Appendix A

Geology of Santa Maria Basin

Nipomo Mesa Groundwater Resource Capacity Study
San Luis Obispo County, California

Appendix A: Geology of Santa Maria Basin

The Santa Maria Geologic Basin was formed by right-lateral, strike-slip faulting and concurrent deposition of marine sediments in a subsiding fault bounded block during a period of several million years in middle of the Tertiary Period of geologic time. Continued faulting, but a change in tectonic regime in middle to late Tertiary time resulted in compression of the basin, which formed large-scale folding, such as the Santa Maria syncline. Late Tertiary to relatively recent west-northwest trending reverse and thrust faults, local folding, uplift, subsidence and tilting complicates the middle Tertiary geologic framework of the basin and crustal blocks. The Santa Maria Basin extends several miles offshore where it is bounded by the Hosgri fault zone.

The Santa Maria Groundwater Basin is the upper, relatively recent and most permeable portion of the Santa Maria Geologic Basin. The aquifer system in the basin consists of unconsolidated plio-pleistocene alluvial deposits including gravel, sand, silt and clay with total thickness ranging from 200 to nearly 3,000 feet. The underlying consolidated rocks typically yield relatively insignificant quantities of water to wells. Jurassic and Cretaceous age basement complex rocks of the Franciscan and Knoxville Formations unconformably underlie the Tertiary and Quaternary rocks. A generalized geologic map of the Nipomo Area and geologic cross sections from the DWR 2002 report are provided as Figures A1 to A4.

The unconsolidated alluvial deposits in the Santa Maria Groundwater Basin include the Careaga Sand, the Paso Robles Formation, the Orcutt Formation, Quaternary Alluvium, and river channel deposits, sediment, terrace deposits and wind-blown dune sands at or near the surface.

The Careaga Sand is a late Pliocene accumulation of shallow-water marine unconsolidated to well-consolidated, coarse- to fine-grained sediments with locally common sea shell fragments and sand dollar fossils. The majority of the Careaga consists of white to yellowish-brown, loosely consolidated, massive, fossiliferous, medium- to fine-grained sand with some silt. The Careaga Sand is identified as the lowermost fresh water bearing formation in the Santa Maria Groundwater Basin, but water quality in the Careaga Sand is typically poor. It is approximately 150 feet thick under Nipomo Mesa south of the Santa Maria River Fault and thickens toward the south to approximately 700 feet beneath the Santa Maria River.

The Plio-Pleistocene Paso Robles Formation overlies the Careaga Sand and comprises the majority of the alluvial basin fill deposits. Thickness of the Paso Robles Formation is approximately 200 feet at northwestern extent of the Santa Maria basin. The Paso Robles Formation thickens to the south and reaches a maximum of approximately 2000 feet near the syclinal axis of the basin beneath the town of Orcutt south of Santa Maria. It consists of unconsolidated to poorly consolidated heterogeneous alluvium deposited under a variety of conditions including fluvial, lagoonal, and nearshore marine. The Paso Robles Formation is highly variable in color and texture, ranging from gravel and clay, sand and clay, gravel and sand, silt and clay. Most of it is fluvial in origin and in most places correlation between individual beds is not possible.

The late Pleistocene Orcutt Formation, which also is primarily fluvial in origin, locally overlies the Paso Robles Formation. In the Orcutt Upland area it is ranges in thickness from 100 to 200 feet. Based on well logs the Orcutt is report to consist of an upper fine-grained sand member and a lower coarse-grained sand and gravel member. Both members of the Orcutt become finer grained toward the coast. In most of the northern portion of the Santa Maria Groundwater Basin, the Orcutt may not be present, or has been eroded away.

Middle to late Pleistocene age alluvium, which is termed Older Alluvium by some, occurs unconformably on older rocks on the floor of Nipomo Valley. These Older Alluvium deposits are relatively minor in extent and thickness—typical thickness is 10 to 90 feet. Terrace deposits of similar age to the Older Alluvium are remnants of wave-cut platforms or older fluvial deposits, subsequently uplifted and preserved as terraces. The terrace deposits range in thickness from 1 to 15 feet and consist of reworked clasts of underlying formations. Marine terrace deposits are exposed along the coast at Pismo Beach and along the north side of Arroyo Grande Creek. The terrace deposits likely extend beneath the sand dune deposits in the Nipomo Mesa area.

Extensive deposits of Holocene Alluvium (Younger Alluvium), mainly of fluvial origin, comprise the majority of the Santa Maria Valley floor and are typically 100 to 200 feet thick. In Santa Maria Groundwater Basin, the younger alluvium overlies the Orcutt Formation if present, or the Paso Robles Formation throughout most of the northern portion of the basin. Although the 2002 DWR report treats the Holocene alluvium as single unit, sometimes it is divided into two members. The upper portion (member) becomes progressively finer-grained toward the coast with boulders gravel and sand in the Sisquoc Plain Area (upstream portion of the Santa Maria River), sand and gravel in the central and eastern Santa Maria Valley, sand with silt from SM to approximately halfway to Guadalupe, and clay with silt and minor sand westward. The lower portion (member) is mainly coarse-grained sand, gravel, cobbles and boulders with minor clay lenses near the coast. The Holocene Alluvium is approximately 130 feet thick near Hwy 101, and progressively thickens along the Santa Maria River toward the coast where it is approximately 230 feet thick.

The fine-grained facies of the upper portion of the Holocene Alluvium functions as a hydraulic confining layer above the underlying system of aquifers. Based on lithologic logs of well reports, clay beds within the Holocene alluvium range in thickness from 1 to 170 feet in the Santa Maria Plain. Cross sections in the 2002 DWR report show through-going clayey beds within the alluvium, however other reports conclude that the intervals of clay beds may not be continuous layers. In either case, it is apparent that intervals with high proportions of fine-grained material function as semi-confining units that limit the hydraulic connection between the upper portion of the Holocene Alluvium and system of aquifers below.

A mantle of late Pleistocene eolian (wind-blown) dune sands underlies the elevated area, known as Nipomo Mesa. In the 2002 DWR report these dune deposits are referred to as the Older Dunes as opposed to the Younger Dunes that are present along the coastal margin. The Holocene (older) dune deposits are reported to range in age from 40,000 to 120,000 years and were once much more extensive, but most were eroded away during the last ice age by the ancestral Arroyo Grande Creek, Los Berros Creek, and Santa Maria River. Today the Nipomo Mesa older dune sands is a triangular lobe more than 4 miles wide on the coastal side and extending inland more than 12 miles just east of Hwy 101. The dune sand consists of loosely to slightly compacted, massive but cross-bedded, coarse- to fine-grained, well-rounded quartoze sand. The older dune sands have a well-developed soil mantle and are stabilized by vegetation. Lithologic logs of water wells indicate that the Nipomo Mesa dune sands locally contain clay layers on which groundwater may be perched.

An extensive system of Holocene sand dunes occurs along a greater than 10-mile long section of the coastal margin from near just south of Pismo Beach to a couple of miles north of Point Sal.

