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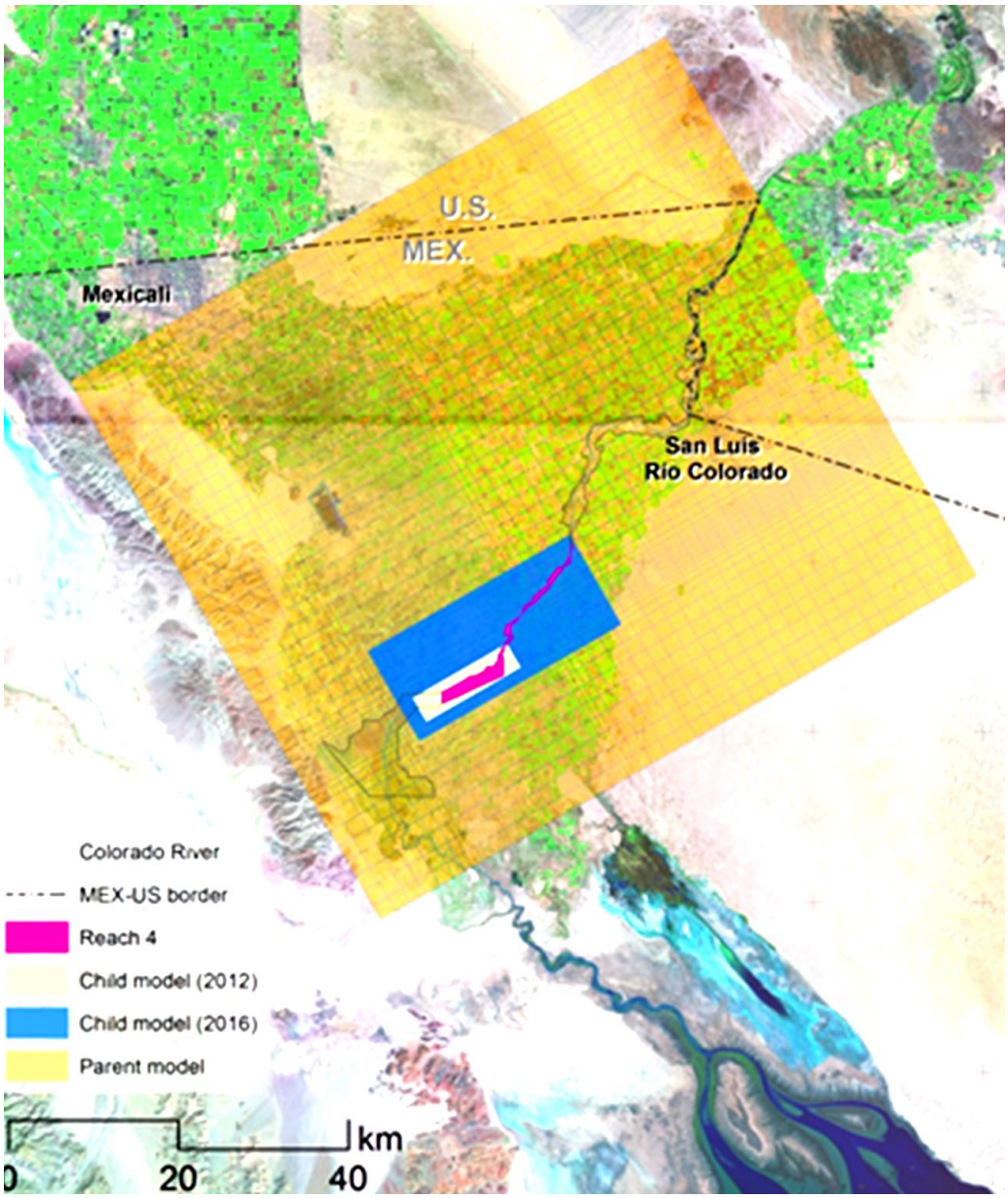

Model report

Ph.D. Jorge Ramírez Hernández
Ph.D. Jesús Eliana Rodríguez Burgueño

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REACH 4

GROUNDWATER MODEL

Overview of modeling program.

