Assessment of Future Groundwater Impacts Due to Assumed Water-Use Changes Turlock Groundwater Basin, California

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Executive Summary

The groundwater impacts within the Turlock basin were evaluated for a particular scenario of future land and water-use changes. The impacts were evaluated using the groundwater model of the Turlock basin. The groundwater model was developed and has been periodically updated by Turlock Irrigation District since 1988. Given inputs of historical or assumed future groundwater and surface water-use throughout the basin, the model calculates the corresponding groundwater levels.

A future scenario was constructed for potential land and water-use conditions through 2036. The basic elements of the scenario are that: Urban communities within the Turlock basin will grow at the rates contained in planning documents produced by the respective communities. Urban growth will occur on irrigated farmland within the Turlock Irrigation District, which results in a corresponding reduction in the irrigated acreage. The urban communities will supplement groundwater use with surface water obtained from the Turlock Irrigation District. Irrigated acreages within the Eastside Water District, Ballico-Cortez Water District, and Merced Irrigation District will remain unchanged. Likewise, irrigated land outside an irrigation district and along either of the Tuolumne, San Joaquin, or Merced rivers will remain unchanged. However, the irrigated acreage within the foothills region of the Turlock basin will increase at the rate of 2 percent per year.

Simulations were run with three versions of the groundwater model because the actual characteristics of the eastern region of the groundwater basin are very uncertain. The model uses inputs of the physical properties of the groundwater basin, which include the extents and thicknesses of the geologic formations constituting the basin, the transmissivity and storage characteristics of each formation. For the eastern region of the Turlock basin, the sparse available data limit the ability to characterize the geologic formations, and that translates into highly uncertain model predictions. To address the unavoidable model uncertainty, simulations were made of future conditions with three different assumptions about the basin characteristics, with the intent of bracketing the reasonable range of possible actual conditions.

For the western region of the Turlock basin (which includes Hughson, Denair, and Delhi, and the region westward), the results for the three simulations are nearly identical. Furthermore, the simulation results indicate that groundwater levels will change little in response to the assumed water-use changes. At the end of the simulation period (2036), groundwater levels will be within 10 ft of current levels. However, during assumed repetitions of the historical 1976-1977 and 1987-1992 droughts, groundwater levels during each drought will decline about 15 ft near the San Joaquin and Merced Rivers from the pre-drought conditions. Such declines are similar to those actually experienced for the historical water-use conditions. Nevertheless, groundwater levels along most of the Highway-99 corridor will rise about 15 ft, due to the surface-water use by the cities.

The simulation results lead to different conclusions regarding the western and eastern regions of the Turlock basin. For the western region of the basin, the simulation results suggest that the Turlock basin can support the projected groundwater demands. The expected long-term trend is for essentially unchanged groundwater levels. Furthermore, the conversion from agricultural to urban uses will not cause drought-induced groundwater-level fluctuations any worse than those actually experienced during the historical 1976-1977 and 1987-1992 droughts. For the eastern region of the basin, the simulation results suggest possible water-supply problems, depending on the actual physical characteristics of the geologic formations underlying that region. The simulations indicate long-term groundwater-level declines (relative to 2006) of about 85 ft within the Eastside Water District and 65-175 ft within the foothills region, depending on the storage characteristics assigned the geologic formations underlying the eastern part of the basin. Furthermore, drought induced declines are about 105 ft within the Eastside Water District and 95-265 ft within the foothills region.

Even though the western region of the basin is not expected to experience problems with respect to groundwater levels, water-quality problems could occur. Poor-quality groundwater occurs at depth within areas of the western region of the Turlock basin. The groundwater is characterized in part by the occurrences of elevated dissolved solids, arsenic, nitrates, and uranium. The depth to the poor-quality groundwater decreases westward across the basin to the San Joaquin River. Near the eastern boundary of the Turlock Irrigation District, the depth to poor-quality water is about 1,000 ft. Near the center of the District, the depth to poor-quality water is about 500 ft. Near the San Joaquin River, the depth to poor-quality water is about 10 ft, which represents the position of the groundwater table. The projected increased groundwater pumping by the urban communities has the potential of inducing the upward groundwater flow and corresponding upward migration of the poor-quality groundwater into current production zones. Ultimately, groundwater quality could represent the limits to groundwater used, even though the basin can sustain the projected volumetric demands.

Groundwater quality could become a constraint on groundwater use within the eastern region of the basin, but little information is available to assess the risk. The source of poor-quality water within the western region is the geologic formations that underlie the groundwater basin, and the naturally occurring saline groundwaters within those formations. The existing distribution of poor-quality water within the Turlock groundwater basin is a result of natural upward groundwater flow from the deeper formations into the basin. Those deeper formations occur also within the eastern region of the basin, but they have not produced poor-quality water within that part of the basin because the likely direction of groundwater flow is downward from the basin into the older geologic formations. However, the groundwater-level declines within the eastern region of the basin probably have reversed the natural downward groundwater flow. Furthermore, that reversal probably has induced the upward migration of saline groundwater from the deep geologic formations into the basin, but the significance is unknown.

To enhance the ability to predict future groundwater conditions, better information is needed on hydrogeologic, groundwater, and water-use conditions within the eastern region of the Turlock basin. The existing information is sparse, and that translates (through the model-calibration process) into uncertain model predictions. Better data are needed on the thicknesses and hydraulic properties of the geologic formations underlying the eastern region of the basin. Better information is needed on groundwater levels. Finally, better information is needed on water use, including information on well locations, well constructions, pumping rates, crop acreages, and irrigation practices.

Table of Contents

Figures

Tables

1.0 Introduction

This report describes the simulation of future groundwater conditions within the Turlock groundwater basin using a groundwater model. For a particular scenario of possible future water use and climatic conditions, the model was used to simulate the corresponding future groundwater levels. The groundwater model was developed and has been periodically updated by the Turlock Irrigation District since 1988. Given inputs of historical or assumed future groundwater and surface-use throughout the basin, the model calculates the corresponding groundwater levels.

1.1 Work Scope

Over the last several decades water-use changes have occurred on the lands overlying the Turlock groundwater basin. The basin is bounded by the Tuolumne River on the north, the Merced River on the south, the San Joaquin River on the west, and the Sierra Nevada Foothills on the east. The water-use changes within these boundaries have been associated with the expansion of both urbanized and irrigated agricultural areas. New urban areas have developed mostly on irrigated farm lands, and new irrigated lands have developed on non-irrigated rangelands and grassland areas.

