A Spatial and Temporal Analysis of Groundwater Elevation in the Colorado River Delta in Response to the Minute 319 Pulse-Flow

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ABSTRACT

Groundwater elevation in the Colorado River Delta was monitored during a planned release of water from the Morelos Dam in Yuma, AZ on March 23, 2014. This environmental "pulse-flow" to the delta was a condition of Minute 319 of the 1944 U.S.-Mexico Boundary Waters Treaty. The goal of the pulse-flow was to restore the riparian corridor of the delta by mimicking a spring flood that would have occurred in the delta's previous wetland ecosystem. Groundwater data were collected by the Autonomous University of Baja California (UABC), the U.S. Geologic Survey (USGS), and the U.S. Bureau of Reclamation (USBR) in order to observe the hydrologic effects of the flow. Piezometric groundwater elevation measurements were collected from 52 sites throughout the delta over a 2-year period. The results of spatial and temporal analyses of the groundwater data showed a rapid increase in elevation as a result of the pulse-flow, but there were little to no long-term impacts on groundwater elevation. The magnitude of elevation change was significant in the upper reach of the river near the dam and was minimal throughout the farther reach. The approximate rate of groundwater elevation change was fairly homogeneous throughout the river, indicating consistent hydrogeologic properties throughout the delta.

1. Introduction

Beginning in the mountains of Colorado, the Colorado River forms from snowmelt, flows through seven Southwestern US states, and continues down to the deserts of Baja California, Mexico, as seen in Figure 1.[1] The Colorado River provides several major U.S. cities with water, and the river also supports native wildlife and outdoor recreation. However, the majority of the river's flow is utilized for agricultural irrigation. Almost 80% of the Colorado River's annual flow is diverted for agriculture in the Imperial Valley, the Southwest, and the Mexicali region.[1] Due to population growth and expansion of the southwest, increases in drought, and over-use of the river's water, the Colorado River's flow has not reached the Sea of Cortez since 1960, after the construction of the Hoover and Glen Canyon Dams in the upper basin of the river.[2] In the delta below Morelos Dam, located on the U.S.-Mexican border in the lower basin, the surface water and groundwater are dependent upon the Colorado River, which directly delivers surface water and is the major source of groundwater recharge in the delta.[3] Before the significantly reduced flow in the river, the Colorado River Delta riparian corridor was a vast wetland ecosystem. During the last several decades, the Colorado River Delta has lost much of its riparian vegetation, and there has been a decrease in available surface water and groundwater for irrigation in the Mexicali Valley.

Figure 1. The upper and lower Colorado River basin boundaries.[1]

In order to address the issues of over-exploitation of the Colorado River's water, the U.S. and Mexican sections of the International Boundary and Water Commission (IBWC) signed Minute No. 319, wherein the sections acknowledged the need for collaborative management of the river in order to provide sufficient water supply to Mexicali Valley's surface water and groundwater and to provide environmental flows from Morelos Dam to restore and sustain vegetation in the Colorado River Delta.[4] Section III.6. of the Minute 319 agreement addressed the Water for the Environment and ICMA/ICS Exchange Pilot Program, which stipulates that "[the] pilot program will arrange for the means to create 158,088 acre-feet (195 mcm) of water for base flow and pulse flow for the Colorado River limitrophe and its delta by means of the participation o the United States, Mexico, and non-governmental organizations".[4] The environmental flow planning was prepared by a binational Environmental Flows Team, and the team also planned ecosystem monitoring methods in order to evaluate the ecosystems biological, hydrological, and environmental responses to the flow.[5] The Environmental Flows Team identified seven distinct reaches of the delta, as seen in Figure 2 based on vegetation and hydrology, for evaluation of ecosystem response.[5] Reach 1 has only perennial surface water maintained by a shallow water table, reach 4 has some surface water and a shallow water table, reach 6 has flowing surface water resulting from agricultural runoff, and reach 7 has surface water flow from its confluence with the Hardy River and occasionally receives tidal flow.[5] Reaches 2, 3, and 5 are normally all dry, in terms of surface water. The release of water began on March 23, 2014 and lasted through May 18, 2014. The requested discharge of 195 mcm of water was met with an actual amount of 132 mcm.[5]

Figure 2. Colorado River Delta riparian corridor study area.[5]

