Modeling Surface Water Depletions Due to Groundwater Pumping in a Transboundary Basin

T. Maddock III[1], A. Serrat-Capdevila[1,2] and J. B. Valdes[1,2]

(1) Department of Hydrology and Water Resources, University of Arizona, Tucson, Arizona, maddock@hwr.arizona.edu
(2) International Center for Integrated Water Resources Management (ICIWaRM-UNESCO), aleix@email.arizona.edu, jvaldes@email.arizona.edu

ABSTRACT

The present study quantifies surface water depletions due to groundwater pumping in the Lower Colorado River Delta, motivated by the desire to conjunctively manage surface and groundwater and restore riparian habitats. Surface water depletions are a form of surface water capture by pumping. Capture can only be calculated by running a hydrologic model of the system under two conditions: (a) simulate the historical record of hydrologic measurements, and (b) simulate a base case that represents the hydrologic records under limited or no groundwater development. Surface water capture is the sum of increased stream losses in loosing reaches and decreased stream gains in gaining reaches. The seasonal capture estimates presented in this publication is water removed from the river by groundwater pumping.

Key words: surface water capture, groundwater pumping, riparian system, hydrologic modeling

INTRODUCTION

The current paper is a demonstration analysis of the depletion of surface water due to groundwater pumping on a transboundary system: the Colorado River Delta (CRD) between the US and Mexico's Sea of Cortez. The desire to conjunctively manage surface and ground waters, to restore the severely impacted riparian habitat along the river, and to test newly developed software motivated the current study.

The Colorado River crosses the border between the United States and Mexico with limited surface water. The amount of water flowing into Mexico is restricted by a complex set of water management policies throughout the Colorado River Basin, and by construction of the Colorado River Dam system which includes six dams within the United States. These policies and dams have reduced surface water flows to Mexico by approximately 75 percent during the last century (Luecke et al, 1999). Altogether, the regulation and divvying up of water within the Colorado River Basin is carried out according to the complex set of laws, international treaties, and agreements known as the Law of the River (see website of U.S. Bureau of Reclamation)

The CRD covers over 8,600 km^2 extending across the international border between the United States and Mexico. Characterized by a desert climate dominated by high temperatures and arid conditions (18mm in summer and 44mm in winter), the persistent hot dry conditions in the CRD result in a moisture deficit where evaporation potentials far exceed the input of precipitation. During pre-development of the delta for irrigated agriculture, widespread wetlands provided essential habitat for resident and migratory bird and animal species, some of them endangered. Nowadays, the remaining 5% of the original wetlands survive due to agricultural return flows and other unplanned flows resulting from human activities.

Modern day Colorado River flows crossing the international boundary are regulated in accordance with the 1944 U.S-Mexico treaty which states that no less 1,850,234,000 m^3 of Colorado River water is to be released into Mexico each year (the US-Mexico Joint Projects 1944 treaty). The surface water flow from the Colorado River into Mexico is used extensively for large scale irrigation. At present, there are over a 200,000 hectares of irrigated farm land within the CRD of Mexico (Olmsted et al, 1973). The surface water is inadequate to support the level of irrigated agriculture, which has led to development of groundwater resources to augment the surface flow. By 1965 there were over 400 large capacity irrigation wells withdrawing approximately 160,000,000 m^3 per year. Agriculture is the largest single user of water in the CRD region. Farms depend on a system of canals the bring a prescribed combination of surface water from the Colorado River and groundwater pumped from the region to their fields, and a series of drains that move irrigation runoff away (Cohen and Henges-Jeck, 2001)

Surface water and groundwater are not separated sources of water and interact through surface water/ groundwater interactions. The large scale pumping of groundwater from an aquifer system hydraulically connected to a surface water system will deplete the surface water system. This depletion is a form of surface water capture. To properly manage the available waters in the CRD region, it is imperative that the water managers understand the capture process and estimate its affect on the water supply.

METHODOLOGY

When a well is pumped a cone of depression is formed and continues to expand until a source of capture is encountered. There are two sources of capture from streambeds are: 1) decrease in groundwater discharge to gaining streams (interception of baseflow), 2) increase in groundwater recharge from losing streams (increased infiltration).