The historical water-use changes within the Turlock basin have caused groundwater changes. Groundwater levels have declined over much of the basin, but they have declined most notably within the eastern part of the basin. The members of the Turlock Groundwater Basin Association (which includes the Turlock Irrigation District, Merced Irrigation District, Eastside Water District, Ballico-Cortez Water District, Merced County, Stanislaus County, Ceres, Turlock, Hughson, Modesto, Hilmar County Water District, and Denair Community Services District), as well as the cooperating agencies Delhi County Water District and Keyes Community Services District, desired a consistent analysis of the potential cumulative effects of projected land use changes on the groundwater basin. This report was prepared for the Association to serve as a common projection to support future planning activities. The report describes the hydrologic impacts associated with one scenario regarding future urban and agricultural water-use changes, where the Turlock basin groundwater model was used to identify the impacts.

The period 2007-2036, which extends 30 years into the future from 2006, was used as the study period. Part of the analysis involved assigning weather to each year of the study period. That was accomplished by assuming that 2007-2036 would have the same sequence of weather as 1966-1995. Correspondingly, the analysis does not account for potential climatic changes during the next several decades. Nevertheless, the historical period represents an important test of whether the Turlock basin can sustain expected changes in agricultural and urban water use. In particular, two significant droughts occurred during 1966-1995. The first was the two-year drought during 1976-1977, where 1977 was the driest year of record with respect to surface-water supplies.

The second was the six-year drought during 1987-1992, where the cumulative surface-water deficit was the largest of record.

The study period includes 2007 because 2006 was the last year for which the Turlock basin groundwater-model was updated with actual water-use information. Correspondingly, water use was estimated for 2007 as for the other years within the study period. In particular, agricultural and urban water uses were estimated based on the weather conditions assigned to the year, the land and water use conditions in 2006, and the assumed changes in land and water use relative to 2006.

1.2 Description of the Groundwater Basin

Most of the water use within the Turlock basin occurs within the boundaries of irrigation districts and urban areas. As shown on Figure 1.1, the Turlock Irrigation District (TID), Eastside Water District, Ballico-Cortez Water District, and the Merced Irrigation District (MID) are located within the basin. However, only part of the MID is located in the Turlock basin, while the largest part is located south of the basin. Also as shown on Figure 1.1, the communities of Ceres, Delhi, Denair, Hickman, Hilmar, Hughson, Keyes, Modesto, and Turlock are located within the basin. However, only part of Modesto is located within the Turlock basin, where the largest part is located north of the basin. Some water use occurs outside the water districts and the urban areas. Water use occurs within the Foothill, Tuolumne River, Merced River, and San Joaquin River non-district areas.

The water uses within the Turlock basin are supplied by both surface water and groundwater as listed in Tables 1.1 and 1.2. Within the TID, crops are irrigated with both canal water diverted from the Tuolumne River and water pumped from the groundwater basin. Both the District and private individuals within the District pump groundwater. Within the Eastside and Ballico-Cortez water districts crops are irrigated with groundwater pumped by private individuals. However, small quantities of surface water are purchased periodically from TID and MID. Within the MID, crops are irrigated with canal water diverted from the Merced River. However, small quantities of groundwater are used for irrigation. Within the cities, residential, commercial, and industrial water is derived from groundwater. However, small quantities of canal water, known as “gardenhead” deliveries, are provided to some large residential parcels for irrigation usages.

Within the Turlock basin, groundwater occurs within alluvial and other deposits that are as much as 2,200 ft in thickness. The basin is comprised of six water-bearing geologic formations. From uppermost to lowermost (geologically youngest to oldest), there are the Modesto, Riverbank, Turlock Lake, Mehrten, Valley Springs, and Ione formations. The outcrops of these formations are shown on Figure 1.2, and an easterly cross section through the basin is shown on Figure 1.3. As indicated on the cross section, the six formations extend westward to the San Joaquin River. As indicated also on the cross section, the eastern extent of each formation is demarked by the eastern extent of its outcrop. Correspondingly, an older formation has a greater geographic extent than a younger formation.

A significant aquitard occurs within the Riverbank Formation, which is referred to as the Corcoran Clay, where an aquitard is a hydrogeologic unit that tends to restrict the vertical movement of groundwater. The Corcoran Clay occurs within the western part of the Turlock basin (Figures 1.2 and 1.3). Where it occurs, this unit separates the groundwater system into upper and lower parts. However, the degree of separation depends on the scale of the area being considered. Within the local area near an individual well, the Corcoran Clay can be quite effective in isolating the upper and lower parts of the groundwater system. Nevertheless, within a more regional area, the clay tends to be less effective. This is the case because some wells are perforated both above and below the clay, which allows leakage through the clay within the well casing. The leakage has the effect of "short circuiting" the Corcoran Clay at a regional scale, but it does not have such an effect at a local scale, except very near a well perforated through the clay. The short circuiting has resulted in regional groundwater levels that are similar above and below the Corcoran Clay. Nevertheless, a well perforated only below the Clay can produce local groundwater levels that are significantly lower than those locally above the Corcoran Clay, unless the well happened to be located near another well perforated above and below the Clay.

A less significant aquitard occurs within the Modesto Formation, which is referred to as the shallow aquitard. The shallow aquitard occurs within the western part of the Turlock basin (Figure 1.3), and has about the same extent as the Corcoran Clay. The shallow aquitard occurs immediately below the land surface, and it tends to restrict the downward movement of irrigation water. The restriction is a cause of a high groundwater table within the western part of the TID.

The general direction of groundwater flow is westward from the foothills to the San Joaquin River. This is indicated by Figure 1.4, which show contours of groundwater elevation within the Turlock basin for fall 2006. Groundwater levels are higher within the eastern part of the basin than within the western part, and groundwater correspondingly flows from the area of higher groundwater levels to the area of lower groundwater levels. Nevertheless, the general pattern of westward groundwater flow is complicated by the effects of agricultural pumping east of the TID. The effect of that pumping has been to produce a region of lower groundwater levels within the central part of the Turlock basin. Additionally, groundwater-level declines probably have occurred within the far eastern part of the basin, but the limited monitoring data make it difficult to characterize the trends in groundwater levels in this region.