These dunes are sometimes called the Nipomo Dunes, but are distinct from the older stabilized sand dune deposits that comprise Nipomo Mesa.

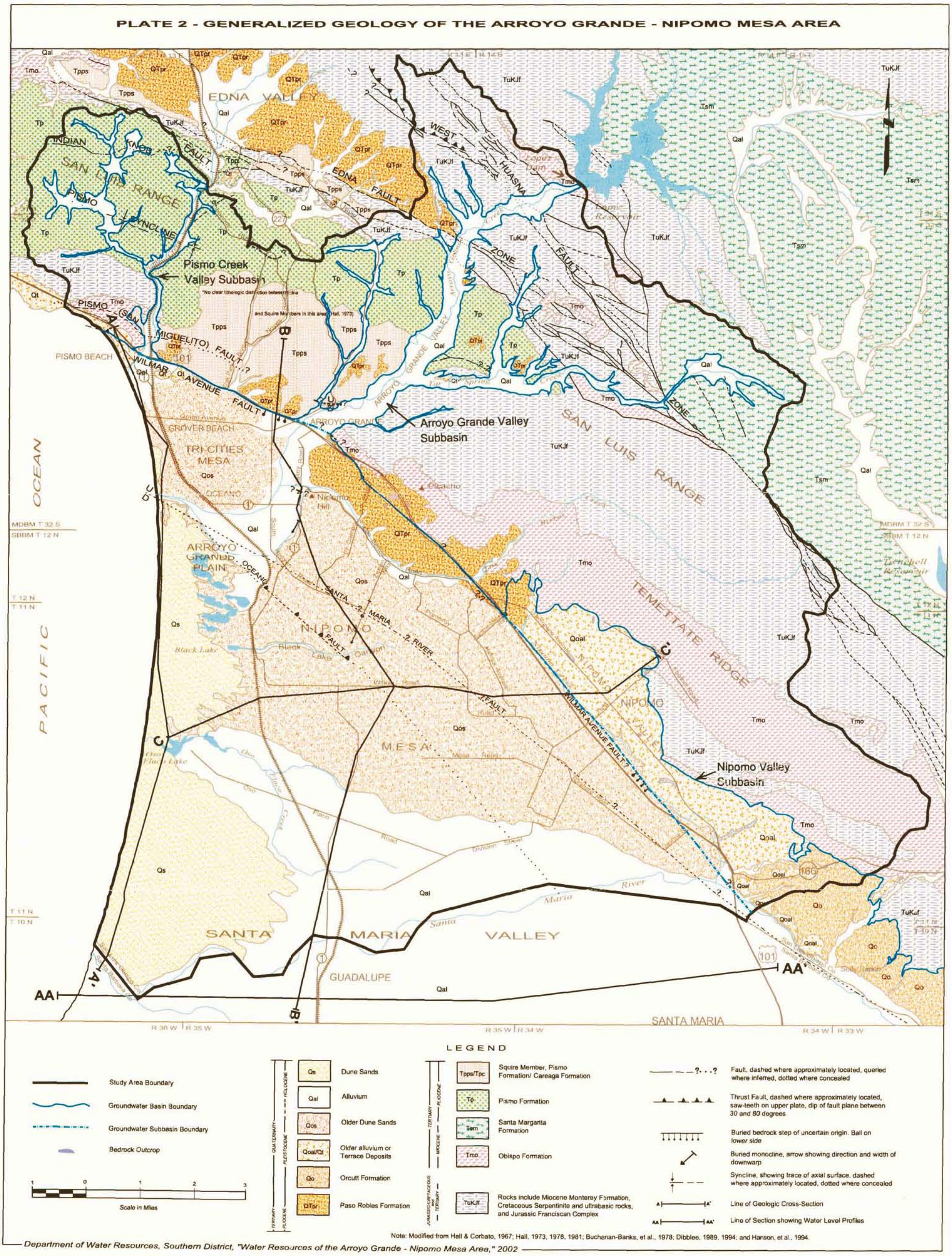
A minor alluvial deposit in Black Lake Canyon is the only alluvium in the Nipomo Mesa area.

Faults

Faults in the vicinity can be grouped into two categories: (1) largely inactive, right-lateral, strike-slip faults, and (2) potentially active reverse and thrust faults. Both groups generally trend west-northwest. Several faults are concealed within the Santa Maria Basin and the location and associated displacements are estimated from well logs and extrapolation of observations were the faults are exposed at margins of the basin or detected by offshore geophysical exploration.

The Santa Maria and Bradley Canyon Faults are both northwest-trending concealed faults that cross the Santa Maria Valley. They are reported to be high-angle reverse faults the vertically offset the Paso Robles Formation and underlying rocks, but not overlying Orcutt Formation or Quaternary Alluvium. The Santa Maria River and Oceano faults are high-angle faults beneath the northern portion of the Santa Maria basin. They extend beneath in the Nipomo Mesa area in a northwestward direction toward Oceano. Both vertically offset Paso Robles Formation and older rocks, but apparently do not displace the overlying Alluvium or Older Dune Sands. However, the Santa Maria River Fault is also reported to have a significant strike-slip component of offset. DWR reported that the Santa Maria River and Oceano Faults merge near the coastline and then merge offshore with the Hosgri Fault zone. The maximum vertical offset on the Oceano Fault is reported to be 300 to 400 feet and offset on Santa Maria River Fault, the Santa Maria Fault, and Bradley Canyon is within the range of 80 to 150 feet (L&S, 2000). Decreasing vertical offset along Oceano Fault to the southeast is believed indicate that this fault dies out near the Santa Maria River.

The DWR 2002 report discusses significant differences in water levels on opposite sides of the estimated trace of the Santa Maria River Fault, suggesting that the fault is to some degree a hydraulic barrier. However, L&S (2000) report that based on their evaluation of water level data, these faults do not appear to influence groundwater flow within the Santa Maria Groundwater Basin.



