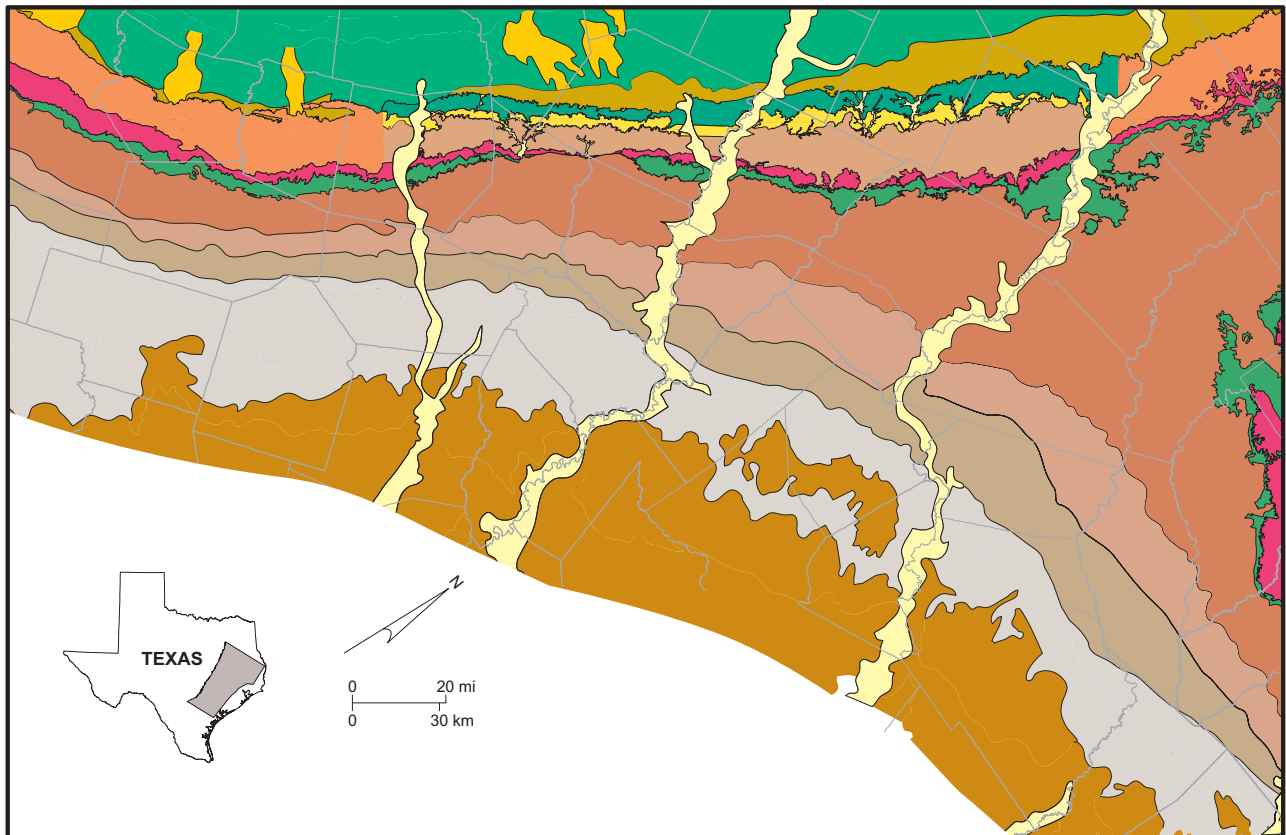


GROUNDWATER AVAILABILITY MODEL FOR THE CENTRAL PART OF THE CARRIZO-WILCOX AQUIFER IN TEXAS



Prepared for
Texas Water Development Board

By Alan R. Dutton, Bob Harden¹, Jean-Philippe Nicot, and David O'Rourke²

**Bureau of Economic Geology
Scott W. Tinker, Director**

John A. and Katherine G. Jackson School of Geosciences
The University of Texas at Austin
Austin, Texas 78713-8924

¹ R. W. Harden and Associates, Inc.

² HDR Engineering Services, Inc.

**GROUNDWATER AVAILABILITY MODEL
FOR THE CENTRAL PART OF THE
CARRIZO-WILCOX AQUIFER IN TEXAS**

Prepared for
Texas Water Development Board

Under
Contract No. 2001-483-378

By Alan R. Dutton, Bob Harden¹, Jean-Philippe Nicot, and David O'Rourke²

**Bureau of Economic Geology
Scott W. Tinker, Director**

John A. and Katherine G. Jackson School of Geosciences
The University of Texas at Austin
Austin, Texas 78713-8924

¹ R. W. Harden and Associates, Inc.

