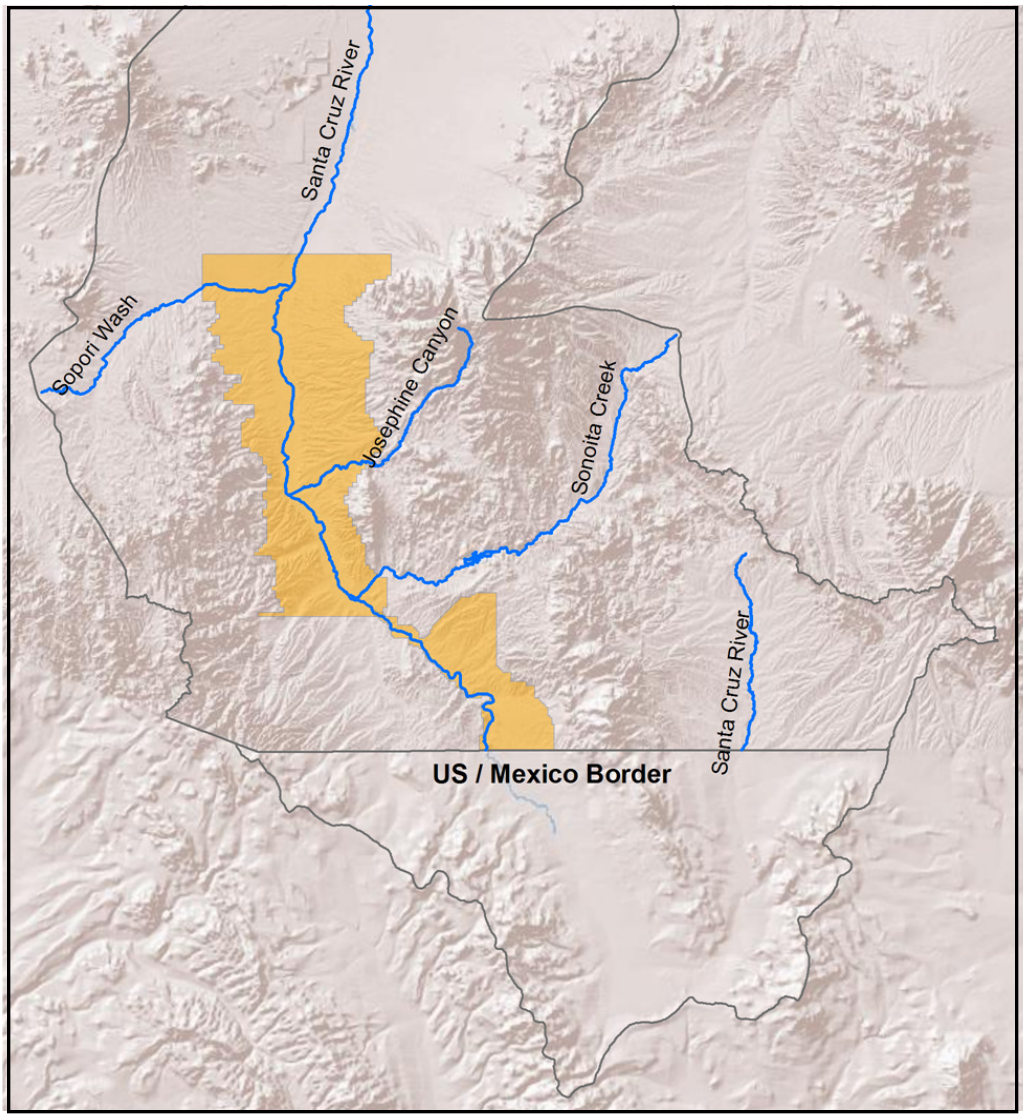
ARIZONA DEPARTMENT OF WATER RESOURCES

RISK ANALYSIS OF PUMPING IMPACTS ON SIMULATED GROUNDWATER FLOW IN THE SANTA CRUZ ACTIVE MANAGEMENT AREA



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List of Acronyms

ACM	Alternative Conceptual Model
ADWR	Arizona Department of Water Resources
AF/YR	Acre-Feet per Year
AMA	Active Management Area
CFS	Cubic Feet Per Second
CHB	Constant Head Boundary
CPU	Central Processing Unit
CSTR	Streambed Conductance
ET	Evapotranspiration
FT	Feet
GB	Gigabyte
GHB	General Head Boundary
GHZ	Gigahertz
GPM	Gallons Per Minute
HRC	Hydrologic Research Center
K	Hydraulic Conductivity
K AF/YR	1,000 Acre-feet/year
LPF	Layer-Property Flow
NIWTP	Nogales International Waste Water Treatment Plant
RCH	Recharge
SIP	Strongly Implicit Procedure
Strm_Kz	Vertical Streambed Conductivity
Sy	Specific Yield
USGS	United States Geological Survey

Abstract

Due to the unique hydrology of the Upper Santa Cruz watershed and regional groundwater development pressures, the Arizona Legislature created the Santa Cruz Active Management Area in 1994. The Arizona Department of Water Resources has been tasked with managing the Active Management Area's duel goals, which include maintaining safe yield conditions and preventing long-term declines in local water levels. Towards that end, the Arizona Department of Water Resources has been developing modeling tools that will enable different water management strategies to be evaluated in a risk-based context.

In 1997 a monitoring program was established to better understand the hydrologic system and to provide calibration targets for the development of groundwater flow models. Using available hydrologic information, alternative conceptual groundwater flow models were evaluated using inverse modeling techniques, as well as trial-and-error calibration techniques. The groundwater flow models simulate flood recharge and seasonality and were calibrated over diverse environmental conditions, including periods of extreme drought and flood recharge.

To address future streamflow recharge uncertainty, the Arizona Department of Water Resources contracted the development of a stochastic streamflow model. Streamflow realizations associated with the stochastic model were combined with plausible groundwater flow models to provide projected simulated flow along reaches of the Santa Cruz River that experience intermittent baseflow (groundwater discharge). The process has been automated, enabling hydrologic impacts to be statistically evaluated as functions of stress, including groundwater pumpage. Accordingly, model output distributions can be used to

provide risk-based information about projected groundwater levels and baseflow for water management purposes.

This report describes the hydrologic models, the simulation process, and provides information about projected groundwater levels and the frequency-of-occurrence of baseflow (net groundwater discharge from aquifer-to-stream) along two intermittent reaches of the Santa Cruz River. Based on hypothetical pumping scenarios projected over a 100-year simulations period, statistical information is presented about groundwater discharge patterns in the Santa Cruz Valley, including an analysis that quantifies risks associated with the capture of groundwater discharge due to increased pumpage.

Acknowledgements

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1.0 Introduction

In 1994 the Arizona Legislature created the Santa Cruz Active Management Area (AMA). Because of the unique hydrology (including shallow water tables), the Santa Cruz AMA goals include preserving "safe-yield" conditions and "preventing long-term declines in local water tables" (§45-562(C)).

Many groundwater basins in Arizona impacted by long-term intensive pumpage have considerable groundwater reserves in storage and/or direct access to renewable surface water supplies to mitigate groundwater level declines. In the Santa Cruz AMA there is no direct access to imported surface water supplies, and the storage capacity of productive aquifers is relatively small. As a result, hydrologic impacts from natural recharge, discharge and groundwater pumping are acutely sensitive. However natural recharge processes including complex stream-aquifer interactions are subject to uncertainty.

1.1 Challenges of Predicting Future Groundwater Conditions

Due to the challenges of predicting future groundwater conditions combined with the strict directives of the Santa Cruz AMA goals, hydrologic evaluations in the Santa Cruz AMA must be treated in a rigorous manner. Groundwater levels in the upper Santa Cruz Valley are influenced by natural and artificial recharge (i.e., flood and effluent recharge, etc.) and discharge (i.e., groundwater pumpage, underflow, evapotranspiration (ET) and groundwater discharge).

Although there are regularly periods when the inner-valley hydrologic system is out of balance, most of the Santa Cruz AMA is considered to be in a state of long-term dynamic equilibrium. For example from April to late June inner-valley groundwater levels typically decline, whereas during the summer monsoon season (July to September) groundwater levels usually rise due to flood recharge. However the cumulative net change-in-storage for most inner-valley areas is relatively small when evaluated over long-term periods (1930's to 2002). (Also note that a temporary, seasonal equilibrium has been observed during winter periods in the northern Santa Cruz model area.)

Given the complexity of the system, it is important that the hydrologic models themselves do not adversely influence the outcome. Since it is impossible to predict exact hydrologic conditions 100 years into the future, a statistical approach is required for this problem. When predicting hydrologic conditions it is important to evaluate a broad range of potential (natural) hydrologic conditions because streamflow conditions in the future are uncertain and information about the groundwater flow system is limited.

Accordingly, the most rigorous way to address hydrologic uncertainty and reduce model bias is to examine many plausible realizations. This approach enables water managers to evaluate the collective distribution of plausible hydrologic outcomes (ensemble results), including the central tendencies and outliers. Understanding the ensemble distribution may be important for decision-making purposes. While this process accommodates model errors that are approximately random over space and time (including models residuals of heads, flows, a-priori data, etc.), adverse model bias can undermine the results (Hill, 1998). Thus, simulating numerous plausible hydrologic conditions minimizes the potential for adverse model bias, albeit at the expense of added simulation time.

1.2 Objective and Scope

Information from the stochastic streamflow model and groundwater flow models were combined to provide plausible flow solutions for risk analysis purposes. In this report, risks of groundwater level declines are associated with the occurrence of groundwater discharge (i.e., frequency of baseflow capture) based on the consequences of increasing the rate of groundwater pumpage over a 100-year projection period. Note that relatively high water tables are associated with net gaining conditions, while relatively low water tables are correlated to net losing conditions.

For this example, groundwater flow was simulated over basecase conditions (i.e., recently recorded pumping averages), as well as a series of hypothetical pumping scenarios where increasing pumpage results in an increased risk of capture of groundwater discharge along two intermittent reaches of the Santa Cruz River including between the Nogales International Waste Water Treatment Plant (NIWTP) **(Figure 1.1)** and Tubac and between the Highway 82 Bridge and Guevavi Narrows **(Figure 1.2)**.

2.0 Hydrologic Models

The hydrologic models used to simulate the groundwater flow process consist of a stochastic streamflow model and groundwater flow models for two areas including the Northern model area and the Micro-basin area **(Figure 1.1)**. The stream-aquifer system is a combined function of recharge (or discharge groundwater) and runoff (i.e., streambed conductance) and the underlying aquifer's finite capacity to conduct and store recharge. The former is related to the stream boundary conditions, while the later is related to the groundwater flow model

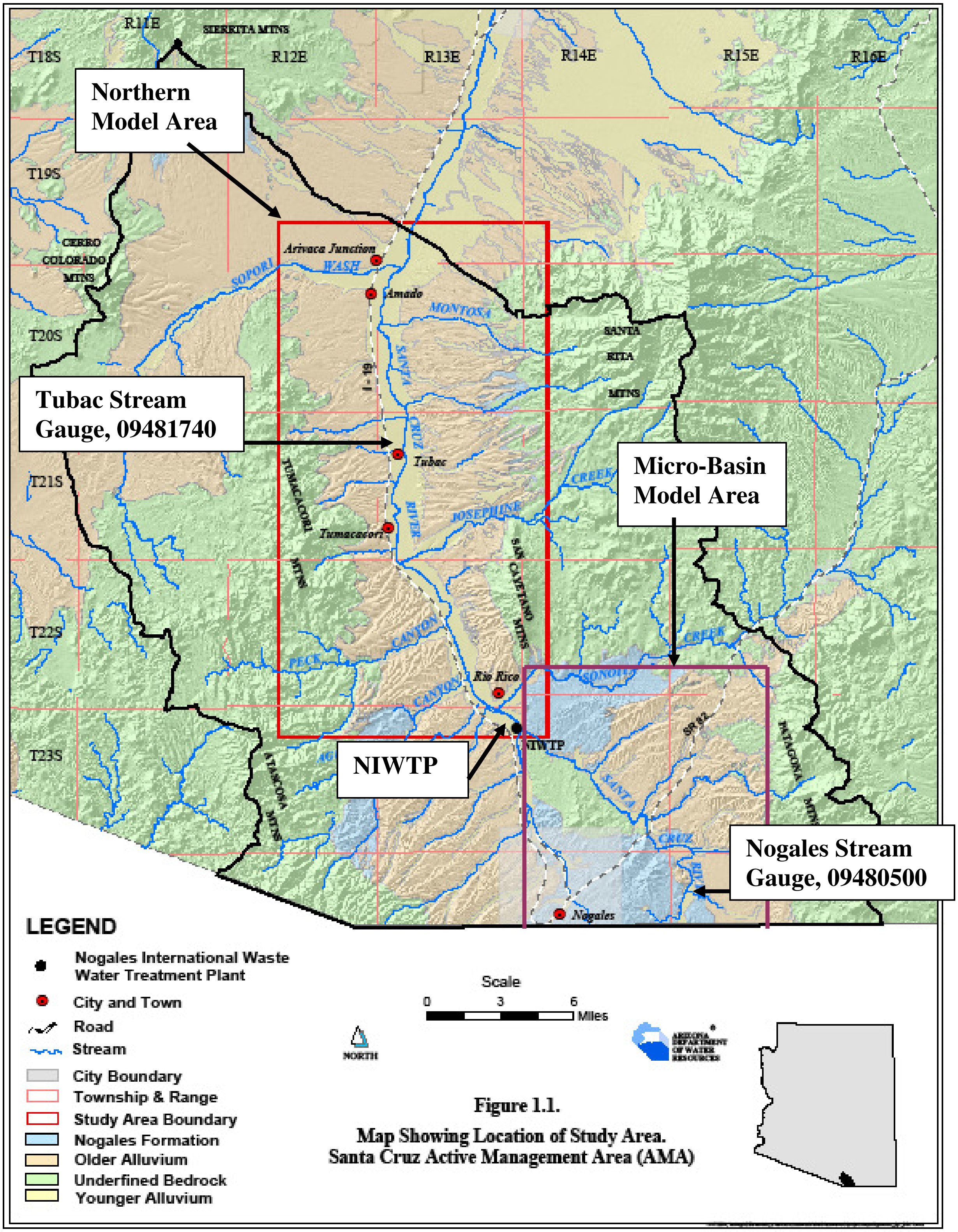

Figure 1.1: Northern Model Area and Micro-Basin Model

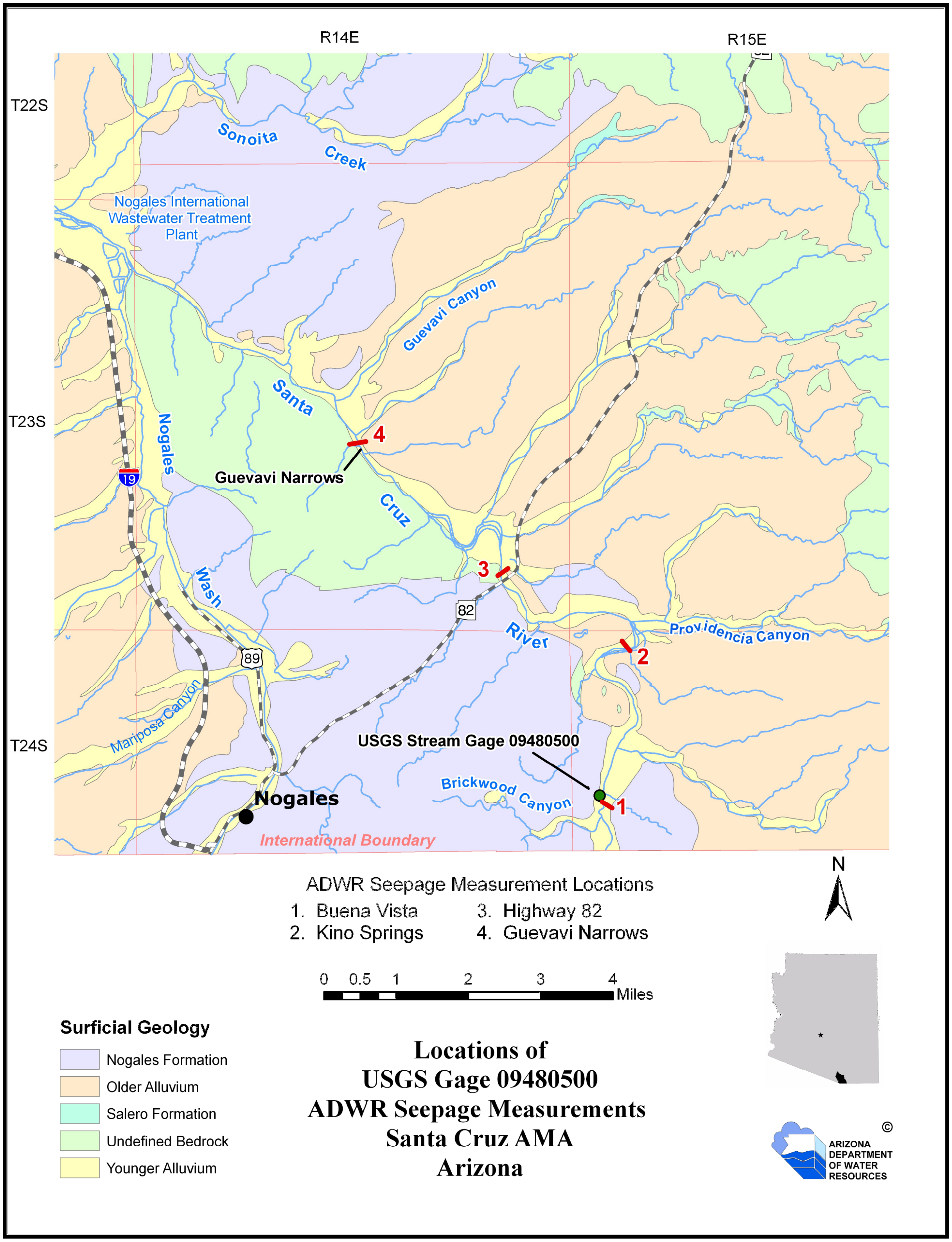

Figure 1. 2: Detail of Micro-Basin Model Area. Note groundwater discharge reach between Highway 82 Bridge (3) and Guevavi Narrows (4).

conceptualization: Together, they form the stream-aquifer system. The stochastic streamflow model and groundwater flow models were combined to evaluate impacts of different pumping scenarios; the resulting solutions provided information for risk analysis purposes. For this example groundwater flow was simulated over basecase and hypothetical pumping scenarios. All hypothetical pumping rates are assumed to represent municipal, industrial or domestic demands, because no additional incidental agricultural recharge was applied to the hypothetical scenarios.

The groundwater flow models include seasonally-based ET and flood recharge, as defined by the stochastic streamflow model. For the northern model area, seasonally-based agricultural pumpage and incidental agriculture recharge (25% of agricultural-related pumpage) were applied. In terms of seasonality the northern model is represented by seven stress-periods per year including fall (starting October and November), winter (December and January), spring (February - April), early summer (May and June) and the three individual monsoon-dominated months of July, August and September. Thus a total of 700 stress-periods were simulated for each realization. For the Micro-basin model, stress-periods were simulated at monthly intervals, for a total of 1,200 stress-periods per realization.

Conversion of surface water flow rates to stream-aquifer boundaries (i.e., stream conductance; stage) was based on the calibration of the groundwater flow models. The magnitude of the streambed conductance was dependant on the relative rate of the assigned (stochastic) monthly surface water flow rate. For information about the conversion of surface water flow to stream-aquifer boundary conditions, see **Appendix A**.

While the streambed conductance is a function of the stochastic-based streamflow rate, simulated flow between the stream and aquifer is also affected when simulated water table elevations approach streambed elevations. Note that for simplicity, released effluent was not included in this analysis because of the uncertain extent associated with an effluent-based clogging layer observed – especially along losing reaches. Field data shows that a nutrient-rich clogging layer can form along the streambed surface and further complicate streambed conductance assignments. This condition is not assumed to be as problematic in the absence of effluent. Also see **Appendix A**.

For this example simulated groundwater flow is primarily a function of: 1) streamflow recharge, as defined by the streamflow realizations of the stochastic model; 2) conceptual groundwater flow model and associated boundary conditions; and 3) rate of assigned groundwater pumpage. There may be other factors or uncertainties that impact the groundwater flow system in the future including: urbanization, watershed vegetation changes, ET changes, streambed modifications, upgradient capture of streamflow (which appears to be occurring near the US/Mexico boundary), runoff changes, effluent recharge, climate change patterns, *parameter* uncertainty (storage, transmissivity, recharge associated with each alternative conceptual model (ACM); see Nelson, 2007), aquifer geometry, lateral boundary conditions (i.e., southern and/or northern general head boundary) or initial conditions. Unless otherwise stated, none of these potential factors were formally addressed in this example.

For all hypothetical scenarios, the assigned pumpage was scaled in proportion to basecase rates, at locations where historic demand occurred. The ensemble results cannot be inferred to locations differing from those applied herein.

2.1 Stochastic Streamflow Model

To better understand the hydrologic system, the ADWR created a hydrologic monitoring program in the mid-1990's (Nelson and Erwin, 2001) and a suite of finite difference, MODFLOW (Harbaugh et al, 2000) groundwater flow models (Erwin, 2007; Nelson, 2007). Field data indicates that groundwater level elevations in the inner valley are strongly correlated to natural steam recharge.

During the model calibration, it became clear that stream recharge along the Santa Cruz River must be simulated at seasonal rates and must include flood recharge: Applying uniform, long-term average streamflow recharge is not an option because it does not reflect the hydrologic reality. Therefore to address future streamflow recharge uncertainty, the ADWR contracted the development of a stochastic streamflow model (Shamir, et al, 2005).

Historical streamflow information from the Santa Cruz River near Nogales was used to generate 100 independent, 100-year streamflow realizations, which were converted to stream-aquifer boundary conditions for application in the groundwater flow model. The estimated streamflow distributions generally reflect trends observed over time (seasonal and annual flow distributions; mass-balance, etc.) at the United States Geological Survey (USGS) Nogales Gauge, 09048500. By design the stochastic model is populated with streamflow rates which reflect the historical distribution. The model also contains a percentage of streamflow rates (and trends) that fall outside record. These outliers, however, are consistent with plausible, future statistical patterns supported by available data within the context of the modeling assumptions (i.e., exponential distribution of inter-arrival times, etc., see Shamir et al, 2005).

Note that the development of the stochastic streamflow model was explicitly based on historical observations (precipitation at Nogales 6N and streamflow at USGS 09480500). However if environmental conditions are expected to *significantly* change in the future, the statistical patterns encoded in the stochastic model may need to be modified accordingly.

2.2 Northern Santa Cruz AMA Groundwater Flow Model

For the northern Santa Cruz model the streamflow realizations were translated through a group of six plausible, alternative conceptual models (ACM's). In order to account for groundwater flow model uncertainty, the streamflow realizations were converted to stream-aquifer boundaries, and then were translated through six plausible ACM's for each hypothetical pumping scenario. Thus each 100X6 ACM-ensemble is comprised of 600 realizations and is simulated over 100 years.

Each of the six ACM's have positive and negative attributes and, for purposes of this analysis, the outputs were evenly weighted. It has been assumed that each ACM is an approximation of the truth and that a true model does not exist and cannot be expected in the set of models and as the number of observations increases the weighting scheme may be modified accordingly. These ideas are consistent with Poeter and Anderson (2005).

Collectively, the 100X6 ACM ensemble is assumed to result in a more random and unbiased distribution of model errors than any single ACM (100X1) ensemble. In terms of predictive modeling, simulating the 100X6 ACM ensemble provides solutions that 1) more accurately reflect the current level of uncertainty (greater variance); and 2) a larger, more statistically-significant sample size. **Figure B.1** in **Appendix B** compares the translation of the streamflow realizations through 1) a single (base) model; against 2) six ACM's (including the base model).

The calibrated ACM head and flow solutions were in good agreement within the Santa Cruz River Valley and generally consistent with available observation data. However simulated underflow rates, which cannot be directly observed, varied among the ACM's. For predicted streamflow patterns differing from history-matching calibrated conditions (although statistically plausible, as defined by the stochastic model) the ACM solutions tended to diverge. This was especially true over extended dry periods and for areas outside the inner valley where parameter uncertainty is greater (Nelson, 2007).

Different boundary condition assumptions also influence model solutions especially near boundary areas to the north and south. For example assigning alternative head boundary elevations (such as general head boundary (GHB) or constant head boundary (CHB) and/or external head distances such as GHB), influence model solutions. Simulating additional groups of plausible future boundary conditions (i.e., alternative southern and/or northern GHB conditions), in combination with the existing 100X6 ensemble would further increase uncertainty. Evaluating alternative pumping locations may also result in increasing disparity among the ACM solutions over long-term periods.

For the northern model area a total of seven different pumping regimes were examined including 11,000 acre-ft per year (AF/yr), 13,000 AF/yr, 15,000 AF/yr (basecase), 17,000 AF/yr, 19,000 AF/yr, 21,000 AF/yr and 23,000 AF/yr. Basecase pumping conditions in the northern model area are associated with long-term dynamic equilibrium conditions in the upper Santa Cruz River Valley, consistent with head and flow observations between 1982 and 2002. Groundwater demands from this period include recorded pumpage (averaging about 15,000 AF/yr) and recent ET coverage, simulated in the saturated zone at about 12,000 AF/yr.

For the hypothetical scenarios assigned to the northern area, the assigned pumpage was modified in proportion to basecase rates, at basecase well locations: thus all simulated pumpage originated from locations where historic demand occurred. For the northern model area, seasonal pumpage was distributed such that the summer rate (May 1st through September 30th, 153 days) was twice as high as the off-summer rate (October 1st through April 30th, 212 days), consistent with higher agricultural demands imposed during summer-periods.

Also note that if the proposed pumpage is significantly greater than the current model-calibrated range, the resulting saturated thickness associated with the top model layers will be generally thinner. If this occurs, the groundwater flow models may be "out-of-tolerance" in terms of calibrated transmissivity and recharge (due to the increased unsaturated zone); thus the models may need to be recalibrated or re-conceptualized for conditions significantly different than history-matching, calibration periods.