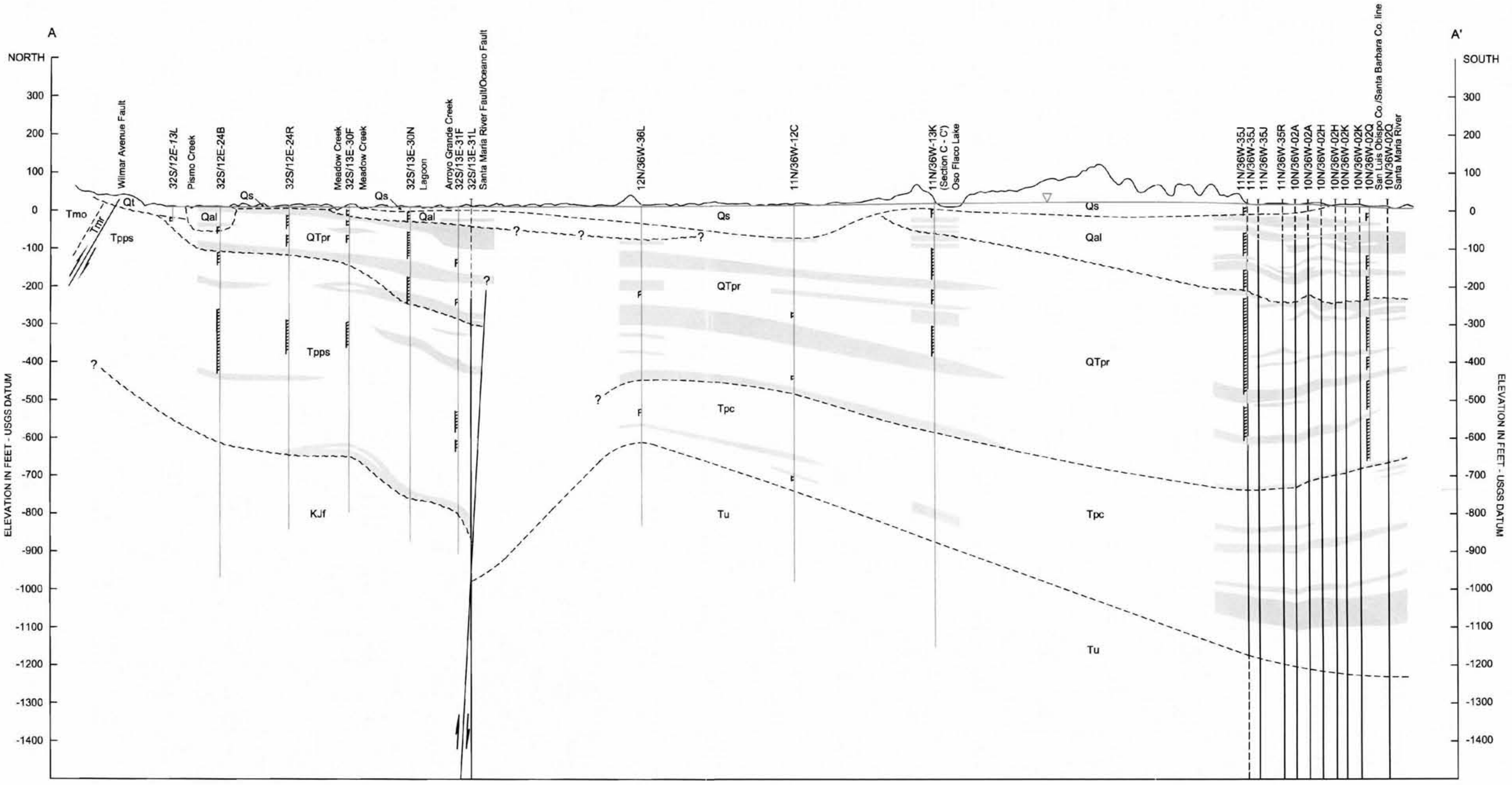
Note: Modified from Hall & Corbato, 1967; Hall, 1973, 1978, 1981; Buchanan-Banks, et al., 1978; Dibblee, 1989, 1994; and Hanson, et al., 1994.

Department of Water Resources, Southern District, "Water Resources of the Arroyo Grande - Nipomo Mesa Area," 2002

GENERALIZED GEOLOGY OF THE ARROYO GRANDE - NIPOMO MESA AREA (DWR, 2002)

SAN LUIS OBISPO, CALIFORNIA

Figure A-1



EXPLANATION

Formation and Symbol

Qs	Dune Sand
Qal	Alluvial Deposits
Qt	Terrace Deposits
QTpr	Paso Robles Formation
Tpc	Careaga Formation
Tpps	Squire Member, Pismo Formation
Tmo	Obispo Formation
Tmr	Rincon Formation
Tu	Undifferentiated Tertiary Deposits
KJf	Franciscan Complex

12N/36W-36L	Water well with electric and geologic log
32S/12E-13L	Water well with geologic log
10N/36W-02G	Oil well with electric log, dashed above record

Hydrogeologic Unit

▨	Unconsolidated to weakly cemented clayey silt to silty clay with minor sand and gravel
☐	Unconsolidated to weakly cemented sand, gravel, silt, sandstone with minor clay and silty clay
☐	Bedrock

⁞	Perforated interval
⇅	Fault, arrows indicate relative vertical movement
- - -	Unconformity
– – –	Contact
▽	1995 Groundwater Elevation

Note: References include: Department of Water Resources, 1970; Buchanan-Banks et al., 1978; Hall, 1981; Nitchman, 1988; Hanson et al., 1994; Lettis et al., 1994.

Location of geologic section shown on Plate 2

Vertical scale 20 times horizontal scale

Horizontal scale in feet

4000 0 4000

WATER RESOURCES OF THE
ARROYO GRANDE - NIPOMO MESA AREA

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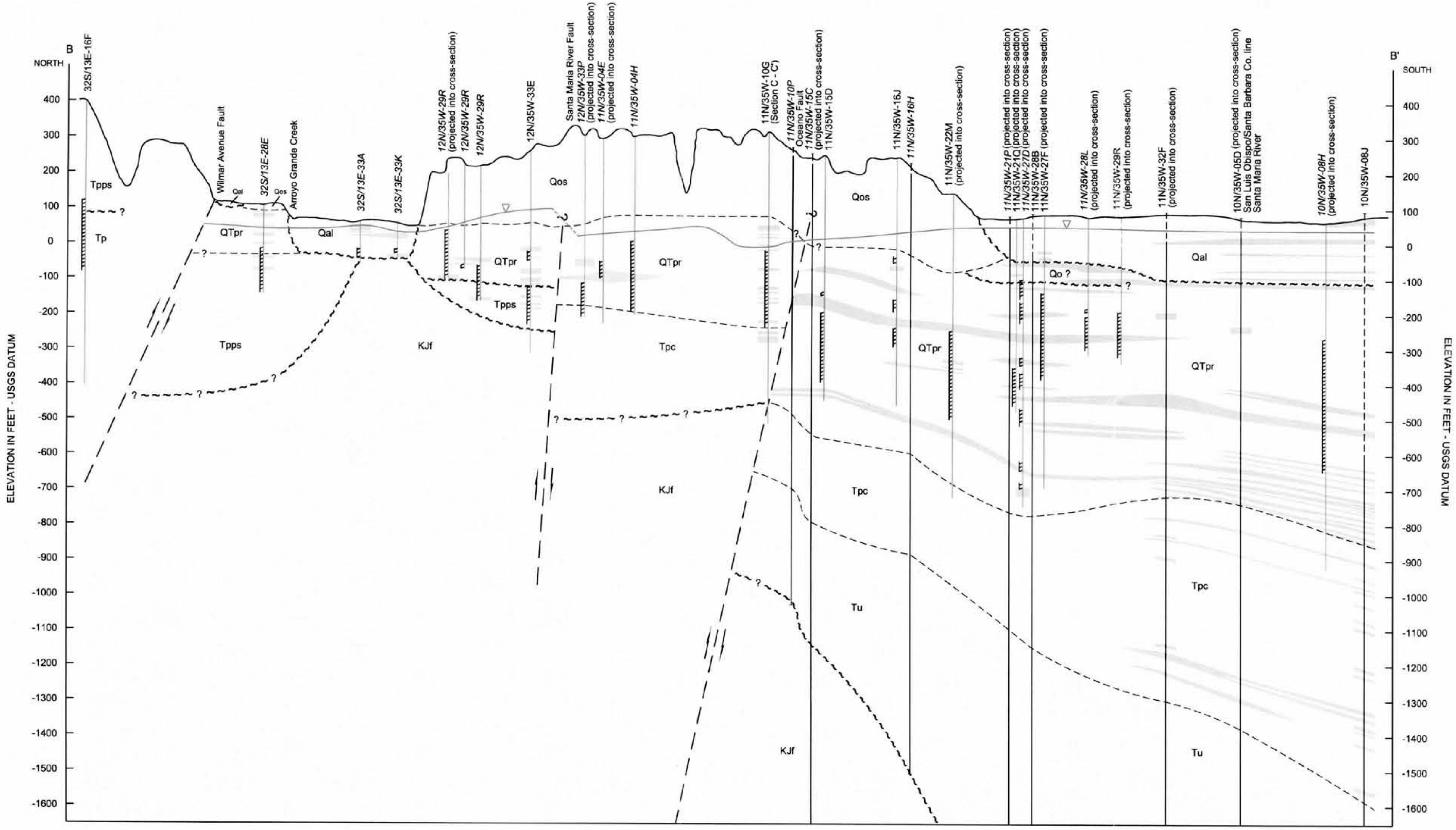
PLATE 3