² HDR Engineering Services, Inc.

CONTENTS

| | |
|---|-----|
| Abstract | 1 |
| 1.0 Introduction | 4 |
| 2.0 Study area | 8 |
| 2.1 Physiography and Climate..... | 13 |
| 2.2 Geology | 19 |
| 3.0 Previous Work..... | 29 |
| 4.0 Hydrologic setting | 32 |
| 4.1 Hydrostratigraphy..... | 32 |
| 4.2 Structure | 34 |
| 4.3 Water Quality | 53 |
| 4.4 Water Levels and Regional Groundwater Flow | 57 |
| 4.4.1 Data and Methods..... | 58 |
| 4.4.2 Predevelopment or Steady-State Distribution of Hydraulic Head | 61 |
| 4.4.3 Postdevelopment Changes in Hydraulic Head | 68 |
| 4.5 Recharge..... | 79 |
| 4.5.1 Field Methods..... | 84 |
| 4.5.2 Field Results | 85 |
| 4.6 Interaction of Surface Water and Groundwater | 91 |
| 4.6.1 Low-Flow Studies | 93 |
| 4.6.2 Base-Flow Studies..... | 95 |
| 4.6.3 Surface-Water Reservoirs..... | 101 |
| 4.7 Groundwater Evapotranspiration | 103 |

| | | |
|---------|---|-----|
| 4.8 | Hydraulic Properties..... | 103 |
| 4.9 | Well Discharge..... | 114 |
| 5.0 | Conceptual Model of Groundwater Flow..... | 125 |
| 6.0 | Model Design..... | 129 |
| 6.1 | Code and Processor..... | 129 |
| 6.2 | Layers and Grid..... | 130 |
| 6.3 | Boundary Conditions..... | 138 |
| 6.3.1 | Recharge..... | 140 |
| 6.3.2 | Interaction of Surface Water and Groundwater..... | 144 |
| 6.3.2.1 | Stream-Flow Routing..... | 144 |
| 6.3.2.2 | Surface-Water Reservoirs..... | 146 |
| 6.3.3 | Evapotranspiration..... | 147 |
| 6.3.4 | General-Head Boundary..... | 148 |
| 6.3.5 | Horizontal-Flow Barrier..... | 150 |
| 6.3.6 | Wells..... | 151 |
| 6.4 | Model Parameters..... | 164 |
| 7.0 | Modeling Approach..... | 173 |
| 8.0 | Steady-State Model..... | 177 |
| 8.1 | Calibration..... | 177 |
| 8.2 | Sensitivity Analysis..... | 187 |
| 8.3 | Water Budget..... | 193 |
| 9.0 | Transient Model..... | 197 |
| 9.1 | Calibration and Verification..... | 197 |
| 9.2 | Water Budget..... | 220 |

| | | |
|------|-------------------------------|-----|
| 9.3 | Sensitivity Analysis..... | 228 |
| 10.0 | Predictions..... | 234 |
| 10.1 | Predictive Results..... | 234 |
| 10.2 | Water Budget..... | 255 |
| 11.0 | Limitations of the Model..... | 265 |
| 11.1 | Input Data..... | 265 |
| 11.2 | Assumptions..... | 268 |
| 11.3 | Scale of Application..... | 271 |
| 12.0 | Future Improvements..... | 273 |
| 13.0 | Conclusions..... | 276 |
| 14.0 | Acknowledgments..... | 280 |
| 15.0 | References..... | 282 |
| | Appendix A..... | A-1 |
| | Appendix B..... | B-1 |
| | Appendix C..... | C-1 |
| | Appendix D..... | D-1 |