Of particular concern is the area near the northern Santa Cruz AMA boundary. If an extended dry period occurs in combination with significant regional-scale pumpage (extending into the Tucson AMA), there may be a depth-to-water threshold which, if crossed, reduces recharge below calibrated rates. Increasing the unsaturated zone thickness in combination with *un*saturated vertical hydraulic conductivities may increasingly reduce stream infiltration rates as a function of depth-to-water. The area north of Amado is more susceptible to long-term dewatering because the aquifer system is larger, and therefore requires more frequent (rare) stream recharge events for recovery. Thus, special treatment may be required for simulating future conditions near the northern Santa Cruz AMA boundary.

2.3 Micro-Basin (Santa Cruz AMA) Groundwater Flow Model

For the Micro-basin area the streamflow realizations were translated through a modified version of the Micro-basin model. For a description of the Micro-basin model see, Erwin (2007). For details on the Micro-basin model modification, see **Appendix C**. When the streamflow realizations were translated through the modified Micro-basin model the resulting solutions generally approximated head and flow trends observed over space and time. As with all groundwater flow models uncertainty exists regarding the conceptualization of the Micro-basin area. For purposes of this analysis the streamflow ensemble was translated through the modified Micro-basin model. Therefore groundwater flow model uncertainty was not explicitly evaluated. In the future it would be instructive to explore other plausible alternative model conceptualizations for this complex and dynamic area. For example alternative, plausible storage parameters (Sy) should be explored, as this is a sensitive model parameter.

For the Micro-basin area the basecase pumping rate represents the approximate demand recorded between 1997 and 2002, or about 2,700 AF/yr. ET demand in the Micro-basin area averages about 3,200 AF/yr in the saturated zone. In addition to the basecase pumping rate, five other hypothetical scenarios were developed for the Micro-basin area. Three hypothetical planning scenarios increase the basecase pumpage by 20% (3,250 AF/yr), 40% (3,780 AF/yr) and 60% (4,280 AF/yr), while two scenarios decrease basecase pumpage to 2,270 AF/yr and 1,950 AF/yr.

As with the northern area all hypothetical scenarios in the Micro-basin area simulated hypothetical pumpage in proportion to basecase rates, at basecase well locations: Thus all simulated pumpage originates from locations where historic demand occurred. As noted in Erwin (2007), pumpage assigned to each of the three municipal supply wells in Nogales' Santa Cruz well field was horizontally-divided into two model cells in order to reduce model-solver problems; therefore a total of six wells are used to simulate Nogales' pumpage from the Santa Cruz well field.

In the Micro-basin area, groundwater pumpage is dominated by the municipal sector, and pumping schedules are dependent on the saturated thickness of the water table aquifer. For example in Nogales' Santa Cruz well field, the pump capacity of (D-23-13)36bcb2 was 1,410 gallons per minute (gpm) when the dynamic depth-to-water level was 11.7 feet (ft) (recorded on 12/7/1988), and 212 gpm when the dynamic depth-to-water was 61.6 ft (recorded on 5/15/2003). Similar relations were recorded at the other two municipal wells in Nogales' Santa Cruz well field, including (D-23-14)36bcd and (23-14)36cab. (Note that (D-23-13)36bcb2, (D-23-14)36bcd and (23-14)36cab are shallow wells having total well depths of 120, 120 and 116 ft, respectively. The water production rates represent the uppermost portions of the aquifer; note that there may be potentially productive aquifer-zones below existing perforated intervals.)

For simplicity, constant annual pumping rates (uniform) were assigned to Micro-basin ensemble. An analysis of the Micro-basin model ensemble indicates that alternative pumping distributions (seasonally-assigned) are relatively sensitive over *short-term* periods. For example when the summer pumping rate was increased by 50% in combination with a corresponding decrease during winter periods, net gaining conditions were simulated more often than with the uniformly-assigned pumping rates, due to a more complete recovery of water levels in winter (seasonal test 1). Conversely when winter pumpage was increased by

50% in combination with a corresponding decrease during summer, net gaining conditions decreased, with respect to uniform pumpage due to an increase in capture during winter periods (seasonal test 2).

These results suggest that the distribution of pumpage in the Micro-basins results in complex groundwater flow patterns due to the combined interaction of ET, pumpage, stochastically-modulated flood recharge and the system hydraulics, including boundary conditions. See **Figure D.5** and **Figure D.6 in Appendix D**. However for basecase pumping rates, the *average* number of years having gaining conditions for the combined seasonal ensembles (i.e., sum of seasonal tests 1 and 2) is, for all practical purposes, the same as for the uniformly-assigned pumping ensemble.

These results suggest that uniform pumping rates can be used for determining long-term *average* groundwater flow conditions with the understanding that applying seasonally-based pumpage may result in short-term differences. Thus for the Micro-basin area, it is assumed that randomly-assigned seasonal pumpage and uniformly-assigned pumpage provide consistent, *average* capture rates, over long-term periods.

Although long-term *average* groundwater-flow conditions are (assumed) similar between uniform and randomly-assigned seasonal-based pumpage, the *variance* of the combined seasonal-ensembles was greater than that of uniformly-assigned pumping ensemble. This implies that randomly-assigned pumpage will have similar average capture rates, but that the risks associated with outliers will be different.

These results suggest that evaluating different pumping magnitudes should be based on consistent pumping schedules. For example in order to evaluate the *relative* capture rate between two different long-term demands of 2,700 and 4,300 AF/yr either: 1) a projected uniform pumping rate of 2,700 AF/yr should be directly compared with a projected uniform pumping scenario of 4,300 AF/yr, or 2) a seasonally-based pumping rate of 2,700 AF/yr should be compared with seasonally-based pumping scenario of 4,300 AF/yr. These results also imply that the hydrologic model can be used to evaluate alternative groundwater management strategies, based on user-defined pumping criteria.

Also note that alternative pumping distributions and/or schedules can result in the temporary de-activation of a model cell. When a model-cell becomes inactive, stresses imposed to that cell are not included until the affected cell becomes re-activated. Simulated water budgets show relatively small differences in cumulative pumping rates for selected realizations in the Micro-basin ensemble: It is assumed that these differences are insignificant with respect to the collective model solution, and do not compromise the general use of this tool to evaluate general groundwater flow conditions.

3.0 Statistical Evaluation of Simulated Groundwater Discharge

In order to efficiently simulate each ensemble, a batch-file program was created to automate the process. Operating from the command line, the DOS-based batch program takes advantage of MODFLOW's modular features by interchanging relevant "packages" in the MODFLOW (Harbaugh et al, 2000) name file. For example each 100-year streamflow realization consists of a unique stream-aquifer boundary package (*.str) that gets updated after the completion of every transient simulation. Similar updates occur for the simulation of unique ACM's (i.e., *.LPF package, *.rch package, etc.), and for different pumping-regime ensembles (i.e., well package, *.wel). After each 100-year transient MODFLOW simulation, the batch program processes the raw head (Hansen and Leake, 1999) and flow (Harbaugh, 1990) data, converting the binary-formatted data to a text-based format for additional post processing.

The ensemble simulation times were based on the following computer specifications: 2-CPU 6700 at 2.66GHZ X 2.66 GHZ with 3.00GB of RAM. Post-processing programs were developed in MATLAB and FOXPRO to analyze the model-output data based on user-defined criteria (i.e., simulated head and flow statistics; statistics based on the difference between basecase simulated heads and planning simulated heads; inter-arrival statistics for simulated heads and flows; distribution of continuous periods between net gaining conditions; transformation from the time to frequency domain, etc.).

For the northern Santa Cruz model it takes about eight hours to simulate one, 100X6 ACM (600 realization) ensemble. Each 100-year realization consists of 700 stress periods, and for this task 10 time-steps were executed for each stress period. For the northern Santa Cruz model the SIP solver was used with a head-closure value of 0.1 ft, resulting in acceptable mass-balance errors. It takes approximately eight hours to simulate a 600-realization ensemble for the northern model.

For the Micro-basin model each 100-year realization consists of 1,200 stress periods at 10 time-steps per stress period. (Note that MODFLOW-2005 (Harbaugh, 2005) or earlier versions of MODFLOW, specifically compiled to accommodate > 1,000 stress-periods, are required to simulate all 1,200 stress periods on a continuous basis and convert the binary-coded flow data for post-processing purposes.) The GMG solver was applied to the Micro-basin model, and the head and flow closure-criteria were 10 ft and 2E3 ft^3/d, respectively. Although cumulative mass balance errors for the Micro-basin model are considered acceptable a cursory review show mass balance discrepancies exceeding one percent for selected time steps. It is assumed that the mass balance errors associated with the Micro-Basin model do not adversely affect the resulting solutions. Simulating a 100-realization ensemble takes the Micro-basin model approximately ten hours to complete.

The net groundwater discharge flow rate was evaluated along the Santa Cruz River for each ensemble. For the northern Santa Cruz model area, the net flow rate was evaluated along the Santa Cruz River between the Nogales International Waste Water Treatment Plant (NIWTP) and Tubac (**Figure 3.1**), a distance of approximately 15 river-miles. In the Micro-basin area the net flow rate was evaluated along the Santa Cruz River between the Highway 82 Bridge and Guevavi Narrows (**Figure 3.2**), a distance of about 3 river- miles.

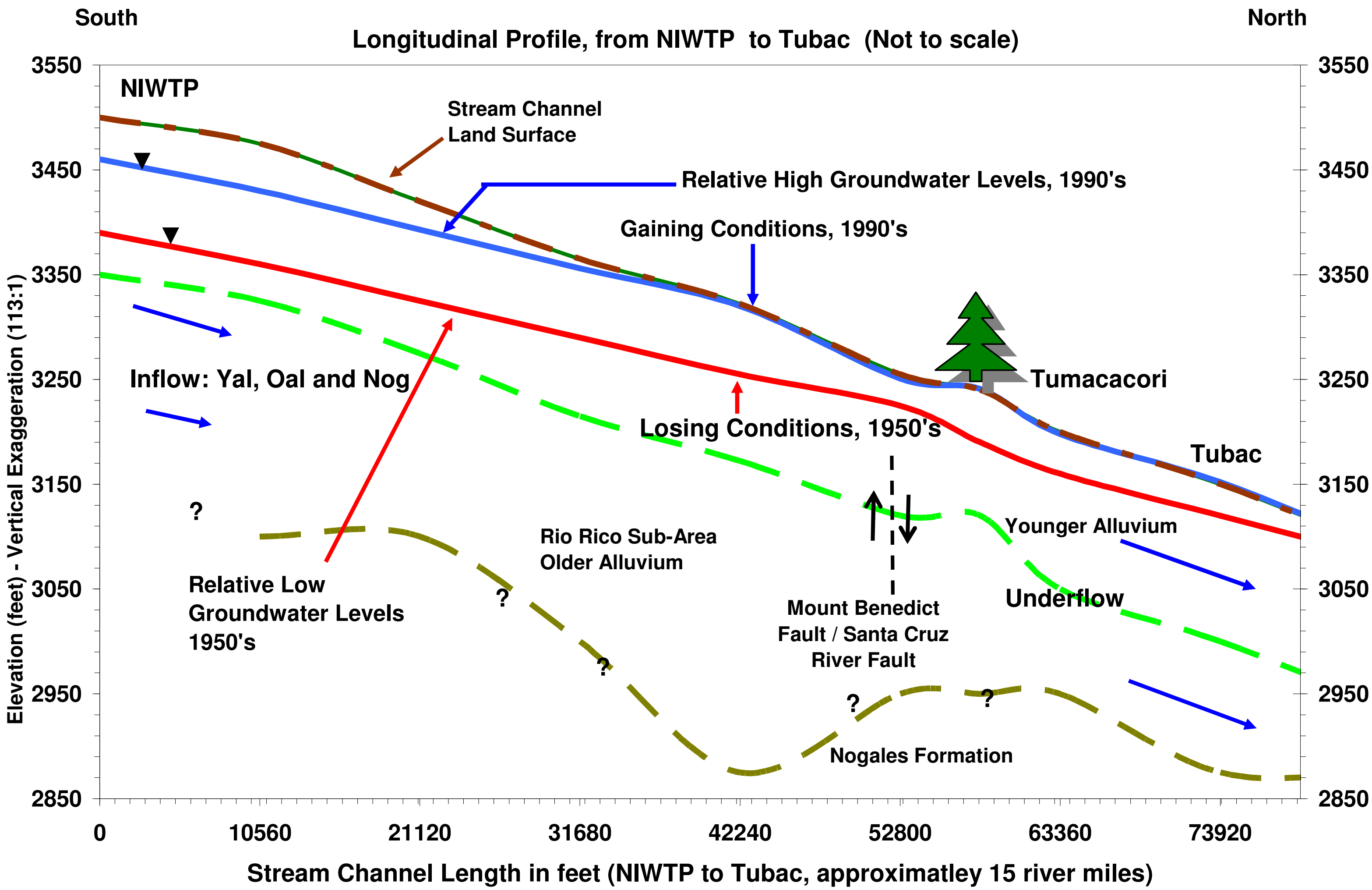

Figure 3.1 Longitudinal Profile, the NIWTP to Tubac

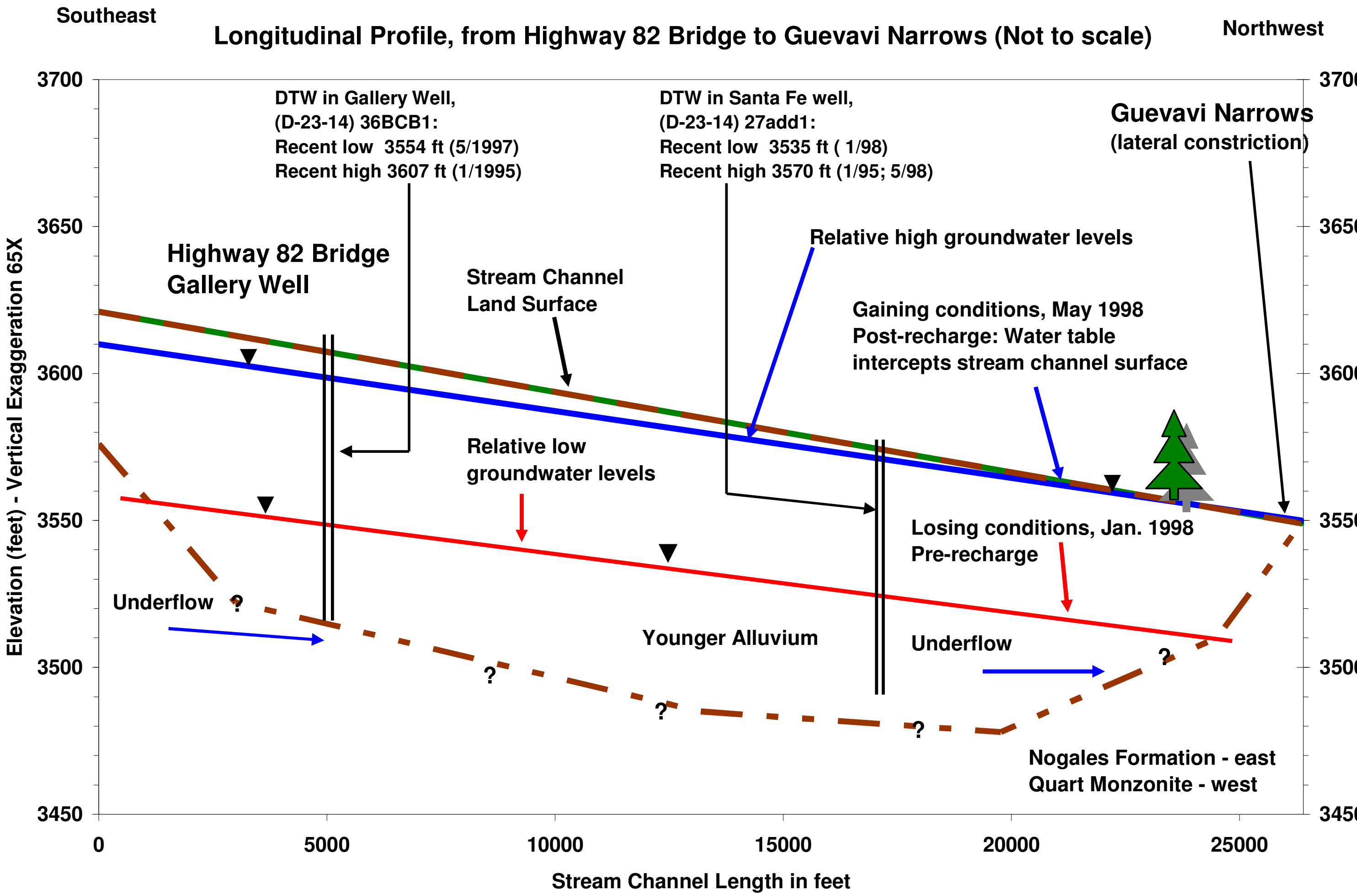

Figure 3.2 Longitudinal Profile, Highway 82 Bridge to Guevavi Narrows

3.1 Gaining and Losing Reaches

Groundwater level elevations are based on the characteristics of the aquifer (i.e., transmissivity, storage coefficients, boundary conditions, influxes, underflows, etc.), natural and artificial recharge, and groundwater demands including pumpage and ET. A detailed study of recorded groundwater level elevations and associated statistics in the Santa Cruz AMA is provided by Corkhill and Dubas (2007).

Because groundwater level elevations are obtained from wells that may, or may not, be subject to pumping, factors such as the timing of measurements (seasonality) and pumping condition (static, dynamic or recovering) influence groundwater level elevations at specific well sites. With respect to groundwater elevations at specific well sites, it is thus assumed that any differences (i.e., residual errors) between observed and simulated heads are smaller when represented over broader, local areas.

A local-scale measure of groundwater level elevations attenuated over broader areas - with respect to site specific well elevations - can be represented by net flow accrued along a head-dependant boundary. If a reach is subject to intermittent streamflow (i.e., a reach having both losing and gaining conditions), the net flow computed along that reach can be used as a general indicator of local water level elevations. Relations between groundwater levels (head) and streambed parameters (i.e., streambed conductance), and flow, with respect to gaining and losing conditions, is shown in **Figure 3.3.**

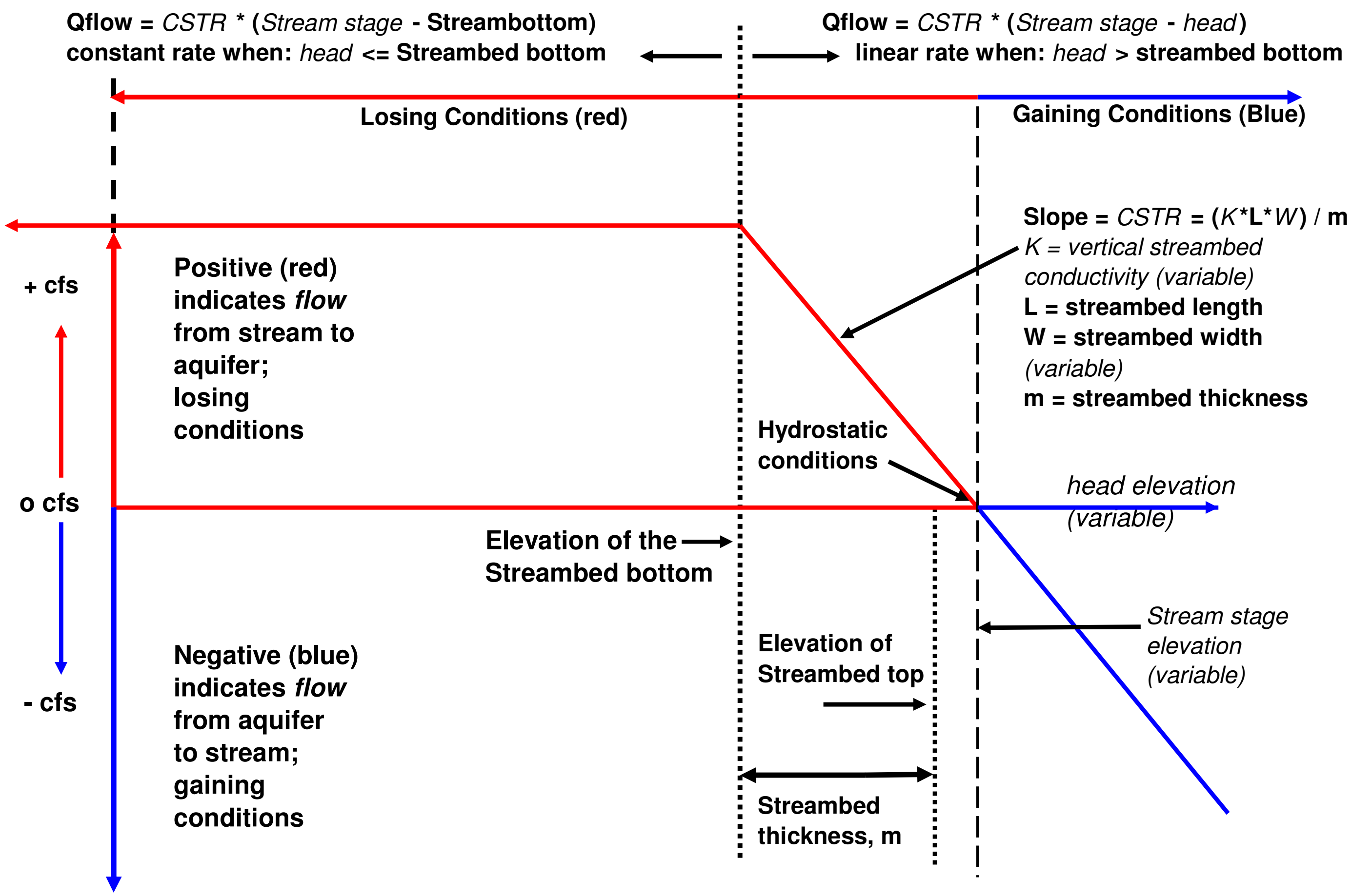

Figure 3.3 Stream-Aquifer Boundary: Relations between 1) simulated head; 2) gaining and losing flow conditions; and 3) stream-aquifer parameters. Figure modified from Figure 3 in Prudic (1989).

Groundwater discharge from the aquifer-to-stream (gaining) or stream-to-aquifer (losing) is a meaningful indicator of local groundwater levels along an intermittent reach because the stream-aquifer system is simulated as a head-dependent boundary within the inner valley. Groundwater flow to-and-from the aquifer and stream represent inner valley water table elevations over seasonal periods. High transmissivities within the inner Santa Cruz River Valley ensure that groundwater discharge thresholds are representative of "smoother", local water table elevations over seasonal time scales. As such, net groundwater discharge rates evaluated along the stream-aquifer system are not as adversely affected by site-specific groundwater anomalies or irregular (short-term) pumping schedules.

With respect to evaluating simulated groundwater levels at specific locations, assessing net groundwater discharge and recharge along the stream-aquifer boundary is assumed to result in errors that are more randomly distributed over space and time. As noted above, comparing observed and simulated heads at concentrated pumping locations are subject to additional model bias due to unavoidable differences that exist between real-world and simulated pumping schedules. Furthermore simulated pumpage assigned in Nogales' Santa Cruz well field (Micro-basin area) was dispersed in order to reduce problems associated with assigning high demand to model cells immediately surrounded by relatively impermeable, horizontal boundaries (also see Erwin, 2007). Hence, simulated heads *at* Nogales' (Santa Cruz River) production wells are different than observed heads because the pumping distributions are different. Over broader scales site-specific differences attenuate.

Accordingly, local impacts can be represented with less bias along head-dependant boundaries over broader areas due to the attenuation of errors over space. Evaluating simulated groundwater discharge also provides a measure to quantify the hydrologic impacts of low magnitude, widespread pumpage where subtle long-term groundwater level trends (i.e., hydraulic gradients) might not be clearly identified using site-specific head data. Thus identifying net gaining and losing conditions, is an effective way to evaluate systemic water table elevations along relevant reaches. Conceptual models of the groundwater flow regime for the northern model area and the Micro-basin area are presented in **Figure 3.1** and **Figure 3.2**.

3.1.1 Northern Santa Cruz Model Reaches

During the pre-groundwater development period (prior to 1920), near perennial streamflow conditions existed near Tumacacori and Tubac along with surface water diversions and a dense riparian habitat. Since groundwater development, the reach between the (current) NIWTP and Tubac has experienced both net gaining and net losing conditions over winter periods. Photographs from the spring 1936 and the winter of 1954 show net gaining and losing conditions, respectively. Photographs from 1965 indicate losing conditions, while pictures from spring of 1967 and December 1973 show groundwater discharge along this reach.

More recently, this reach experienced gaining conditions during winter periods from (at least) 1992 to the winter of 2001/02. Minimal flood recharge between mid-2001 and July 2006 resulted in significant groundwater level declines. By mid-2005 groundwater levels along losing reaches near Rio Rico, were at their lowest level since the mid 1950's; during the spring of 2005, a significant tree die-off was noted along this reach. Relatively low groundwater elevations between the NIWTP and Tubac resulted in losing conditions along the Santa Cruz River from mid-2002 through 2008. The cumulative affect of three relatively active monsoons in 2006, 2007 and 2008 resulted in intermittent gaining conditions by January 2009. Minimal flood recharge occurred during the 2009 summer monsoon, transitioning the system back into a losing state during the winter of 2009/2010. **Figure 3.4** shows the relation between surface water flow and groundwater levels (in an unequipped well), adjacent to a losing reach of the Santa Cruz River near Rio Rico. The aquifer system adjacent to intermittent reaches of the Santa Cruz River (i.e., near Tumacacori) also respond to streamflow recharge and "drought" patterns; however the magnitude of groundwater level fluctuations, compared to **Figure 3.4**, are attenuated.

3.1.2 Micro-Basin Santa Cruz Reaches

Prior to the extraction of groundwater perennial baseflow existed along the Santa Cruz River at Guevavi Narrows. In the Micro-basin area groundwater demand in the United States and Mexico - in the form of groundwater pumpage and infiltration galleries - has led to the capture of groundwater discharge along the upper reaches of the Santa Cruz River. With current groundwater development trends, groundwater discharge as baseflow only occurs following significant recharge periods. See **Figure E.1** in **Appendix E**.