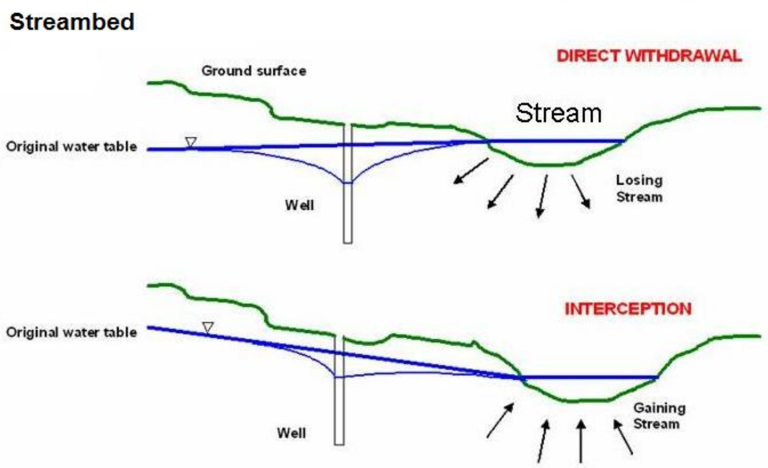

Figure 1: Sources of capture from streambeds.

If drains are present within the irrigation system, the cones of depression will likely encounter them first. If the drain water is to be returned to the river and used again, these cones of depression will reduce streamflow by the capture of the drain water.

Capture can only be calculated by hydrological modeling, it cannot be measured directly in the field. There is no capture meter. The hydrologic model of the system is run under two conditions: 1) simulate the historical record of hydrologic measurements, and 2) simulate a base case that represents the hydrologic records under limited or no groundwater development. The historical run and the base-case run simulate the system over the same distributions in time. For example, if the historical run simulation the systems groundwater and surface water system annually for a 25 year period, then the base-case run simulates the system annually for the same 25 years.

Surface water capture is the sum of the absolute values of two terms. The first term is the base-case time series of recharge from losing stream portions subtracted from the historical time series of recharge for the same stream segment. The second term is the historical time series of discharge from the gaining stream portion subtracted from the base-case time series of discharge for the same stream segment.

The historical run seeks to match the historical spatial and temporal data sets, thus the historical run is a calibrated run. The base-case may be fictional or artificial in nature, and based on little or no data. It is a hypothetical system that represents how the system would have been operated under limited or no groundwater pumping. The form or structure of the base-case may be the result of a negotiation process, or administratively or Court imposed.

The base-case run uses the same parameters and time steps as the historical run. Because capture cannot be measured in the field directly, there will be no capture data values to compare or calibrate with the calculated values.

The U.S. Geological Survey numerical model MODFLOW 2000 was used to simulate the groundwater flow and groundwater/surface water interactions in the CRD portion shown in Figure 2.

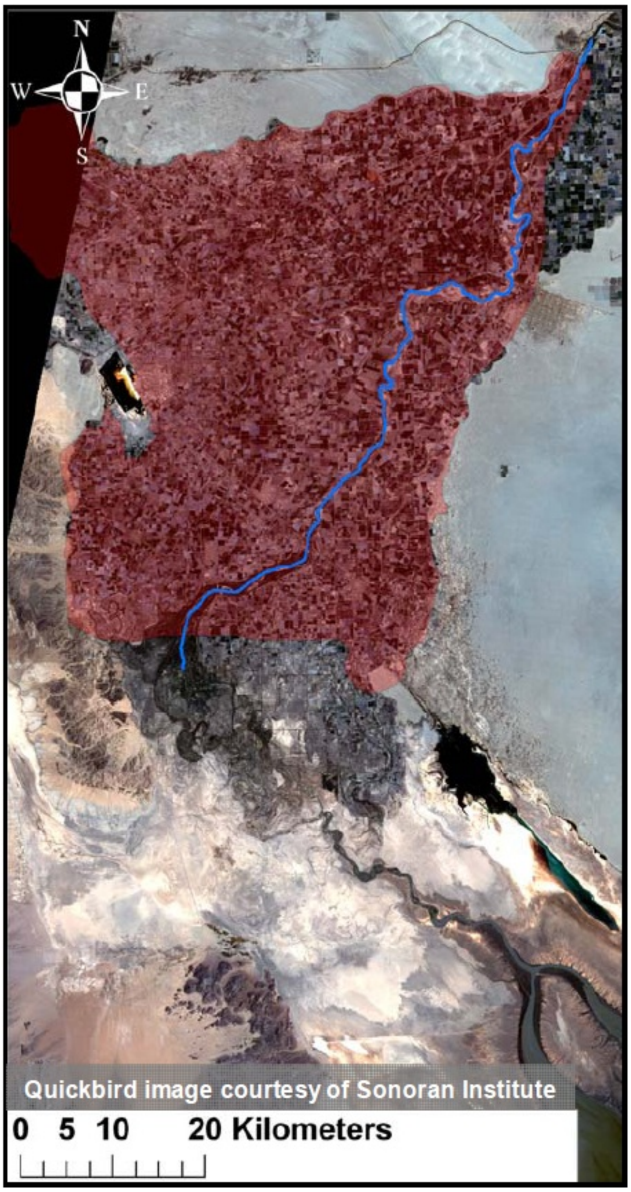

Figure 2, Colorado River Delta model area is shown in red with Colorado River shown in blue.