Figures

| | | |
|----|---|----|
| 1. | Location of the Carrizo–Wilcox aquifer in Texas showing the overlapping position of the three regional models..... | 6 |
| 2. | Location of the study area relative to roads, major cities and towns, lakes, and rivers..... | 9 |
| 3. | Extent of previous models of groundwater flow in the Carrizo–Wilcox aquifer in the study area..... | 10 |

| | | |
|-----|--|----|
| 4. | Location of groundwater conservation districts in the study area..... | 11 |
| 5. | Location of Regional Water Planning Groups in the study area..... | 12 |
| 6. | Land-surface elevation in the study area relative to divides between surface-water drainage basins | 14 |
| 7. | Average annual precipitation (1940 through 1997) in the study area | 16 |
| 8. | Historical annual precipitation measured at rain gages at Seguin, Smithville, Cameron, Athens, and Nacogdoches | 17 |
| 9. | Average net lake evaporation rate in the study area..... | 18 |
| 10. | Generalized stratigraphic chart for the study | 20 |
| 11. | Generalized map of surface geology in the study area..... | 21 |
| 12. | Thickness of major sandstones in the Simsboro Formation in the study area..... | 23 |
| 13. | Thickness of major sandstones in the Carrizo Formation in the study area..... | 26 |
| 14. | Geologic structure in the study area..... | 35 |
| 15. | Vertical strike-oriented profile of the formations making up the Carrizo–Wilcox aquifer and adjacent formations. | 36 |
| 16. | Vertical dip-oriented profile of the formations making up the Carrizo–Wilcox aquifer and adjacent formations. | 38 |
| 17. | Elevation of the base of the Hooper Formation (base of Wilcox Group) | 43 |
| 18. | Elevation of the base of the Simsboro Formation (top of Hooper Formation)..... | 45 |
| 19. | Elevation of the base of the Calvert Bluff Formation (top of Simsboro Formation)..... | 46 |

| | |
|--|----|
| 20. Elevation of the base of the Carrizo Formation (top of Calvert Bluff Formation) | 47 |
| 21. Elevation of the top of the Carrizo Formation (base of the Reklaw Formation) | 48 |
| 22. Elevation of the top of the Reklaw Formation | 49 |
| 23. Total thickness of the Hooper Formation..... | 50 |
| 24. Total thickness of the Simsboro Formation | 51 |
| 25. Total thickness of the Calvert Bluff Formation..... | 52 |
| 26. Total thickness of the Carrizo Formation..... | 54 |
| 27. Total dissolved solids (TDS) content of groundwater in the Carrizo–Wilcox aquifer and in the saline section downdip of the aquifer | 56 |
| 28. Water-level elevation under “predevelopment” conditions in the Simsboro aquifer | 62 |
| 29. Water-level elevation under “predevelopment” conditions in the Carrizo aquifer..... | 63 |
| 30. Water-level elevation under “predevelopment” conditions in the Queen City aquifer..... | 67 |
| 31. Water-level elevation in the Simsboro aquifer measured during 1987 to 1990 and used for the 1990 model-year calibration..... | 69 |
| 32. Water-level elevation in the Simsboro aquifer measured during 1995 to 2000 and used for the 2000 model-year calibration..... | 70 |
| 33. Water-level elevation in the Carrizo aquifer measured during 1987 to 1990 and used for the 1990 model-year calibration..... | 71 |

| | |
|--|-----|
| 34. Water-level elevation in the Carrizo aquifer measured during 1995 to 2000 and used for the 2000 model-year calibration..... | 72 |
| 35. Hydrographs for 10 representative wells in the Hooper Formation..... | 74 |
| 36. Locations of water wells for which hydrographs are presented..... | 75 |
| 37. Hydrographs for 10 representative wells in the Simsboro Formation..... | 76 |
| 38. Hydrographs for 10 representative wells in the Calvert Bluff Formation..... | 77 |
| 39. Hydrographs for 10 representative wells in the Carrizo Formation..... | 78 |
| 40. Recharge rates estimated in previous hydrologic studies of the Carrizo–Wilcox aquifer..... | 80 |
| 41. Map of soil permeability in the recharge area of the model..... | 82 |
| 42. Variation with depth in water content in soil cores..... | 86 |
| 43. Variation with depth in soil-water chloride in soil cores | 88 |
| 44. Location of stream-flow gages used for base-flow separation..... | 98 |
| 45. Comparison of total discharge and estimated base flow for Plum Creek near Luling, Texas..... | 99 |
| 46. Base-flow increase across the Carrizo–Wilcox outcrop, unitized by area of drainage basin in the outcrop..... | 100 |
| 47. Histograms of hydraulic conductivity in the Carrizo, Calvert Bluff, Simsboro, and Hooper, and of specific storage in the Carrizo–Wilcox aquifer..... | 105 |
| 48. Map of average hydraulic conductivity in the Hooper Formation | 109 |
| 49. Map of average hydraulic conductivity in the Simsboro Formation..... | 111 |
| 50. Map of average hydraulic conductivity in the Calvert Bluff Formation..... | 112 |
| 51. Map of average hydraulic conductivity in the Carrizo Formation | 113 |