GEOLOGIC SECTION A - A'

Department of Water Resources, Southern District, 2002



EXPLANATION

Formation and Symbol

Qal	Alluvial Deposits
Qos	Older Dune Sand
Qo	Orcutt Formation
QTpr	Paso Robles Formation
Tpc	Careaga Formation
Tpps	Squire Member, Pismo Formation
Tp	Pismo Formation
Tu	Undifferentiated Tertiary Deposits
KJf	Franciscan Complex

12N/36W-36L	Water well with electric and geologic log
32S/12E-13L	Water well with geologic log
10N/36W-02G	Oil well with electric log, dashed above record
11N/35W-10P	Oil well with geologic log, dashed above record

Hydrogeologic Unit

▨	Unconsolidated to weakly cemented clayey silt to silty clay with minor sand and gravel
☐	Unconsolidated to weakly cemented sand, gravel, silt, sandstone with minor clay and silty clay
☐	Bedrock

⋮	Perforated interval
⇅	Fault, arrows indicate relative vertical movement
~~	Unconformity
- - -	Contact
▽	1995 Groundwater Elevation

Note: References include: Department of Water Resources, 1970; Buchanan-Banks et al., 1978; Hall, 1981; Nitchman, 1988; Hanson et al., 1994; Lettis et al., 1994.

Location of geologic section shown on Plate 2

Vertical scale 20 times horizontal scale

Horizontal scale in feet

4000 0 4000

WATER RESOURCES OF THE

ARROYO GRANDE - NIPOMO MESA AREA

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PLATE 4

GEOLOGIC SECTION B - B'

Department of Water Resources, Southern District, 2002

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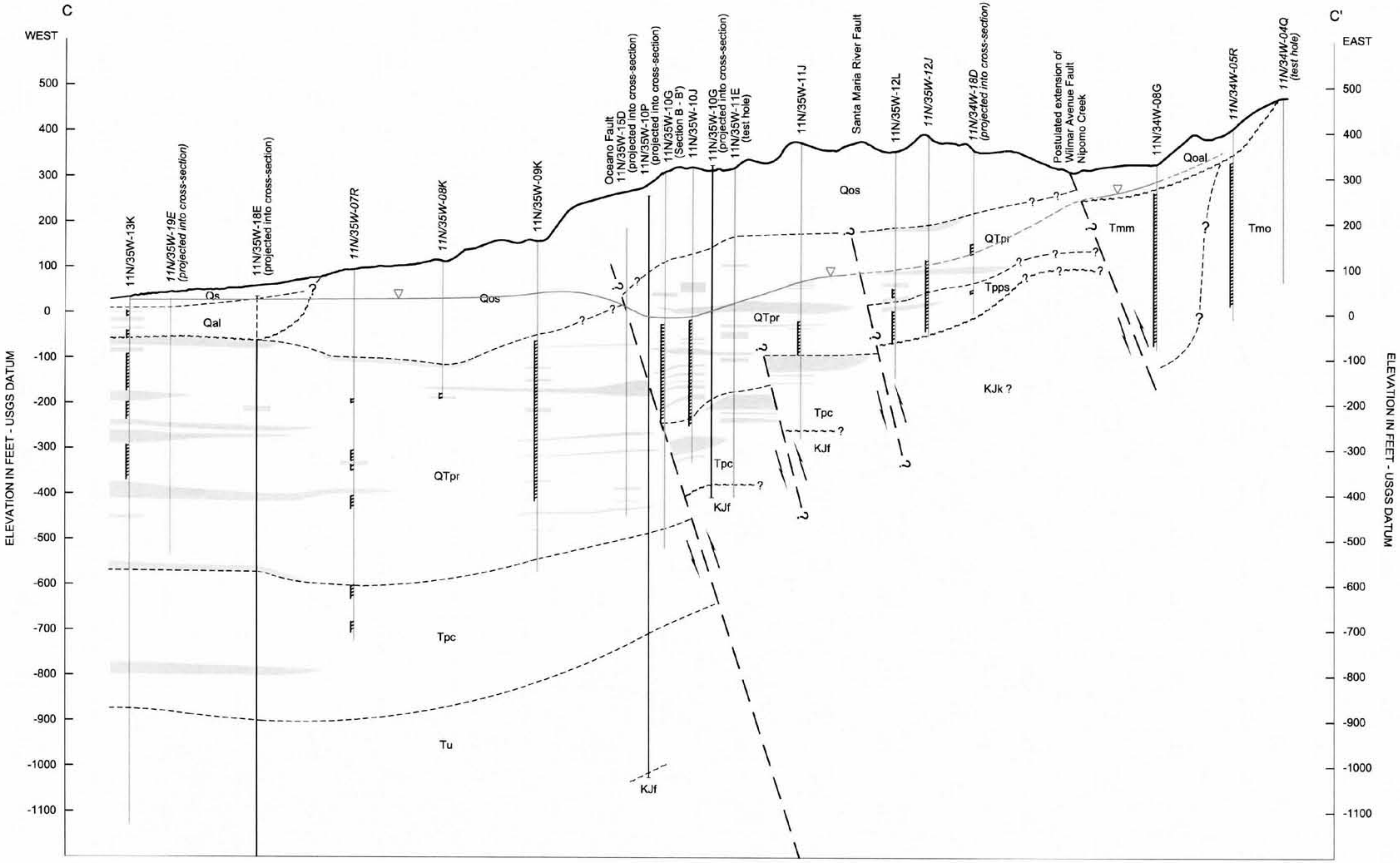