3.1.3 Gaining and Losing Reaches Applied to the Models

Gaining conditions are associated with relatively high groundwater levels, while losing reaches represent relatively low water table elevations: Thus, periods having relatively high simulated water levels are correlated with gaining conditions (**Figure 3.5**).

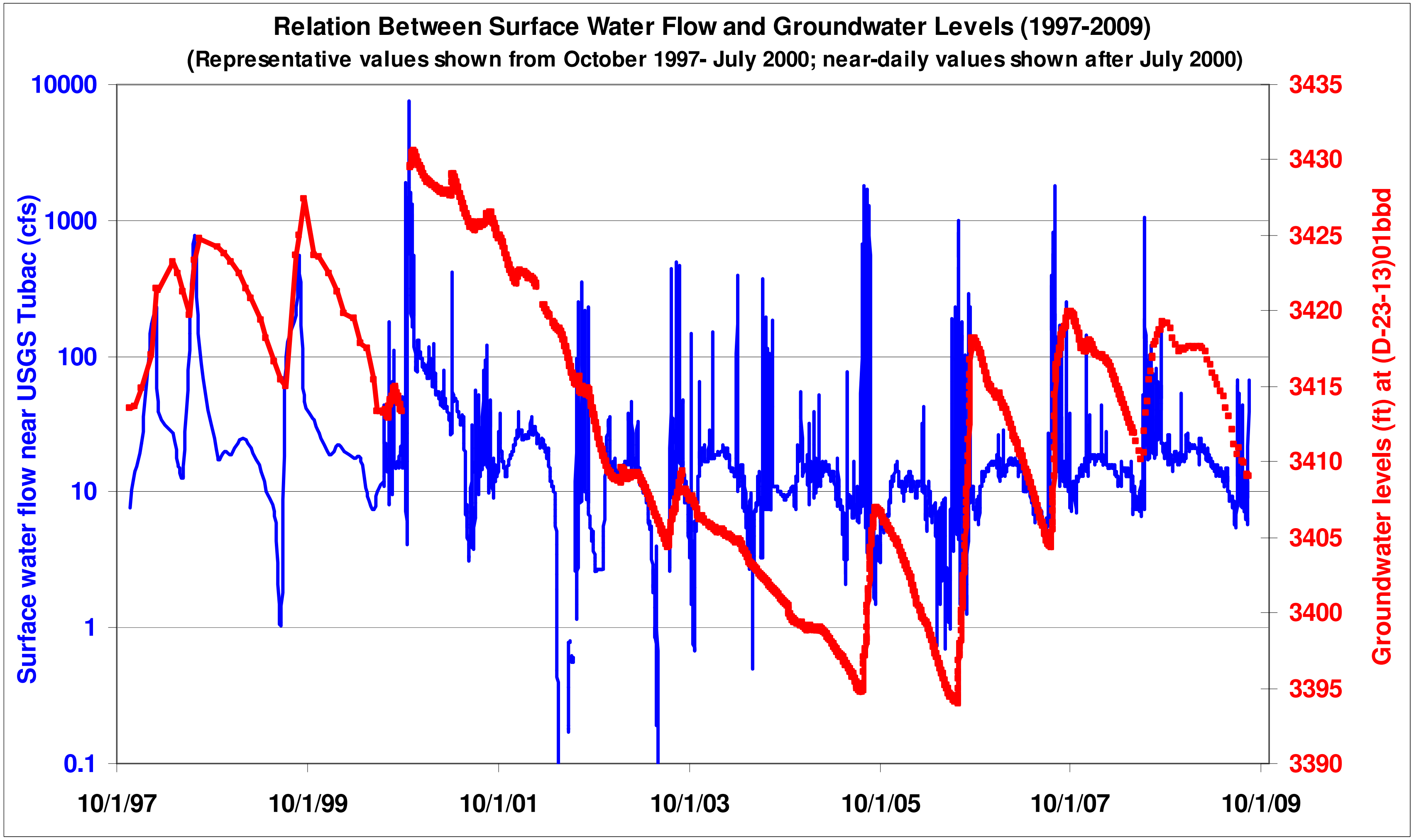

Figure 3.4 Observed Streamflow (blue) and Groundwater Levels (red) in Northern Model Area

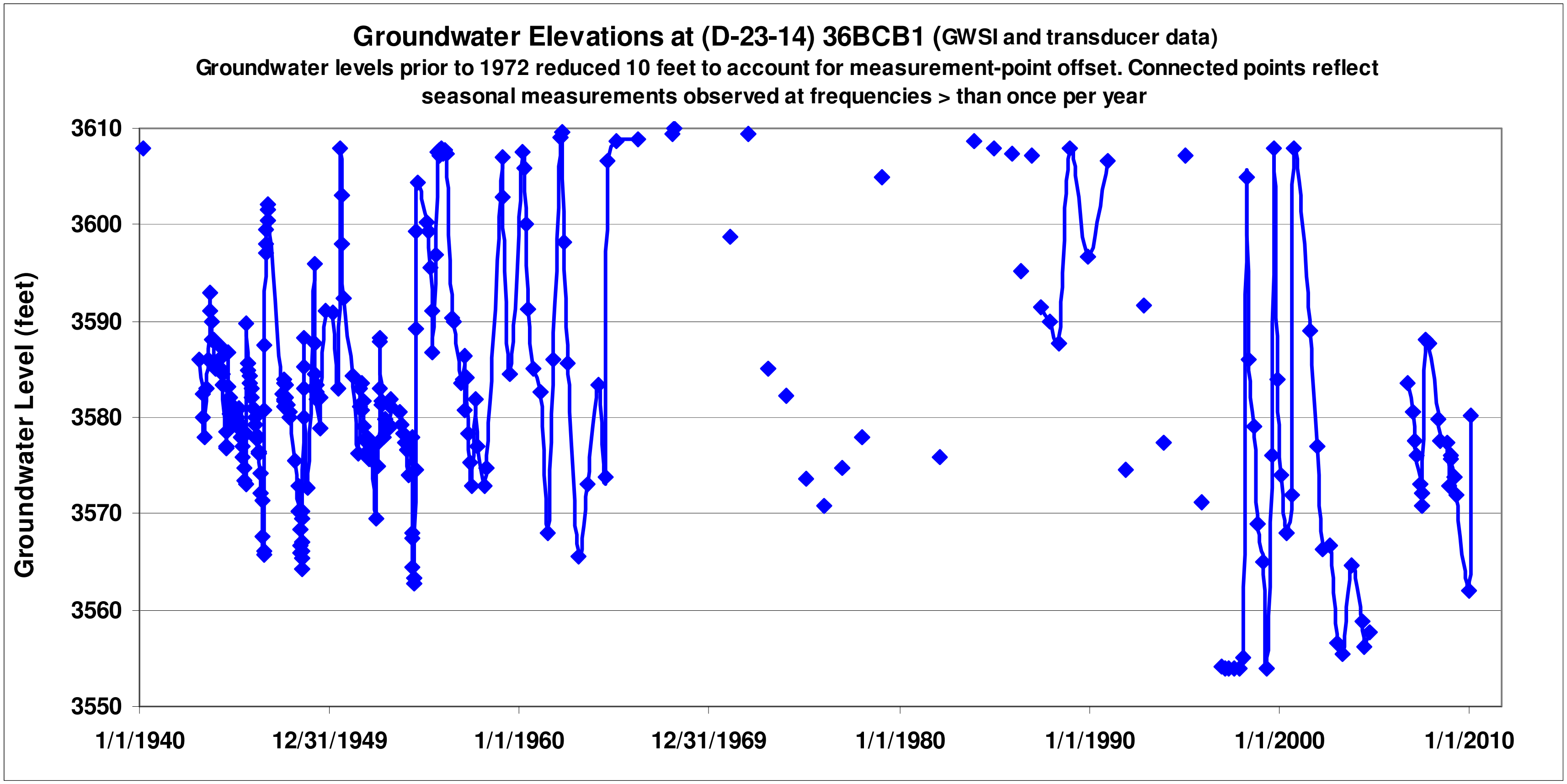

Figure 3.5 Groundwater Levels in the Micro-basins (1940-2010)

For purposes of this analysis, the net groundwater discharge threshold level was set to 0 cubic feet per second (cfs), and the net flow was evaluated at time-step #10 of every stress period. This threshold represents an intermediate value of net flows recorded over recent periods (1992-2009), and is physically representative of the water table intercepting the stream channel. When groundwater discharge exceeds groundwater recharge along a given stream reach over the same time step, net gaining conditions result. For purposes of this analysis, if a net gain occurs during any portion of a simulation year it qualifies as a gaining year in the resulting statistics. In this risk analysis the impact from pumpage is based on the average number of groundwater discharge (gaining) years per realization (out of 100 years), per ensemble (i.e., 600 realizations for the northern model area and 100 realizations for the Micro-basin area). The following results assume that the ensemble outputs conform to normal distributions (see **Figure B.2** and **Figure B.3** in **Appendix B**). See **Appendix A** through **Appendix H** for miscellaneous information about the models, the resulting statistics, and other information.

3.2 Simulated Groundwater Flow in the Northern Model Area

For the northern model area, when the basecase pumping rate (15,000) was imposed to the 100X6 ensemble, gaining conditions occurred, on average, during 43 of the 100 simulation years. When the pumpage was increased to 17,000, 19,000, 21,000 and 23,000, gaining conditions occurred on average in 33, 25, 17 and 12 of the simulation years, respectfully (**Table 3.1**). Therefore increasing pumpage results in an increasing (average) rate of capture.

Assigned Groundwater Pumpage, Northern Santa Cruz AMA Model	Average number of years (out of 100) per realization having net groundwater discharge (gain) between the NIWTP and Tubac
11,000 AF/yr	70
13,000 AF/yr	56
15,000 AF/yr*	43
17,000 AF/yr	33
19,000 AF/yr	24
21,000 AF/yr	17
23,000 AF/yr	12
Based on 600 realization-ensembles (100X6ACM). Out of 100 possible years. Pumpage includes two seasonal rates including summer and winter. *Basecase pumping rate, consistent with 1997-2002 pumping average.	

Table 3.1. Average Number of Years with Net Gaining Conditions, Northern Model area

When the pumpage was reduced to 13,000 AF/yr, gaining conditions occurred more often than not (56%). For basecase (15,000 AF/yr) conditions there is a 3-out-of-4 chance that fewer than half (50) of the simulated years will experience gaining conditions during the 100-year period. However even when pumping rates are reduced by 2,000 AF/yr (13,000 AF/yr), there is still about a 30% chance that less than half of the simulated years will result in gaining conditions during the 100-year simulation period. If the pumpage is ramped up to 19,000 AF/yr, there is a 50% chance that gaining conditions will occur in at least 25 of the 100 simulations years. When the pumpage is further increased to 21,000 AF/yr and 23,000 AF/yr, the chances are reduced to about 15% and 2%, respectively.

Regarding the frequency of non-gaining conditions, over half of the ensemble realizations (52%) had at least one consecutive ten-year period without gaining conditions, while 14% percent of the realizations had at least two separate consecutive ten-year periods without gaining conditions when the basecase (15,000 AF/yr) pumping rate was assigned. When the pumping rate was increased to 19,000 AF/yr almost all of the realizations (94%) had at least one consecutive ten-year period without gaining conditions, while over one-third of the realizations (36%) had at least one consecutive *twenty-year* period without gaining conditions. When pumping is increased above basecase rates, the risk of increased-periods without baseflow also increases, as shown in **Table 3.2**.

Pumpage, Northern Santa Cruz AMA	**Percentage of realizations in ensemble having at least one continuous period greater than X years *without* net gaining conditions:**			
	X = 5 years	**X = 10 years**	**X = 15 years**	**X = 20 years**
11,000 AF/yr	50%	6.7%	0.2%	0%
13,000 AF/yr	84%	23%	3.8%	0.2%
15,000 AF/yr*	98%	52%	15%	4%
17,000 AF/yr	100%	76%	39%	15%
19,000 AF/yr	100%	94%	66%	36%
21,000 AF/yr	100%	98%	86%	60%
23,000 AF/yr	100%	98%	92%	74%
Based on 600 realization-ensembles. Out of 100 possible years. Pumpage includes two seasonal rates including summer and winter. *Basecase pumping rate, consistent with average rate recorded, 1997-2002.				

Table 3.2. Frequency of Period not Having Net Gaining Conditions, Northern Model area

Sensitivity analysis shows that groundwater flow model solutions are strongly influenced by: 1) the flood recharge inter-arrival period; 2) the flood recharge duration period; 3) the *relative* magnitude of stochastic forcing terms; 4) the groundwater flow model conceptualization including boundary conditions such as ET; and 5) long-term pumping rates and distributions. In general individual flood recharge events of short duration (i.e., days) have minimal long-term impact. However extended dry or wet periods are sensitive. **Figure 3.6** and **Figure 3.7** show simulated heads from two selected realizations.

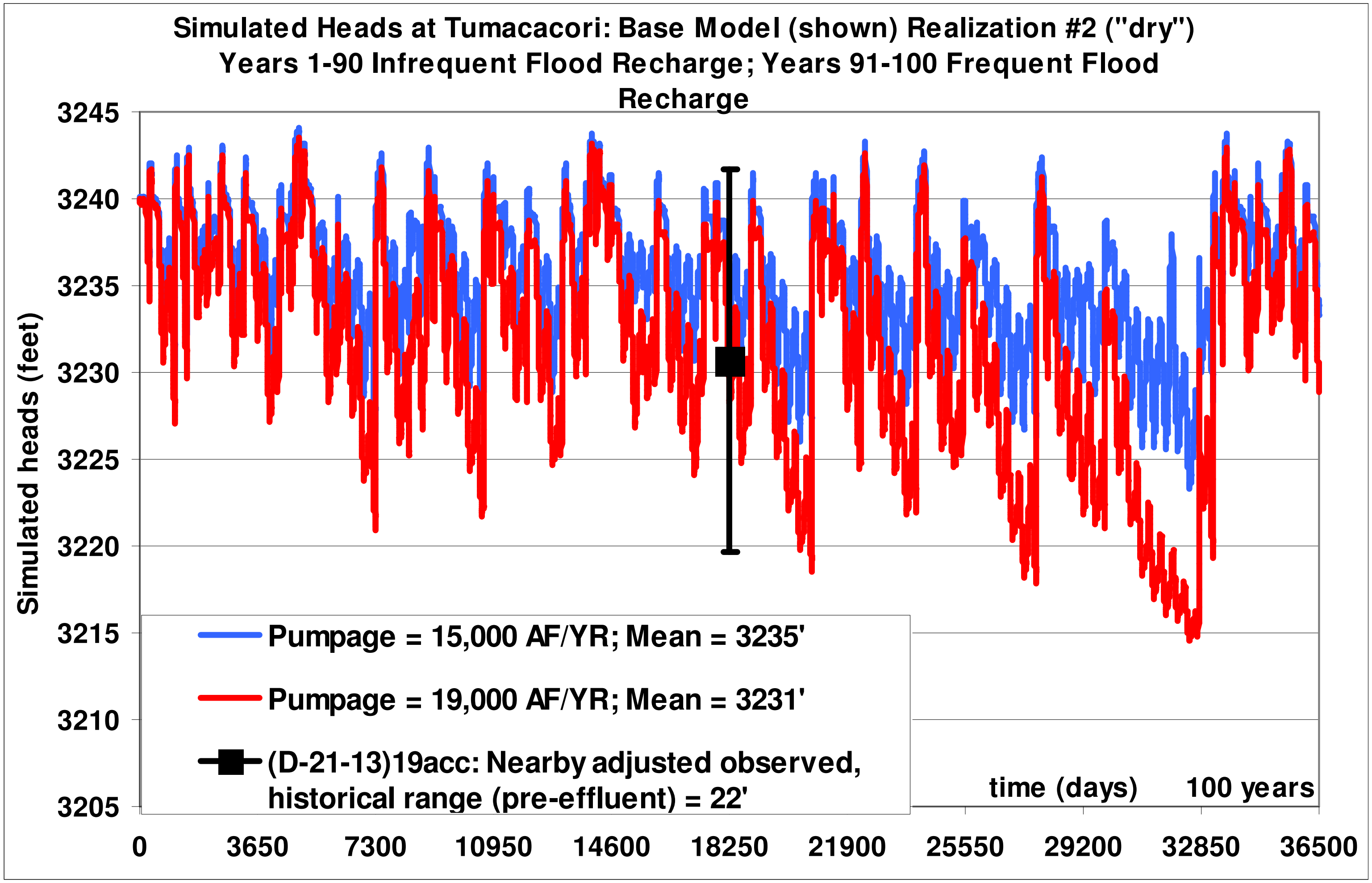

Figure 3.6. Comparison of Simulated Heads Subjected to 15,000 AF/yr and 19,000 AF/yr at Tumacacori for Selected Realization #2: Northern Santa Cruz Model

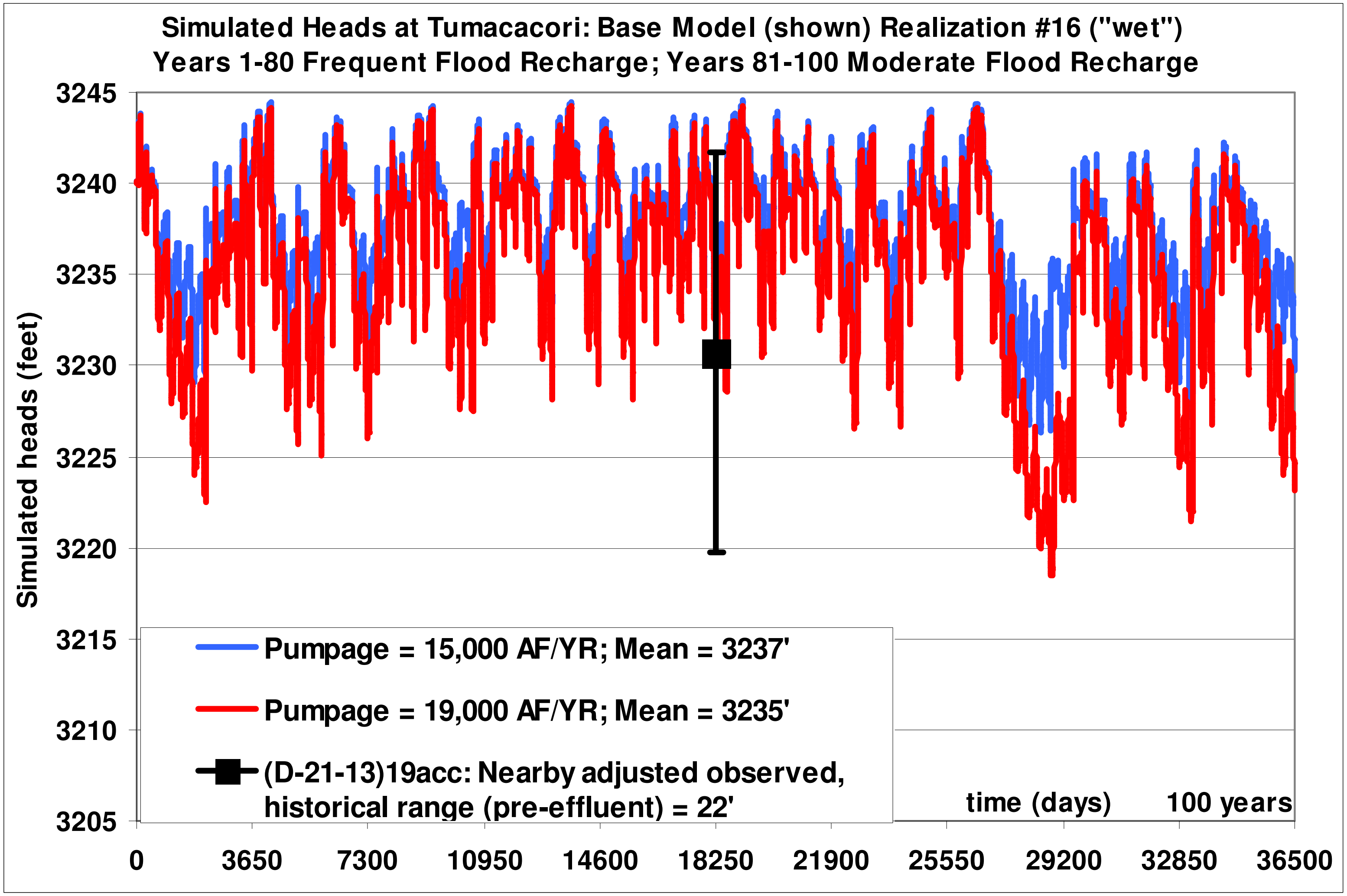

Figure 3.7. Comparison of Simulated Heads Subjected to 15,000 AF/yr and 19,000 AF/yr at Tumacacori for Selected Realization #16: Northern Santa Cruz Model

Relatively high simulated groundwater levels are associated with net gaining conditions while relative low simulated heads are associated with net losing conditions. **Figure B.4** shows the ensemble distribution of continuous-time intervals between net gaining periods for basecase and added-demand pumping scenarios for the Northern model area. Note that these inter-arrival distribution patterns are consistent with the exponential distribution patterns associated with generating streamflow inter-arrival (duration) periods, as described in Shamir et al. (2005): Different pumping rates result in different inter-arrival occurrence-rates, but all generally follow exponential distribution patterns; these results infer how the stochastic model and groundwater flow function in a congruent manner.

3.3 Simulated Groundwater Flow in the Micro-basin Area

For the Micro-basin area, net groundwater discharge was evaluated between the Highway 82 Bridge and Guevavi Narrows (**Figure 1.2**). This zone is represented in the Micro-basin model from row 38 to row 52, inclusive to the Yal, or model layer 1. When the basecase pumping rate was imposed to the 100-realization ensemble, gaining conditions occurred, on average, during 49 of the 100 projected simulation years (**Table 3.3**). When pumpage in the Micro-basin was increased to 3,250 AF/yr, 3,780 AF/yr and 4,280 AF/yr gaining conditions occurred, on average, in 36, 27, and 21 of the simulation years, respectfully. Thus with respect to absolute pumpage, the Micro-basin area is more sensitive to the capture of groundwater discharge than the northern model area.

Assigned Groundwater Pumpage Micro-Basin Model Santa Cruz AMA**	**Mean number of years having net groundwater discharge (gain) between the Highway 82 Bridge and Guevavi Narrows**
1,900 AF/yr	67
2,300 AF/yr	60
2,700 AF/yr*	48
3,300 AF/yr	35
3,800 AF/yr	26
4,300 AF/yr	20
Based on 100 realization-ensembles. Out of 100 possible years. *Basecase pumping rate consistent with average rate recorded, 1997-2002; pumpage applied at a uniform rate. **Rounded to nearest 100th.	

Table 3.3. Average Number of Years with Net Gaining Conditions, Micro-basin area

With basecase pumpage assigned to the ensemble, 98% of the realizations had at least one, 5-year period without net gaining conditions, while 32% of the realizations had at least one, 10-year period without net gaining conditions. When the pumpage was increased to 3,250 AF/yr, all of the realizations had at least one, 5-year period without net gaining conditions, and 69% of the realizations had at least one, 10-year period without net gaining conditions. When 3,780 AF/yr (40% greater than basecase pumpage) was applied 85% of the realizations had at least one, 10-year period without net gaining conditions, while 8% of the realizations had at least one 20-year period without net gaining conditions. When the basecase pumpage was proportionally increased by 60% (4,280 AF/yr) almost all the realizations (95%) had at least one, 10-year period without net gaining conditions, while one-quarter of the realizations had at least one 20-year period without net gaining conditions (**Table 3.4**).

Pumpage, Micro-basin Santa Cruz AMA**	**Percentage of realizations in ensemble having at least one continuous period greater than X years *without* net gaining conditions:**			
	X = 5 years	**X = 10 years**	**X = 15 years**	**X = 20 years**
1,900AF/yr	63%	2%	0%	0%
2,300AF/yr	89%	9%	0%	0%
2,700AF/yr*	98%	32%	3%	0%
3,300 AF/yr	100%	69%	15%	3%
3,800 AF/yr	100%	85%	36%	8%
4,300 AF/yr	100%	95%	58%	25%
Based on 100 realization-ensembles. Out of 100 possible years. *Basecase pumping rate consistent with average rate recorded, 1997-2002; pumpage applied at a uniform rate. **Rounded to nearest 100th.				

Table 3.4. Frequency of Period not Having Net Gaining Conditions, Micro-basin area

When pumping is increased above basecase rates, the risk of increased-periods without baseflow also increases. However unlike the northern model area, when basecase rates are proportionally increased by more than 50%, only one-quarter of the realizations have an extended period without baseflow greater than 20 years. These results imply that less extreme flood events are required to recharge the Micro-basins even after extended droughts impacted by intense pumpage.

Figure 3.8 and **Figure 3.9** show simulated heads from two selected realizations. As with the northern model area, gaining conditions are consistent with relatively high simulated groundwater levels, while losing conditions are associated with relatively low simulated heads. **Figure B.5** shows the distribution of time in between net gaining periods for basecase pumpage.