| | | |
|-----|--|-----|
| 52. | Total groundwater withdrawals from the Carrizo–Wilcox aquifer in the study area..... | 115 |
| 53. | Conceptual model of the aquifer showing how the hydrostratigraphy translates into the computer model of the aquifer | 126 |
| 54. | Location of active cells in model layer 6, representing groundwater in the Hooper Formation, and the position of boundary cells..... | 132 |
| 55. | Location of active cells in model layer 5, representing groundwater in the Simsboro Formation, and the position of boundary cells..... | 133 |
| 56. | Location of active cells in model layer 4, representing the Calvert Bluff Formation, and the position of boundary cells..... | 134 |
| 57. | Location of active cells in model layer 3, representing the Carrizo Formation, and the position of boundary cells..... | 135 |
| 58. | Location of active cells in model layer 2, representing the Reklaw Formation, and the position of boundary cells..... | 136 |
| 59. | Location of active cells in model layer 1, representing alluvium in the Colorado, Brazos, and Trinity River systems, and the position of boundary cells..... | 137 |
| 60. | Distribution of groundwater withdrawal in 2000 for municipal and manufacturing and power supplies..... | 152 |
| 61. | Map of population density in rural parts of the study area, excluding cities and towns with more than 500 people..... | 156 |
| 62. | Variation in total rate of groundwater withdrawal in 1990 in Carrizo aquifer, Calvert Bluff aquitard, Simsboro aquifer, and Hooper aquitard..... | 158 |

| | | |
|-----|---|-----|
| 63. | Variation in total rate of groundwater withdrawal in 2000 in Carrizo aquifer, Calvert Bluff aquitard, Simsboro aquifer, and Hooper aquitard..... | 160 |
| 64. | Storativity assigned to model cells representing the Hooper aquitard | 168 |
| 65. | Storativity assigned to model cells representing the Simsboro aquifer..... | 169 |
| 66. | Storativity assigned to model cells representing the Calvert Bluff aquitard..... | 170 |
| 67. | Storativity assigned to model cells representing the Carrizo aquifer..... | 171 |
| 68. | Storativity assigned to model cells representing the Reklaw aquitard..... | 172 |
| 69. | Recharge rate estimated on the basis of soil properties and results of previous studies | 180 |
| 70. | Histogram of recharge rates applied in the model..... | 181 |
| 71. | Simulated water levels for the Simsboro aquifer in the study area under predevelopment or steady-state (1950) conditions and comparison with measured contours..... | 182 |
| 72. | Simulated water levels for the Carrizo aquifer in the study area under predevelopment or steady-state (1950) conditions and comparison with measured contours..... | 183 |
| 73. | Comparison of simulated and measured water levels in the steady-state simulation of model layers representing the Carrizo–Wilcox aquifer | 184 |
| 74. | Location of water-level measurements used in calibration of the steady-state version of the model..... | 185 |
| 75. | Map of residual differences between simulated and measured water levels for the Simsboro aquifer (layer 5) for the steady-state calibration..... | 188 |
| 76. | Map of residual differences between simulated and measured water levels for the Carrizo aquifer (layer 3) for the steady-state calibration..... | 189 |

| | | |
|-----|--|-----|
| 77. | Sensitivity of predicted water levels in the Simsboro aquifer (layer 5) of the steady-state model to changes in parameter values for the Simsboro aquifer (layer 5), Carrizo aquifer (layer 3), and recharge rate, streambed conductance, and the GHB boundary on the Reklaw aquitard (layer 2)..... | 192 |
| 78. | Sensitivity of predicted water levels in the Carrizo aquifer (layer 3) of the steady-state model to changes in parameter values for the Carrizo aquifer (layer 3), Simsboro aquifer (layer 5), and recharge rate, streambed conductance, and the GHB boundary on the Reklaw aquitard (layer 2)..... | 194 |
| 79. | Block diagram of the Carrizo–Wilcox aquifer representing the components of the steady-state model..... | 196 |
| 80. | Maps for the Simsboro aquifer (layer 5) showing simulated and observed 1990 water level and drawdown from 1950 through 1990 | 199 |
| 81. | Map of residual differences simulated and measured water levels for the Simsboro aquifer (layer 5) for the 1990 calibration | 200 |
| 82. | Comparison of simulated and observed water levels for the 1990 calibration..... | 201 |
| 83. | Location of wells used to develop the 1990 calibration of the model..... | 202 |
| 84. | Maps for the Carrizo aquifer (layer 3) showing simulated and observed 1990 water level and drawdown from 1950 to 1990..... | 204 |
| 85. | Map of residual differences between simulated and measured water levels for the Carrizo aquifer (layer 3) for the 1990 calibration..... | 205 |
| 86. | Maps of water level in the Hooper Formation (layer 6) in 1990 and 2000..... | 206 |
| 87. | Maps of water level in the Calvert Bluff Formation (layer 4) in 1990 and 2000..... | 207 |