EXPLANATION

Formation and Symbol

Qs	Dune Sand
Qal	Alluvial Deposits
Qos	Older Dune Sand
Qoal	Older Alluvial Deposits
QTpr	Paso Robles Formation
Tpc	Careaga Formation
Tpps	Squire Member, Pismo Formation
Tmm	Monterey Formation
Tmo	Obispo Formation
Tu	Undifferentiated Tertiary Deposits
KJk	Knoxville Formation
KJf	Franciscan Complex

12N/36W-36L	Water well with electric and geologic log
32S/12E-13L	Water well with geologic log
10N/36W-02G	Oil well with electric log, dashed above record
11N/35W-10P	Oil well with geologic log, dashed above record

Hydrogeologic Unit

▨	Unconsolidated to weakly cemented clayey silt to silty clay with minor sand and gravel
☐	Unconsolidated to weakly cemented sand, gravel, silt, sandstone with minor clay and silty clay
☐	Bedrock

Ⅎ	Perforated interval
⇅	Fault, arrows indicate relative vertical movement
- - -	Unconformity
– – –	Contact
▽	1995 Groundwater Elevation

Note: References include: Department of Water Resources, 1970; Buchanan-Banks et al., 1978; Hall, 1981; Nitchman, 1988; Hanson et al., 1994; Lettis et al., 1994.

Location of geologic section shown on Plate 2

Vertical scale 20 times horizontal scale

Horizontal scale in feet

4000 0 4000

WATER RESOURCES OF THE
ARROYO GRANDE - NIPOMO MESA AREA

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PLATE 5

GEOLOGIC SECTION C - C'

Department of Water Resources, Southern District, 2002

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Figure A-4

Appendix B

Recharge Rate is Not Equivalent to Safe Yield

Nipomo Mesa Groundwater Resource Capacity Study
San Luis Obispo County, California

Collection of References:

Sophocleous, M., 1997, Managing water resources systems: why "safe yield" is not sustainable: Ground Water, v. 35, no. 4, p. 561.

Bredehoeft, J., 1997, Safe yield and the water budget myth: Ground Water, v. 35, no. 6, p. 929.

Bredehoeft, J., 2002, The Water Budget Myth Revisited: Why Hydrogeologists Model: Ground Water, v. 40, no. 4, p. 340-345.

EDITORIAL

MANAGING WATER RESOURCES SYSTEMS: WHY "SAFE YIELD" IS NOT SUSTAINABLE

by Marios Sophocleous[a]

Although major gaps in our understanding of soil and water ecosystems still exist, of more importance are the gaps between what is known and what is applied. One such gap is in the use of the concept of "safe yield" (SY) in ground-water management. Despite being repeatedly discredited in the literature, SY continues to be used as the basis of state and local water-management policies, leading to continued ground-water depletion, stream dewatering, and loss of wetland and riparian ecosystems.

Traditionally, "safe yield" has been defined as the attainment and maintenance of a long-term balance between the amount of ground water withdrawn annually and the annual amount of recharge. Thus, SY limits ground-water pumping to the amount that is replenished naturally. Unfortunately, this concept of SY ignores discharge from the system. Under natural or equilibrium conditions, recharge is balanced, in the long term, by discharge from the aquifer into a stream, spring, or seep. Consequently, if pumping equals recharge, eventually streams, marshes, and springs dry up. Continued pumping in excess of recharge also eventually depletes the aquifer. This has happened in various locations across the Great Plains. Maps comparing the perennial streams in Kansas in the 1960s to those of the 1990s show a marked decrease in miles of streamflow in the western third of the state. (For more information on SY, see the edited volume by Sophocleous, 1997, "Perspectives on Sustainable Development of Water Resources in Kansas," Kansas Geological Survey, Bulletin 239, in press.) Policymakers are primarily concerned about aquifer drawdown and surface-water depletion, both unrelated to the natural recharge rate. Despite its irrelevance, natural recharge is often used in ground-water policy to balance ground-water use under the banner of SY. Adopting such an attractive fallacy does not provide scientific credibility.

To better understand why "safe yield" is not sustainable yield, a review of hydrologic principles (concisely stated by Theis in 1940) is required. Under natural conditions, prior to development by wells, aquifers are in a state of approximate dynamic equilibrium: over hundreds of years, recharge equals discharge. Discharge from wells upsets this equilibrium by producing a loss from aquifer storage. A new state of dynamic equilibrium is reached only by an increase in recharge (induced recharge), a decrease in natural discharge, or a combination of the two. Initially, ground water pumped from the aquifer comes from storage, but ultimately it comes from induced recharge. The timing of this transition, which takes a long time by human standards, is a key factor in developing sustainable water-use policies. However, it is exceedingly difficult to distinguish between natural recharge and induced recharge to ascertain possible sustained yield. This is an area that needs further research. Calibrated stream-aquifer models could provide some answers in this regard.

The concept of sustainable yield has been around for many years, but a quantitative methodology for the estimation of such yield has not yet been perfected. A suitable hydrologic basis for determining the magnitude of possible development would be a quantification of the transition curve (from ground-water storage depletion to full reliance on induced recharge), coupled with a projected pattern of drawdown for the system under consideration. The level of ground-water development would be calculated using specified withdrawal rates, well-field locations, drawdown limits, and a defined planning horizon. Stream-aquifer models are capable of generating the transition curve for most situations.

Another problem with SY is that it has often been used as a single-product exploitation goal—the number of trees that can be cut, the number of fish that can be caught, the volume of water that can be pumped from the ground or river, year after year, without destroying the resource base. But experience has repeatedly shown that other resources inevitably depend on the exploited product. We can maximize our SY of water by drying up our streams, but when we do, we learn that the streams were more than just containers of usable water.

A better definition of SY would address the sustainability of the system—not just the trees, but the whole forest; not just the fish, but the marine food chain; not just the ground water, but the running streams, wetlands, and all the plants and animals that depend on it. Given the dynamic connectedness of a watershed, management activities can fragment the habitat "patches" if they are not planned and implemented from an ecosystem and watershed perspective. Such a holistic approach, however, is fraught with difficulty. We cannot use a natural system without altering it, and the more intensive and efficient the use, the greater the alteration.

Science will never know all there is to know. Rather than allowing the unknown or uncertain to paralyze us, we must apply the best of what we know today, and, at the same time, be flexible enough to allow for change and for what we do not yet know. Instead of determining a fixed sustainable yield, managers should recognize that yield varies over time as environmental conditions vary.

Our understanding of the basic principles of soil and water systems is fairly good, but our ability to use this knowledge to solve problems in complex local and cultural settings is relatively weak. Communication is vital. We need people who can transfer research findings to the field and who can also communicate water-users' needs to the researchers. Delivering a journal publication to a manager's desk is not sufficient to ensure that research results are quickly put into practice. I believe this breakdown in communication accounts for the persistence of such misguided concepts as SY in ground-water management today. Researchers increasingly must cross the boundaries of their individual disciplines, and they must look to their clients—the managers and water users—for help in defining a practical context for research. A strong public education program is also needed to improve understanding of the nature and complexity of ground-water resources and to emphasize how this understanding must form the basis for operating conditions and constraints. This is the only way to positively influence, for the long term, the attitudes of the various stakeholders involved.