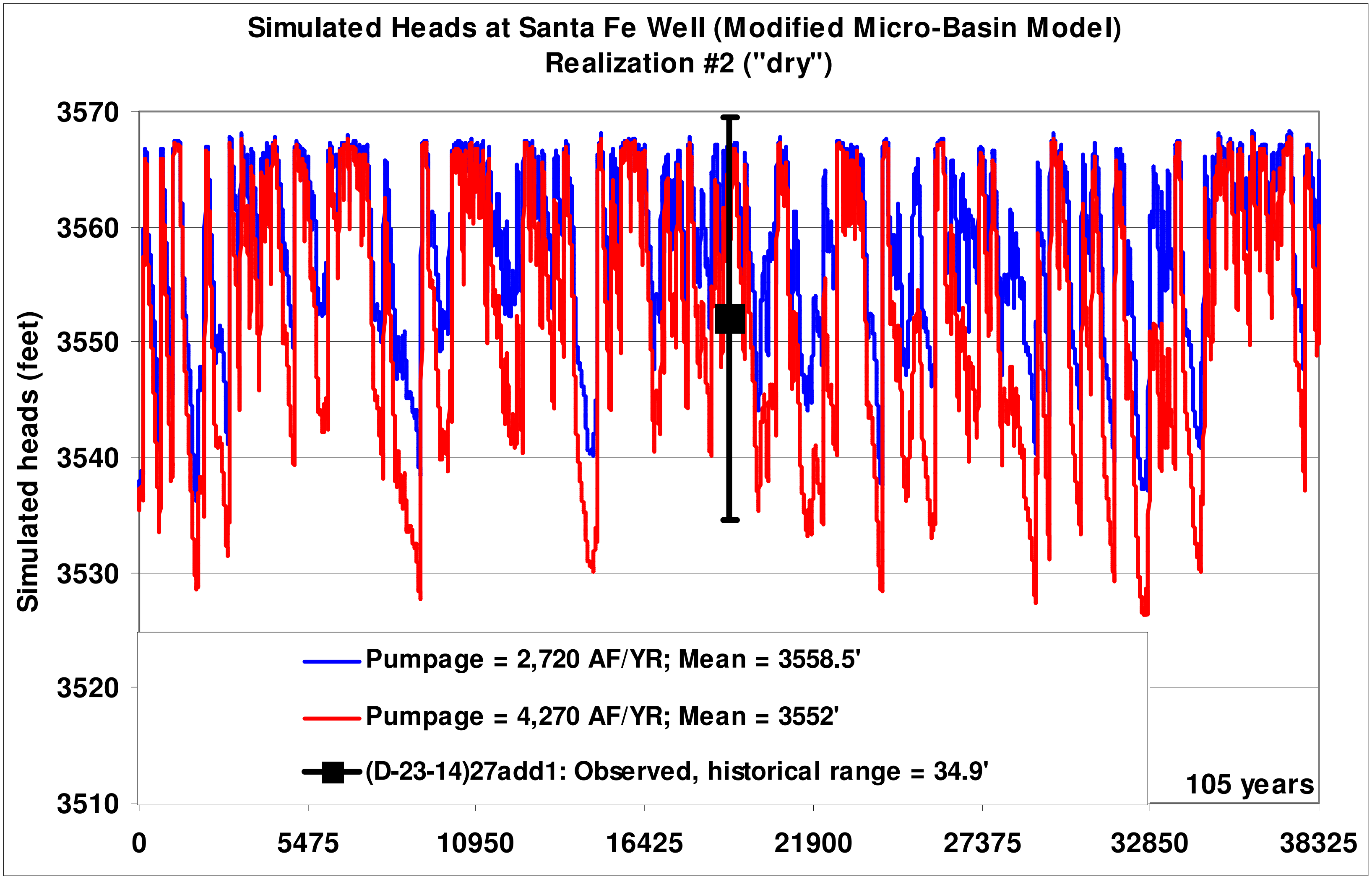

Figure 3.8. Comparison of Simulated Heads Subjected to 2,720 and 4,270 AF/yr in Highway 82 Micro-basin for Selected Realization #2: Micro-Basin Model

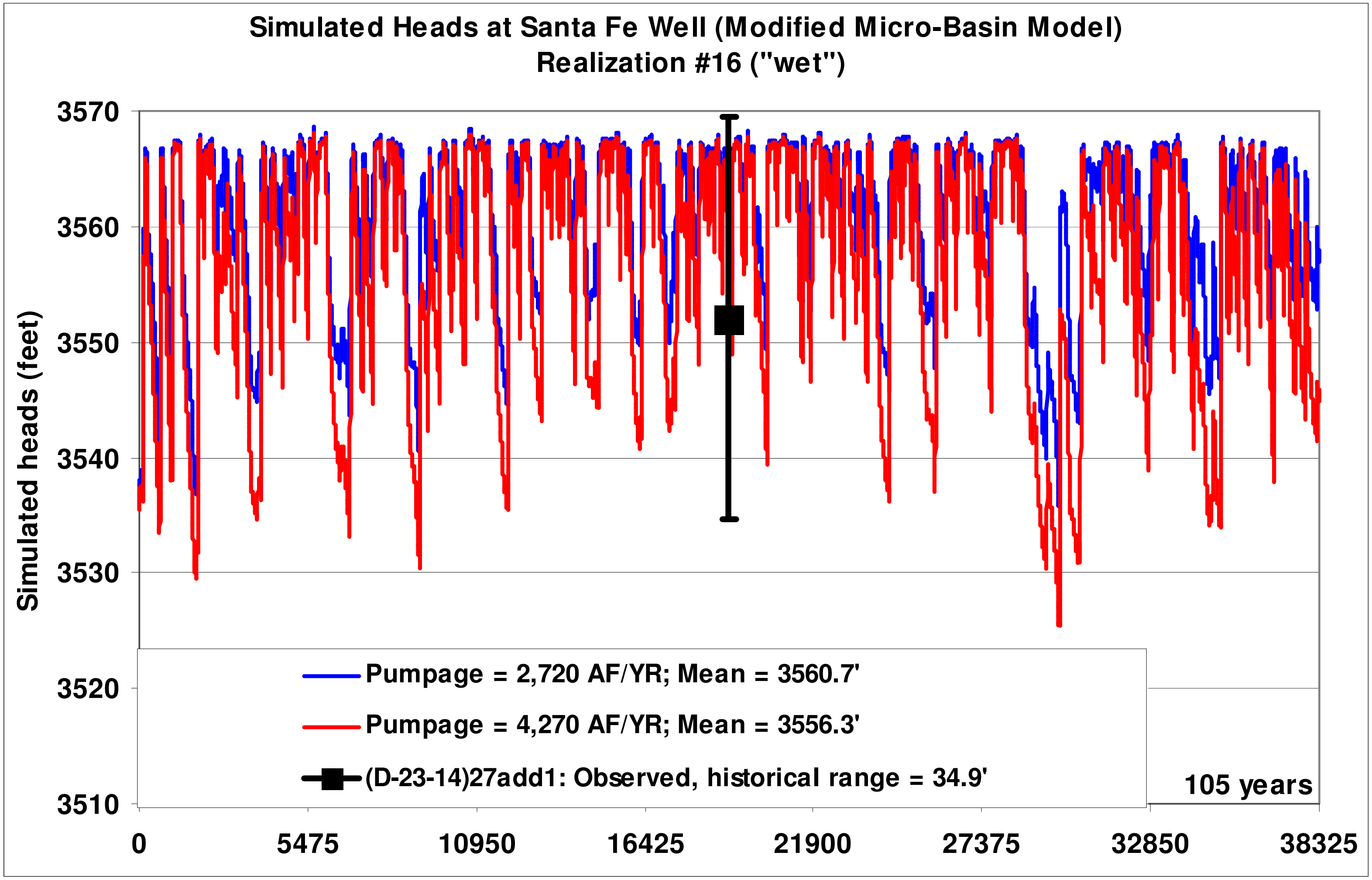

Figure 3.9. Comparison of Simulated Heads Subjected to 2,720 and 4,270 AF/yr in Highway 82 Micro-basin for Selected Realization #16: Micro-basin Model

4.0 Discussion

Predicted groundwater flow in the Santa Cruz Valley is sensitive to natural recharge, the conceptualization of the groundwater flow system and boundary conditions, and the rate of groundwater pumpage. There may be other factors that impact future groundwater flow conditions including alternative ET distributions, alternative runoff and recharge distributions, artificial recharge, increased urbanization and climate change; these factors, however, were not explicitly evaluated in this study. All other factors being equal, increasing groundwater pumpage results in lower long-term average groundwater levels. Increasing groundwater pumpage to rates higher than recently-recorded averages (for the northern model area 15,000 AF/yr; for the Micro-basin 2,700 AF/yr) increases the risk of capturing natural groundwater discharge along intermittent reaches of the Santa Cruz River.

Within inner valley areas, the model solutions are not especially sensitive to initial conditions when evaluated over long-term periods due to high aquifer transmissivities and periodic flood recharge. Outside inner valley areas, the groundwater flow system responds slower to stresses due to lower transmissivities and thicker unsaturated zones; thus peripheral areas may be susceptible to initial conditions assumptions and/or model biases, even over long-term periods. Differences in simulated groundwater flow between basecase and added-demand scenarios are greater during projected dry periods than during periods of high recharge. Thus the adverse impacts of increased pumpage are exacerbated during dry periods, but are not as pronounced during periods of significant flood recharge.

With respect to simulated heads and flows, the Micro-basin area is much more sensitive to absolute pumpage, than the Northern model area. For example in the northern model area, adding 2,000 AF/yr of pumpage to existing wells, increases the rate of capture (as defined above) by an average of 10%. However adding 1,600 AF/yr of pumpage to existing well locations increases the rate of capture by an average of 28% in the Micro-basin area. The aquifers in the northern model area are larger than those in Micro-basin area. The extra storage space acts as a buffer during periods of minimal stream recharge. However after extended "dry" intervals, larger aquifers require longer recovery periods.

Figure 3.6 and **Figure 3.7** show simulated heads at Tumacacori for selected streamflow realizations #2 ("dry") and #16 ("wet"). While the last ten years of realization #2 are subject to frequent stream recharge and high water levels, the first 90 years represent infrequent stream recharge; thus realization #2 is associated with a relatively low, long-term simulated groundwater level average. By contrast realization #16 has a relatively high, long-term simulated groundwater level average due to frequent recharge, but is subjected to infrequent recharge during the last 20 years. That a relatively "wet" realization (#16) has lower projected heads after 100 years with respect to realization #2 (a comparatively dry ensemble member), underscores the importance of evaluating unbiased, ensemble distributions over long-term periods.

The analysis of inter-arrival periods and groundwater cycles, also provide useful information about the associated risks related to projected pumping and occurrence of continuous baseflow interruptions. For example when basecase pumping rates are exceeded in either model area, the chances are very high that there will be at least one continuous, 5-year period without baseflow during any 100-year projection period. When the basecase pumping rate is increased by 1,600 AF/yr in the Micro-basin area, there is a 25% chance that there will be at least one continuous 20-year period without natural baseflow, assuming each realization is statistically independent. If the basecase pumping rate is increased by 8,000 AF/yr in the northern model area there is about a 3-out-4 chance that at least one, continuous 20-year period will occur without baseflow during a 100-year projection period.

5.0 Summary

Due to uncertain weather conditions and imperfect knowledge about the groundwater flow system, the evaluation of future groundwater flow conditions in the Santa Cruz AMA necessitates the use of a probabilistic model.

Because of the system complexity, hydrologic models were developed such that alternative water management strategies can be evaluated without being adversely compromised by model bias. Results indicate that combining the streamflow and groundwater models provides more useful, risk-based planning information than the independent simulation of either the stochastic streamflow model or the groundwater flow model: Not unlike the collective hydrologic system itself, the integrated system (model) is worth more than the sum of the individual parts.

5.1 Stochastic Model

Using available hydrologic information, alternative conceptual groundwater flow models (ACM) were developed using inverse modeling and trial-and-error techniques. The groundwater flow models were calibrated over diverse environmental (seasonal) conditions, including periods of extreme drought and flood.

To address future streamflow recharge uncertainty, the ADWR contracted the development of a stochastic streamflow model. The stochastic streamflow realizations were combined with plausible groundwater flow models to provide statistical information about the groundwater flow system as a function of basecase and hypothetical pumpage. Results show that the coupled, stochastic streamflow model and groundwater flow model are congruent, and provide results that approximate available observation data over basecase conditions. Predictive scenarios include basecase pumping conditions (recent average annual rates), as well as hypothetical scenarios in which the assigned pumpage was modified in proportion to basecase rates, at basecase well locations; thus, site-specific impacts were not evaluated, and cannot be inferred based on this regional-scale study.

Increasing pumpage results in an increased risk of capture associated with groundwater discharge. For purposes of this report, the primary hydrologic indicator of simulated water table elevations was based on the occurrence of net groundwater discharge along two intermittent reaches of the Santa Cruz River including between the NIWTP and Tubac and between the Highway 82 Bridge and Guevavi Narrows.

Evaluating the frequency of net groundwater discharge (gaining) conditions is a meaningful indicator of local water levels over seasonal periods. Relatively frequent, net gaining conditions along the stream are generally consistent with relatively high (long-term) groundwater levels, whereas infrequent net gaining conditions represent lower water levels over long-term periods.

With respect to site-specific locations, assessing net groundwater discharge patterns over broader areas is assumed to result in errors that are more randomly distributed, and are not as prone to site-specific discrepancies between real-world and simulated pumping schedules. Evaluating simulated groundwater discharge also provides a measure to quantify the hydrologic impacts of low magnitude, widespread pumpage where subtle long-term groundwater level trends (i.e., hydraulic gradients) might not be clearly identified using site-specific head data.

Model results indicate that the frequency-of-occurrence of gaining conditions is a function of stream recharge, alternative model conceptualization and groundwater pumpage.

5.2 Northern Santa Cruz Model

For the northern model area, when the basecase pumping rate of 15,000 AF/yr was applied to the 100X6 ensemble, gaining conditions occurred on average in about 43% of the 100 simulation years. These results are reasonably consistent with observation data over basecase pumping conditions. When the pumpage was increased to 17,000 AF/yr, 19,000 AF/yr, 21,000 AF/yr and 23,000 AF/yr the gaining conditions occurred on average about 33%, 25%, 17% and 12% of the time, respectfully. When the system pumping rate was reduced below the basecase rate to 13,000 AF/yr, groundwater discharge occurred more often than not (55%). However the risk-based distributions suggest that fewer occurrences of groundwater discharge could also occur with lower pumping rates. For example over basecase conditions (15,000 AF/yr), there is a 3-out-of-4 chance that fewer than half (50) of the simulated years will experience gaining conditions during the 100-year period. However, when the pumping is reduced to 13,000 AF/yr, there is still a 30% chance that this condition will occur. When basecase conditions are applied in the northern model area, it is very rare to have periods of 20 years without a single occurrence of baseflow (net gain). However when the basecase pumpage is increased by 40% (21,000 AF/yr) in the northern model area, there is a 60% chance that baseflow will be interrupted for periods of at least 20 years.

5.3 Micro-Basin Santa Cruz Model

For the Micro-basin area when the basecase pumping rate of 2,700 AF/yr was applied to the 100 realization ensemble, gaining conditions occurred on average in about 48% of the 100 simulation years. These results are reasonably consistent with observation data for basecase conditions. When the pumpage was increased to 3,300 AF/yr, 3,800 AF/yr and 4,300 AF/yr the gaining conditions occurred on average in 35%, 26% and 20% of the 100 simulation years, respectfully. When the system pumping rate was reduced below the basecase rate to 2,300 AF/yr, groundwater discharge occurred in 60% of the simulation years. When basecase conditions (uniform pumpage) are applied in the Micro-basin area, it is very rare to have periods of 20 years or more, without a single occurrence of baseflow (net gain) for the Micro-basin area. When the basecase pumpage is increased by 40%, there is about an 8% chance that baseflow will be interrupted for periods of at least 20 years. These results suggest that the Micro-basins respond quicker to natural recharge than the northern area.

5.4 Recommendations

Hydrologic model development was based on the most recent information available at the time of this writing. However as additional information becomes available in the future, the hydrologic models should be refined accordingly. This may involve the addition, elimination or re-weighting of ACM's, modifications of lateral boundary condition assumptions, and/or the refinement of the stochastic streamflow model. The simulation process has been automated, and most ACM modifications can be incorporated into an ensemble, due to the modular structure of the hydrologic model.

5.5 Conclusion

The Arizona Department of Water Resources has been developing modeling tools to help evaluate the complex hydrologic conditions in portions of the Santa Cruz AMA. These modeling tools were built to test alternative water management strategies, and can help quantify risks associated with hydrologic impacts. Some hypothetical pumping scenarios were tested and results indicate that groundwater flow is sensitive to different factors including: 1) streamflow recharge patterns (i.e., flood recharge periods; drought periods, etc.) 2) the conceptualization of the groundwater flow system; 3) assigned boundary conditions (i.e., ET; seasonality; etc.); treatment of the southern and/or northern lateral head-dependant boundaries, etc.), and 4) the rate of assigned (projected) groundwater pumpage. Accordingly, different combinations of the above-listed factors can be further tested to provide valuable, probabilistic information. For example given the same long-term assigned pumping rate some 1) projected pumping locations may yield a lower risk of baseflow capture than other locations; and/or 2) for a given area there may be certain pumping schedules (i.e., seasonal verses uniform) which yield a lower risk of baseflow capture than other pumping patterns. As opposed to providing an exact solution 100 years into the future, these risk-based modeling tools provide a more complete and honest picture of future hydrologic impacts.

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Appendix A

Conversion of Streamflow Realizations to

Stream-Aquifer Boundaries

Appendix A: Conversion of Streamflow Realizations to Stream-Aquifer Boundaries

Conversion factors for the (stochastic) surface water flow rate to stream-aquifer boundaries are different for the northern Santa Cruz and Micro-basin models. This difference is due to distinct calibration criteria including, 1) stream recharge response time; 2) boundary condition affects; 3) system hydraulics; 4) stress-period interval; 5) magnitude of streamflow event and 6) model-cell resolution. Note that the Santa Cruz River watershed at Tubac is approximately 2.3-times larger than at the Nogales gauge. It has been assumed that during significant high flow periods (relatively rare events) surface water flow rates are 2.3 times greater in the northern model area, than in the Micro-basin area.

Apart from assigned pumpage, the most sensitive model parameters include the conceptual groundwater flow model and the relative interval-arrival period trends (i.e., "wet" periods verse "dry" period), as defined by the stochastic streamflow model. As long as the *general* streamflow trends in the stochastic model are statistically represented in the stream-aquifer boundary conversion, the *specific* conversion factors are not sensitive over long-term periods. (Note that surface water flow rates measured during high flow periods have a relatively high degree of uncertainty, compared to low-flow (baseflow) periods; therefore the actual rate of streamflow recorded during flood events are never known with high precision anyway.) During a limited sensitivity analysis, modest changes to the stream-aquifer conversion factors including streambed stage, width and conductivity were found to be relatively insensitive. This result is due to the finite stream recharge potential (i.e., regulating effect of stream boundary) for large flow events greater than 75 cfs/month. Thus, excess (runoff) streamflow implies that the exact value of surface water inflow is not critical to the simulation process; only the relative magnitude is important.

The insensitivity of modest changes to the stream-aquifer conversion factors is also seen when comparing estimated parameter results between the base model and Manning's ACM. **Table A.1** shows little difference between estimate parameters for different stream-aquifer boundaries, suggesting that modest changes in stream-aquifer conversion factors are not that sensitive over long-term periods. Of all the ACM's tested, Manning's solution (i.e., where stream-aquifer boundary was different from all other ACM's) is the most similar to the base model over steady and transient periods. In fact sensitivity analysis results suggest that the different ACM's were more sensitive over long-term periods than the modest variations in the streamflow-to-stream-aquifer boundary conversion process. Thus, coarse conversion factors were assigned for the northern model.

Stream-Aquifer Boundary Parameters and Conversion Factors: Northern Santa Cruz AMA Model				
HRC Flow monthly mean streamflow at Nogales in cfs (% of occurrence)	**[1]Conversion Multiplier for flow at Segment #1**	**Streambed width (feet)**	**Streambed Kz (Feet/day)**	**Assigned Stage above streambed top or [2]Apply Manning's N Option (feet)**
Monthly-based Monsoon Stress Periods: July (31 d), August (31 d) and September (30 d)				
>400 (0.05%)	2.3	200 *150*	3.0	4.5 *3.0*
300-400 (.63%)	2.3	150 *125*	3.0	4.0 *3.0*
200-300 (0.9%)	2.3	150 *100*	3.0	3.5 *2.5*
150-200 (1.7%)	2.3	125 *90*	3.0	3.0 *2.5*
100-150 (1.7%)	2.3	100 *80*	3.0	3.0 *2.5*
75-100 (2.3%)	2.3	70 *60*	3.0	3.0 *2.5*
50-75 (1.5%)	1.0	60 *55*	3.0	2.5 *2.0*
35-50 (3.5%)	1.0	45 *45*	2.0	2.0 *2.0*
20-35 (4.5%)	1.0	25 *25*	2.0	1.5 *1.5*
10-20 (8.1%)	1.0	25 *25*	2.0	1.0 *1.0*
<10 (0.25%)	1.0	20 *20*	2.0	0.5 *0.5*
Seasonally-based Stress Periods: Fall (Oct.-Nov., 61 d); winter (Dec.-Jan., 62 d); spring (Feb.-April , 89 d); and early summer May-June (61 d)				
>200 (2.6%)	2.3	150 *150*	3.0	3.5 *2.5*
150-200 (0.9%)	2.3	125 *125*	3.0	3.0 *2.5*
100-150 (0.32%)	2.3	100 *100*	3.0	3.0 *2.5*
75-100 (0.55%)	2.3	70 *60*	3.0	2.5 *2.5*
50-75 (0.61%)	1.0	60 *55*	3.0	2.5 *2.0*
35-50 (1.9%)	1.0	45 *45*	2.0	2.0 *2.0*
20-35 (9.7%)	1.0	25 *25*	2.0	1.5 *1.5*
10-20 (40%)	1.0	20 *20*	2.0	1.0 *1.0*
<10 (18%)	1.0	20 *20*	2.0	0.5 *0.5*

Assigned parameters for stream segments downstream from segment 15in italics. **The stream-aquifer parameters were calibrated for seasonal stress-periods, not individual events. Assignment of stream-aquifer parameters herein account for hydraulic features such as bank storage during high flow periods, embedded within seasonal or monthly time scales. [1]For significant flow events (>75 cfs/stress period), the assigned streamflow rate at segment #1 was increased by a factor of 2.3, to account for additional streamflow contributions from the Nogales Wash, Sonoita Creek, etc. Streamflow is also added at segment #12 (HRC multiplier X0.5), north of Tubac, for downstream contributions. [2]Stages apply's when Manning's N option is not used. When Manning's N option is applied: Stage depth (feet) = $((Q*n)/(C*w*S^{1/2}))^{3/5}$, where Q is in cfs, Manning's n = 0.04 (dimensionless), c is a unit conversion constant (to cfs), w is channel width (ft), S is slope in ft/ft. A sensitivity analysis was conducted for streambed width following the relation, W = $6.62Q^{0.508}$, R^2 = 0.907 (see Nelson, 2007). As with stream stage, this parameter was not sensitive to modest changes over long-term periods.**

Table A.1 Conversion Factors for Stream-aquifer Boundary: Northern Model

Note that seepage data collected along the effluent-dominated portion of the stream shows that the vertical streambed conductivity (strm_Kz) is lower along losing reaches than along gaining reaches, during baseflow periods. The clogging layer is especially pronounced 1) during extended periods without floor scour; 2) along reaches where the depth-to-water is significant; and 3) along reaches closer to the NIWTP outflow point, where the organic constituents associated with effluent have their highest concentration.

During calibration, strm_Kz can be adjusted to historical conditions, accordingly. For projective purposes, however, it is difficult to anticipate gaining and losing reaches in advance. Therefore an interactive stream-aquifer boundary that automatically adjusts strm_Kz, based on either gaining or losing conditions, maybe required for future simulations involving effluent released along the stream. The ADWR has inquired about potentially modifying the stream-aquifer boundary for special conditions involving effluent (Prudic, 2008). (Note that released effluent from the NIWTP has promoted riparian growth and has, to an extent, offset gains associated with effluent recharge. In April 2009 the NIWTP was upgraded. At the time of this writing, it unclear how infiltration rates have been affected due to the plant upgrade.)

Along non-effluent portions of the Santa Cruz River and major tributaries including the Micro-basin portion of the Santa Cruz River, Sonoita Creek and Peck Canyon, high infiltration rates have been observed along losing reaches. It is assumed that without the release of effluent, the formation of clogging layer results in negligible impacts on infiltration.

Regardless of whether effluent is included in the simulation or not, the system has historically tended towards long-term dynamic (cyclic) equilibrium conditions, where groundwater levels fluctuate about long-term, mean elevations. Note that relatively low groundwater level elevations, recorded in the 1950s, rebounded significantly by the mid 1960's due to natural recharge, prior to the release of effluent. Furthermore despite the continuous release of effluent, water tables generally declined during the recent dry period (2001-2006). These results indicate that the temporal variability of natural stream recharge is a very important factor in the hydrologic system of the upper Santa Cruz River Valley.

Figure A.1 shows hydraulic relations between simulated head, the state of the system (i.e., losing) and streambed conductance. The figure visually depicts the mathematical relationships between various features of the system including streambed parameters and the CSTR coefficient, simulated head elevation as well as 1) gaining, 2) losing and 3) hydro-static conditions/reaches.

Micro-Basin Model

Monthly streamflow rates from the HRC model were converted to stream-aquifer boundary parameters for the Micro-basin model as follows: Streambed width = $7.65 \cdot Q^{0.4722}$, $R^2 = 0.86$, where Q is in units of cfs. All streambed Kz values are equal to 2.0 ft/day. Stage discharge conversion factors are provided in **Table A.2** below. Also see Erwin (2007).