Streamflow in the CRD model was simulated using the stream package in MODFLOW developed by D. Prudic (1989). The stream-aquifer package, referred to as the STR package, routes flow through one or more rivers, streams, drains or ditches and computes leakage between these surface water features (commonly referred to as streams) and the aquifer beneath it simulating both gaining and losing portions

(Prudic, 1989). The STR package also calculates the water depth in the streams. Therefore, streamflow data at gage sites are additional calibration variables. The Mexican surface water allotment and any flood waters enters in at the northeast boundary of the model, and are routed through the system where losses associated with groundwater pumping are accounted for.

The CRD historical model includes 639 groundwater extraction wells, of these 418 are Federal and 221 are private (Figure 3). These wells are monitored by CONAGUA which maintains records of monthly volume pumped from each well, and takes a water level measurement from many of the wells once a year.

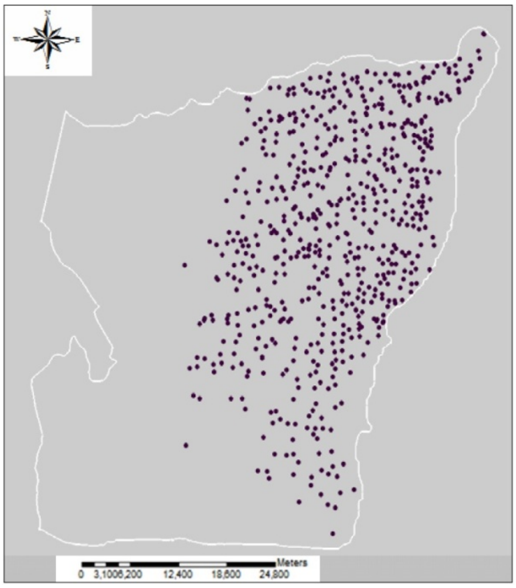

Figure 3, Distribution of 639 large production wells within the CRD model domain.

The historical model was calibrated for the years between 1957 and 2000 using data from CONAGUA (regional office Mexicali), the Autonomous University of Baja California, Dr. Jorge Ramirez, and the ITESM-Campus Guaymas. The model was calibrated for two seasons: 1) season 1 (winter) consisted of October – December of the previous year and January – March of the following year, and 2) season 2 (summer) April – September for the same year as the second half of season 1. Agriculture is the main water user within the CRD and recharge to the aquifer associated with agriculture, mainly irrigation, may be considered a primary source of recharge to the CRD aquifer.

Calibration was conducted by comparing model generated water levels to observed levels. Calibration was achieved through iterations of a process during which the model was run, computed vs. observed water levels were compared, and hydraulic parameters and boundary conditions were manually adjusted.

The base case model had the following properties. The 1957 through 2000 time frame and associated seasons were the same as the historical model. There was no groundwater pumping. The same quantity of water in flowed at the northeast boundary as with the historical model. The agricultural recharge was adjusted to reflect only surface water availability.

In a previous study of the CDR, capture was calculated using spreadsheet analysis (Feirstein et al, 2008). For this study, the capture was recalculated using a software called CAPT_CALC (see Figure 4). CAPT_CALC automates the capture calculations for MODFLOW historical and base model runs from the STR package.

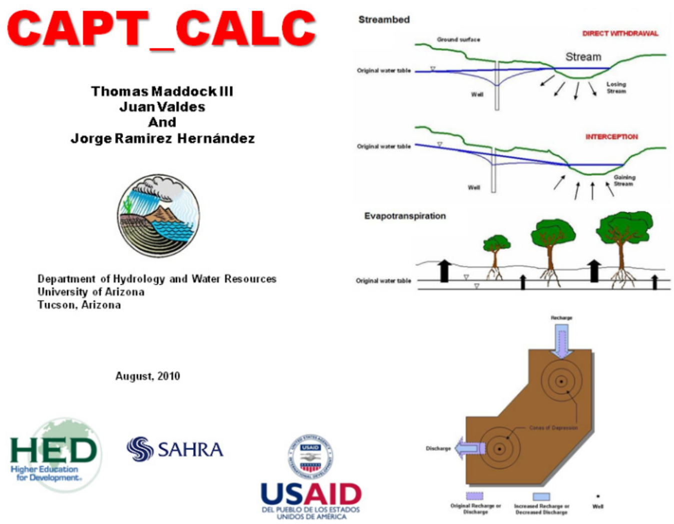

Figure 4, CAPT_CALC, a software that calculates capture from MODFLOW outputs.