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GROUND WATER

Editorial

Safe Yield and the Water Budget Myth

by John Bredehoeft[a]

The editorial by Marios Sophocleous in the July-August issue of *Ground Water* is an especially important one. I agree with Marios, the idea of safe yield as it is generally expressed in which the size of a development if it is less than or equal to the recharge is considered to be "safe" is fallacious. As Marios indicates, Theis pointed out the fallacy of this notion of "safe yield" in a 1940 paper entitled: *The source of water to wells: essential factors controlling the response of an aquifer to development (Civil Engineering*, p. 277–280)—every practitioner of ground water should go back and read this paper. Theis' 1940 principle is one of the least understood concepts in ground-water hydrology.

Hilton Cooper, Stavros Papodopulos, and I reiterated Theis' paradigm in a 1982 paper entitled: *The water-budget myth (Scientific Basis of Water Management, National Academy of Sciences Studies in Geophysics*, p. 51–57). At the time, Theis said to me that this paper eliminated the need for a paper he had been contemplating. Unfortunately, our 1982 paper was printed in an obscure publication; and yet it may be one of the more important papers we wrote.

I have some additional remarks to add to Marios Sophocleous' editorial. As Marios correctly indicated, Theis stated: "*A new state of dynamic equilibrium is reached only by an increase in recharge (induced recharge), a decrease in discharge, or a combination of the two.*" Cooper, Theis, and others had a name for the sum of increased recharge plus the decreased discharge—they refer to it as capture. In order for a development to reach a new equilibrium, the capture must ultimately equal the new stress on the system, the development. Capture is dynamic, and depends upon both the aquifer geometry and the parameters (permeability and specific storage) of the system. This is why both well response and aquifer system response are so much a part of ground-water hydrology.

In my experience, the recharge, and certainly the change in recharge due to a development (induced recharge) is difficult, if not impossible, to quantify. Usually the recharge is fixed by rainfall and does not change with development. Marios leaves an impression that the change in recharge (induced recharge) is where our focus as ground-water hydrologists should be. It is on this point that we may differ.

Commonly the virgin discharge is what changes and makes it possible to bring a ground water system into balance. Capture is a dynamic quantity that changes through time until the system reaches a new equilibrium. Usually this is what we attempt to quantify with flow models—we estimate the magnitude of the capture from the virgin (natural) discharge. It is usually much more important to focus on the discharge, and the change in discharge—the capture. Capture from the natural discharge is usually what determines the size of a sustainable development.

Pumping does not have to exceed the recharge for streams to be depleted. Pumping is an additional stress on the system. The water pumped will usually be supplied from both storage and from reduced natural discharge. We define equilibrium as a state in which there is no more change in ground-water storage with time—water levels are stable in time. If no new equilibrium can be reached, as Theis showed for the high plains aquifer of New Mexico, the aquifer will continue to be depleted. Once a new equilibrium is reached, the natural discharge is reduced by an amount equal to the development—capture equals development. This statement has nothing to do with recharge. Often streams are depleted long before the pumping reaches the magnitude of the recharge.

It is important that the profession understand the concept of safe yield. Sustainable ground-water developments have almost nothing to do with recharge; as Marios correctly states, it is irrelevant. However, I continue to hear my colleagues say they are studying the recharge in order to size a development—I heard this again last week. The water budget as it is usually applied to scale development is a myth—Theis said this in 1940. Yet the profession continues to perpetuate this wrong paradigm.

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The views expressed here are the author's and not necessarily those of the AGWSE, NGWA, and/or the Ground Water Publishing Company.

ground water

Issue Paper/

The Water Budget Myth Revisited: Why Hydrogeologists Model

by John D. Bredehoeft[1]

Abstract/

Within the ground water community, the idea persists that if one can estimate the recharge to a ground water system, one then can determine the size of a sustainable development. Theis addressed this idea in 1940 and showed it to be wrong—yet the myth continues. The size of a sustainable ground water development usually depends on how much of the discharge from the system can be "captured" by the development. Capture is independent of the recharge; it depends on the dynamic response of the aquifer system to the development. Ground water models were created to study the response dynamics of ground water systems; it is one of the principal reasons hydrogeologists model.

Introduction

The idea persists within the ground water community that if one can determine the recharge to an aquifer system then one can determine the maximum magnitude of a sustainable development. One commonly hears the statement, "the pumping must not exceed the recharge (if the development is to be sustainable)."

The idea that the recharge (by which one usually means the virgin recharge before development) is important in determining the magnitude of sustainable development is a myth. A number of hydrogeologists have tried to debunk the myth, starting with Theis (1940) in a paper titled "The Source of Water Derived from Wells: Essential Factors Controlling the Response of an Aquifer to Development." Brown (1963) and Bredehoeft et al. (1982) wrote papers debunking the myth. Unfortunately, the message in Brown's paper was apparent only to those deeply schooled in ground water hydrology. The Bredehoeft et al. paper, while more readily understandable, was published in an obscure National Academy of Science publication that is out of print. At the time the Bredehoeft et al. paper was published, Theis congratulated the authors, commenting that he had intended to write another paper on the subject, but now he did not see the need. Needless to say, in spite of these efforts the myth goes on; it is so ingrained in the community's collective thinking that nothing seems to derail it.

It is presumptuous and perhaps arrogant of me to imply that the entire community of ground water hydrologists does not understand the principles first set forth by Theis in 1940; clearly this is not the situation. There are good discussions in recent papers that indicate other hydrogeologists understand Theis' message. The 1999 USGS Circular 1186, *Sustainability of Ground-Water Resources* (Alley et al. 1999), states the ideas lucidly. Sophocleous and his colleagues at the Kansas Geological Survey have published extensively on the concept of ground water sustainability; Sophocleous (2000) presents a summary of his ideas that contain the essence of Theis' principles.

On the other hand, I do not find Theis' principles on sustainabilty expressed clearly in the texts on ground water. These ideas were taught to me, early in my career, by my mentors at the U.S. Geological Survey. Also I find in discussions with other ground water professionals that these ideas, even though they are 60 years old, are not clearly understood by many individuals. It is my purpose in this paper to address again the myth that recharge is all important in determining the size of a sustainable ground water development, and show that this idea has no basis in fact.

Analytical Methods in Hydrogeology

Before digital computer modeling codes, hydrogeologists used traditional analytical methods to assess the impacts of wells on ground water systems. The traditional method of analysis used is the principle of superposition. In this approach, one assumes that the hydraulic head (or the water table) before development resulted from the inputs and outputs (recharge and discharge) from the system. One

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analyzes the impact of pumping independent of the initial (virgin) hydraulic head. The cone of depression is calculated as a function of time. This cone of depression is then superposed upon the existing hydraulic head (or water table). The resulting head after superposition is the solution to the development.