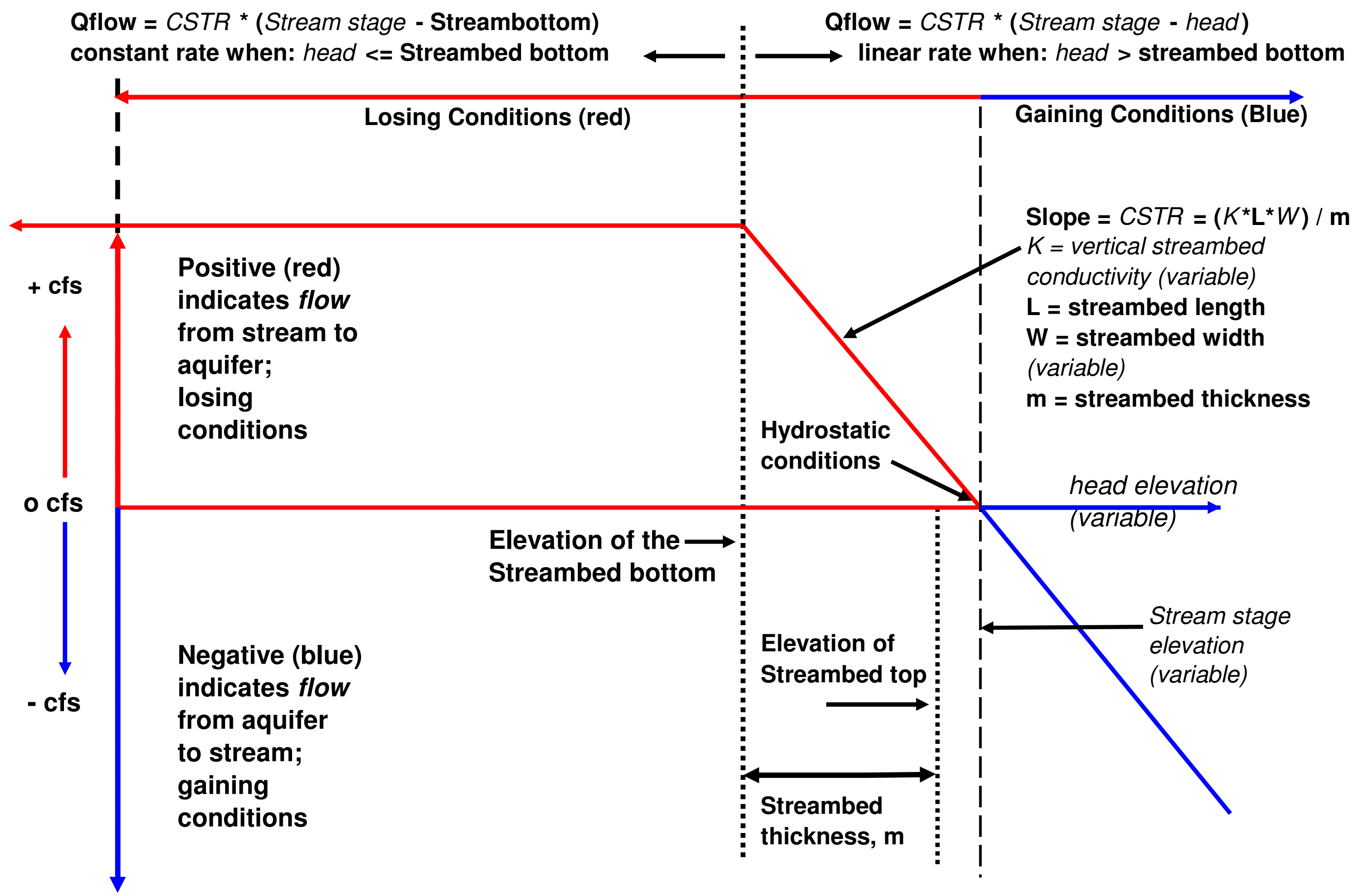

Figure A.1 Stream-Aquifer Boundary: Relations between 1) simulated head; 2) gaining and losing flow conditions; and 3) stream-aquifer parameters. Figure modified from Figure 3 in Prudic (1989).

Stream-Aquifer Boundary Stage: Micro-Basin Model	
HRC Flow (monthly mean in cfs)	Assigned Stage above streambed top (feet)
< 1	0.5
< 20	1.0
< 90	1.5
< 1,000	2.0
< 3,000	3.0

Table A.2 Conversion factors for Stage-Discharge Relation: Micro-basin Model

Appendix B:

Statistical Evaluation of Groundwater Discharge

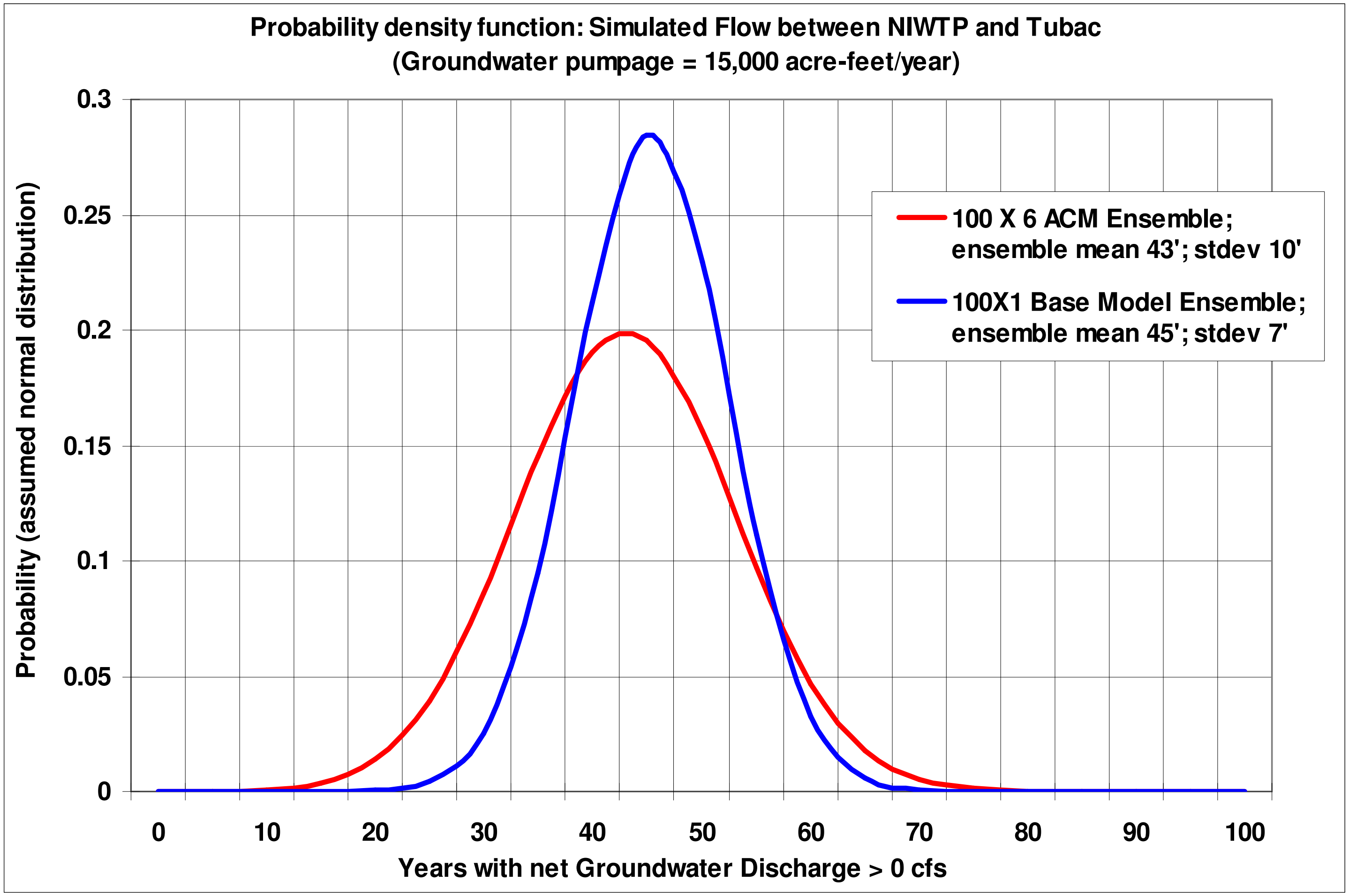

Figure B.1 Comparison of normal PDF for the 100X1 Base model, and the 100X6 ACM Ensembles: Northern Santa Cruz Model, basecase pumpage (15,000 AF/yr)

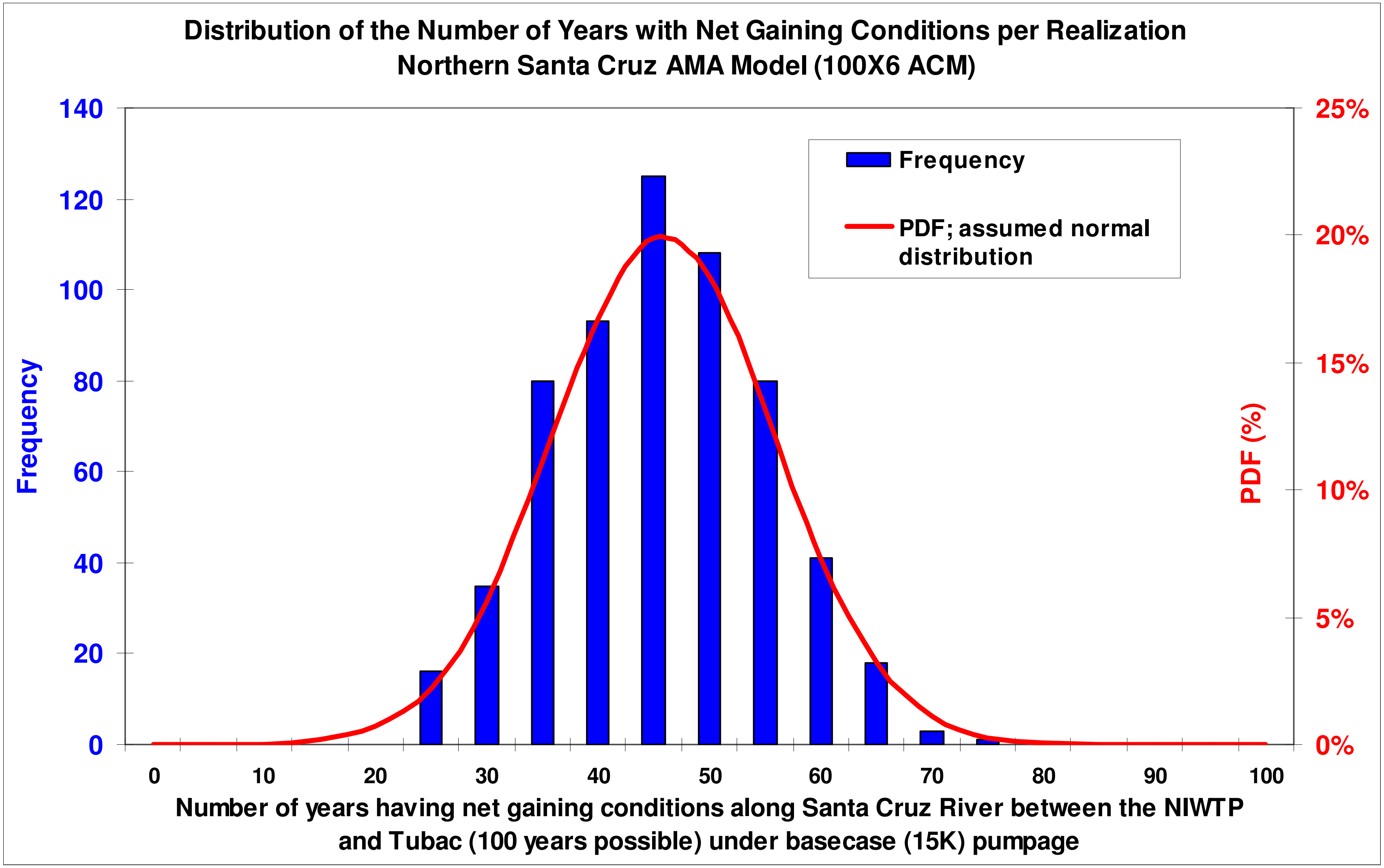

Figure B.2 Distribution of Years with Net Gaining Conditions, Northern Model area

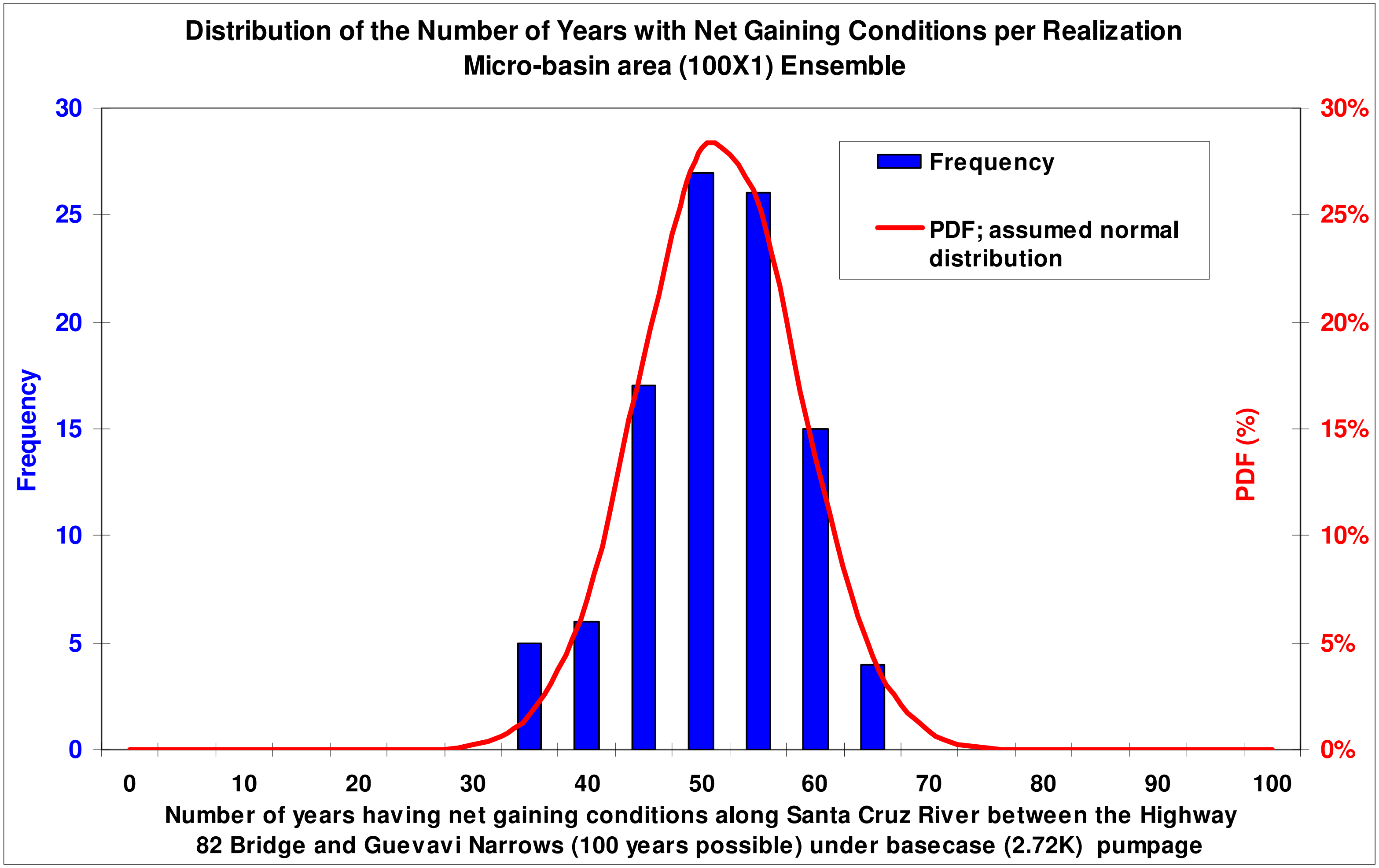

Figure B.3 Distribution of Years with Net Gaining Conditions, Micro-basin area

Note that for both the Micro-basin and Northern model, the 1-year continuous time interval between baseflow periods for the higher-demand ensembles (i.e., 19K AF/yr and 3.8K AF/yr), has a lower frequency-of-occurrence rate, than the lower-demand (15K AF/yr) ensembles (**Figure B.4 and Figure B.5**). This result suggests that higher rates of pumpage lead to fewer short-term (1 year or less) intervals without baseflow, at the expense of more frequent long-term (>1 year) periods without baseflow.

For the northern model area (**Figure B.4**), note that the frequency (F), as a function of time-period between net-gaining years (P), follows a near-exponential distribution when P is greater than 3. For example with respect to P, the frequency (F) for the basecase (15K AF/yr) ensemble approximates, $F = 7{,}170e^{(-0.174*P)}$. When the pumpage is increased to 19K AF/yr the relation between F and P approximates, $F = 8{,}960e^{(-0.3*P)}$.

For the Micro-basin area (**Figure B.5**), the relation between F and P also approximates an exponential distribution; however smaller sample sizes combined faster groundwater level recovery periods are assumed to degrade the exponential distribution patterns for longer-duration periods, i.e., P >10 years. Furthermore, deviations from true exponential distributions are also assumed to exist because of the univariate distributions employed, along with the exponential distributions, in the stochastic re-sampling schemes. See Shamir et al, 2005.

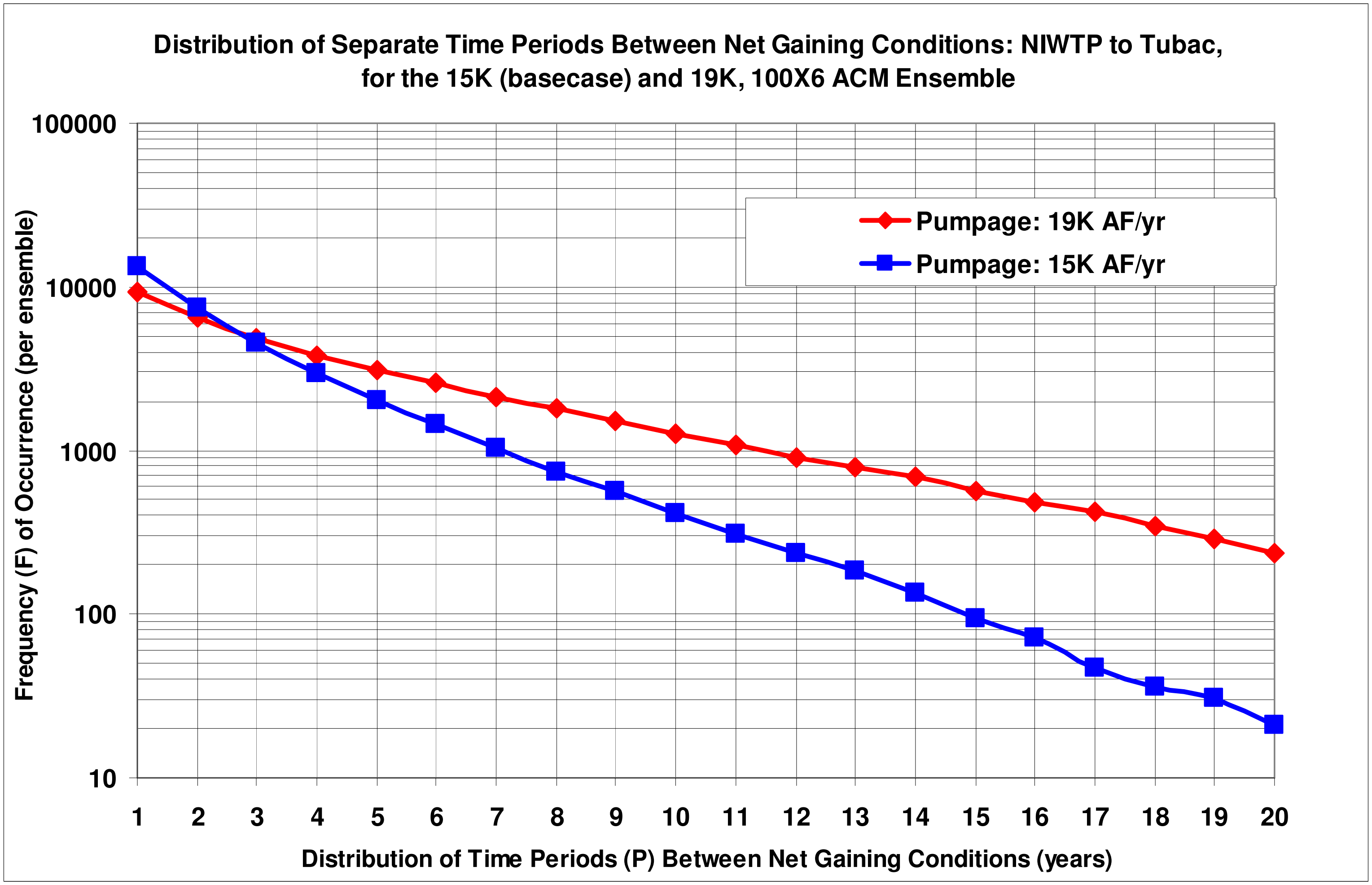

Figure B.4 Distribution of Continuous Time Intervals between Baseflow Periods, Northern Model Area; 600-realizations per ensemble.

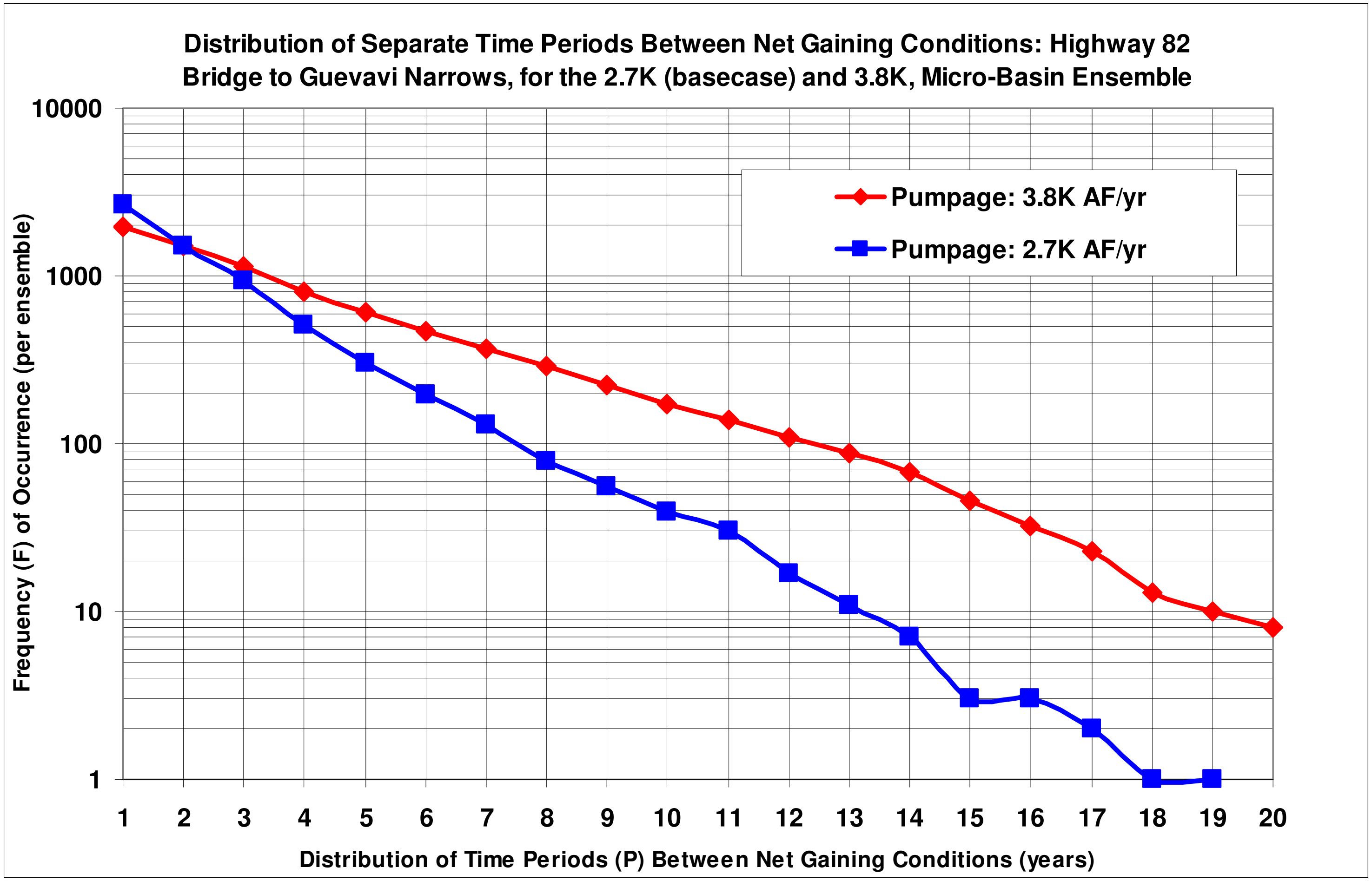

Figure B.5 Distribution of Continuous Time Intervals between Baseflow Periods, Micro-basin area; 100-realizations per ensemble.