| | | |
|-----|---|-----|
| 88. | Comparison of simulated and observed water levels for the 2000 calibration..... | 208 |
| 89. | Location of wells used to develop the 2000 calibration of the model..... | 209 |
| 90. | Maps for the Simsboro aquifer (layer 5) showing simulated and observed 2000 water level and drawdown from 1950 through 2000 | 210 |
| 91. | Map of residual differences between simulated and measured water levels for the Simsboro aquifer (layer 5) for the 2000 calibration | 211 |
| 92. | Maps for the Carrizo aquifer (layer 3) showing simulated and observed 2000 water level and drawdown from 1950 through 2000 | 213 |
| 93. | Map of residual differences between simulated and measured water levels for the Carrizo aquifer (layer 3) for the 2000 calibration..... | 214 |
| 94. | Comparison of simulated and observed water-level hydrographs for 10 wells in the Hooper aquitard (layer 6)..... | 216 |
| 95. | Comparison of simulated and observed water-level hydrographs for 10 wells in the Simsboro aquifer (layer 5) | 217 |
| 96. | Comparison of simulated and observed water-level hydrographs for 10 wells in the Calvert Bluff aquitard (layer 4)..... | 218 |
| 97. | Comparison of simulated and observed water-level hydrographs for 10 wells in the Carrizo aquifer (layer 3)..... | 219 |
| 98. | Changes in simulated ET and base-flow discharge to stream with variation in recharge and pumping rates..... | 221 |
| 99. | Map of aquifer discharge simulated as groundwater evapotranspiration for 2000..... | 224 |

| | |
|---|-----|
| 100. Block diagram of the Carrizo–Wilcox aquifer representing the components of the transient model for 2000 | 226 |
| 101. Sensitivity of predicted water levels in the Simsboro aquifer (layer 5) in the transient model to changes in parameter values for the Simsboro aquifer (layer 5), Carrizo aquifer (layer 3), and other parts of the model..... | 229 |
| 102. Sensitivity of predicted water levels in the Carrizo aquifer (layer 3) in the transient model to changes in parameter values for the Carrizo aquifer (layer 3), Simsboro aquifer (layer 5), Carrizo aquifer (layer 3), and other parts of the model..... | 230 |
| 103. Sensitivity of simulated water levels to order-of-magnitude changes in storativity for the Carrizo aquifer (layer 3) and Simsboro aquifer (layer 5) | 231 |
| 104. Sensitivity of simulated water levels in the Carrizo and Simsboro aquifers to differences in storativity..... | 233 |
| 105. Simulated hydrographs showing predicted water levels through 2050 for wells in the Hooper aquitard (layer 6) | 235 |
| 106. Simulated hydrographs showing predicted water levels through 2050 for wells in the Simsboro aquifer (layer 5) | 236 |
| 107. Simulated hydrographs showing predicted water levels through 2050 for wells in the Calvert Bluff aquitard (layer 4) | 237 |
| 108. Simulated hydrographs showing predicted water levels through 2050 for wells in the Carrizo aquifer (layer 3) | 238 |
| 109. Maps for the Simsboro aquifer (layer 5) showing predicted 2010 water level and drawdown from 2000 through 2010 assuming drought-of-record recharge from 2008 through 2010..... | 240 |