To make such a superposition calculation, one needs: (1) the transmissivity and storativity distribution within the aquifer, (2) the boundary conditions that will be reached by the cone of depression, and (3) the rate of pumping. Those trained in classical hydraulic theory are well aware of reflection boundaries and image wells to account for the boundary conditions.

Missing from the classical analysis is any mention of recharge. The recharge is taken into account by the initial hydraulic head (or the water table). The initial head is a solution to an initial boundary value problem that includes the recharge and discharge.

Prior to the widespread use of digital computer models most analyses in ground water flow were made using the principles of superposition. This was also the methodology used in the analog computer models of the 1950s, '60s, and '70s. With the advent of digital computer models, it became feasible to specify the varying distributions of recharge and discharge with the idea of solving for the virgin water table. The calculated water table can then be compared to the observed water table (or hydraulic head). To do such an analysis requires knowledge of the distribution of both the virgin rate of recharge and the virgin rate of discharge—in addition to the transmissivity distribution and the boundary conditions.

With an estimate of the rainfall, there is still no idea of how large the recharge is, except that it cannot exceed some unknown fraction of rainfall. The researcher may know the transmissivity of the aquifer at a few places and the aquifer discharge that makes up the baseflow of streams associated with the aquifer. Based on this set of limited information, a steady-state model analysis is made in an attempt to estimate the transmissivity of the aquifer. This is a common model analysis. In this context, knowledge of the virgin recharge is useful in estimating the transmissivity.

The recharge and the discharge are the inputs and outputs from a ground water system. Both quantities are important in understanding how a particular ground water system functions. However, it is not my purpose in this paper to discuss recharge or discharge. My focus is on how recharge and discharge enter into the determination of the sustainable yield of a ground water system.

In the classical analytical method, the important variables for determining the impacts of pumping are those that describe the dynamic response of the system—the distribution of aquifer diffusivity and the boundary conditions. This argument was the thrust of Brown's 1963 paper. The argument makes sense to one trained in classical analytical methods; it is more obscure to others. Brown's paper made almost no impact. I will attempt to further simplify the mathematical argument.

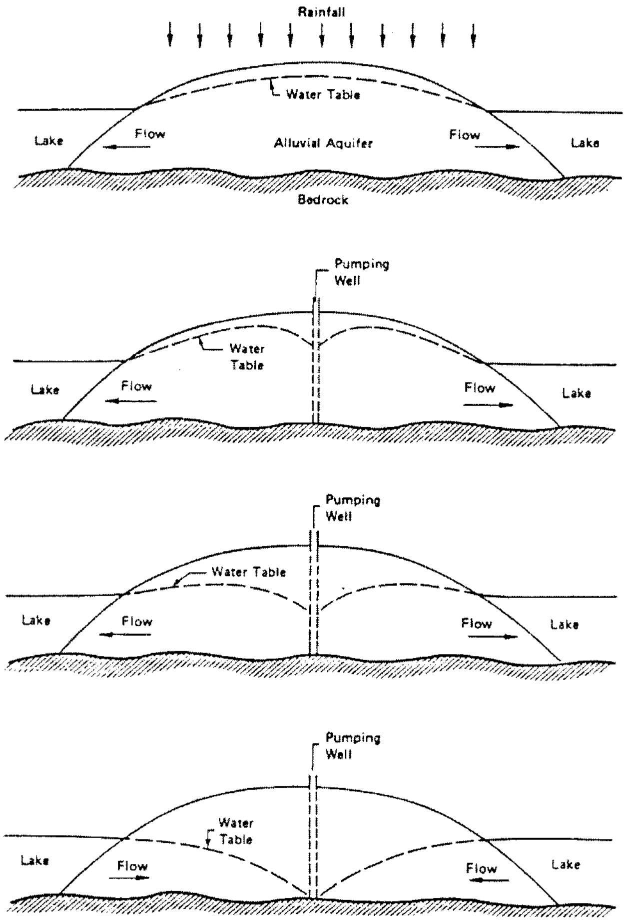

Figure 1. Schematic cross section of an aquifer situated on a circular island in a fresh water lake that is being developed by pumping. (Reprinted with permission from *Scientific Basis of Water-Resource Management*. Copyright 1982 by the National Academy of Sciences. Courtesy of the National Academy Press, Washington, D.C.)

The Water Budget

To illustrate the basic premise, I want to consider a simple aquifer system. A permeable alluvial aquifer underlies a circular island in a fresh water lake. Our intent is to develop a well on the island. The island aquifer is shown schematically in various stages of development in Figure 1.

Before development, recharge from rainfall creates a water table. The recharge over the island is balanced by discharge from the permeable aquifer directly to the lake (Figure 1—top cross section). We can write the following water balance for virgin conditions on our island:

$$R_0 = D_0 \qquad \text{or} \qquad R_0 - D_0 = 0$$

where R_0 is the virgin recharge (this is the recharge generally referred to in the myth), and D_0 is the virgin discharge. A water table develops on the island in response to the distribution of recharge and discharge and the transmissivity of the alluvial aquifer (Figure 1—top cross section).

The discharge to the lake can be obtained at any point along the shore by applying Darcy's law:

$$d = T\,(dh/dl)$$

where d is the discharge through the aquifer at any point along the shore; T is the transmissivity at the same point; and dh/dl is the gradient in the water table at that point. If we integrate the point discharge along the entire shoreline of the island we obtain the total discharge from the island:

$$\int T\,(dh/dl)\,ds = D_0$$

We now go into the middle of the island, install a well and initiate pumping (Figure 1—second cross section). At any new time, we can write a new water balance for the island:

$$(R_0 + \Delta R_0) - (D_0 + \Delta D_0) - P + dV/dt = 0$$

where ΔR_0 is the change in the virgin rate of recharge caused by our pumping; ΔD_0 is the change in the virgin rate of discharge caused by the pumping; P is the rate of pumping; and dV/dt is the rate at which we are removing water from ground water storage on the island.

We know that the virgin rate of recharge, R_0, is equal to the virgin rate of discharge, D_0, so our water budget equation following the initiation of pumping reduces to

$$\Delta R_0 - \Delta D_0 - P + dV/dt = 0$$

or

$$\Delta R_0 - \Delta D_0 - P = dV/dt$$

For a sustainable development, we want the rate of water taken from storage to be zero; in other words, we define sustainability as

$$dV/dt = 0$$

Now our water budget for sustainable development is

$$\Delta R_0 - \Delta D_0 = P$$

We are now stating that, to reach a sustainable development, the pumping must be balanced by a change in the virgin rate of recharge, ΔR_0, and/or a change in the virgin rate of discharge, ΔD_0, caused by the pumping. Traditionally, the sum of the change in recharge and the change in discharge caused by the pumping, the quantity $(\Delta R_0 - \Delta D_0)$, is defined as the "capture" attributable to the pumping. To be a sustainable development, the rate of pumping must equal the rate of capture.