Groundwater levels have been declining since the mid 1990s, and declines may have accelerated during recent years. However, the groundwater system has been in a near-equilibrium state with the water use since about 1990. Water use within the basin has been increasing, but hydrodynamic adjustments within the basin have been nearly keeping up with the changing water use. The principal hydrodynamic adjustment has been an increase in the recharge from the Tuolumne and Merced rivers. Correspondingly, groundwater levels have not shown any significant temporal trend. Figures 1.5a-c show modeled groundwater levels after calibration at central locations within Turlock Irrigation District, Eastside Water District, and the foothills non-district area, where the particular hydrograph locations are shown on Figure 1.4. As shown on Figures 1.5a-c, groundwater levels have fluctuated seasonally in response to the seasonal water use, and they have fluctuated from year to year in response to variations in the annual rainfall. Furthermore, a slight long-term downward trend in groundwater levels has occurred in response to the water-use associated with increased urbanization within the western part of the Turlock basin and expanded agricultural irrigation within the eastern part.

1.3 Description of the Groundwater Model

1.3.1 General Description

The Turlock basin groundwater model was used to assess the possible impacts of future changes in water use within the Turlock basin. The model was developed by the Turlock Irrigation District. The initial development occurred in 1988 and the model has been periodically updated since then. Most recently, the model was updated to include the historical water use through 2006, and that model version was used here (Timothy J. Durbin, Inc., 2008).

The model is a mathematical representation of the Turlock groundwater basin that is based on (1) the general physics of groundwater flow, (2) the particular physical characteristics of the Turlock basin, and (3) particular water-use conditions of interest. The general physics are incorporated into a computer program that is applicable to any groundwater basin. In this case, the name of the computer program is FEMFLOW3D, which was has been used to construct models of many groundwater basins. The particular physical characteristics of the Turlock basin are inputs to the program. The inputs are the extents and thicknesses of the geologic formations that constitute the basin, the hydraulic characteristics of the geologic formations, and the hydraulic characteristics of the interactions between the basin and the Tuolumne River, Merced River, and San Joaquin River, and drainage canals. These inputs represent the invariant physical characteristics for a particular conceptualization of the groundwater basin. They do not change unless the assessment of basin characteristics changes.

In contrast, the water-use inputs to the computer program change depending on the water-use scenario to be analyzed. A scenario can represent either historical conditions or particular assumptions about future conditions. The water-use inputs for a scenario are the groundwater pumping from the basin and the recharge to the basin from the water use within the basin. The recharge in turn depends on the irrigation with groundwater or surface water, the crops irrigated, the weather conditions, and the soil characteristics. The weather conditions include both precipitation and the evapotranspiration of individual crops. Within non-irrigated areas, the recharge depends on the precipitation, the vegetation type, and the evapotranspiration of the vegetation. FEMFLOW3D and auxiliary computer programs consider all these variables in determining the recharge for particular water uses. For the purpose of this report, one scenario was simulated representing a particular set of assumptions regarding future conditions.

The outputs from the model are the temporal variations in groundwater levels throughout the basin for a specified simulation period. The outputs include maps showing groundwater levels at particular intervals during the simulation period. Additionally, the outputs include groundwater-level hydrographs representing the temporal variations in groundwater levels at specified locations within the basin.

1.3.2 Model Development

The model incorporates the general physics of groundwater flow using what is referred to as the finite-element method (Durbin and Bond, 1998). To represent a groundwater basin using this method, a three-dimensional mesh is constructed to represent the geographic extent, thickness, and internal hydrogeologic structure of the groundwater system. The particular mesh for the Turlock basin is shown on Figures 1.6 and 1.7, where Figure 1.6 is a map view of the mesh and Figure 1.7 is an oblique view. The mesh represents an assemblage of wedge-shaped elements. The mesh contains about 41,000 of such elements.

The hydraulic characteristics of the groundwater system are those derived from the latest update of the groundwater model. During that update the model was calibrated to fit measured groundwater levels during 1991-2006, and the calibrated aquifer parameters were used in the simulation of future conditions. Model calibration is the process of identifying the hydraulic characteristics of the geologic formations within the basin based on the measured groundwater levels and estimated water use for a selected historical period. Direct measurements of hydraulic characteristics are limited for the Turlock basin, but those characteristics can be inferred from the historical groundwater levels that occurred in response to the historical water use. For a particular specification of the hydraulic parameters for each geologic formation, the calibration involves simulating the historical groundwater levels. However, a comparison between the simulated and measured levels will show differences between individual pairs of simulated and measured values. Using a particular auxiliary computer program, successive adjustments are made to the set hydraulic parameters so as to minimize the overall difference between the simulated and measured groundwater levels, where the overall difference is described by a particular statistic. That statistic is the sum of squared differences, which can be expressed alternatively as the standard deviation of the differences.

The model calibration utilized two sets of groundwater-level measurements for 1991-2006. First are the measurements made by the Turlock Irrigation District in their wells for monitoring the groundwater table within the western part of the Turlock basin. These wells are typically are about 15 ft in depth, and monthly measurements are made in about 200 wells. Second are the measurements made by the California Department of Water Resources (DWR) in wells they use for monitoring regional groundwater conditions. The monitored wells typically are agricultural production wells, and they are measured annually and sometimes semiannually. About 100 wells are monitored in a particular year, but the number varies greatly from year to year depending on budgetary constraints within the Department.

An auxiliary computer program called PEST was used to calibrate the model, yielding estimates for the hydraulic conductivity, specific yield, and specific storage for each geologic unit within the basin. The hydraulic conductivity (which has units of feet/day) quantifies the ability of a formation to transmit water. The specific yield (which is dimensionless, but often is expressed as a percentage) quantifies the ability of a formation to store or release water with a change in the water-table elevation, which is related to the effective porosity of the formation. The specific storage (which has the units of 1/feet) quantifies the ability of a formation to store or release water with a change in water pressure within the formation, which is related to the elasticity of the formation. PEST was used to identify these formational characteristics such that the model best fits the groundwater-level measurements, where the best fit represents the smallest sum of squared differences between the measured and simulated groundwater levels.