One analysis that studied infiltration rate and recharge during the Minute319 flow indicates that infiltration rates were highest during the start of the pulse-flow and decreased over time.[6] For the purposes of this study, it was concluded that if the goal of future environmental flows is to reconnect the body of the river with tidal waters, then a slower, consistent baseflow would minimize infiltration rates as well as channel transmission losses.[6] In another study, the extent of the flow's impact on vegetation restoration was analyzed.[7] Reaches 6 and 7 were the primary focus, as these make up the Laguna Grande area of the Perennial Delta, where vegetation restoration was most viable. These reaches in the delta had the most sustainable surface water flow; the upper reaches returned to pre-flow conditions by the end of May but reaches 6 and 7 had between 50% and 100% higher surface water flow in comparison to pre-flow conditions.[7] The groundwater in the perennial delta reaches showed a different response to the flow because the water table in this reach is consistently high, so the groundwater levels were not impacted as greatly.[7]

This study will focus on the groundwater elevation changes at 52 sites throughout the reaches of the delta and how these changes relate to time and space. It is anticipated that this analysis will show an increase in groundwater levels over time that has a direct relationship with the progression of the surface water flow in the delta. Because of the high infiltration rates during the start of the flow, the groundwater elevation will rise quickly, and as infiltration rates decrease over time, the groundwater elevation will fall at a much slower rate than its rise. Due to high upstream infiltration, vegetation density, and meanders in the river, groundwater level response is predicted to show a correlation to distance from the pulse-flow release site at Morelos Dam. After the temporal analysis of groundwater level change, a set time frame will be calculated in order to determine the necessary frequency and magnitude of future pulse-flows needed to keep groundwater levels at or above pre-flow conditions.

2. Methods

2.1 Spatial Reference

This analysis is focused strictly on the reaches of the Colorado River that are located below Morelos Dam. All data utilized in this study were obtained from fieldwork conducted by the UABC, USGS, and USBR. The data provided by each of these agencies was arranged appropriately, and the piezometer locations were added to the basemap (Fig. 3) through the Excel to Table and Table to XY point geoprocessing tools in GIS. The associated data that corresponds to each site was also added to the point feature class attribute table, calculations were conducted within GIS, and the results were exported. The UABC and USGS installed a combined total of 47 continuously sampling groundwater monitoring wells in early May of 2014 in anticipation of the environmental flow. The USBR also has 5 groundwater monitoring wells that require manual measurements, so the data obtained from these piezometers is not continuous. The watershed boundary provided in the basemap and the associated DEMs were retrieved from the Hydro1K database. After downloading the DEMs, the rasters were clipped, and flow direction and flow accumulation processing was conducted. The resulting flow accumulation data was not spatially accurate, so an NHD flowline shapefile was used to symbolize the main body of the Colorado River.

2.2 Groundwater Elevation

Groundwater elevation data were collected at the piezometers starting one week before the pulse-flow through the end of 2014. Groundwater measurements were taken either automatically with pressure transducers in the continuously sampling wells or manually with hand augers in the non-continuously sampling wells. The piezometers were small diameter, between 2.5 and 5 cm, relatively shallow at about 5-15 meters, and had 1.5 meter screened intervals at the bottom of the wells.[8] The piezometer data used in this study can be found at http://go.usa.gov/xZPUV.[9]

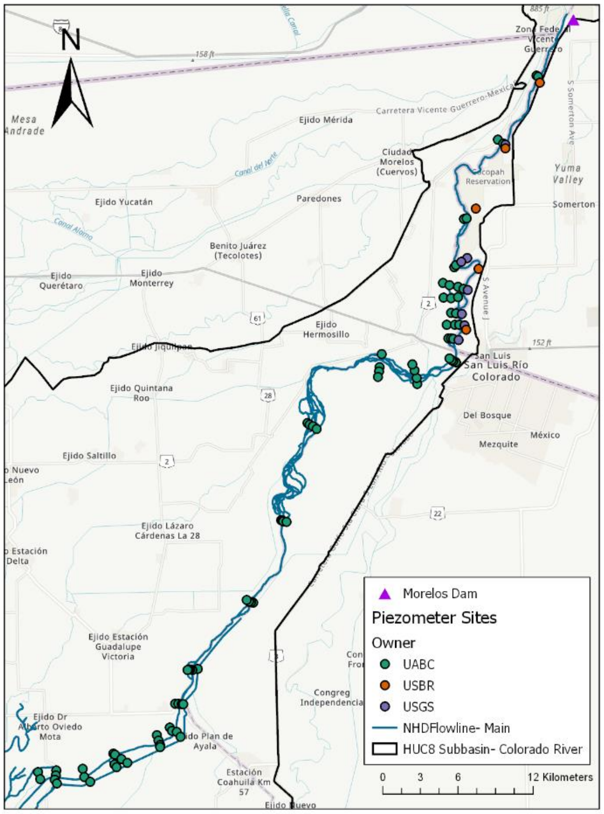


Figure 3. Groundwater measurement sites. Shows the location of the piezometers along the delta.