| | |
|---|-----|
| 110. Maps for the Simsboro aquifer (layer 5) showing predicted 2020 water level and drawdown from 2000 through 2020 assuming drought-of-record recharge from 2018 through 2020..... | 241 |
| 111. Maps for the Simsboro aquifer (layer 5) showing predicted 2030 water level and drawdown from 2000 through 2030 assuming drought-of-record recharge from 2028 through 2030..... | 242 |
| 112. Maps for the Simsboro aquifer (layer 5) showing predicted 2040 water level and drawdown from 2000 through 2040 assuming drought-of-record recharge from 2038 through 2040..... | 243 |
| 113. Maps for the Simsboro aquifer (layer 5) showing predicted 2050 water level and drawdown from 2000 through 2050 assuming drought-of-record recharge from 2048 through 2050..... | 244 |
| 114. Maps for the Carrizo aquifer (layer 3) showing predicted 2010 water level and drawdown from 2000 through 2010 assuming drought-of-record recharge from 2008 through 2010..... | 247 |
| 115. Maps for the Carrizo aquifer (layer 3) showing predicted 2020 water level and drawdown from 2000 through 2020 assuming drought-of-record recharge from 2018 through 2020..... | 248 |
| 116. Maps for the Carrizo aquifer (layer 3) showing predicted 2030 water level and drawdown from 2000 through 2030 assuming drought-of-record recharge from 2028 through 2030..... | 249 |
| 117. Maps for the Carrizo aquifer (layer 3) showing predicted 2040 water level and drawdown from 2000 through 2040 assuming drought-of-record recharge from 2038 through 2040..... | 250 |

| | |
|--|-----|
| 118. Maps for the Carrizo aquifer (layer 3) showing predicted 2050 water level and drawdown from 2000 through 2050 assuming drought-of-record recharge from 2048 through 2050..... | 251 |
| 119. Maps for groundwater in the Hooper Formation (layer 6) showing predicted 2050 water level and drawdown from 2000 through 2050 assuming drought-of-record recharge from 2048 through 2050 | 253 |
| 120. Maps for groundwater in the Calvert Bluff Formation (layer 4) showing predicted 2050 water level and drawdown from 2000 through 2050 assuming drought-of-record recharge from 2048 through 2050 | 254 |
| 121. Difference for the end of 2050 in simulated water levels in Carrizo aquifer (layer 3) and Simsboro aquifer (layer 5) assuming average versus drought-of-record rates of recharge | 256 |
| 122. Block diagram of the Carrizo–Wilcox aquifer representing the components of the predictive model for 2050 | 260 |

Tables

| | |
|--|-----|
| 1. Water content, chloride concentration, and estimated recharge based on unsaturated zone chloride concentrations, chloride concentrations in groundwater and associated recharge rates, and age of the chloride profile..... | 87 |
| 2. Results of ^3He , ^4He , ^{20}Ne , ^{40}Ar , and N_2 measurements, and calculated tritogenic helium-3 ($^3\text{He}^*$) and $^3\text{H}/^3\text{He}$ ages | 90 |
| 3. Average flow of streams in study area | 94 |
| 4. Summary of low-flow studies in Cibolo Creek..... | 96 |
| 5. Characteristics of reservoirs in study area..... | 102 |

| | | |
|------|--|-----|
| 6. | Summary of hydraulic conductivity of the central Carrizo–Wilcox aquifer in the study area..... | 106 |
| 7. | Rates of groundwater withdrawal from the Carrizo–Wilcox aquifer as assigned within the study area | 116 |
| 8. | Rate of groundwater withdrawal for municipal public water supply and rural domestic, mining, manufacturing, irrigation, power, and stock-water supply from the Carrizo–Wilcox aquifer as assigned in the model | 117 |
| 9. | Projection parameters for the model grid and hydrogeologic data | 139 |
| 10. | Calibrated values of minimum and maximum recharge rate by layer | 141 |
| 11. | Summary of model calibration and verification statistics..... | 186 |
| 12. | Simulated groundwater discharge to streams..... | 190 |
| 13. | Water budget for the calibrated steady-state model..... | 195 |
| 14a. | Water budget for the calibrated steady-state and transient models..... | 222 |
| 14b. | Water budget for the transient model for drought years 1988 and 1996..... | 223 |
| 15. | Simulated leakage of water to the Carrizo–Wilcox aquifer from surface- water reservoirs | 227 |
| 16. | Water budget for the predictive model..... | 257 |
| 17. | Simulated groundwater discharge to streams for the predictive model | 262 |
| 18. | Sensitivity of predicted 2050 water budget (with drought of record) to changes in storativity and pumping rate..... | 263 |