Based on the available groundwater-level measurements, the calibration was divided into two parts: a steady-state calibration and a transient-state calibration. A steady-state calibration was used to identify the horizontal and vertical hydraulic conductivity for each geologic formation within the basin. The groundwater basin was assumed to be balanced with respect to the average pumping and recharge during 1991-1995 (an assumed steady-state condition), and the model was calibrated to the temporally averaged groundwater levels during that period. The net change in groundwater levels during 1991-1995 was about zero, which is the basis of the steady-state assumption.

Given the hydraulic-conductivity values derived from the steady-state calibration, a transient-state calibration was used to identify the specific storage and specific yield for each geologic formation within the basin. The basin was assumed to be in a transient-state during 1991-2006, and the model was calibrated to the individual groundwater-level measurements during that period. While the basin on average was in a steady-state during over the 1991-1995 period, seasonal and inter-annual groundwater-level fluctuations occurred. The model was calibrated to those fluctuations and to the subsequent fluctuations during 1996-2006.

The calibrated fit of the model to the groundwater-level measurements was different between the steady-state and transient-state calibrations and between the TID and DWR monitoring data. For the steady-calibration to the TID measurements, the resulting standard deviation of the residuals was about 2 ft, which means that difference between the measured and simulated water levels was less than 2 ft for about 70 percent of the monitoring wells. For the DWR measurements, the resulting standard deviation of the residuals was about 8 ft, which again means that difference between the measured and simulated water levels was less than 8 ft for about 70 percent of the monitoring wells. The overall coefficient of determination (r^2) for the steady-state calibration was 0.98 percent, which means that the model explains that percentage of the overall spatial variation in the measured groundwater levels. For the transient-state calibration to the District measurements, the standard deviation of the residuals was about 6 ft. For the Department measurements, the resulting standard deviation of the residuals was about 13 ft. The overall coefficient of determination (r^2) for the transient-state calibration was 0.75 percent, which means that the model explains that percentage of the overall spatial and temporal variation in the measured groundwater levels.

While these statistics represent the basin-wide calibration results, the uncertainty in the calibrated parameter values is different between the western and eastern parts of the Turlock basin. In general the parameter values are more reliable (less uncertain) for the western part than for the eastern part. This is the case for several reasons. Firstly, the western part is less dynamic with respect to seasonal and inter-annual groundwater-level changes. Secondly, the water use and water-use recharge is better documented for the western part. Thirdly, much more groundwater-level data are available with the western part. Fourthly, the groundwater-level data for the western part better represent locally averaged conditions, which follow from the less dynamic groundwater conditions.

The predictive reliability of the groundwater model is related in part to the calibration statistics. However, they tend to understate that reliability because of uncertainty in the measured groundwater levels. That uncertainty is of three types. Firstly, the data contains measurements errors, which include mistakes in measuring or recording the depth to water in a well and uncertainty in determining the land-surface elevation at the well. Secondly, the groundwater-level measurements and the simulation levels have different spatial and temporal scales. This is the case because the measurement in a well represents conditions at a point in space and time, where the model represents average conditions over a local region and specified period. Thirdly, particular measurements misrepresent even the point conditions at the well because of local disruptive effects. For the TID measurements, the effects are those of recent irrigations of fields near a monitoring well (which temporarily can cause higher than otherwise representative groundwater levels) and pumping from irrigation or drainage wells located near the monitoring well (which can cause lower than representative levels). For the DWR measurements, the effects are mostly those of pumping from irrigation wells located near the monitoring well (which can cause lower than otherwise representative groundwater levels).

The interpretation of the calibration results, including the differences between the steady-state and transient-state calibrations, follows mostly from the uncertainty in the groundwater-level measurements, but also from the uncertainty in the water-use inputs to the model. The steady-state calibration yields a better model fit than the transient-state calibration, as expressed either as the standard deviation of the residuals or the coefficient of determination, because the temporal averaging of both the groundwater-level measurements and the water-use inputs filters out much of the noise in the calibration. Because the averaged groundwater-level measurements and water-use inputs are a good representation of the actual groundwater system, a good fit is achieved between the measured and simulated groundwater levels. However, the groundwater-level data and water-use inputs for the transient-state calibration are unfiltered, and all the errors in the groundwater-level data as discussed above impact the calibration statistics. Furthermore, the large uncertainty in the actual groundwater pumping with respect to volume, timing, and location is propagated through the calibration process into the calibration statistics and into the specific-storage and specific-yield values identified from the calibration. Nevertheless, although the transient-state statistics are poor, the predictive reliability of the model is substantially better than suggested by those statistics. This is the case because the statistics reflect both sum of data and model uncertainty, and the model error correspondingly is smaller than the overall uncertainty. Even if the specific-storage and specific-yield values derived from the calibration perfectly matched average conditions within the actual groundwater basin, the standard deviation of the residuals would be large and the coefficient of determination (again r^2) would be small.

However, some caveats apply. Within the TID, reliable information is available on crop acreages, canal deliveries, drainage pumping, and TID pumping from rented wells. Good but less reliable estimates have been made of the private irrigation pumping. Additionally, the urban communities within the TID maintain reliable information on their groundwater pumping. Furthermore, abundant groundwater level data are available within the TID. Correspondingly, both the steady-state and transient-state calibrations yielded acceptable estimates of both the transmissive and storage characteristics of groundwater basin within its western part. Within the eastern part of the basin, the situation is different. While conditions within the MID are well documented, the crop acreages within other areas are uncertain, and the groundwater pumping is uncertain, and groundwater-level data are lacking. Correspondingly, both the steady-state and transient-state calibrations yielded uncertain estimates of both the transmissive and storage characteristics of the groundwater basin within its eastern part.

Of concern are the resulting estimates of storage characteristics for the geologic formations within the eastern part of the Turlock basin. In particular, the calibration produced specific yields for the Mehrten, Valley Springs, and Ione formations on the order of 1.5 percent. While the specific-yield values are physically possible, given sufficient cementation within the formations, they are unlikely to be the actual properties of the formations. Based on the results of groundwater studies elsewhere within the San Joaquin Valley, the expected specific yield for those formations is about 5 percent. Assuming a log-normal distribution of specific yield (mean of 5 percent and standard deviation of 0.176 $\log_{10}$ units), the calibrated values are about three standard deviations below the expected value. Nevertheless, they may represent the actual characteristics of the groundwater basin, or they may represent just a chance artifact of the sparse and uncertain groundwater-level measurements within the eastern part of the Turlock basin. However, the question cannot be resolved without additional data collection.