2.3 Calculations & Statistical Analysis

In order to analyze the relationship between the groundwater measurement site location and the rate of change in groundwater elevation, distance from the piezometers to Morelos Dam had to be calculated. Distance calculations were made using the ArcGIS geoprocessing Euclidian distance tool. Distances are therefor provided in Euclidian distance, rather than as a distance along the flow path of the river. Distance was then plotted against both change in elevation measurements as well as rate of change measurements, and a linear regression analysis was conducted.

3. Results

The long-term temporal analysis of the groundwater elevations at all piezometer sites indicates that the water table fell back to its original elevation at all sites within a year after the environmental flow (Fig. 4). Groundwater elevation change was also studied at a smaller scale based on site locations, which can be seen in Figures 5a-d and in Table 1. The BD and L-US site groups are primarily located in Reach 1 of the river; their respective peaks in groundwater elevation occurred during May 28-April 1, and the overall maximum change in elevation ranged from 0.73 m.a.s.l. – 5.1 m.a.s.l. The wetted front of the surface water flow in the river arrived in Reach 1 of the river during March 23-March 25, so there was about a 5-day lag time between when the surface water reached these sites and

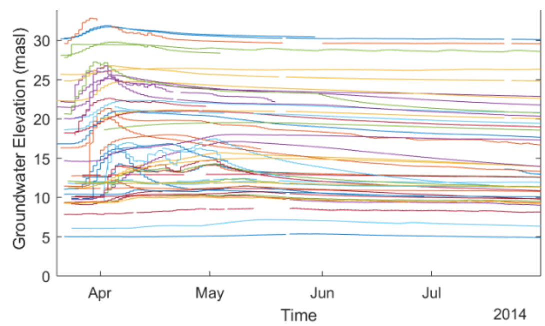


Figure 4. Continuous Groundwater Levels During Flow. Groundwater elevation measured in meters above sea level from March – December of 2014.

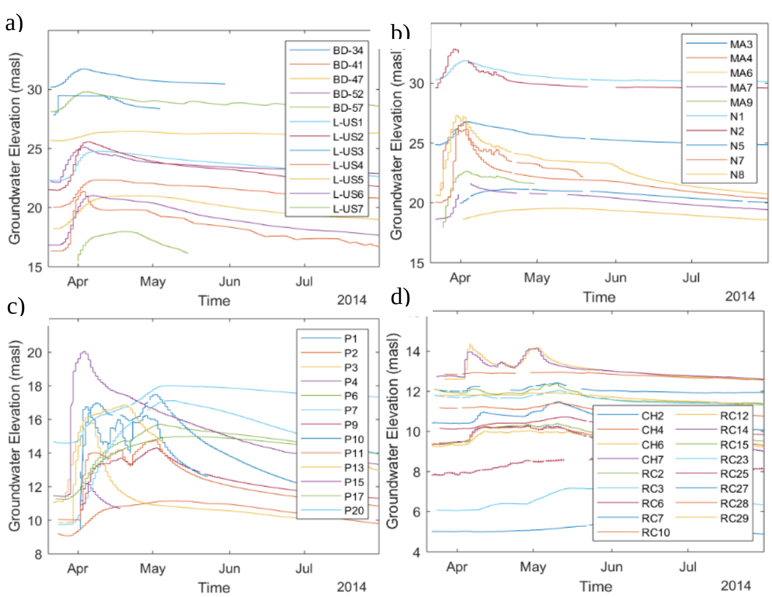


Figure 5. Groundwater elevation change over time by reach. Elevation is measured in meters above sea level. a) Site groups located in Reach 1. BD sites are USBR manual sites, and L-US are USGS continuous sites. b) Site groups located in Reaches 2 and 3. All wells are continuous and UABC owned. c) Site groups located solely in Reach 4. All wells are continuous and UABC owned. d) Site groups located partially in Reach 4 and in Reach 6. All wells are continuous and UABC owned.

when the groundwater elevation reached its maximum.[4] The N and MA site groups are located throughout Reaches 2 and 3; their respective peaks in groundwater elevation occurred during April 1-2, and the changes in groundwater elevation ranged from 0.97 m.a.s.l. – 6.73 m.a.s.l. The surface water flow progressed to Reaches 2 and 3 between March 26-March 30, so the N and MA site

Table 1. Groundwater elevation data. This table shows the initial elevation values, maximum elevation values, and the greatest change in elevation for each piezometer. All groundwater measurements are reported as meters above sea level. Sites are listed in ascending order based on distance from the Morelos dam.