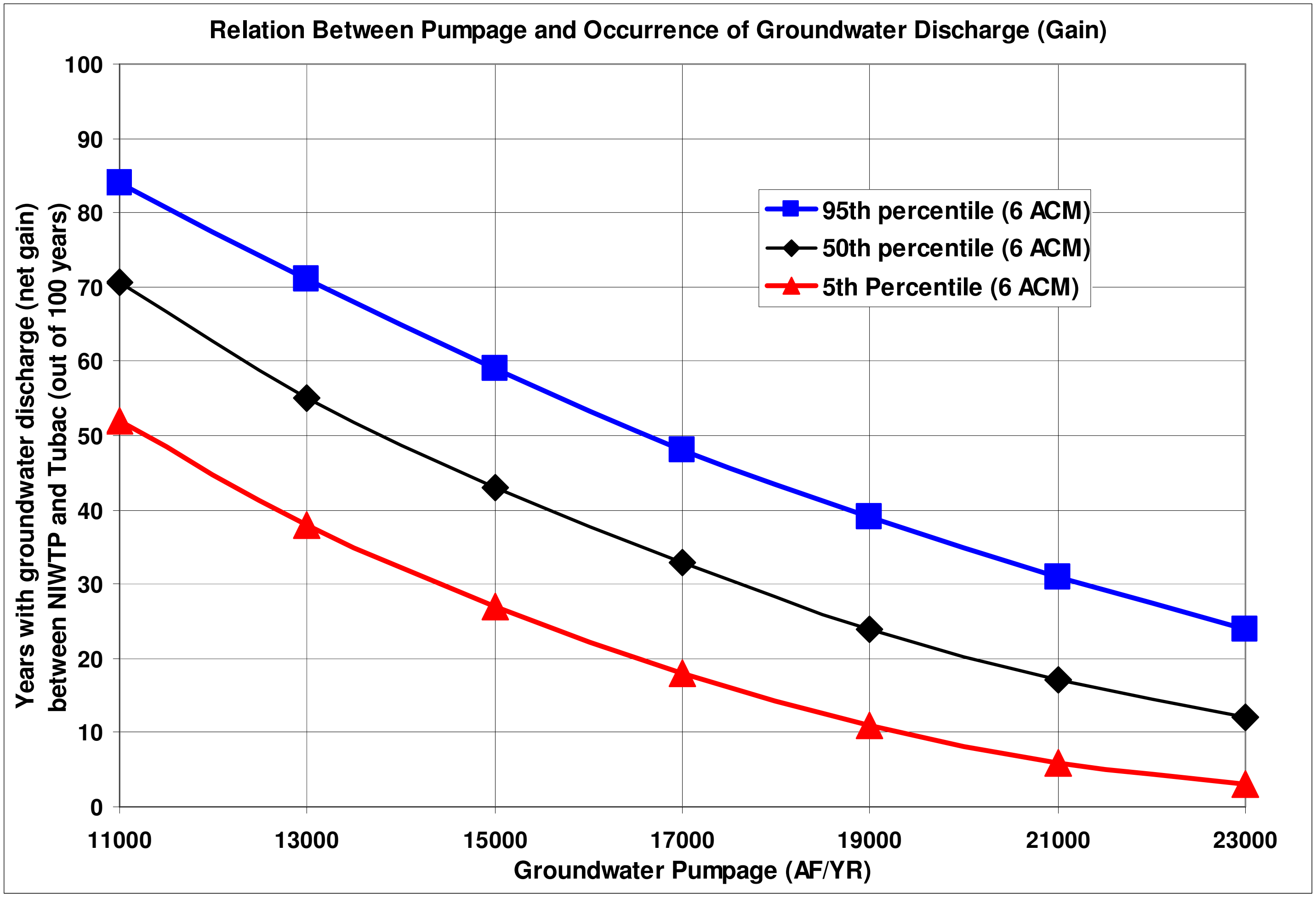

Figure B.6 Relation Between Pumpage and Occurrence of Groundwater Discharge (Net Gain) along the Santa Cruz River in the Northern Santa Cruz AMA (100 projected years)

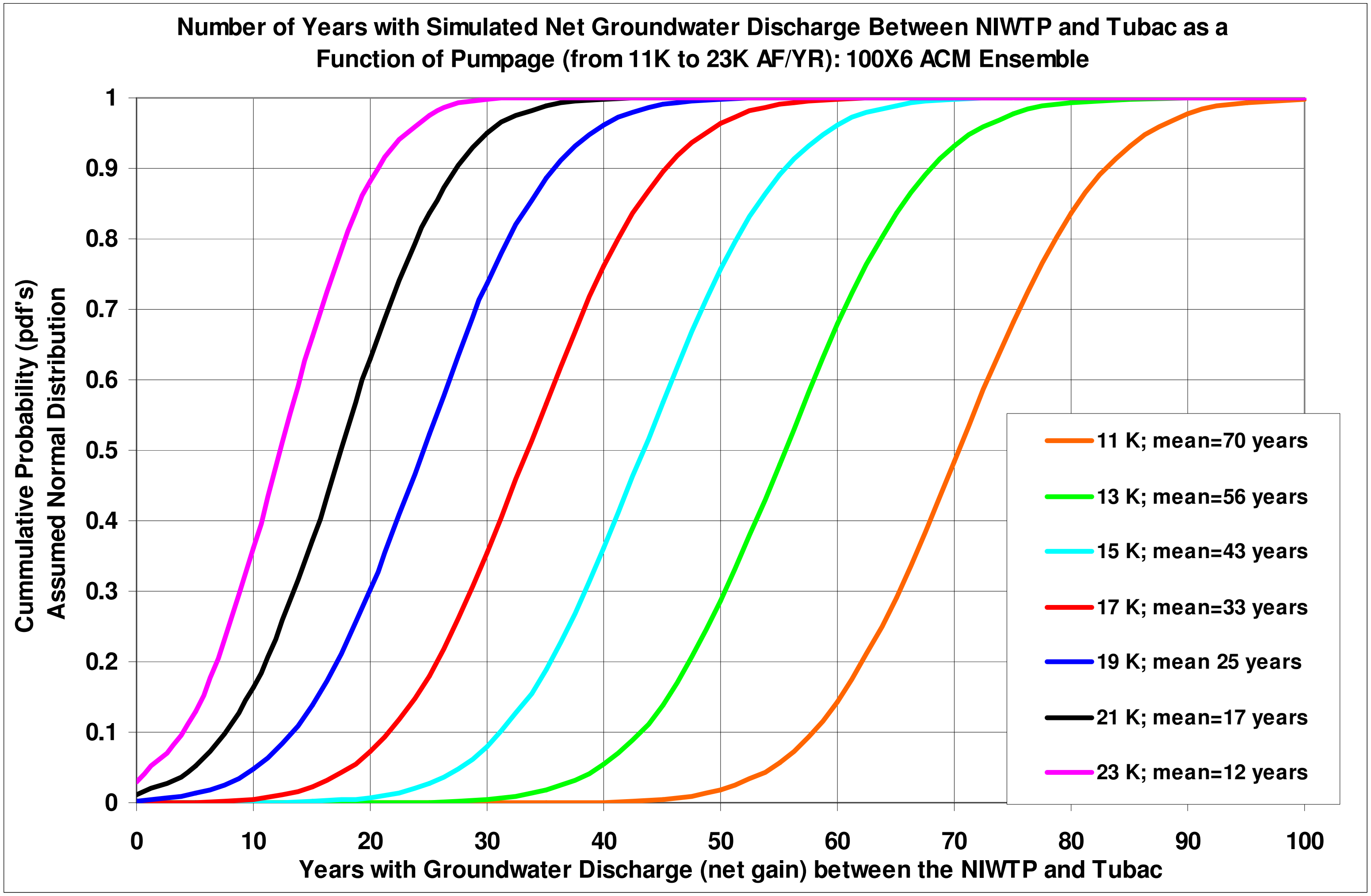

Figure B.7 Cumulative Normal PDF for the Number of Gaining Years (out of 100) as a Function of Pumpage, Northern Santa Cruz Model

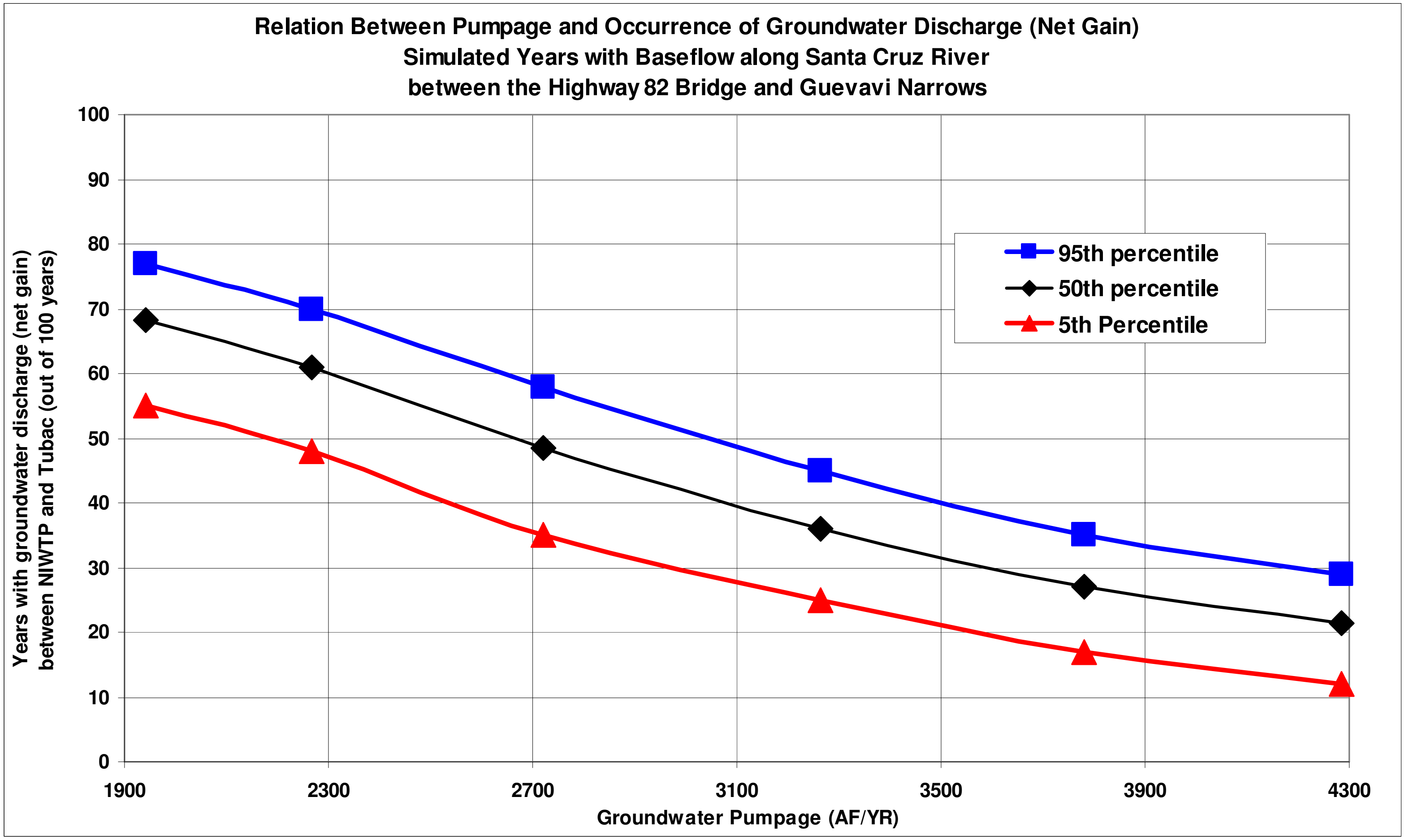

Figure B.8 Relation Between Pumpage and Occurrence of Groundwater Discharge (Net Gain) along the Santa Cruz River between Highway 82 Bridge and Guevavi Narrows (100 projected years)

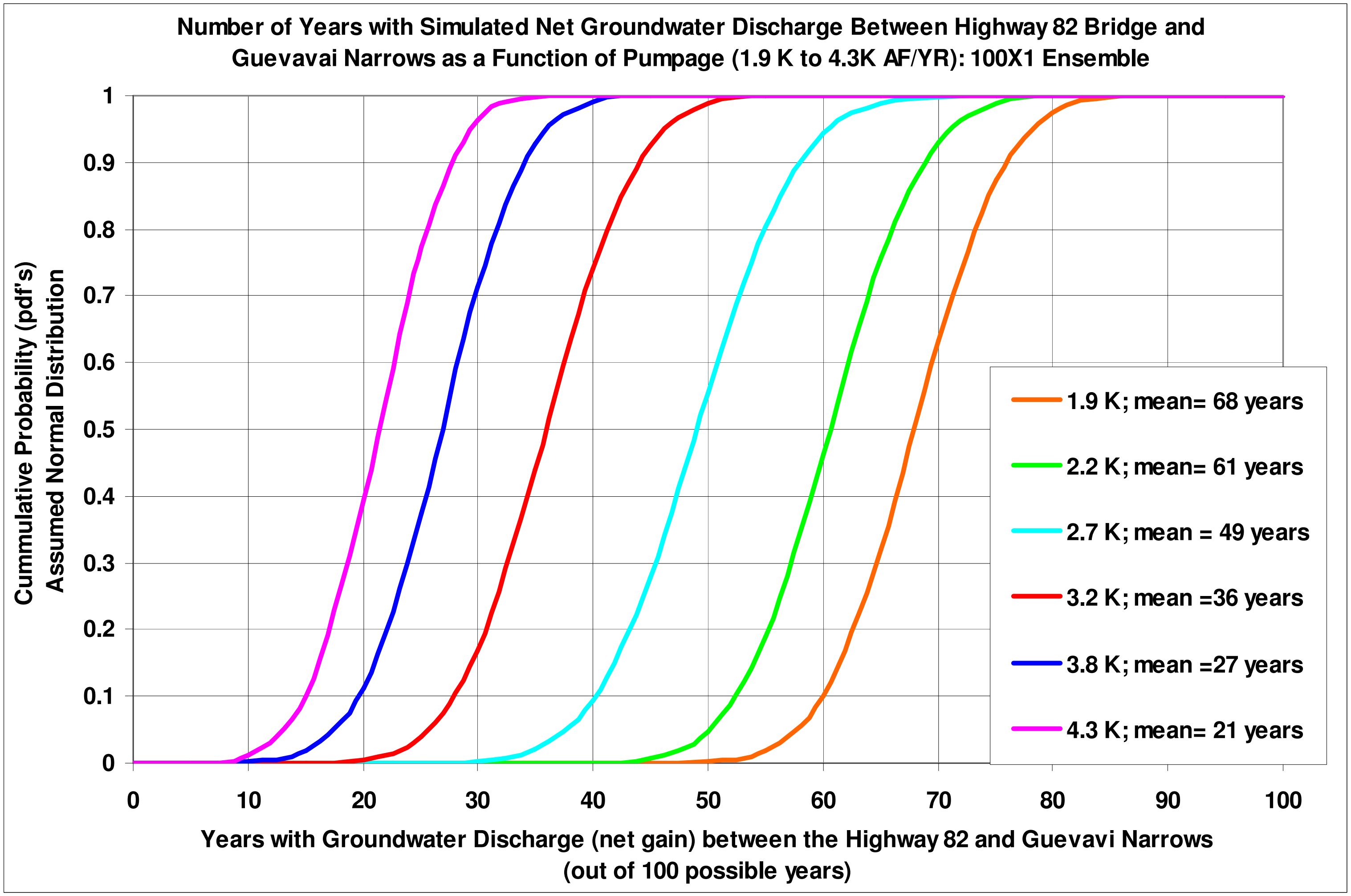

Figure B.9 Cumulative Normal PDF for the Number of Gaining Years (out of 100) as a Function of Pumpage, Micro-Basin Model.

Appendix C

Modifications to the Micro-basin Model

The Micro-basin model (Erwin, 2007) was modified to allow higher rates of groundwater flow in the sub-surface layers beneath layer 1 (i.e., the Yal unit). The modification facilitates simulated head declines in the absence of streamflow (i.e., stream recharge) and realistic groundwater level recoveries during simulated recharge periods, consistent with field data. The modification also represents groundwater discharge patterns consistent with those observed at Guevavi Narrows. Modifications to the Micro-basin include the addition of the Mod_KZone_1, Mod_KZone_2 and Mod_KZone_3 in model layers 2 and 3 (**Figure C-1** and **Figure C-2**).

Based on the simulation results of the re-conceptualized Micro-basin model, geophysical surveys and exploratory well-drilling activities are being conducted by the City of Nogales, the USGS and the University of Arizona, at the time of this writing. Provisional results of the well-log and geophysical data independently show unconsolidated sediments and loose alluvium at significant depth (at least 300 feet in depth) in the Guevavi and Santa Fe Ranch areas (personal communication with Greg Hess of Clear Creek Associates; and James Callegary of the USGS, April, 2010). These findings are consistent with the modification of the Micro-basin model. Currently, Mod_KZone_1, Mod_KZone_2 and Mod_KZone_3 are defined as narrow (~one cell width) high-K zones. However there may be alternative configurations of Mod_KZone_1, Mod_KZone_2 and Mod_KZone_3 (see Figures C-1 and C-2 below) that produce similarly-viable solutions in the Micro-basin area. For example, similar groundwater flow solutions may be produced by assigning more moderate K-values in combination with broader, cell extents. Regardless of the specific K-zone configuration in the Micro-basins, both the model results and field data suggest that the subsurface flow beneath the Yal is higher than previously assumed.

Other modifications to the Micro-basin model include the addition of constant head boundaries (CHB), such that the CHB head elevations increase linearly from 3,760 ft (column 57) to 3,850 ft (column 68) in layers 2 and 3. Regarding the outflow boundaries, general head boundary (GHB) external elevations (green cells) were unmodified from Erwin (2007), and thus retained at 3,448 ft for layers 1, 2 and 3 for along column 1, rows 18-20 (**Figure C-3**). In reality, however, groundwater levels associated with this area can fluctuate significantly. Therefore future evaluations of groundwater flow conditions *in the northern portion of the Micro-basin area* may need to modify the northern model boundary to accommodate these changes, accordingly. Note that the external GHB conductance for layer 3 was increased to 1.74E5 ft^2/day, for consistency with Mod_KZone_3. No other modifications were made to the Micro-basin model.

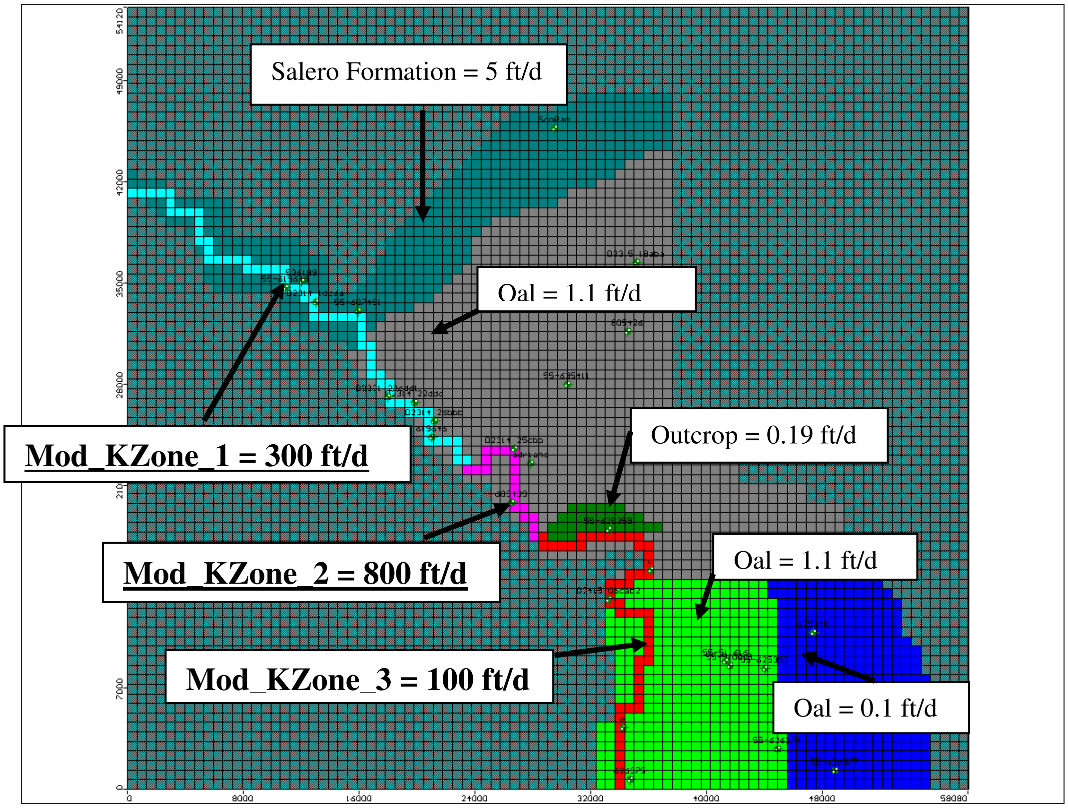

Figure C-1: Layer 2 Modifications to the Micro-basin Model. Modified K-zone include: Mod_KZone_1, Mod_KZone_2 and Mod_KZone_3. Model cell scale is 660 ft X 660 ft.

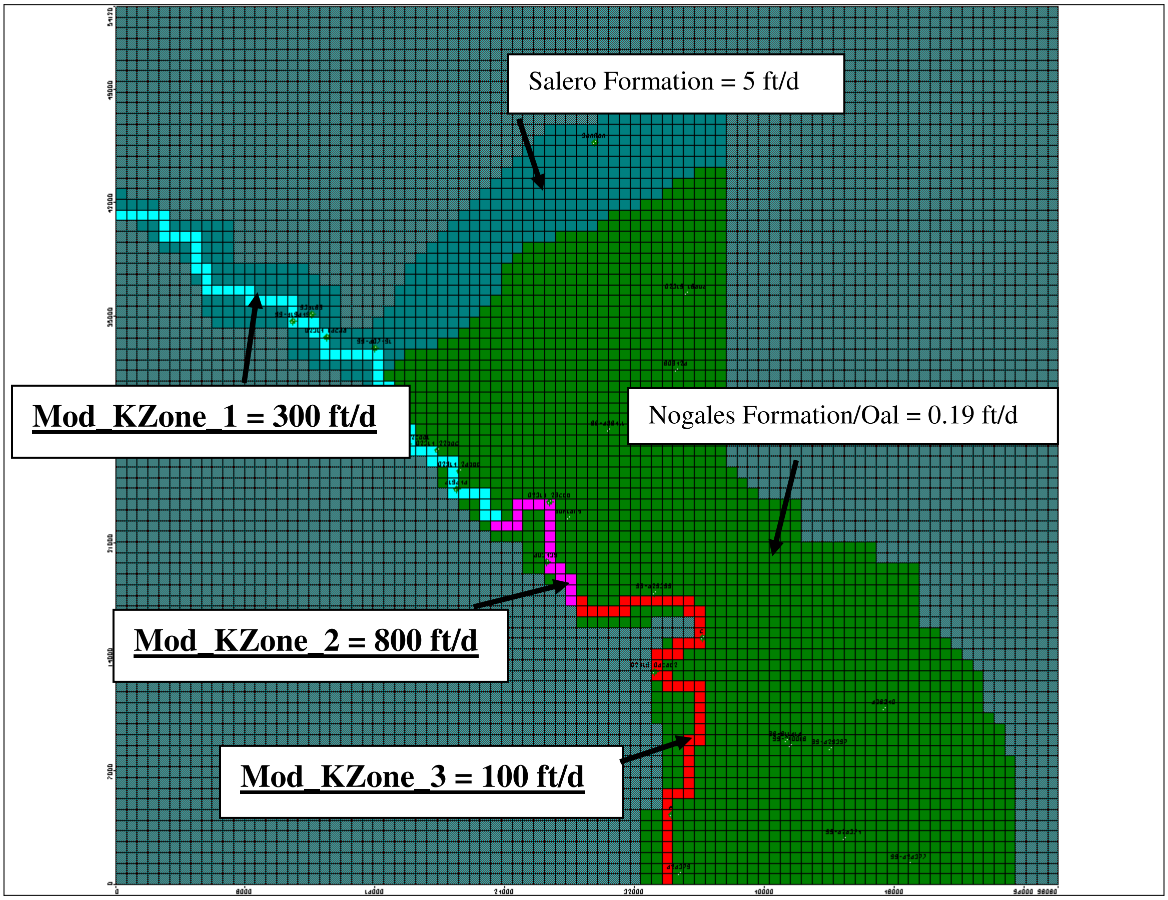

Figure C-2: Layer 3 Modifications to the Micro-basin Model. Modified K-zone include: Mod_KZone_1, Mod_KZone_2 and Mod_KZone_3. Model cell scale is 660 ft X 660 ft

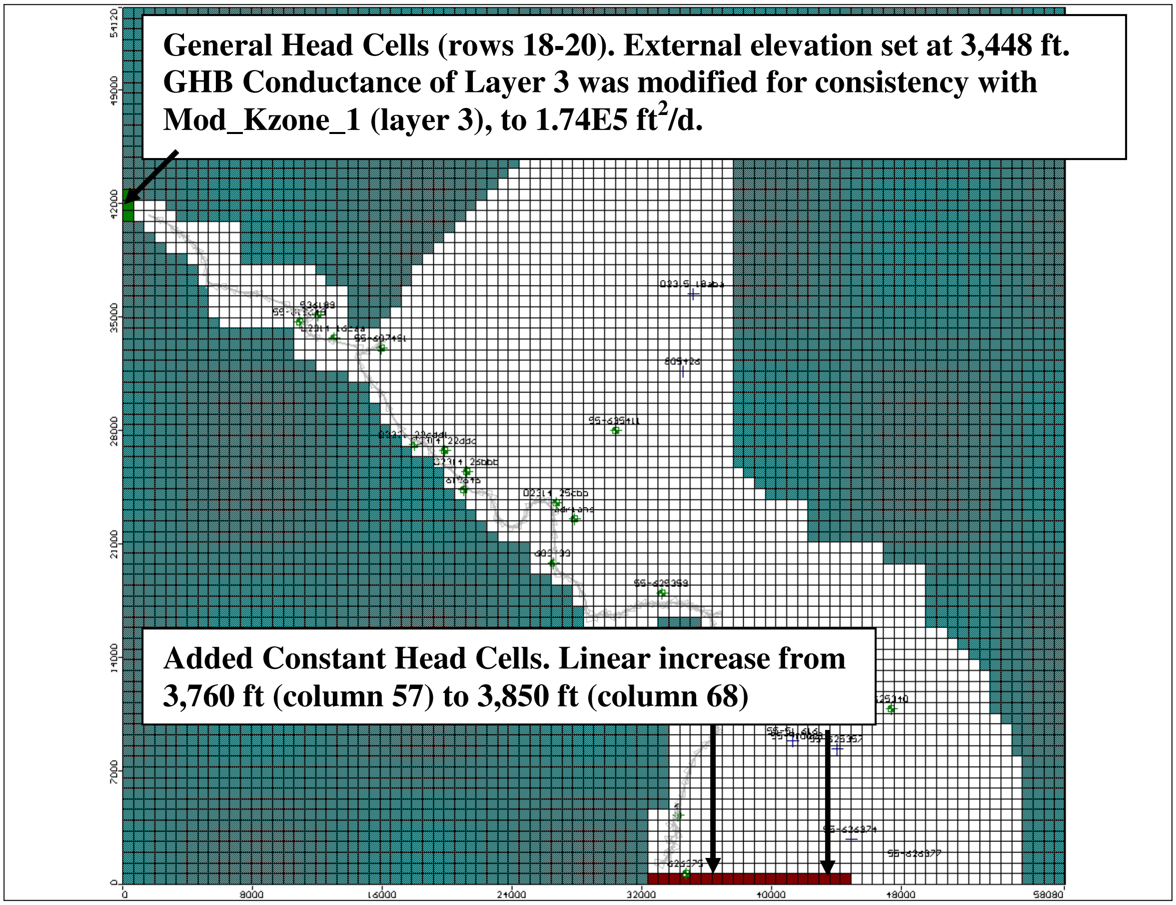

Figure C-3: Modified Lateral Head-dependent Boundaries assigned in Micro-basin model. Model cell scale is 660 feet X 660 feet

Appendix D

Frequency Spectrum of Time Series

Simulated Groundwater Levels

The simulated heads shown in **Section 3** depict complex modulations comprised of many different forcing signals including consistent annual cycles (seasonal-based ET and pumping patterns; monsoon recharge), as well as longer cycles associated with less frequent major flood recharge events (El Nino periods) or drought periods. However it is difficult to understand the embedded cycles when evaluating the raw simulated head data alone.