To address these possibilities, future groundwater conditions were simulated separately for each of three possible specific yield values. The first are the values derived from the model calibration, which are about 1.5 percent. The second are values set at two standard deviations above the mean, which are about 11 percent. The third are values set at two standard deviations below the mean, which are about 2.2 percent. While the second and third values bracket the mean such that the actual basin conditions have a 95 percent change of being within the bracket, the first has a physical basis in the groundwater-level measurements, even though that basis has weaknesses.

2.0 Description of Water-Use Scenario

The simulation of future groundwater conditions within the Turlock basin involves specifying the initial conditions, simulation period, weather conditions, and water use. The same scenario was run through the model three times with different groundwater-storage characteristics assigned within the model for the eastern part of the groundwater basin. In particular, the scenario was simulated with specific-yield values of about 1.5, 2.2, and 11 percent, as described above in Section 1.3.2.

2.1 Initial Conditions

The initial conditions specify the groundwater levels at the start of the simulation period. For the simulation of future conditions, the initial conditions are the simulated groundwater levels for the end of 2006 as derived from the last update of the groundwater model. The model was calibrated for calendar years 1991-2006, and the end of the calibration period represents the start of the future period.

2.2 Simulation Period

The simulation period is 2007-2036, which represents a 30-year period. That period is subdivided into three-month time steps consisting annually of January-March, April-June, July-September, and October-December. The model calculates groundwater levels for the end of each time step. The January-March time step represents spring groundwater levels. Correspondingly, the April-June time step represents summer, the July-September time step represents fall, and the October-December time step represents winter groundwater levels. The layout of time steps for 2007-2036 is listed in Table 2.1.

The simulation period includes 2007, even though that year is in the past. The reason is that the model was last updated with actual water-use information through 2006, which represented the data availability at the time the updating was done. Correspondingly, the water-use for 2007 is estimated, based on the assigned climatic conditions, the actual land-use and water-use conditions in 2006, and the assumed change in land-use and water-use conditions between 2006 and 2007. Furthermore, the land and water uses for subsequent years are specified based on the assigned climatic conditions for the year, the land-use and water-use conditions for the previous year, and the assumed changes in land and water used from the previous year.

2.3 Weather Conditions

The weather conditions specify the precipitation, surface-water diversions, and crop water requirements during the simulation period. Precipitation data for the basin were derived from historical precipitation recorded at the City of Turlock (Table 2.2). Watershed conditions, which affect the availability of surface water diversions, were based on the San Joaquin Valley Water Year Hydrologic Classification Index (Table 2.2). Because precipitation in the basin and watershed can differ in any given year, the timing and duration of drought periods differ between the two datasets. The simulated drought periods within the basin and watershed are shown as shaded cells in Table 2.2.

Weather conditions were specified by assuming a repeat of the weather conditions as they occurred during the historic 30-year period 1966-1995. By this specification, 2007 has the same weather as 1966, and 2036 has the same weather as 1995. The period 1966-1995 was selected because it contains two significant surface-water supply drought periods. The 1976-1977 drought includes the driest individual years of record. The 1987-1992 drought represents the driest extended period of record.

Table 2.2 lists each simulation year, the corresponding weather year, the annual precipitation, the annual precipitation at Turlock, the annual precipitation as a percentage of average, and the year type, and Figure 2.1 shows a graph of annual precipitation. The year type is defined in terms of the annual precipitation. For the purposes of the analysis, the year type is considered “wet” if the annual precipitation is greater than 120 percent of average, “normal” if the precipitation is less than or equal to 120 percent but greater than 80 percent of average, “dry” if the precipitation is less than or equal to 80 percent but greater than 60 percent of average, and “very dry” if the precipitation is less than or equal to 60 percent of average. By these definitions, the 1975-1977 drought represents a period of two very dry years and one dry year within the basin. The 1987-1992 drought represents a period of one very dry year, four dry years, and one normal year within the basin.

Table 2.2 lists also the water year classification used in developing the TID surface-water and pumping projections, which is the San Joaquin Valley Water Year Hydrologic Classification Index. With respect to surface water conditions represented by runoff within the Tuolumne River watershed, the 1976-1977 drought represents a period of two critically dry years, while the 1987-1992 drought represents a period of six critically dry years.

2.4 Water Use

The future water use is based fundamentally on assumptions about future land use. The communities of Ceres, Delhi, Denair, Hickman, Hilmar, Hughson, Keyes, Modesto, and Turlock were assumed to expand by reducing the irrigated-crop acreage within the Turlock Irrigation District, but the irrigated acreage within the TID was assumed otherwise to be unchanged during the simulation period. Likewise, the irrigated-crop acreage within the Eastside Water District, Ballico-Cortez Water District, and Merced Irrigation District were assumed to be unchanged. While the irrigated-crop acreages within the Tuolumne, Merced, and San Joaquin River non-district areas (that is adjacent to the rivers but outside of irrigation district boundaries) were assumed to remain unchanged during the simulation period, the irrigated acreage within the foothills non-district area was assumed to expand.

The water-use components of the simulation scenario are summarized in Tables 2.3 through 2.6 and on Figures 2.2 and 2.3. The particular assumptions for the simulation period regarding land use and the associated water use are listed in Table 2.3. The irrigated acreages, pumping, canal deliveries, and the associated groundwater recharge are listed in Tables 2.4 through 2.6. The cumulative pumping and canal deliveries are shown respectively on Figures 2.2 and 2.3.

With respect to acreages, urban areas were assumed to grow at the rate indicated in the Community Plan or in the Urban Water Management Plan (UWMP), when available. When neither document was available, the community was presumed to grow at a linear pace consistent with historical growth. Documents used were the Turlock UWMP, Ceres UWMP, Modesto UWMP, Hughson UWMP, and Delhi Community Plan. Irrigation and water districts were assumed to maintain their size, except where urbanization was projected to occur. The non-district agricultural areas along the rivers were assumed to maintain a constant irrigated acreage. Within the foothills non-district area, however, the irrigated acreage was assumed to increase in acreage by 2 percent each year. The rural residential acreage within the Turlock basin was assumed to be constant, which represents an assumed dynamic of new residences constructed at the same rate as existing rural residences are incorporated into expanding urban areas.

