
11	summer	1982	Q=(AF/Y for 1982) x 43560/365.25
12	winter	1989 & 1990	Q=(AF/Y for 1989 + AF/Y for 1990) x 43560/(2 x 365.25)
13	summer	1990	Q=(AF/Y for 1990) x 43560/365.25
14	winter	1990 & 1991	Q=(AF/Y for 1990 + AF/Y for 1991) x 43560/(2 x 365.25)
15	summer	1991	Q=(AF/Y for 1991) x 43560/365.25
16	winter	1991 & 1992	Q=(AF/Y for 1991 + AF/Y for 1992) x 43560/(2 x 365.25)
17	summer	1992	Q=(AF/Y for 1992) x 43560/365.25
18	winter	1994 & 1995	Q=(AF/Y for 1994 + AF/Y for 1995) x 43560/(2 x 365.25)
19	summer	1995	Q=(AF/Y for 1995) x 43560/365.25
20	winter	1995 & 1996	Q=(AF/Y for 1995 + AF/Y for 1996) x 43560/(2 x 365.25)
21	summer	1996	Q=(AF/Y for 1996) x 43560/365.25
22	winter	2000 & 2001	Q=(AF/Y for 2000 + AF/Y for 2001) x 43560/(2 x 365.25)
23	summer	2001	Q=(AF/Y for 2001) x 43560/365.25
24	winter	2001 & 2002	Q=(AF/Y for 2001 + AF/Y for 2002) x 43560/(2 x 365.25)
25	summer	2002	Q=(AF/Y for 2002) x 43560/365.25
26	winter	2002 & 2003	Q=(AF/Y for 2002 + AF/Y for 2003) x 43560/(2 x 365.25)
27	summer	2003	Q=(AF/Y for 2003) x 43560/365.25

Notes:
AF/Y = acre-feet per year
43560 = number of cubic feet in an acre foot
365.25 = average number of days per year
High-flow years excluded: 1979, 1980, 1983-1988, 1993, 1997-1999.

Table 3
Surface flow data for simulations with and without operation of Drop 2 reservoir

Stress period	Divmex (ft3/d) (seg 30)*	Alamo (ft3/d) (seg 32)*	Below Morelos D w/o reservoir (ft3/d)	Below Morelos D w reservoir (ft3/d)	Wellton-Mohawk discharge to river below Morelos D (ft3/d)	Below Morelos D w/o reservoir + W-M discharge (ft3/d) (seg 38)*	Below Morelos D w/ reservoir + W-M discharge (ft3/d) (seg 38)*	11-MILE WASTEWAY (ft3/d) (seg 39)*	21-MILE WASTEWAY (ft3/d) (seg 42)*
1	158674320	79337160	564879	414205	25132182	25697061	25546387	112427	573
2	161841360	80920680	991969	459977	25370466	26362435	25830443	124013	871
3	165008384	82504192	1419060	505749	25608748	27027808	26114497	135600	1169
4	164940176	82470088	4714444	2211513	25052158	29766602	27263671	140966	2349
5	164871952	82435976	8009828	3917276	24495568	32505396	28412844	146333	3530
6	164892400	82446200	9115937	5695424	18138910	27254847	23834334	162553	1765
7	164912864	82456432	10222045	7473573	11782250	22004295	19255823	178772	0
8	164009040	82004520	10480358	6626606	5990231	16470589	12616837	156053	364
9	163105216	81552608	10738671	5779640	198211	10936882	5977851	133334	728
10	184529472	92264736	16185603	9878108	0	16185603	9878108	163089	37806
11	168175120	84087560	3632469	1520313	0	3632469	1520313	159690	48658
12	168168304	84084152	2517840	273572	9875	2527715	283447	264783	32236
13	166829936	83414968	1123138	0	10638	1133777	10638	149482	4007
14	165441952	82720976	1192447	56893	7830	1200276	64723	155039	2212
15	164053968	82026984	1261755	113787	5021	1266776	118808	160597	417
16	165252352	82626176	4074461	1271934	138790	4213251	1410724	209183	334
17	166450720	83225360	6887168	2430082	272559	7159726	2702640	257770	250
18	173312064	86656032	5200915	2555574	151604	5352519	2707178	99344	8271
19	181264320	90632160	8893825	4973473	14311	8908136	4987784	91366	6583
20	173413824	86706912	4446913	2486737	7156	4454068	2493892	79863	26446
21	165563344	82781672	0	0	0	0	0	68360	46309
22	192019056	96009520	14688116	2433988	0	14688116	2433988	1197855	235969
23	173668400	86834192	13206129	4163764	0	13206129	4163764	1623569	308921
24	173403184	86701584	8669687	2164202	4013	8673700	2168215	1499424	624748
25	173137968	86568984	4133245	164640	8026	4141271	172666	1375280	940574
26	170097568	85048784	3117382	82320	4013	3121395	86333	1077324	656930
27	167057168	83528584	2101518	0	0	2101518	0	779369	373286

* Seg 30 = flow at upstream end of segment number 30 in Modflow Streamflow-Routing Package; etc.

Table 4
Maximum and mean drops in water table due to operation of reservoir at Drop 2

Reach	Maximum drop (ft)	Mean drop (ft)
1	0.2	0.1
2	0.6	0.2
3	0.8	0.2

Maximum and mean values are with respect to all of the river cells making up the specified reach and all 27 stress periods.