MODFLOW is the USGS's three-dimensional (3D) finite-difference groundwater model. MODFLOW is considered an international standard for simulating and predicting groundwater conditions and groundwater/surface-water interactions. MODFLOW-2005 is the standard version of MODFLOW supported by the USGS Office of Groundwater and is the most stable and well-tested version of the code (USGS, 2017).

MODFLOW-2005 is written in the Fortran 90 programming language. Programs written in standard Fortran are highly portable. The groundwater flow process of MODFLOW has been divided into "packages." A package is the part of the program that deals with a single aspect of simulation. For example, the Well Package simulates the effect of wells, the River Package simulates the effect of rivers, and the Strongly Implicit Procedure Package solves the system of simultaneous finite-difference equations. Many of the packages represent options that the user may or may not have occasion to use. The fundamental method in Fortran for dividing a program into pieces is subroutines, so each package consists of multiple subroutines. The MAIN Program calls the various subroutines of the packages in the proper sequence to simulate ground-water flow (Harbaugh, 2005).

Figure 1 shows a spatial discretization of an aquifer system with a grid of blocks called cells, the locations of which are described in terms of rows, columns, and layers. An *i*, j, *k* indexing system is used. For a system consisting of "NROW" rows, "NCOL" columns, and "NLAY" layers, i is the row index, i = 1,2,. . . NROW; j is the column index, j = 1,2,. . . NCOL; and k is the layer index, k = 1,2,. . . NLAY (Harbaugh, 2005).

In formulating the equations of the model, an assumption was made that layers would generally correspond to horizontal geohydrologic units or intervals. Thus in terms of Cartesian coordinates, the k index denotes changes along the vertical, z; because the convention followed in this model is to number layers from the top down, an increment in the k index corresponds to a decrease in elevation. Similarly, rows would be considered parallel to the x axis, so that increments in the row index, i, would correspond to decreases in y; and columns would be considered parallel to the y axis, so that increments in the column index, j, would correspond to increases in x. Within each cell there is a point called a "node" at which head is to be calculated. Many schemes for locating nodes in cells could be used (Harbaugh, 2005).

Simulations of ground-water flow and transport often need highly refined grids in local areas of interest to improve simulation accuracy. Refinement of the finite-difference grid used by MODFLOW can be achieved using globally refined grids, variably spaced grids, or locally refined grids. Using a locally refined grid can be less computationally intensive than the other two methods. This method, termed local grid refinement (LGR) in this report, links two or more different-sized finite-difference grids: a coarse grid covering a large area which incorporates regional boundary conditions, and a fine grid covering a smaller area of interest. These grids are often called parent and child grids, respectively, and this terminology is used in this report. Grid refinement can be vertical as well as horizontal (Mehl and Hill, 2005).

LGR uses an iteratively coupled method. Two-way iterative coupling is used to ensure that the models have consistent boundary conditions along their adjoining interface. The method implemented here couples the models using shared nodes. That is, the grids are constructed such that nodes of the parent grid are coincident with selected boundary nodes of the child grid. LGR provides the capability to simulate ground-water flow using one block-shaped higher-resolution local grid (a child model) within a coarser-grid parent model. LGR accomplishes this by iteratively coupling two separate MODFLOW-2005 models such that heads and fluxes are balanced across the shared interfacing boundary. LGR can be used in two- and three-dimensional, steady-state and transient simulations and for simulations of confined and unconfined ground-water systems (Mehl and Hill, 2005).