With respect to surface-water use, the deliveries within the Merced Irrigation District were assumed to be the same as deliveries in the corresponding weather year. The same holds true for garden-head deliveries within Ceres, Delhi, and Turlock. The surplus-water canal deliveries to Eastside Water District and Ballico-Cortez Water District were assumed to occur in above normal or wet years, based on the San Joaquin Valley Water Year Hydrologic Classification Index, except that deliveries were assumed not to occur in 2019 and 2036 because Don Pedro Reservoir is not projected to fill in those wet years. Canal deliveries within the Turlock Irrigation District were based on projected Tuolumne River diversions, drainage pumping, and rented-well pumping provided by the District (J. Hinds, 2008, written communication). The District provided projected diversions at La Grange, rented-well pumping, and drainage pumping. The total available canal water (the sum of diversions, rented pumping, and drainage pumping) was then apportioned to TID irrigation service areas based on the historical average proportion of total canal water delivered to the service area. Surface water deliveries to urban areas were based on projected use documented in the municipal UWMPs and the CEQA documentation for the Regional Surface Water Supply Project, which were provided by the Turlock Irrigation District (J. Hinds, 2008, written communication).

With respect to groundwater pumping, urban pumping was assumed to be the remaining demand unmet by surface-water deliveries. Urban demand was assumed to be population-driven, and historical demand was multiplied by a population factor to determine future demand. No efficiency factor was applied, because the efficiency was assumed to be unchanged. Urban population projections were obtained from an Urban Water Management Plan, from the Community Plan when available, or from a linear projection of the historical population growth. Non-district area pumping for areas along the rivers was assumed to be the same as historical pumping for the corresponding weather year, scaled to reflect the increased irrigated acreage relative to the historical weather years. For the Foothills area, historical pumping was scaled upward to reflect the

2 percent annual increase in irrigated acreage and then was scaled downward to reflect increases in irrigation efficiency relative to historical irrigation efficiency. Rural residential pumping was scaled to reflect the increased population relative to the weather year, but no increase in rural residences from 2007 to 2036 was projected as new homes were expected to be built while other homes would be incorporated into urban water systems at an approximately equal rate. Pumping within the Eastside and Ballico-Cortez water districts was scaled upward from historical periods to reflect the increases in irrigated acreages relative to the weather year and then was also scaled downward to reflect increases in irrigation efficiency. The irrigation efficiency during the simulation period was assumed to be 85 percent, while the irrigation efficiency ranged from 75 percent in early years to 85 percent in later years. Supplemental-source pumping and sole-source irrigation pumping within the Turlock Irrigation District was calculated to be the difference between canal deliveries (including diversions, rented, and drainage pumping) and the irrigation demand for the crops.

3.0 Simulation Results

Three separate simulations were made with the water-use scenario described above in Section 2.0. The simulations represented three possible realizations of the specific yield for the geologic formations occurring within the eastern part of the Turlock basin, which are the Mehrten, Valley Springs, and Ione formations. The specific-yield values for the first simulation are about 1.5 percent, which are the values derived from the model calibration, as described in Section 1.3. This simulation is referred to with the phrase “very low specific yield” on figure captions within this report. The specific-yield values for the second simulation are about 11 percent, which represents values about two standard deviations above the values documented for similar formations in other regions, as described in Section 1.3. This simulation is referred to with the phrase “high specific yield” on figure captions. The specific-yield values for the third simulation are about 2.2 percent, which represents values about two standard deviations below the anticipated mean value, again as described in Section 1.3. This simulation is referred to with the phrase “low specific yield” on figure captions.

3.1 Simulation with Very Low Specific Yield

The simulation results with a very low specific yield are shown on Figures 3.1 through 3.5. Figures 3.1 and 3.2 relate to the 1976-1977 drought. Figures 3.1a-c respectively show fall groundwater levels before, during, and after the drought. Figures 3.2a-c respectively, show the change in fall groundwater levels (relative to fall 2006 groundwater levels) before, during, and after the drought. Figures 3.3 and 3.4 relate to the 1987-1992 drought. Figures 3.3a-c respectively show fall groundwater levels before, during, and after the drought. Figures 3.4a-c respectively, show the change in fall groundwater levels (relative to fall 2006 groundwater levels) before, during, and after the drought. Figures 3.5a-c respectively, show groundwater-level hydrographs within the Turlock Irrigation District, Eastside Water District, and Foothills non-district area. The hydrograph locations are shown on Figure 1.4.

The simulation results show that groundwater levels in the fall prior to each drought are lower than in fall 2006, except for portions of the Turlock Irrigation District. With respect to the 1976-1977 drought (2017-2018, as indicated in Table 2.2), groundwater levels are down as much as 5 ft within parts of the Turlock Irrigation District (Figure 3.2a), 65 ft within the Eastside Water District (Figure 3.2a), and 75 ft within the foothills non-district area (Figure 3.2a). However, groundwater levels are up 15 ft in other parts of the Turlock Irrigation District. With respect to the 1987-1992 drought (2028-2033), groundwater levels are down about 5 ft within parts of the Turlock Irrigation District (Figure 3.4a), 85 ft within the Eastside Water District (Figure 3.4a), and 175 ft within the Foothills non-district area (Figure 3.4a). However, groundwater levels are up 15 ft within other parts of the Turlock Irrigation District. Again, these are the groundwater-level declines (relative to fall 2006) prior to the assumed future droughts.

The simulation results show groundwater levels within each drought are significantly lower than in fall 2006, except for portions of the Turlock Irrigation District. With respect to the 1976-1977 drought (2017-2018), groundwater levels are down as much as 15 ft within the Turlock Irrigation District (Figure 3.2b), 85 ft within the Eastside Water District (Figure 3.2b), and 115 ft within the Foothills non-district area (Figure 3.2b). However, groundwater levels are up 5 ft within other parts of the Turlock Irrigation District. With respect to the 1987-1992 drought (2028-2033), groundwater levels are down about 25 ft within the Turlock Irrigation District (Figure 3.4b), 105 ft within the Eastside Water District (Figure 3.4b), and 265 ft within the foothills non-district area (Figure 3.4b). However, groundwater levels are up by 5 ft within other parts of the Turlock Irrigation District. These are the groundwater-level declines (relative to fall 2006) for the fall of the last year of the droughts.