Transformation from the time-to-frequency domain allows the different signals to be discerned and quantified along the frequency domain. **Figure D.1** through **Figure D.6** show periograms for realizations 2 and 16 at Tumacacori (northern model) and in the Highway 82 Micro-basin at the Santa Fe well (Micro-basin model). With respect to frequency, the periodograms represent power spectral density, $S(e^{jw})$, estimates given by:

$$S(e^{j\omega}) = \frac{1}{2\pi N} \left| \sum_{n=1}^{N} x_n e^{-j\omega n} \right|^2$$

where j is $\sqrt{-1}$, ω is in units of radians/sample, e is the base of the natural logarithm, and (x_1, ..., x_N) is the time-series sequence, i.e., simulated heads over time. Note that frequencies showing significant spectral-density signatures represent influential cycles associated with the raw, time-series data. For more information about MATLAB periodograms (smoothing, etc.) and references about discrete Fourier transformation (etc.), see: http://www.mathworks.com/access/helpdesk/help/toolbox/signal/periodogram.html.

Northern Model Area: For the Tumacacori site, influential signals include the annual cycle (2.7E-3 cycles/day), as well as cycles that generally last 5-years (<0.55E-3 cycles/day) and longer. Noise characterizes the spectrum outside these dominant frequencies. It is assumed that groundwater stresses (pumping; ET, flood recharge, etc.), boundary conditions and aquifer parameters interfere with one another and largely prevent the generating of periodic cycles between one and five years.

Micro-Basin Area: When applying uniform pumpage, the smaller Micro-basin aquifers show similar signals to that observed at the Tumacacori site. However simulated groundwater levels in the Micro-basin area also reveal prominent cycles near the 2.5 year period (i.e., 1E-3 cycles/day) that *may* be associated with the storage buffering capacity of the Highway 82

Micro-basin. **Figure D.3**, **Figure D.5** and **Figure D.6** show how applying pumpage - either based on uniform or seasonal distributions - affect the annualized groundwater cycle: Note how the seasonal, winter-dominated-pumping scenario attenuates the annualized cycle, whereas the seasonal, summer-dominated-pumping scenario accentuates the annualized cycle.

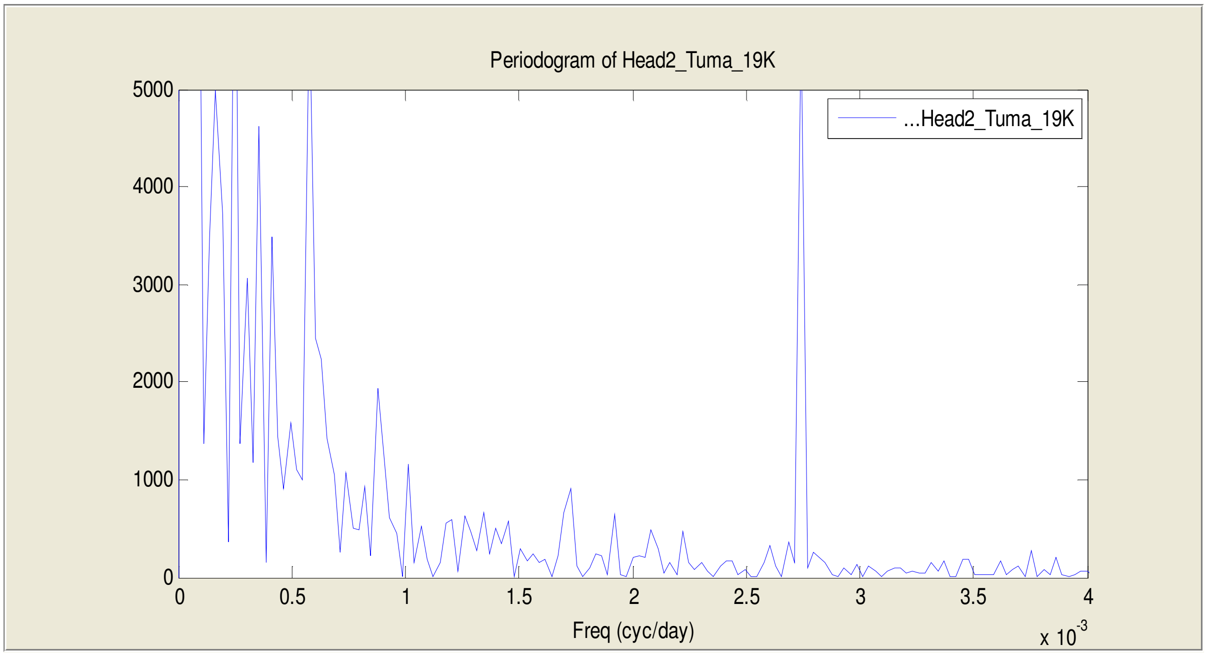

Figure D.1 Spectral plot of Realization #2 ("dry") at Tumacacori (19K)

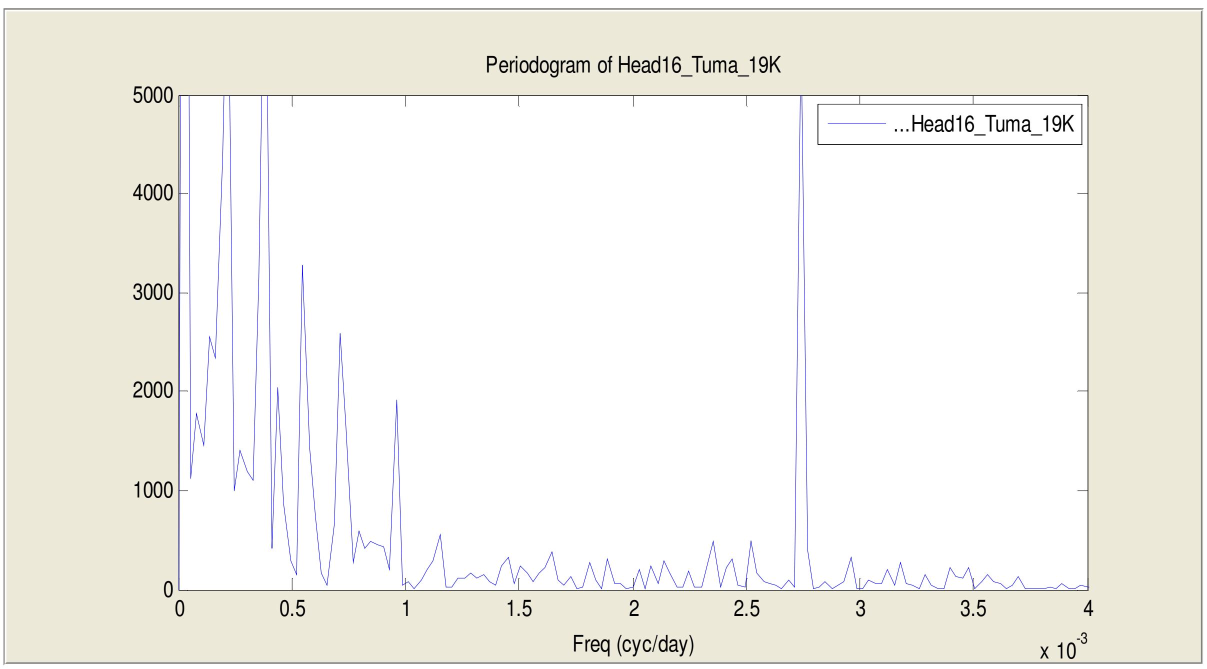

Figure D.2 Spectral plot of Realization #16 ("wet") at Tumacacori (19K)

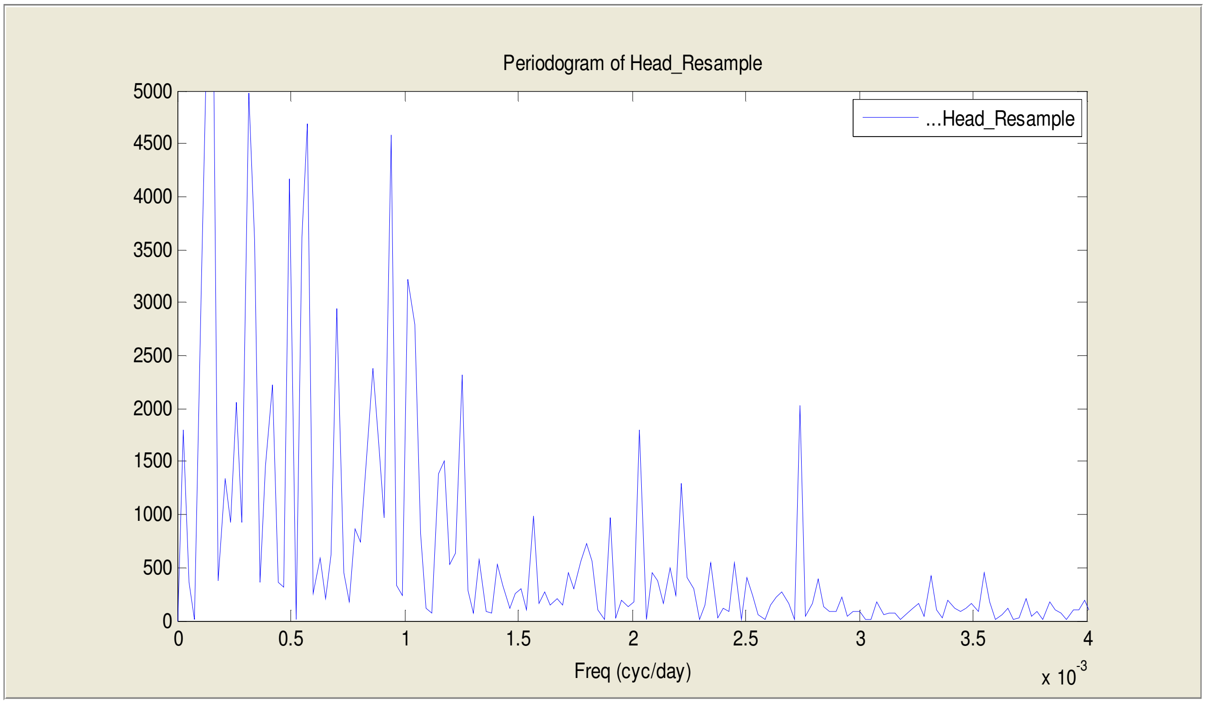

Figure D.3 Spectral Plot of Realization #2 at Santa Fe well (uniform pumpage 2.7K)

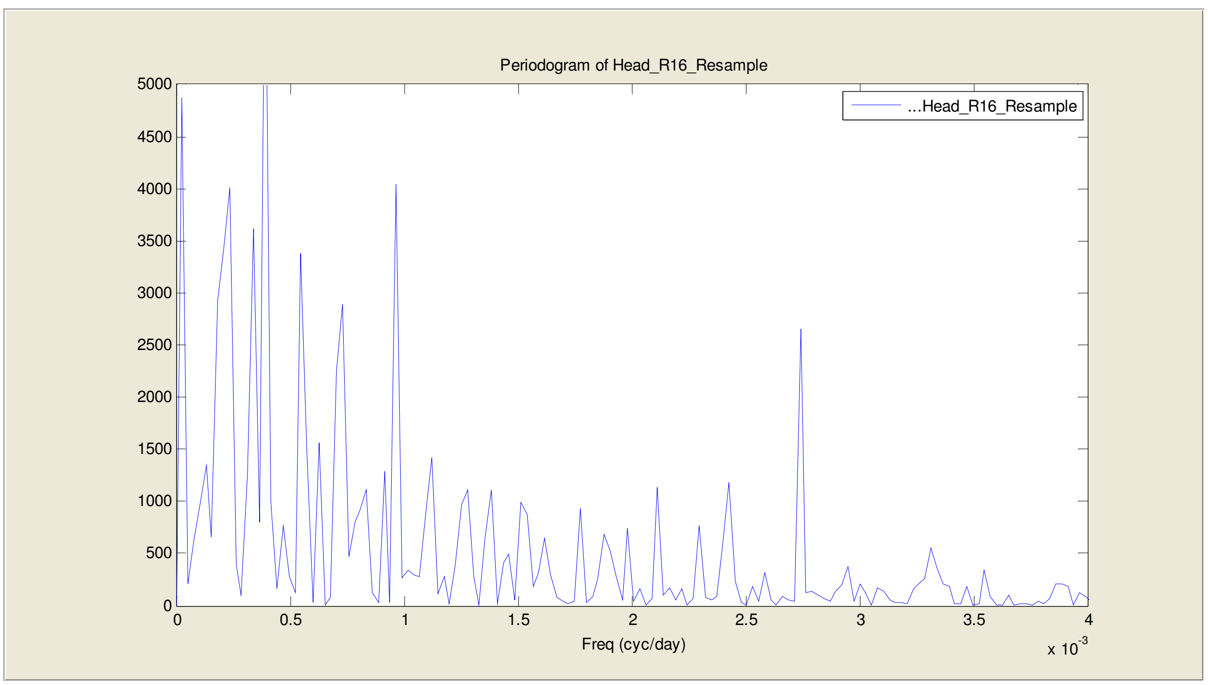

Figure D.4 Spectral Plot of Realization #16 at Santa Fe well (uniform pumpage 2.7K)

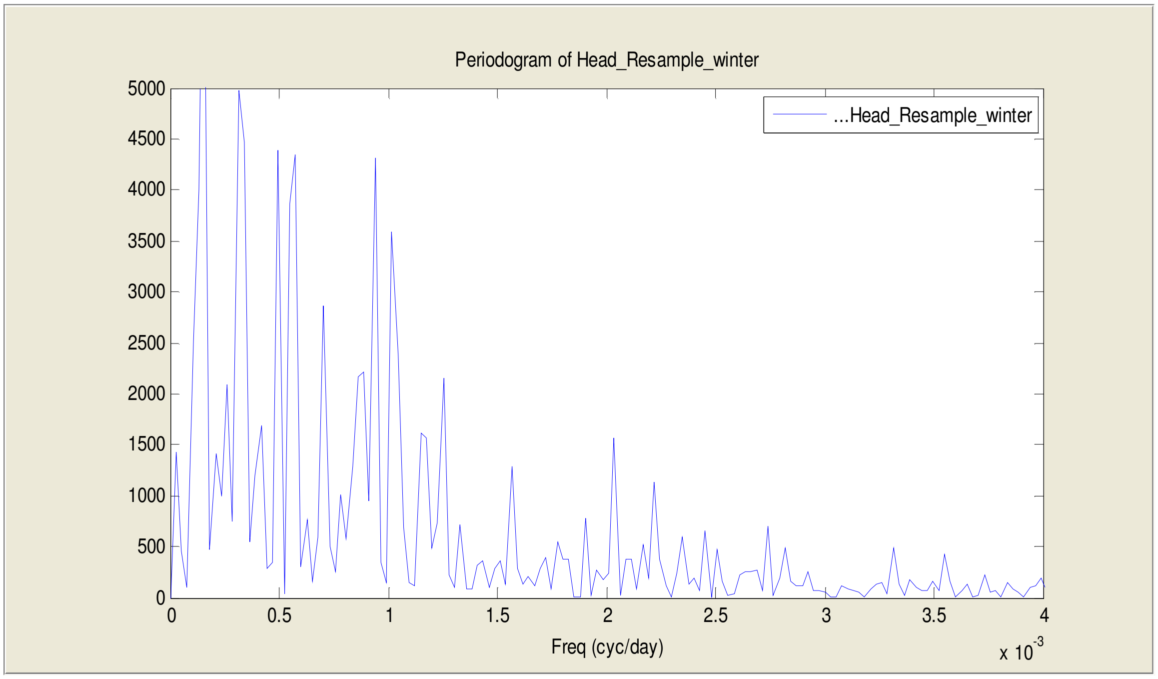

Figure D.5 Spectral Plot of Realization #2 at Santa Fe well. Applied pumpage equal to 2.7K AF/yr; higher pumping rates applied during <u>winter</u> season

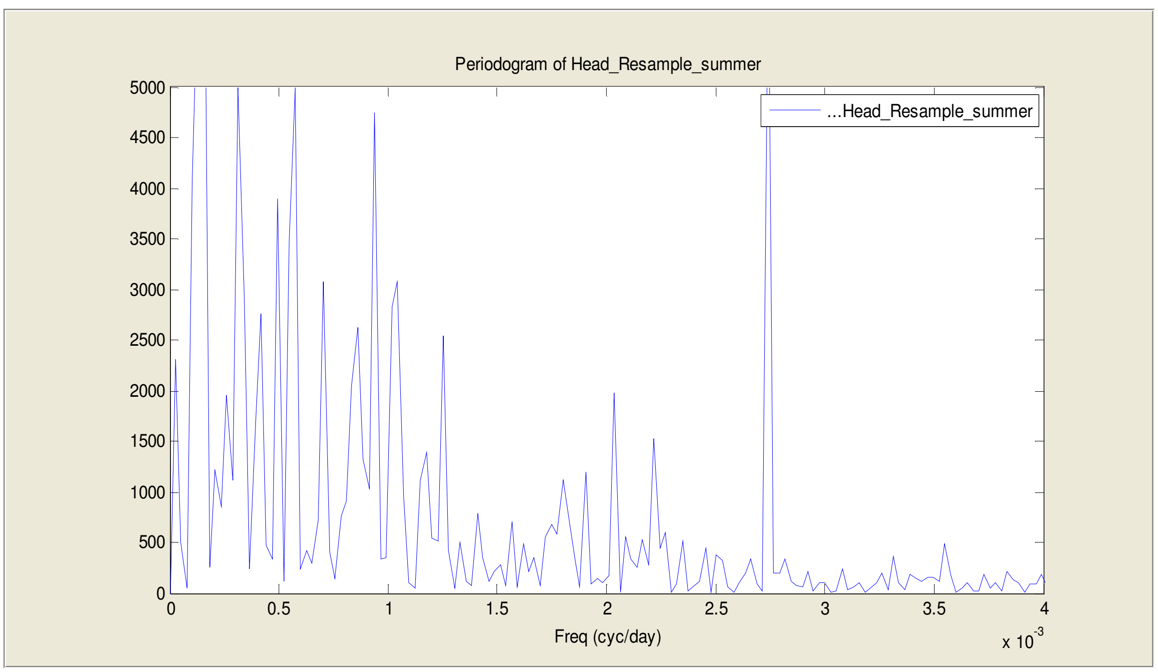

Figure D.6 Spectral Plot of Realization #2 at Santa Fe well. Applied pumpage equal to 2.7K AF/yr; higher pumping rates applied during <u>summer</u> season

Appendix E

Historical Photographs of Baseflow

Along Santa Cruz River

Figure E.1 shows groundwater discharge at Guevavi Narrows in late May 1998. Groundwater discharge (baseflow) at this site was in response to the El Nino-driven streamflow recharge events that occurred, primarily in February and March of 1998. During the spring and early summer of 1999 baseflow along the surface at Guevavi Narrows had disappeared. The 1999 monsoon brought significant flood recharge, subsequently leading to groundwater discharge at Guevavi Narrows during the fall of 1999. See Nelson and Erwin, 2001 for streamflow details. The relatively dry period observed between 2001 and 2006 has largely precluded groundwater discharge along most portions of the Santa Cruz River including Guevavi Narrows.

Figure E.2 and **Figure E.3** shows groundwater discharge along the Santa Cruz River in the spring of 1936, in the vicinity of (present-day) Rio Rico, Tumacacori and Tubac. These photographs document baseflow conditions during post-development, pre-effluent period. Despite historical surface water diversion and groundwater development, intermittent baseflow coexisted with a significant riparian habitat, decades before the release of effluent. By the 1950's baseflow had been effectively eliminated due to a combination of 1) significant groundwater demand for agricultural purposes; 2) a relatively "dry" climate observed between 1930 and 1960; and 3) stream channel incision (and probable downcutting). (Although the straightening and subsequent downcutting of the stream channel might result in a temporary increase in groundwater discharge from the aquifer to stream, a long-term reduction in wetted area - from sinuous to straight - would ultimately reduce long-term recharge to the floodplain aquifer. Moreover, this process would have undercut the highly transmissive younger alluvial aquifer by a vertical extent equal to the incision depth.)

A series of large floods starting in 1967 destroyed the artificial channelization of the river. Increased flood recharge combined with decreased agricultural pumpage led to a general rise in water tables, and subsequently set the stage for the current riparian system observed today. With respect to conditions observed in the 1950's, reduced pumpage in combination with increased flood recharge indicate that the stream-aquifer system was reverting back to more natural conditions. Photographs from June 1967 and December 1973 show baseflow conditions, similar to those observed in 1936. Since the 1970's effluent discharge has reinforced shallow groundwater levels and augmented dense riparian vegetation, creating an artificial demand even during dry periods.

Historical locations of groundwater discharge along the Santa Cruz River (US portion) include 1) Buena Vista (near the International border); 2) Guevavi Narrows; 3) near the Peck Canyon confluence (see Figure E.4 below); 4) along the river near Tumacacori; and 5) along the river near Tubac. Shallow water tables also existed during pre-development times along the Santa Cruz River near the Canoa Ranch, south of Green Valley, approximately 3 miles north of the Santa Cruz AMA boundary.

Figure E.1 Groundwater Discharge along Santa Cruz River at Guevavi Narrows, May 1998

Figure E.1 faces southeast. Note the Nogales Formation outcrop and surface water diversion structure (destroyed in the 1983 flood) in background. Above the outcrop lay the ruins of the Guevavi Mission, founded in 1691. A relation between the depth-to-water at monitoring well, (D-23-14) 27add and groundwater discharge at Guevavi Narrow is discussed in Nelson and Erwin (2001). One-half-mile upstream from this site there was no flow at the surface.

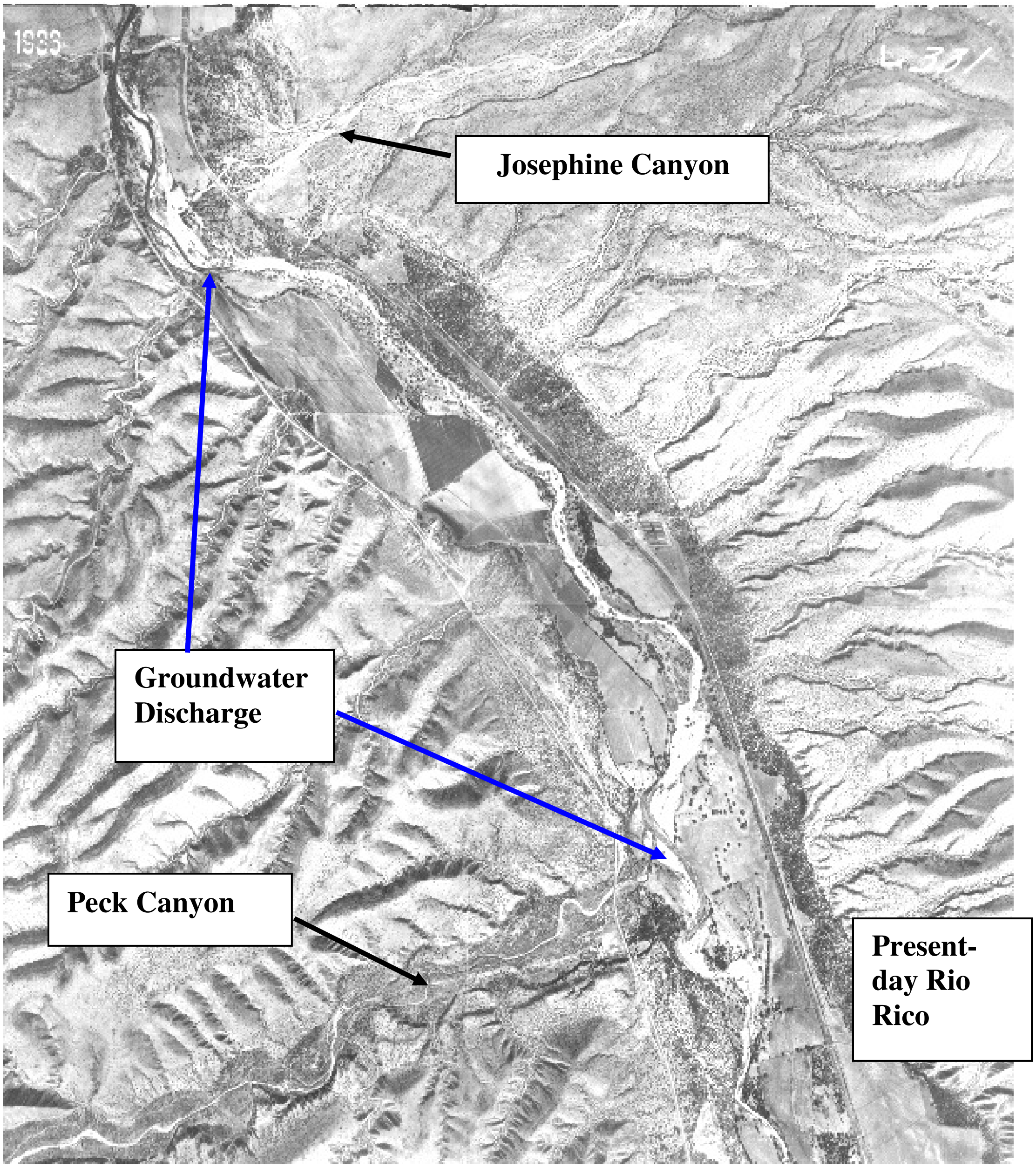

Figure E.2 Groundwater Discharge along Santa Cruz River between Peck and Josephine Canyons, Spring 1936

Upstream (south) of Figure E.2, photographs from 1936 show surface water (baseflow) from both the Santa Cruz River (Micro-basin) and Nogales Wash infiltrating immediately below their confluence. Today, near-perennial surface water flow from the Nogales Wash infiltrates near the Santa Cruz River/Nogales Wash confluence, above the Sonoita Creek/Santa Cruz River confluence. Photographs from 1967 and 1973, exhibit similar streamflow patterns during baseflow periods. This photographic evidence along with model results, suggest that high transmissivities in the (present-day) Rio Rico area, conduct/facilitate high rates of subsurface flow.