Site	$Elev_i$ (masl)	$Elev_{max}$ (masl)	$\Delta Elev_{max}$ (masl)	Distance (km)	Site	$Elev_i$ (masl)	$Elev_{max}$ (masl)	$\Delta Elev_{max}$ (masl)	Distance (km)
N-1	30.30	31.91	1.61	5.35	P-17	9.75	17.12	7.37	31.45
N-2	29.61	32.85	3.25	5.35	P-2	10.44	14.31	3.87	31.61
BD-34	30.21	31.74	1.53	5.69	P-3	10.06	14.76	4.70	31.92
L-US-3	27.84	29.50	1.66	11.32	P-4	11.05	16.85	5.80	32.33
BD-41	16.32	21.42	5.10	11.59	P-7	11.26	15.00	3.74	38.36
BD-47	25.73	26.46	0.73	16.90	P-6	11.47	20.05	8.58	38.38
N-5	24.88	26.77	1.89	18.07	P-11	9.87	15.82	5.96	45.98
L-US-1	22.65	24.77	2.12	20.73	P-10	9.22	11.16	1.94	45.98
BD-52	22.24	25.13	2.89	21.17	P-9	14.69	18.02	3.33	46.00
L-US-2	21.56	25.58	4.01	21.19	CH-6	12.60	14.40	1.79	52.81
N-8	20.66	27.30	6.64	21.61	CH-7	12.70	14.13	1.42	52.87
N-7	20.08	26.81	6.73	21.82	CH-2	12.06	12.43	0.37	59.80
L-US-4	20.04	22.35	2.31	23.06	CH-4	12.85	12.96	0.11	59.98
MA-4	21.03	26.17	5.14	23.10	RC-3	5.01	5.37	0.36	62.56
MA-3	19.90	21.16	1.26	23.10	RC-2	11.18	11.44	0.25	62.66
MA-7	18.62	21.64	3.02	23.86	RC-10	12.11	12.38	0.27	64.76
MA-6	18.58	19.55	0.97	24.16	RC-12	11.83	12.04	0.21	64.85
L-US-5	18.23	21.03	2.80	24.96	RC-6	9.35	10.28	0.92	66.00
MA-9	17.92	22.65	4.72	25.10	RC-7	9.27	10.05	0.78	66.20
L-US-6	16.83	21.03	4.20	25.76	RC-14	10.15	10.72	0.57	68.73
BD-57	28.13	29.82	1.68	26.05	RC-15	10.42	11.49	1.06	68.75
L-US-7	15.48	18.00	2.52	26.98	RC-28	6.09	7.19	1.09	69.43
P-15	12.77	15.71	2.94	28.67	RC-29	7.81	8.70	0.90	69.52
P-13	10.64	12.23	1.59	28.72	RC-25	9.45	10.33	0.88	71.61
P-20	9.43	16.78	7.35	30.19	RC-23	11.85	11.93	0.07	73.03
P-1	12.49	17.48	4.99	30.62	RC-27	9.37	10.40	1.03	73.66

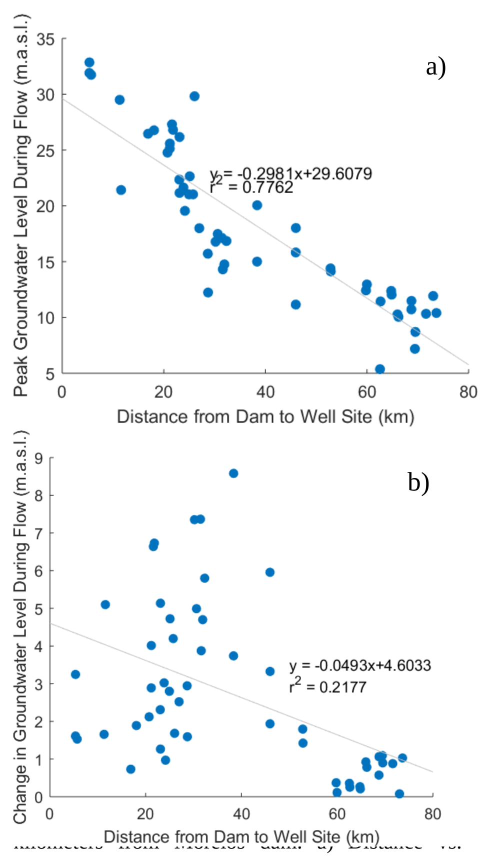
groups showed a lag period between surface flow and maximum groundwater elevation of between 3-6 days.[4] The P site group is located primarily in Reach 4, which received surface water flow between March 31 – April 5; the peaks in groundwater elevation at these sites occurred during April 2-May 2, and the elevation changes ranged from 1.59 m.a.s.l. – 8.58 m.a.s.l.[4] This indicates that the lag period between surface water progression and peak groundwater elevation ranged from 3 – 27 days. The RC and CH site groups are located in Reaches 4 and 6; their respective peaks in groundwater elevation occurred from April 5-April 10, and the maximum changes in elevation ranged from 0.11 m.a.sl. – 1.09 m.a.s.l. The surface water flow reached these farther reaches from