The rise in groundwater levels within parts of the Turlock Irrigation District most likely is the result of the assumed surface-water deliveries to the urban communities. As much as 22,000 acre-ft/yr is delivered in later years, while the pumping is reduced by about 10,000 acre-ft/yr. Correspondingly, the additional future remands are met with surface-water deliveries, and part of the current groundwater pumping is replaced with deliveries.

The hydrographs show specific trends within different parts of the Turlock basin. The hydrograph representing the Turlock Irrigation District (Figure 3.5a) shows no long-term trend in groundwater levels. The hydrograph representing the Eastside Water District (Figure 3.5b) shows a long-term groundwater-level decline of about 30 ft. The hydrograph representing the foothills non-district area (Figure 3.5c) shows a long-term groundwater-level decline of about 50 ft.

3.2 Simulation with High Specific Yield

The simulation results with a high specific yield are shown on Figures 3.6 through 3.10. Figures 3.6 and 3.7 relate to the 1976-1977 drought. Figures 3.6a-c respectively show fall groundwater levels before, during, and after the drought. Figures 3.7a-c respectively, show the change in fall groundwater levels (relative to fall 2006 groundwater levels) before, during, and after the drought. Figures 3.8 and 3.9 relate to the 1987-1992 drought. Figures 3.8a-c respectively show fall groundwater levels before, during, and after the drought. Figures 3.9a-c respectively, show the change in fall groundwater levels (relative to fall 2006 groundwater levels) before, during, and after the drought. Figures 3.10a-c respectively, show groundwater-level hydrographs within the Turlock Irrigation District, Eastside Water District, and Foothills non-district area. The hydrograph locations are shown on Figure 1.4.

The simulation results show that groundwater levels in the fall prior to each drought are lower than in fall 2006, except for portions of the Turlock Irrigation District. With respect to the 1976-1977 drought (2017-2018, as indicated in Table 2.2), groundwater levels are down as much as 5 ft within the Turlock Irrigation District (Figure 3.7a), 75 ft within the Eastside Water District (Figure 3.2a), and 35 ft within the foothills non-district area (Figure 3.7a). However, groundwater levels are up by about 25 ft within other parts of the Turlock Irrigation District. With respect to the 1987-1992 drought (2028-2033), groundwater levels are down about 5 ft within the Turlock Irrigation District (Figure 3.9a), 85 ft within the Eastside Water District (Figure 3.4a), and 65 ft within the Foothills non-district area (Figure 3.9a). However, groundwater levels are up by about 25 ft within other parts of the Turlock Irrigation District.

The simulation results show groundwater levels within each drought are significantly lower than in fall 2006, except for portions of the Turlock Irrigation District. With respect to the 1976-1977 drought (2017-2018), groundwater levels are down as much as 15 ft within the Turlock Irrigation District (Figure 3.7b), 85 ft within the Eastside Water District (Figure 3.7b), and 35 ft within the Foothills non-district area (Figure 3.7b). However, groundwater levels are up by about 15 ft within other parts of the Turlock Irrigation District. With respect to the 1987-1992 drought (2028-2033), groundwater levels are down about 15 ft within the Turlock Irrigation District (Figure 3.9b), 105 ft within the Eastside Water District (Figure 3.9b), and 95 ft within the foothills non-district area (Figure 3.9b). However, groundwater levels are up by about 15 ft within other parts of the Turlock Irrigation District.

The hydrographs show specific trends within different parts of the Turlock basin. The hydrograph representing the Turlock Irrigation Districts (Figure 3.10a) shows no long-term trend in groundwater levels. The hydrograph representing the Eastside Water District (Figure 3.10b) shows a long-term groundwater-level decline of about 20 ft. The hydrograph representing the foothills non-district area (Figure 3.10c) shows a long-term groundwater-level decline of about 50 ft.

3.3 Simulation with Low Specific Yield

The simulation results with a low specific yield are shown on Figures 3.11 through 3.15. Figures 3.11 and 3.12 relate to the 1976-1977 drought. Figures 3.11a-c respectively show fall groundwater levels before, during, and after the drought. Figures 3.12a-c respectively, show the change in fall groundwater levels (relative to fall 2006 groundwater levels) before, during, and after the drought. Figures 3.13 and 3.14 relate to the 1987-1992 drought. Figures 3.13a-c respectively show fall groundwater levels before, during, and after the drought. Figures 3.14a-c respectively, show the change in fall groundwater levels (relative to fall 2006 groundwater levels) before, during, and after the drought. Figures 3.15a-c respectively, show groundwater-level hydrographs within the Turlock Irrigation District, Eastside Water District, and Foothills non-district area. The hydrograph locations are shown on Figure 1.4.

The simulation results show that groundwater levels in the fall prior to each drought are lower than in fall 2006, except for portions of the Turlock Irrigation District. With respect to the 1976-1977 drought (2017-2018, as indicated in Table 2.2), groundwater levels are down as much as 5 ft within the Turlock Irrigation District (Figure 3.12a), 65 ft within the Eastside Water District (Figure 3.12a), and 75 ft within the foothills non-district area (Figure 3.12a). However, groundwater levels are up by about

15 ft within other parts of the Turlock Irrigation District. With respect to the 1987-1992 drought (2028-2033), groundwater levels are down about 5 ft within the Turlock Irrigation District (Figure 3.14a), 85 ft within the Eastside Water District (Figure 3.14a), and 105 ft within the Foothills non-district area (Figure 3.14a).). However, groundwater levels are up by about 15 ft within other parts of the Turlock Irrigation District.

The simulation results show groundwater levels within each drought are significantly lower than in fall 2006, except for portions of the Turlock Irrigation District. With respect to the 1976-1977 drought (2017-2018), groundwater levels are down as much as 15 ft within the Turlock Irrigation District (Figure 3.12b), 85 ft within the Eastside Water District (Figure 3.12b), and 95 ft within the Foothills non-district area (Figure 3.12b). However, groundwater levels are up by about 5 ft within other parts of the Turlock Irrigation District. With respect to the 1987-1992 drought (2028-2033), groundwater levels are down about 15 ft within the Turlock Irrigation District (Figure 3.14b), 105 ft within the Eastside Water District (Figure 3.14b), and 215 ft within the foothills non-district area (Figure 3.14b). However, groundwater levels are up by about 5 ft within other parts of the Turlock Irrigation District.