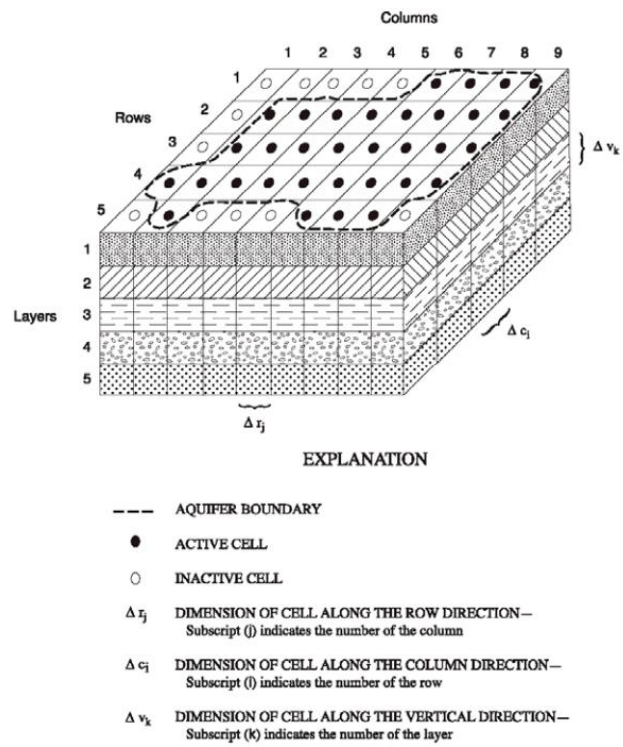

Figure 1. A discretized hypothetical aquifer system (Harbaugh, 2005).

They are several graphical interfaces to allow create input and output files for MODFLOW (e.g. Visual MODFLOW Flex, Processing MODFLOW [PMWIN], Modflow GUI-PIE, GMS, ModelMuse), in this project was used ModelMuse (Winston, 2009). ModelMuse is a graphical user interface (GUI) for the U.S. Geological Survey (USGS) models MODFLOW–2005 and PHAST. This software package provides a GUI for creating the flow and transport input file for PHAST and the input files for MODFLOW–2005. In ModelMuse, the spatial data for the model is independent of the grid, and the temporal data is independent of the stress periods. Being able to input these data independently allows the user to redefine the spatial and temporal discretization at will (Winston, 2009).

Model

Rodríguez-Burgueño (2012), developed a groundwater flow model of the Mexicali Valley aquifer (figure 2), using LGR MODFLOW 2005. In this model the objective was to develop a child model from the parent model of the regional aquifer, in the lower area of Reach 4 in order to obtain useful data for restoration purposes.