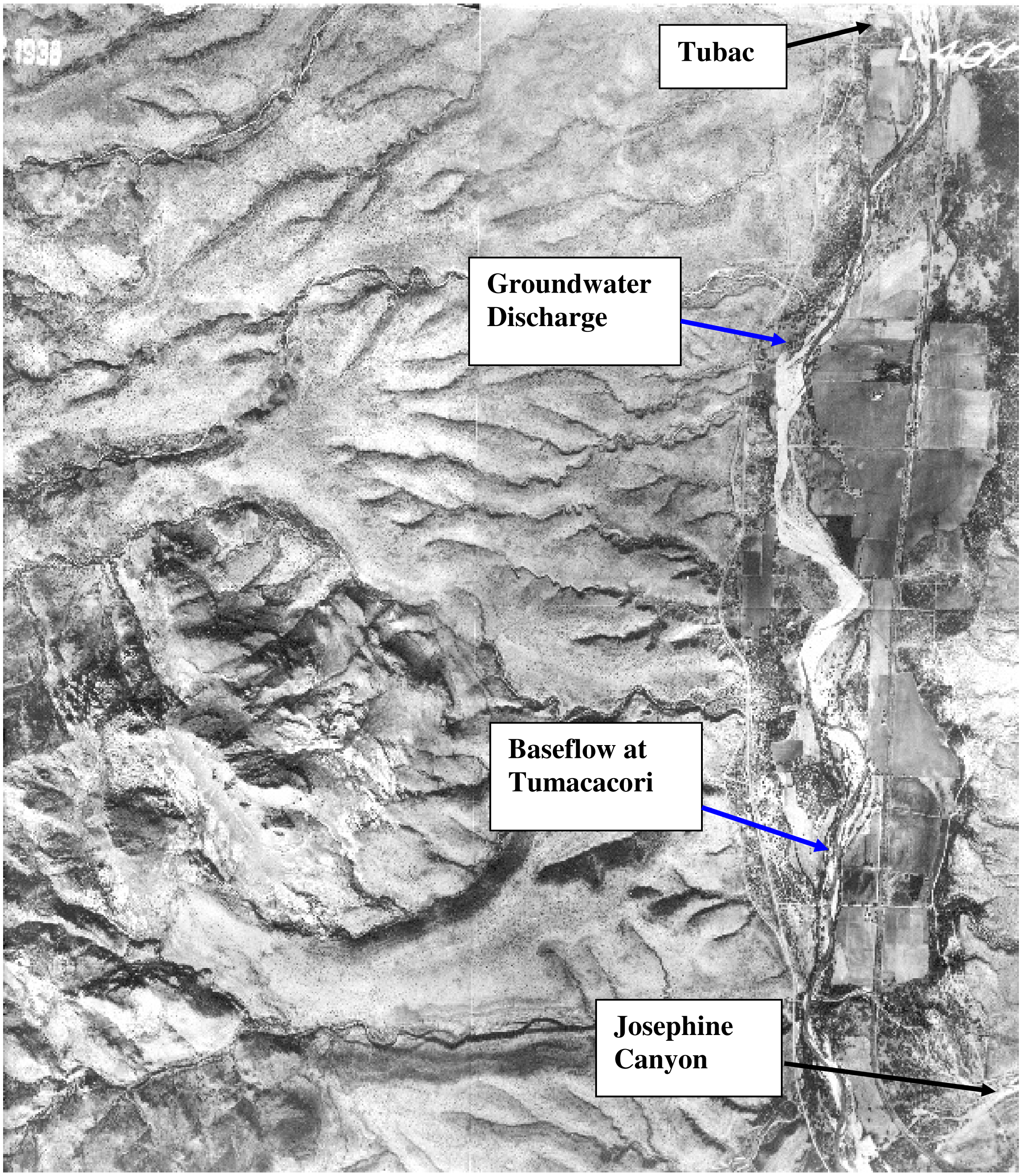

Figure E.3 Groundwater Discharge along Santa Cruz River between Josephine (lower right) Canyon and Tubac (top-right), Spring 1936

Figure E.3 shows the infiltration of baseflow near Tumacacori, and emanation of groundwater discharge south of Tubac. In the 1936-series photographs, surface water continued to flow along the surface, terminating about one mile North of Tubac, which is the historical limit of reliable streamflow during the pre-groundwater development period.

Figure E.4 Groundwater Discharge in Lower Peck Canyon, April 19, 2010.

Figure E.4 shows groundwater discharge in lower Peck Canyon, near the Santa Cruz River confluence on April 19th, 2010. The photograph faces east, and the San Cayetano Mountains can be seen in the background. Streamflow was estimated at approximately 0.5 cfs. This streamflow contributes to baseflow in the Santa Cruz River, which located about 0.3 miles downstream from this site. The streamflow shown in Figure E.4 originated from a series of springs located about 300 feet upgradient - to the west - of this site; above the springs all flow was in the sub-surface. Groundwater discharge at this location was in response to regional groundwater level rises, based on winter recharge from significant (El Nino-based) precipitation events in January and February 2010.

Appendix F

Flow Zone for Evaluating Net

Groundwater Discharge

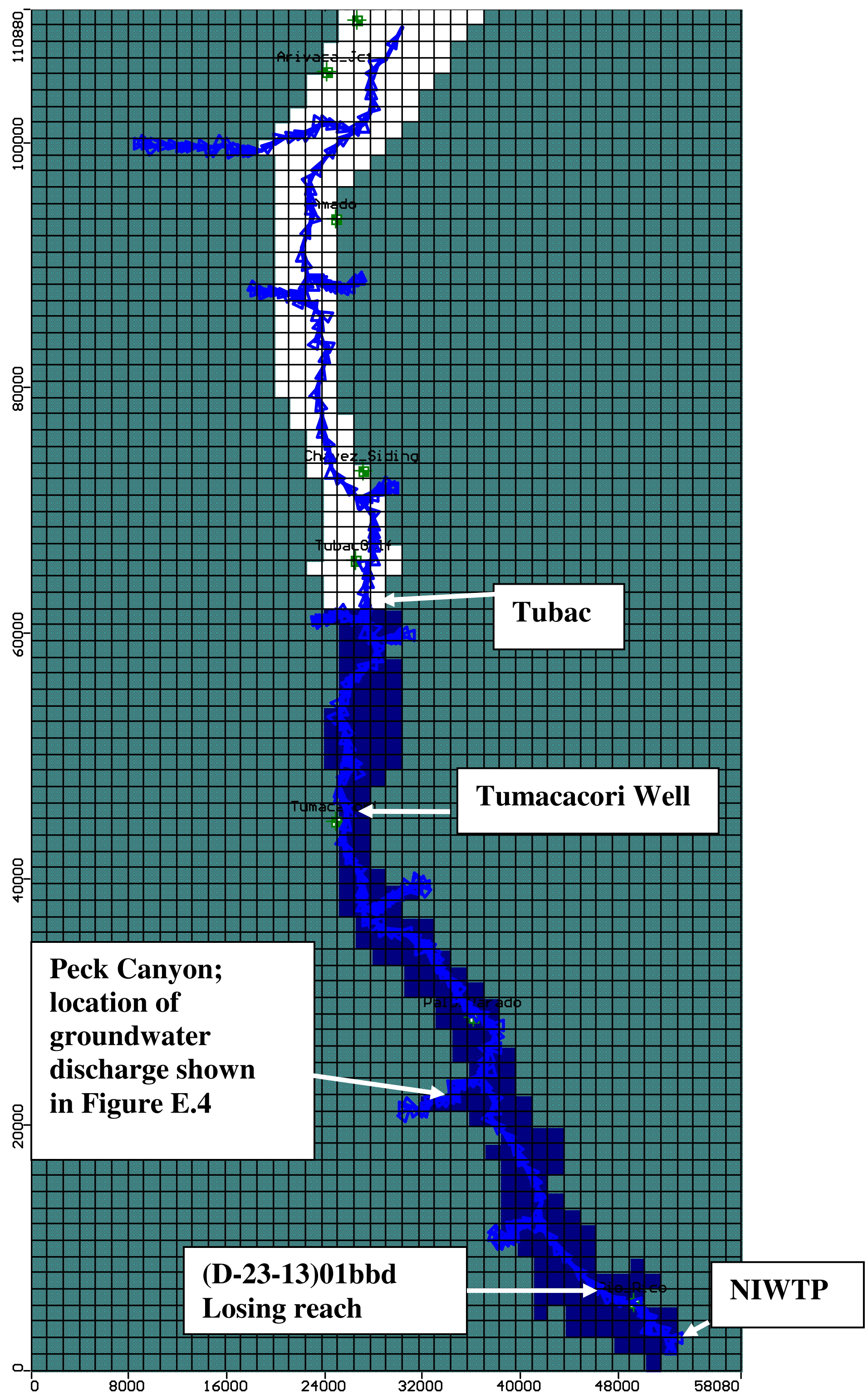

Figure F.1 Northern Santa Cruz Model Grid: Net Groundwater Discharge Zone between the NIWTP and Tubac Bridge (blue), rows 38-84. Model cell scale is 1,320 ft X 1,320 ft

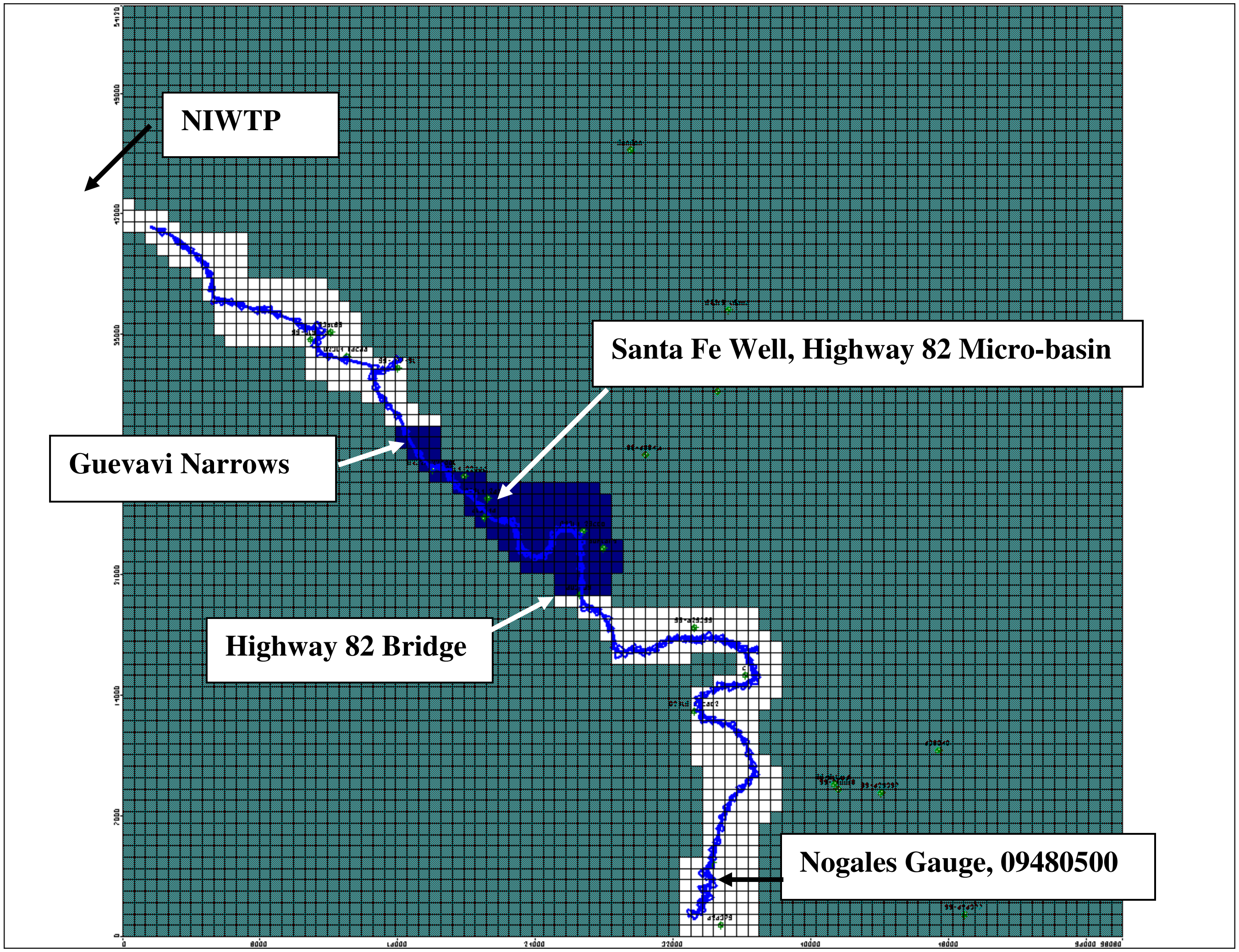

Figure F.2. Micro-basin Model Grid: Net groundwater discharge zone between Highway 82 Bridge and Guevavi Narrows (blue), rows 38-52. Model cell scale 660 ft X 660 ft

Appendix G

Parameters and Attributes Associated with the Northern Santa Cruz Model

Fundamental Model Parameters for Santa Cruz North
Alternative Conceptual Models (ACM's) Parameters

Parameter (optimal estimates)	Base Model	ACM 1	ACM 2	ACM 3	Manning ACM	Quasi-SS ACM
Koal_NE	0.035	0.046	0.0485	0.0485	0.0397	0.0324
Koal_Tubac_E	4.92	4.24	7.11	6.89	4.88	4.08
Koal_RR	10.5	11.4	7.67	9.36	9.75	4.43
Knog	0.101	0.13	0.142	0.140	0.117	0.119
Knog_Sopori	5.36	4.31	6.77	6.09	5.62	9.84
Koal_North	28.9	29.8	32.0	29.5	32.8	30.6
Kyal_North	110		124	168	115	117
Kyal_RR	702	651	548	740	720	961
KoalSCRFault			1,160			
Tributary Recharge (long-term)	8,360	5,050	12,410	10,920	9,070	5,000
MF Recharge (long-term)	1,900	2,420	3,180	2,530	2,150	1,830
Total long-term recharge	10,260	7,470	15,590	13,450	11,220	6,830
Stream Stage[1] Assignment	Stage discharge	Stage discharge	Stage discharge	Stage Discharge	Manning's N option	Stage Discharge
Stream M[2]	5	5	5	5	2.5	5

All parameter estimates were derived from non-linear regression. For location of K-zones and weighting criteria, see Nelson, 2007 (All ACM's used same weighting criteria). Hydraulic conductivity (K) values are in units of feet/day, where Kx = Ky. The Kxy: Kz ratio = 10:1. Recharge units are listed in acre-feet/year. [1]Stream conductance and stage assignment, variable in transient mode, is based on stochastic model. [2]Streambed thickness listed in units of feet. Information about streambed parameter are listed in Nelson (2007) and Appendix A. The Sy for layers 1, 2 and 3 are 0.18, 0.10 and 0.05, respectively. For projective purposes, all assigned head elevations associated with lateral boundary conditions (i.e., CHB; GHB) within the inner valley were reduced by 5 five feet; this reduction is assumed to compensate for the exclusion of released effluent; this, however, remains a difficult modeling assumption and may have significant impacts near southern and northern model boundaries. For the 95% confidence intervals associated with the basecase and quasi steady state solution see Nelson (2007). Each of these six ACM's (plus the ACM posed in Table G.1 - see Nelson, 2007) were further evaluated by inverse model techniques *with* the added assumption that a narrow fault zone exists in layer 3 (K3). K3 was hypothesized for better structural consistency with recent Micro-basin model modifications; see Appendix H. Estimates for K3 and Kyal_RR yield transmissivities that are reasonably consistent with resulting transmissivities (K*B, where B = unit/saturated thickness) presented above. Each of the seven solutions that include K3 have objective function errors that are slightly lower than their counterparts without K3 (above), but the differences are not considered to be statistically significant. Given the similar transmissivity distributions, it is assumed that on a regional-scale basis, the six ACM solutions shown above hydraulically represent groundwater flow for their respective ACM. However the inverse model results containing K3 suggest that deeper subsurface flow may exist in the Rio Rico sub-area. Note that the recharge rates listed represent "long-term" uniformly-applied rates, and are not associated with the variable stream recharge, represented by the stream-aquifer boundary, as defined by the stochastic model

Table G.I Fundamental Model Parameters, Northern Model Area

Northern Santa Cruz Model ACM Attributes			
Model	**ACM Descriptions Also see Nelson (2007)**	**Positive attributes**	**Negative attributes**
Base Model	Most consistent with original conceptual model	Simulated heads and simulated flows generally fell within collective range of the set of all ACM outputs	Simulates neither the most accurate heads, nor the most accurate flows with respect to observed data
ACM 1	Combined Kyal_North and Koal_North into a single parameter; thus model is parsimonious, and required no a-priori data for the non-linear regression: Solution was self-contained with only head and flow data	Contains no prior information; simplest model. Simulates flood recharge in the Tubac and Amado areas with best accuracy of any ACM; most accurate simulated heads north of Tumacacori (valley)	Parameter-estimated value of Kyal_North is least consistent with available (yet limited) data, and the original conceptual model parameter
ACM 2	Includes separate high-K Koal_Scr_Fault zone in the northwest portion of the Rio Rico sub-area (layer 2, Koal_SCR_Fault): Col 21, Row 57,58,61,67,68. Col 22, Row 60,61,62,65,66,67,68. Col 23, Row 62-68.	Best areal distribution of Oal heads in the Rio Rico sub-area; limited field data consistent with Koal_Scr_Fault; lowest collective model error of any ACM	Extensive fault zone speculative. Least accurate parameter-estimated tributary recharge with respect to conceptual estimates
ACM 3	Prior information assigned to Kyal_North has mean value of 250 (based on mean field data); yields parameter-estimated value of 168 ft/d	Parameter estimate of Kyal_North is most consistent with available field data, Most accurate steady state flow south of Tubac (1997-2002)	Largest overall model error; largest simulated head error/offset within inner valley
Manning's N option ACM	Applied Manning's N Option for stream-aquifer boundary condition; streambed thickness = 2.5 feet. All other assumptions consistent with Base model.	Provides lower head error with respect to base ACM. Provides 2nd most accurate steady state flow south of Tubac. Provides variance for stream-aquifer boundary.	Simulates neither the most accurate heads, nor the most accurate flows with respect to observed data. Requires Manning's N coefficient.
Quasi-SS Assumption ACM	Assumed system state was NOT in true equilibrium: $(\partial h/\partial t) \neq 0$ = constant. All other assumptions consistent with Base model.	Most accurate transient simulated heads, in the Rio Rico sub-area, of any ACM; probably the most realistic system state assumption	Estimated parameters less sensitive than other ACM's (PEST); solution requires initial conditions and storage parameters
The ACM's were developed using a multi-objective approach advocated by Hill (1998) and Neuman and Wierenga (2003). For realizations simulated with the quasi-steady solution, the basecase steady state solution provided initial conditions. Unlike true steady state solutions, the quasi-steady parameter estimated solution assumes that the groundwater flow system was releasing relatively small rates of water from storage; in this case, storage release rates were linear and constant (see Nelson, 2007). All ACM used same weighting criteria.			

Table G.2 Attributes of the Northern Santa Cruz Model ACM

Appendix H

Observed Net Groundwater Discharge

along Santa Cruz River

Groundwater Discharge Along the Santa Cruz River Between the NIWTP and Tubac			
Post-Groundwater Development Period	Observed groundwater discharge rate		Net Groundwater Discharge Condition between NIWTP/Rio Rico and Tubac
	Continuous	Manually	
March/April 1936			Gaining (photograph)
February 1954			Losing (photographs)
1965			Losing (photographs)[5]
March & June 1967			Gaining (photograph)[5]
June 1971			Gaining (photograph)[5]
December 1973			Gaining (photograph)
November, 1992 January, 1993		-5.4 [1]	Gaining Gaining/Flood dominated
Winter 1993/94		-5.0 [2]	Gaining
Winter 1994/95			Gaining; Flood dominated
Winter 1995/96	-6.4 [1]	-6.6 [1]	Gaining
Winter 1996/97	-4.6 [1]	-6.4 [1]	Gaining
Winter 1997/98	-5.8 [1]	-4.0 [1]	Gaining
Winter 1998/99	-3.8 [1]	-7.0 [1]	Gaining
Winter 1999/00	-4.8 [1]	-6.0 [1]	Gaining
Winter 2000/01			Gaining; Flood dominated
Winter 2001/02	-4.2 [1]	-3.4 [1]	Gaining
Winter 2002/03	+4.5 [3]		Losing
Winter 2003/04	+2.4 [3]		Losing
Winter 2004/05	+1.5 [3]		Losing
Winter 2005/06	+7.1 [3]		Losing
Winter 2006/07	+7.5 [3]		Losing
Winter 2007/08	+3.0 [3]	+0.3 [1a]	Losing/Hydrostatic
Winter 2008/09	-0.5 [3,4]	-1.5 [1b]	Gaining
December 2009			Losing[6]

[1]Seasonal average from Nelson (2007). [1a]Average net flow between Rio Rico and Tubac, January and February, 2008 (Source: ADWR Basic Data unit). [1b]Average net flow from late November 2008 through April 1st 2009 between Rio Rico and Tubac (Source: ADWR Basic data unit). [2]From a presentation by Duncan Patten of Montana State University, entitled "Effluent, A "New" Water Source: Asset or Problem" – slide 17 of 36. [3]Net flow between NIWTP (IBWC) and USGS gauge at Tubac for the months of December, January and February periods with minor flood runoff were separated from baseflow data at Tubac. [4]Assumes evaporation loss of 0.5 cfs between NIWTP and Tubac ~15 river miles. [5]From Applegate (1981). [6]Provisional Source from USGS and NIWTP (IBWC). Note that "-"indicates net gaining reach (blue); "+" indicates net losing reach (red). All units in cfs.

Table H.1 Observed Groundwater Discharge

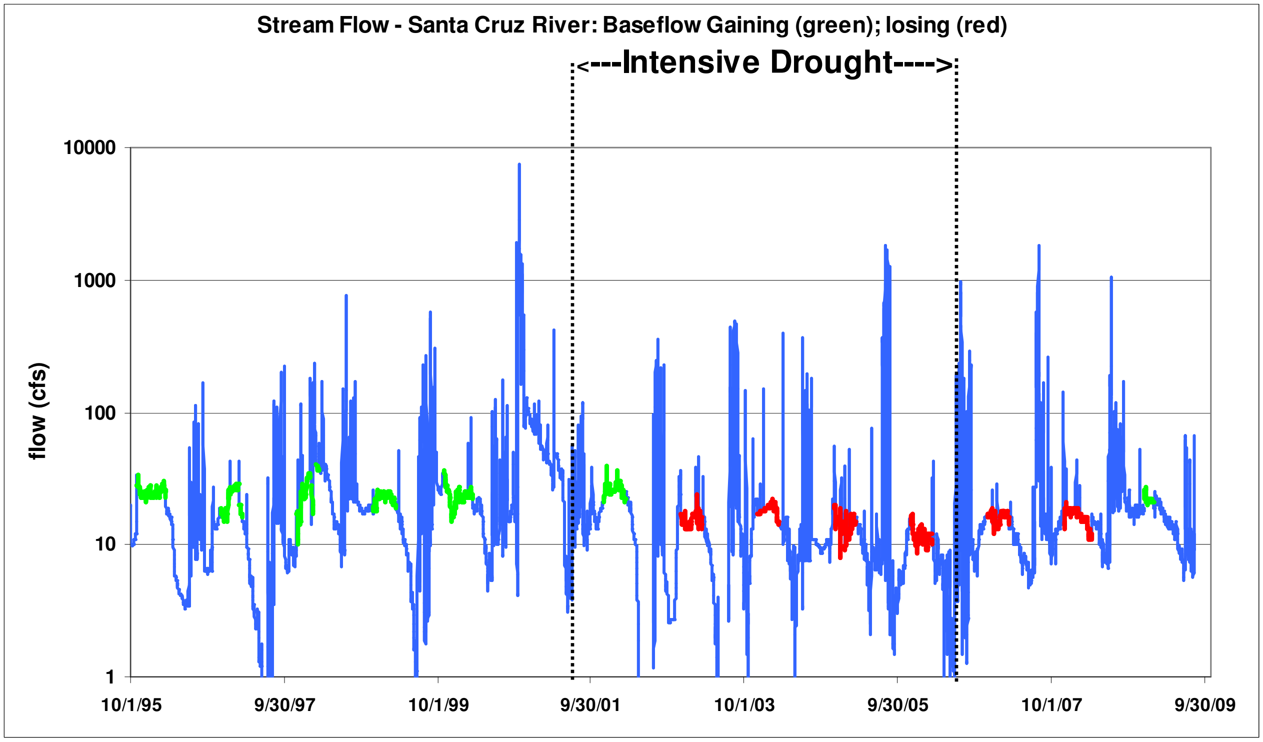

Figure H.1 Streamflow conditions along Santa Cruz River near Tubac, October 1995 to September 2009

Green segments represent winter periods when streamflow rates at Tubac exceeded effluent discharge rates released at the NIWTP, or net gaining conditions along this reach. Red segments represent winter periods when streamflow at Tubac was less than effluent discharge rates, released at the NIWTP; or net losing conditions along this reach. Note that net gaining or net losing periods reflect non-runoff conditions.