The hydrographs show specific trends within different parts of the Turlock basin. The hydrograph representing the Turlock Irrigation Districts (Figure 3.15a) shows no long-term trend in groundwater levels. The hydrograph representing the Eastside Water District (Figure 3.15b) shows a long-term groundwater-level decline of about 20 ft. The hydrograph representing the foothills non-district area (Figure 3.15c) shows a long-term groundwater-level decline of about 50 ft.

4.0 Conclusions

The simulation results for the specified future scenario indicate that groundwater level declines will occur during the reoccurrence of the 1976-1977 drought or the 1987-1992 drought. The water-use scenario was run with three different assumptions about the specific yield of the geologic formations underlying the eastern part of the basin.

With respect to the 1976-1977 drought, the simulations indicate that groundwater levels will decline (with respect to the groundwater levels in fall 2006) about 15 ft within the Turlock Irrigation District, regardless of the storage characteristics assigned to the eastern part of the basin. However, the simulations indicate that groundwater levels within the Eastside Water District will decline about 85 ft, regardless of the storage characteristics assigned. The simulations indicate the groundwater levels will decline within the foothills non-district area between 35 and 115 ft, depending again on the storage characteristics assigned. Groundwater levels within north-central part of the Turlock Irrigation District will rise between 5 and 15 ft, where the rise is the result of the assumed surface-water deliveries from the Turlock Irrigation District to the urban communities.

With respect to the 1987-1992 drought, the simulations indicate that groundwater levels within parts of the Turlock Irrigation District will decline (with respect to the groundwater levels in fall 2006) between 15 to 25 ft, depending on the storage characteristics assigned to the eastern part of the basin. The simulations indicate that groundwater levels within the Eastside Water District will decline about 105 ft, regardless of the storage characteristics assigned. The simulations indicate the groundwater levels will decline within the foothills non-district area between 95 and 265 ft, depending also on the storage characteristics assigned.

For the western region of the Turlock basin (which includes Hughson, Denair, and Delhi, and the region westward), the results for the three simulations are nearly identical. Furthermore, the simulation results indicate that long-term groundwater levels will change little in response the assumed water-use changes. At the end of the simulation period (2036), groundwater levels will be within 10 ft of current levels. However, during assumed repetitions of the historical 1976-1977 and 1987-1992 droughts, groundwater levels during each drought will decline as much as 25 ft from within parts of the western region, but they will rise as much as 15 ft in other parts.

The simulation results lead to different conclusions regarding the western and eastern regions of the Turlock basin. For the western region of the basin, the simulation results suggest that the Turlock basin can support the projected groundwater demands. The expected long-term trend is for essentially unchanged groundwater levels. Groundwater levels rise somewhat in parts of the western region, and they decline somewhat in other parts, but overall trend is for unchanged groundwater levels. Furthermore, the conversion from agricultural to urban uses will not cause drought-induced groundwater-level fluctuations any worse than those actually experienced during the historical 1976-1977 and 1987-1992 droughts. For the eastern region of the basin, the simulation results suggest possible water-supply problems, depending on the actual physical characteristics of the geologic formations underlying that region. The simulations indicate long-term groundwater-level declines of about 85 ft within the Eastside Water District and 65-175 ft within the foothills region, depending on the storage characteristics assigned the geologic formations underlying the eastern part of the basin. Furthermore, drought induced declines are about 105 ft within the Eastside Water District and 95-265 ft within the foothills region.

Even though the western region of the basin is not expected to experience problems with respect to groundwater levels, water-quality problems could occur. Poor-quality groundwater occurs at depth within areas of the western region of the Turlock basin. The groundwater is characterized in part by the occurrences of elevated dissolved solids, arsenic, nitrates, and uranium. The depth to the poor-quality groundwater decreases westward across the basin to the San Joaquin River. Near the eastern boundary of the Turlock Irrigation District, the depth to poor-quality water is about 1,000 ft. Near the center of the District, the depth to poor-quality water is about 500 ft. Near the San Joaquin River, the depth to poor-quality water is about 10 ft, which represents the position of the groundwater table. The projected increased groundwater pumping by the urban communities has the potential of inducing the upward groundwater flow and corresponding upward migration of the poor-quality groundwater into current production zones. Ultimately, groundwater quality could represent the limits to groundwater used, even though the basin can sustain the projected volumetric demands.

Groundwater quality could become a constraint on groundwater use within the eastern region of the basin, but little information is available to assess the risk. The source of poor-quality water within the western region is the geologic formations that underlie the groundwater basin, and the naturally occurring saline groundwaters within those formations. The existing distribution of poor-quality water within the Turlock groundwater basin is a result of natural upward groundwater flow from the deeper formations into the basin. Those deeper formations occur also within the eastern region of the basin, but they have not produced poor-quality water within that part of the basin because the likely direction of groundwater flow is downward from the basin into the older geologic formations. However, the groundwater-level declines within the eastern region of the basin probably have reversed the natural downward groundwater flow. Furthermore, that reversal probably has induced the upward migration of saline groundwater from the deep geologic formations into the basin, but the significance is unknown.

To enhance the ability to predict future groundwater conditions, better information is needed on hydrogeologic, groundwater, and water-use conditions within the eastern region of the Turlock basin. The existing information is sparse, and that translates (through the model-calibration process) into uncertain model predictions. Better data are needed on the thicknesses and hydraulic properties of the geologic formations underlying the eastern region of the basin. Better information is needed on groundwater levels. Finally, better information is needed on water use, including information on well locations, well constructions, pumping rates, crop acreages, and irrigation practices. The data-collection program should be designed specifically to enhance the future calibration of the groundwater model, and the sensitivity of the model to specific uncertainties in the hydrologic, geologic, and water-use information should be used to focus the data-collection efforts.

To understand the water-quality constraints on groundwater use, better information is need on groundwater quality and the processes controlling the existing and potential future distribution of water quality. Specifically, an analysis should be performed to identify the current geographic and vertical distributions of groundwater-quality constituents and the temporal changes in those distributions. The results of such an analysis should be used to design an efficient groundwater-quality monitoring program to detect future changes in water quality.

5.0 References

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