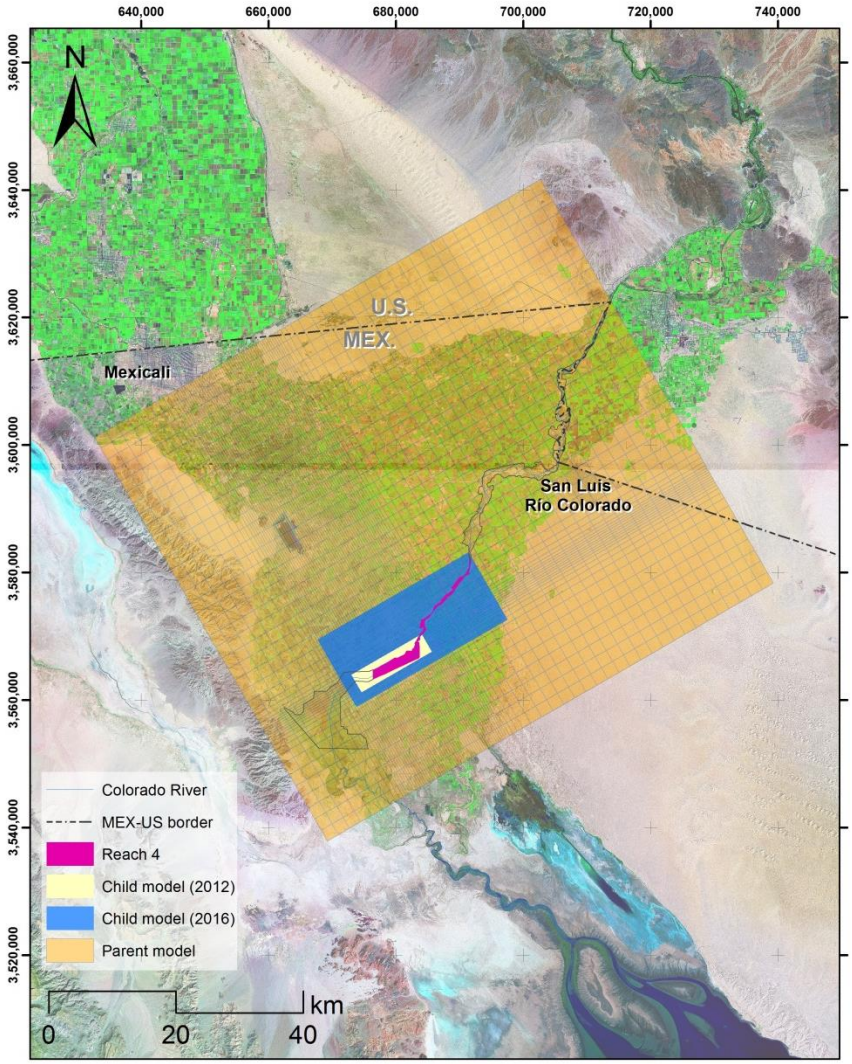

Figure 2. Domain of the groundwater model of Mexicali valley aquifer (parent) and domain of the child models.

From the data available for those models, was develop a new parent and child models (figure 2). For the parent model was created a new data set of information incorporating the scopes of the project in order to evaluate different scenarios. The child model was extended in all reach 4 area, including in the model domain areas outside the riparian corridor. All the information used as input of the model was created

from a GIS data base, and then incorporated to the models using ModelMuse. A briefly description of this models are included in the next paragraphs of this report.

Parent Model

The parent model (Mexicali Valley aquifer) was discretized in 2 layers (depths 0 to -120 m and -120 to -500 m, respectively), 86 columns and 48 rows at a rotation of 30 degrees. The cell size was 2 x 2 km, an in the refined area 375 x 375 m. The geohydrological parameters used were:

Parameter	Value (units)	Layer	Reference
Specific yield	0.20	1 and 2	Díaz, 2001; Feirstein, 2008; DOF, 2009
Vertical hydraulic conductivity	0.03 (m d^{-1})	1 and 2	Feirstein, 2008
Specific storage	1E-5 (m^{-1})	1 and 2	Díaz, 2001; Feirstein, 2008
Horizontal hydraulic conductivity	46 to 550 (m d^{-1}) 0.001 (m d^{-1})	1 2	Rodriguez-Burgueño, 2012 calibrated from Díaz, 2001 Feirstein, 2008

Parent model grid has the coordinates below (UTM 11 zone North WGS84):

Upper left corner: (632696.949, 3601227.073)
Lower left corner: (669259.449, 3537898.965)
Upper right corner: (702736.753, 3641664.573)
Lower right corner: (739299.253, 3578336.465)

The boundary conditions used in the parent model where: No flow and General Head Boundary (GHB); NO FLOW in the Sierra Cucapa area, and GHB at Mexicali, Mesa drain, Gulf of California and Arizona-Sonora boundary, calibrated according to the zone budgets for each boundary, using the water balance described above:

WATER IN (annual million cubic meters [hm^3 per year]):

- Arizona-Sonora (From Ariel, 1969): **120**
- Mesa Drain (calculated according to the All American Canal losses approximations): **20**
- Irrigation District 014 (ID014) recharge (calculated according water use efficiency): **515**

WATER OUT (hm^3 per year):

- Rio Nuevo (USGS): **100**
- Mexicali (Ariel, 1969): **30**
- Colorado River and Hardy drains (ID014): **50**
- Wells: **475**

MODFLOW package used during the modeling where recharge (RCH), well (WEL), drain (DRN), evapotranspiration (EVT), river (RIV), general head boundary (GHB). The solver used was the strongly implicit procedure package (SIP), for this solver was used a maximum of number of iteration of 500, and a head change criterion of 0.1 m. To simulate flow in the saturated zone was used the layer property flow (LPF) package.

The data used was available from Rodriguez-Burgueño (2012), recharge data was calculated assuming that a percentage of the irrigated water from irrigation cycle 2005-2006 is infiltrated to the aquifer accordingly to the scenarios. This calculation assumes losses from channels, drains and evaporation are witting this percentage, are not calculated directly.