CAPT_CALC can calculate capture from MODFLOW outputs from streams (STR, SFR, RIV), evapotranspiration (EVT, RIP-ET), head dependent boundaries (GHB), and specified head boundaries (CHB) packages. CAPT_CALC was funded in part by a Ties Grant (HED and USAID) between the University of Arizona in the United States and the Autonomous University of Baja California in Mexico, and SAHRA, a NSF Science and Technology Center.

RESULTS

The following results show the impacts of pumping on the stream system. Figure 5 shows the impacts of pumping on surface water in the CRD and differentiates the capture due to increased stream losses in loosing reaches, and the capture due to decreased stream gains in gaining reaches. In both cases, the capture shown is water that has been removed from the river flows by groundwater pumping.

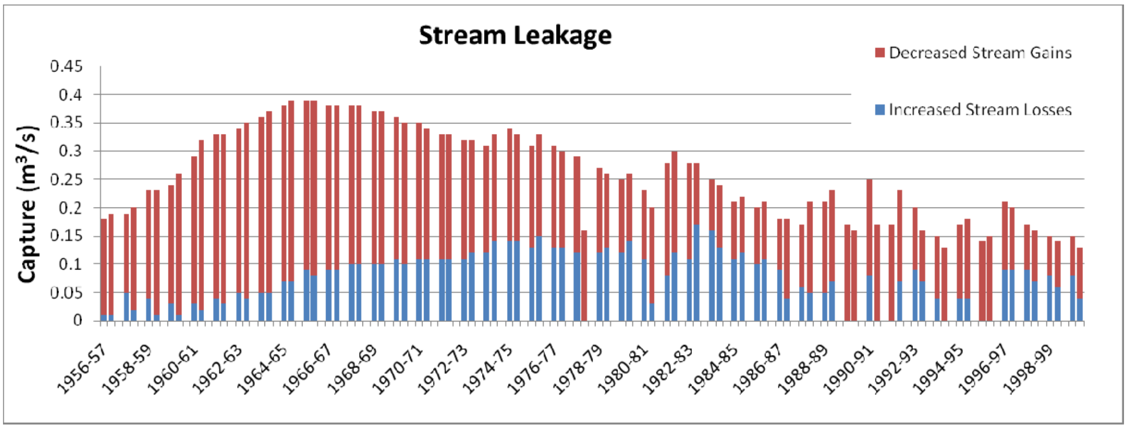

Figure 5: Capture from stream leakage through decreased stream gains (red) and increased stream losses (blue) for seasons 1 and 2 of each year.

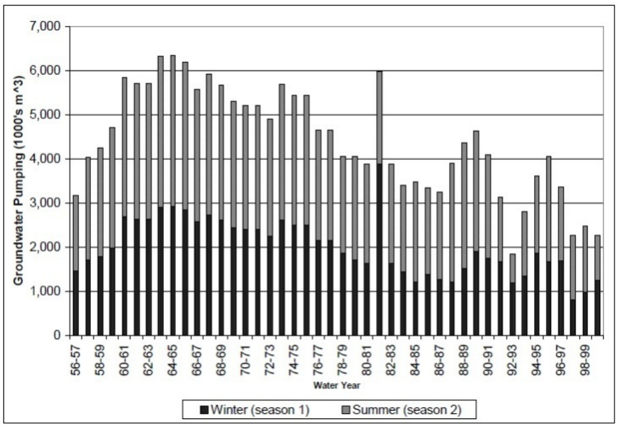

Figure 6, Total groundwater pumping rates for the CRD groundwater flow model

Figure 6 shows the groundwater pumping that produced the surface water depletions, and Figure 7 show the streamflow of the Colorado River for the same time frame. A casual comparison of the streamflow capture (Figure 5), the total pumping (Figure 6) and the stream inflow into the CRD (Figure 7) over time indicate that for periods of flooding where there is less groundwater pumping there is less capture. This is because of the dependence of Colorado River water for agricultural irrigation. When river flows are high, less groundwater is withdrawn to supplement irrigation, and there will be less depletion of streamflow.