April 5 – April 15, so these locations responded to the flow within 1-2 days.[4]

The distance of the well sites from Morelos Dam was plotted against the sites' corresponding peak elevation values (Fig. 6a) and against the sites' corresponding maximum change in elevation (Fig. 6b). There is a strong linear correlation between site location and maximum elevation of the water table reached during the flow, where the regression analysis showed an r^2 value of 0.7762. The relationship between site location and maximum overall change in the elevation of the water table did not show a linear correlation, where the regression analysis gave an r^2 value of 0.2177.

4. Discussion

By the end of 2014, groundwater levels had returned to initial, pre-flow conditions throughout the Colorado River Delta, so there were no long-term impacts on the water table's elevation in the delta as a result of the Minute 319 flow. After investigating groundwater levels at a smaller temporal scale, it was evident that changes in groundwater occurred in response to surface water flow on a scale of days. Initial groundwater levels in the delta showed a correlation with location in reference to the Morelos dam. This is indicative of the more frequent surface flow in the upper reach, whereas the farther reaches were drier, even when receiving occasional agricultural runoff. The magnitude of the changes in groundwater level did not show as strong of a correlation. From figure 6b, the sites that were closest and farthest in proximity to the dam experienced lower changes in groundwater level in



maximum groundwater elevation reached during flow. b) Distance vs. maximum overall change in groundwater elevation during flow.

comparison to the sites that were mid-distance from the dam. This is likely a result of the smaller releases of surface water from the downstream spillways throughout the flow period, and these sites are also situated below the Colorado River's confluence with the Hardy river, which likely supplied water as well.

With a discharge of 132 mcm of water released over a period of 26 days, groundwater levels responded at a high rate of change, and the groundwater levels were sustained above initial levels for a significant period of time. These heightened water table elevations were able to provide a consistent water source to the roots of new and developing riparian vegetation along the corridor. If these groundwater levels were to be maintained, a similar pulse-flow at the same magnitude and rate would need to occur once every. In terms of vegetation response, the two perennial reaches of the river had the highest potential for restoring vegetation and encouraging seedling growth; however, because there was such a high magnitude of groundwater level change in the dry reaches mid-distance from the dam, it is likely that much of the surface flow was lost to these alluvial reaches.[7] In considering future flows, this large range of spatial variation could present a problem for vegetation regrowth. In terms of data collection and use of GIS for analysis in this project, the majority of errors and limitations stem from the lack of international data for the Colorado River. Most DEMs for the study area were incomplete because they were only available on one side of the border, and the data sets provided by the US and Mexican agencies were often conflicting in their organization and presentation of the spatial data.

5. Conclusion

The Minute 319 environmental flow to the Colorado River Delta was a result of successful bi-national cooperation and water resources management, and the experimental flow was successful in providing vast amounts of hydrologic data about the riparian corridor of the river.

The Colorado River received enough surface water flow in order to restore the connection to the tidal waters from the Sea of Cortez; however, a large portion of the pulse-flow was "lost" to the restored riparian vegetation and to the parched aquifers of the delta. The elevation of groundwater throughout the delta responded rapidly to the progression of the surface flow and was able to retain some of the flow water for up to 8 months. Spatially, the central reaches of the river saw the highest overall change in groundwater elevation, whereas the upper and lower reaches of the river had lower overall changes in elevation of groundwater. These results indicate that the geomorphology of the river has a significant impact on the rate and magnitude of groundwater recharge in the delta, which influences the viability of different locations in the delta for vegetation restoration. This flow not only brought life to a river that has long been over-used and exploited, but it provided a vast amount of valuable hydrological, geological, and ecological data that can be explored much more in depth from both U.S. and Mexican agencies and organizations.

6. Sources

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