Child model

The child model domain starts in upper left corner at the coordinates 667700.191, 3569474.679 and Lower right corner: 697574.263, 3572606.269 (Coordinates in UTM 11N WGS84). The cell size varied in the grid, a minimum of 125 x 125 m (row, column) to 125 x 666 m (figure 3), a total of 52 rows and 169 columns.

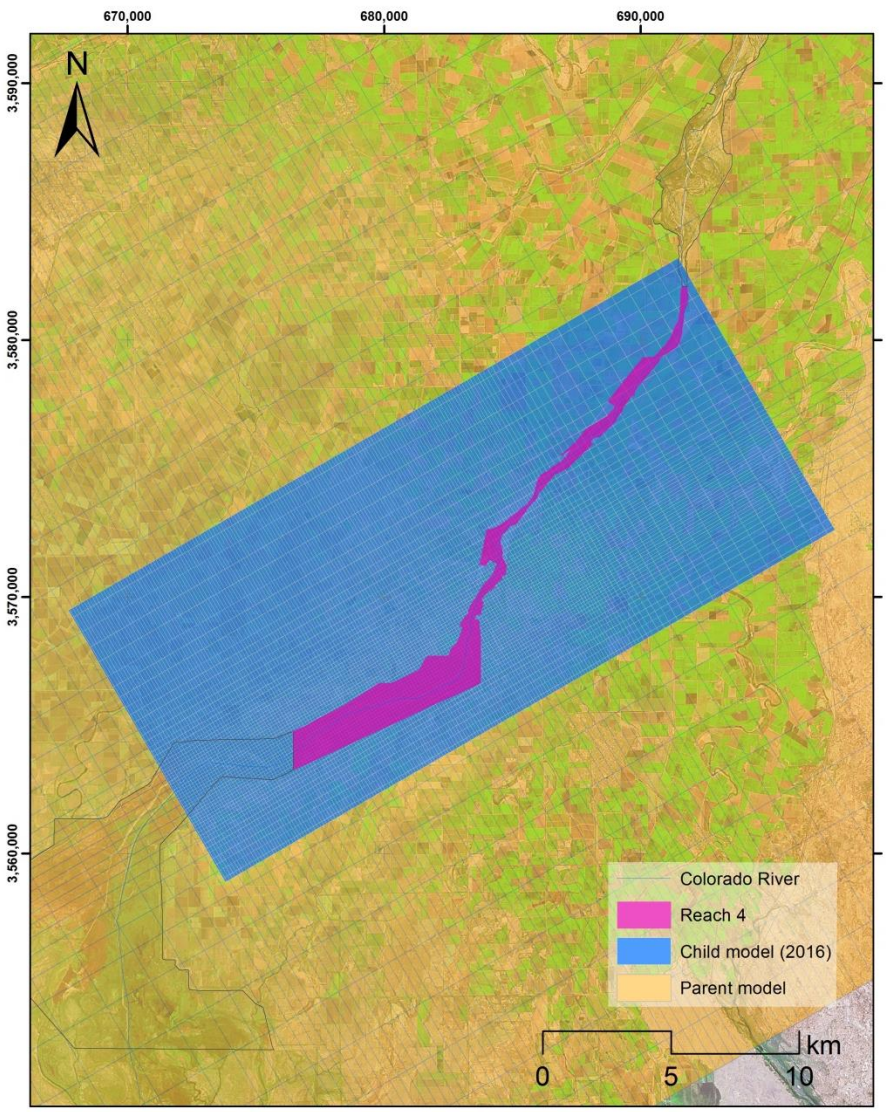

Figure 3. Child model domain.

The size of the cells are bigger at the north boundary of the child model because the parent model cell size are bigger in that zone, for each cell of the parent model there are 3 cells of the child model. The

geohydrological parameters used where the same of the parent model. Horizontal hydraulic conductivity in the child model domain is 550 m d^{-1}, accordingly to Rodriguez-Burgueño (2012).

Data

Input data to the model was developed in a GIS database, including recharge, evapotranspiration, upstream flow boundary condition and river data. The GIS files where imported in to Model Muse with the monthly values for each file accordingly to the scenario to simulate. The time of each simulation for each model was 12 stress periods using days as time unit, for each stress period where used the number of days that corresponds for each month as time steps. Recharge (RCH package) data was two different data sets: 1) recharge from the infiltration of the water deliveries from the irrigation district and 2) percolation from agriculture lands inside the riparian corridor.