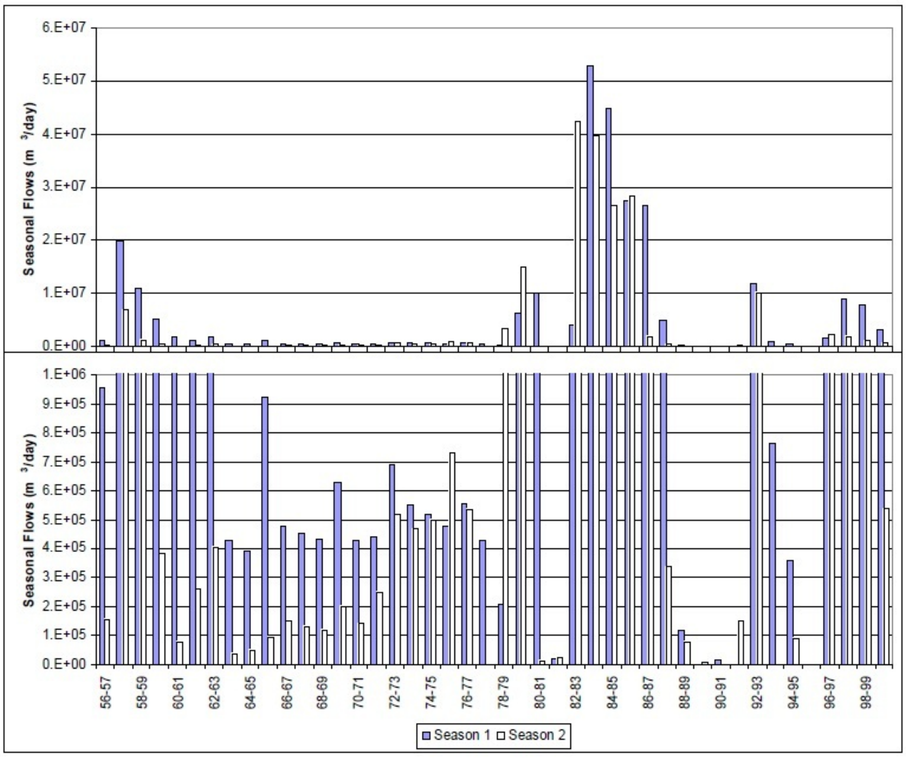

Figure 7, Seasonal discharge at the Southerly International Boundary for the 1956-57 water-year to 1999-00. (Top) scale 0 to 60×10^6, (bottom) scale 0 to 1×10^6.

Although the surface water capture estimated in this study provide a useful indication of the CRD's natural response to stresses such as groundwater pumping, the reader should keep in mind the limitations in any modeling processes such as those associated with conceptualization of the system, data availability, and data quality.

FUTURE WORK

The completed Colorado River Delta model will form the parent model for the use of a modeling technique called Local Grid Refinement (LGR). The LGR technique will be used produce a grid refinement of the selected regions of the Colorado River Delta. The grid refinement produces a child model that is a localized model of higher grid density that interacts with the parent model. These child models may be used to analyze potential sites for riparian restoration, local drawdowns in specified regions, and local stream/aquifer interaction with its associated capture.

REFERENCES

Cohen, M. J., and C. Henges-Jeck (2001), Missing water: the uses and flows of water in the Colorado River Delta region, *Pacific Institute Report*, Oakland CA, USA, ISBN: 1-8937900-05-3, www.pacinst.org.

Feirstein, Eden J., Francisco Zamora, Leticia B. Vionnet, Thomas Maddock III, (2008) Simulation of Groundwater Conditions in the Colorado River Delta, Mexico, *Department of Hydrology and Water Resources, University of Arizona*, HWR No. 08-030.

Luecke, D. F., J. Pitt, C. Congdon, E. P. Glenn, C. Valdes-Casillas, M. Briggs (1999), A delta once more: resoring riparian and wetland habitat in the Colorado River Delta, *Environmental Defense Fund Report*, Washington DC, USA, ISBN: 1-58 144-356-0.

Olmsted, F. H., O. J. Loeltz, and B. Irelan (1973), Geohydrology of the Yuma Area, Arizona and California, Geological Survey Professional Paper 486-H, *United States Government Printing Office* Washington, DC.

Prudic, D. E. (1989), Documentation of a computer program to simulate streamaquifer relations using a modular, finite-difference, groundwater flow model, *U.S. Geological Survey Open-File Report 88-729*, Carson City NV, USA.