Evapotranspiration was incorporated as a GIS file in to ModelMuse to the ET package, in this was added the evapotranspiration rate (according to the scenario), evapotranspiration surface from LiDAR data and evapotranspiration depth (8 m). River data was obtained from a HecRas simulation including scenarios of flow deliveries from 11 delivery locations along reach 4, to include the data at the river package (RIV) were created surface water elevation data for each scenario.

To include an upper boundary conditions was used the time-variant specified-head package (CHD), the input data for this package was accordingly to the scenario matrix at each model for each stress period and time step.

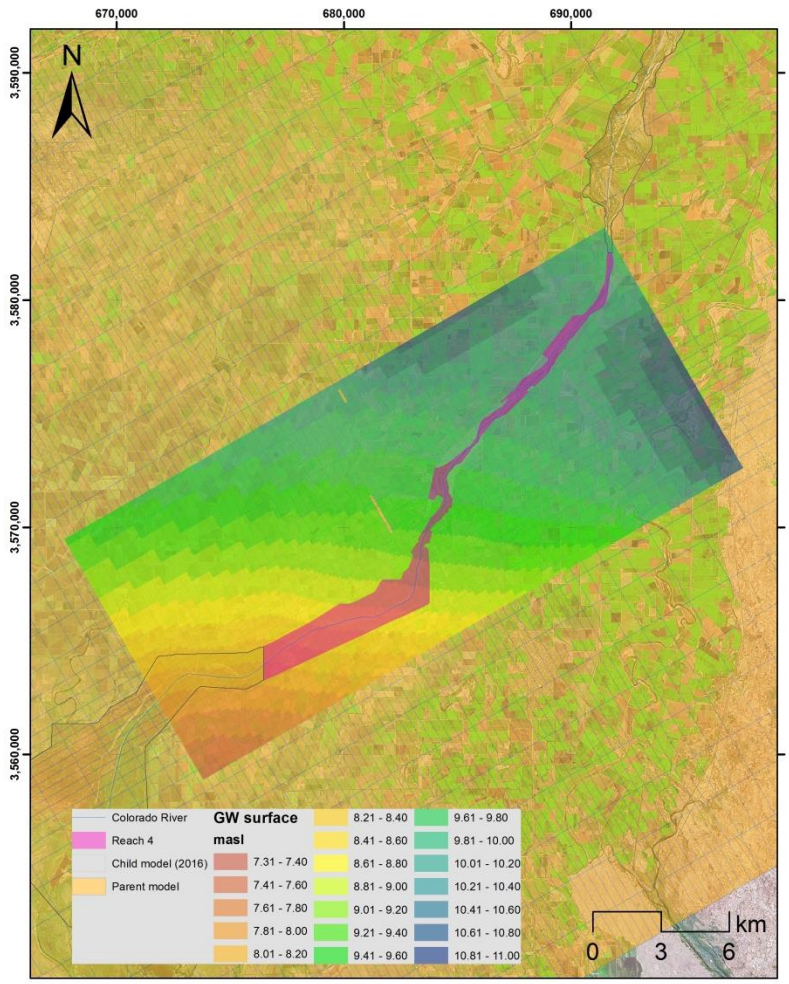

Figure 4. Example of obtained results from a model run of a particular scenarios.

Once the input files where created the model started to run, the development of each model had to be done for each scenario at the scenario matrix. Hence, output data in MODFLOW files where obtained. Using ModelMuse where imported to visualize the results in other model file that only include the child model domain in order to import the results for the child model simulations. Each month groundwater surface elevation was obtained and then exported to GIS format files. GIS files exported contained elevation of groundwater at each cell of the child model domain. Figure 4 is an example of the groundwater surface elevation grid data from a specific model and scenarios.

Accordingly to the parent and child models from Rodriguez-Burgueño (2012) were calibrated at 96% correlation between model outputs and observation data of groundwater elevations in the study area, this models where used as basis for this project.

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