Notice that to determine sustainability we do not need to know the recharge. The recharge may be of interest, as are all the facets of the hydrologic budget, but it is not a determining factor in our analysis.

Recharge is often a function of external conditions—such as rainfall, vegetation, and soil permeability. In many, if not most, ground water situations, the rate of recharge cannot be impacted by the pumping; in other words, in terms of our water budget,

$$\Delta R_0 = 0$$

In most situations, sustainability of a ground water development occurs when the pumping captures an equal amount of virgin discharge:

$$P = \Delta D_0$$

Let's return to the island aquifer and see how the capture occurs conceptually. When we start to pump, a cone of depression is created. Figure 1 (second cross section) shows the cone of depression at an early stage in the development of our island aquifer. The natural discharge from the island does not start to change until the cone of depression changes the slope in the water table at the shore of the island; remember: Darcy's law controls the discharge at the shoreline. Until the slope of the water table at the shoreline is changed by the pumping, the natural discharge continues at its virgin rate. Until the point in time that the cone reaches the shore and changes the water table gradient significantly, all water pumped from the well is supplied totally from storage in the aquifer. In other words, the cone of depression must reach the shoreline before the natural discharge is impacted (Figure 1—third cross section). The rate at which the cone of depression develops, reaches the shoreline, and then changes the slope of the water table there depends on the dynamics of the aquifer system—transmissivity, storativity (or specific yield), and boundary conditions. The rate of capture in a ground water system is a problem in the dynamics of the system. Capture has nothing to do with the virgin rate of recharge; the recharge is irrelevant in determining the rate of capture.

Figure 1 (third cross section) shows the water table in our island aquifer at a point in time when the natural discharge is almost eliminated; the slope of the water table is almost flat at the shoreline. I deliberately created an aquifer system in which one can induce water to flow from the lake into the aquifer (Figure 1—fourth cross section). In this instance, the sustainable development can exceed the virgin recharge (or the virgin discharge). This again suggests that the recharge is not a relevant input in determining the magnitude of a sustainable development.

Often the geometry of the aquifer restricts the capture. For example, were the aquifer on the island to be thin, we might run out of water at the pump long before we could capture any fraction of the discharge. In this case all water pumped would come from storage. It would be "mined." In the island example, with a thin aquifer, the well could run dry before it could impact the discharge at the shoreline. Notice in Figure 1 (fourth cross section) that I have drawn the situation where the drawdown reached the bottom of the aquifer; the aquifer geometry and diffusivity limit the potential drawdown at the well. This again points out that the dynamic response of the aquifer system is all-important to determining the impacts of development. It is for these reasons that hydrogeologists are concerned with the dynamics of aquifer system response. Hydrogeologists model aquifers in an attempt to understand their dynamics.

Clearly, the circular island aquifer is a simple system. Even so, the principles explained in terms of this simple aquifer apply to all ground water systems. It is the dynamics of how capture takes place in an aquifer that ultimately determines how large a sustainable ground water development can be.

Water Law in the West

Nevada recognized in the early 1900s that the water supply for many of the valleys within the state would have to come totally from local ground water. Enlightened individuals in Nevada decided to attempt to make the ground water supply within these valleys sustainable. The total discharge in many of the closed valleys in Nevada is by evaporation from the playas and from the transpiration (evapotranspiration [ET]) of phreatophytic plants that tap the water table. Nevada was willing to let the ground water pumping capture both the evaporation of ground water and the ground water that went to support the phreatophytic plants. This thinking led to the Nevada Doctrine that ground water pumping must not exceed the recharge. Perhaps the Nevada Doctrine perpetuates the myth. In reality the Nevada Doctrine is a roundabout statement that the development must not exceed the potential capture of ET (because as shown previously, the virgin ET is equal to the virgin rate of recharge).

As an aside, it has been difficult for the state engineer in Nevada to administer this doctrine in places of heavy urbanization such as Las Vegas, even though Nevada law codified the doctrine. The law also has been difficult to administer where discharge from a valley occurs as perennial streamflow (surface water) that is already appropriated.

The case of the perennial stream with an associated aquifer raises the problem of stream depletion, where pumping impacts streamflow that is appropriated by downstream users. Again, stream depletion is a dynamic ground water problem in capture—all the principles of the simple island example apply. Western water law recognizes the process of stream depletion with varying degrees of success—from zero to full recognition, depending upon the particular state.

Aquifer Dynamics and Models

Since the development of the Theis equation in 1935, hydrogeologists have been concerned with the dynamics of aquifer response to stress: pumping or recharge. Once Theis (1935) and later Jacob (1940) showed the analogy of ground water flow to heat flow, the ground water community has been busy solving the appropriate boundary value problems that describe various schemes of development. This endeavor has gone through several stages.

The 1940s and 1950s were a time during which the ground water profession was concerned with solving the problems of flow to a single well. Numerous solutions to the single well problem were produced. These solutions were used both to predict the response of the aquifer system and to estimate aquifer properties—transmissivity (or permeability) and storativity.

Hydrogeologists of that day saw the limitations in analyzing wells and sought a more robust methodology by which to analyze an entire aquifer, including complex boundary conditions and aquifer heterogeneity. The search led a group at the U.S. Geological Survey (USGS) to invent the analog model in the 1950s; the genius behind this development was Herb Skibitski, one of those individuals who rarely published. The new tool was the electric analog computer model of the aquifer. The model consisted of a finite-difference network of resistors and capacitors. In the analog computer, aquifer transmissivity is represented by the network of resistors; the storativity is represented by the network of capacitors. The resulting resistor-capacitor network is excited by electrical function generators that simulate pumping or other stresses. Voltage is equivalent to hydraulic head in the analog computer; electrical current is equivalent to the flow of water.

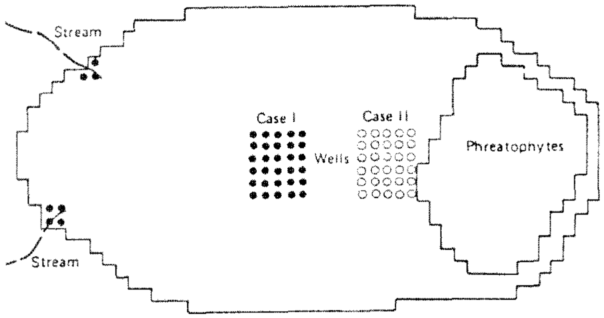

Figure 2. Plan view of a hypothetical closed basin aquifer that is being developed. (Reprinted with permission from *Scientific Basis of Water-Resource Management.* Copyright 1982 by the National Academy of Sciences. Courtesy of the National Academy Press, Washington, D.C.)

In reality, these were elegant finite-difference computer models of aquifer systems. By 1960, the USGS had a facility in Phoenix, Arizona, where analog models of aquifers were routinely built on a production basis. Some of these analog models had multiple aquifers; some had as many as 250,000 nodes. At the time, it was infeasible to solve the same problems with digital computers; the digital computers of the day were too small and too slow. However, by 1970 the power of digital computers increased to the point that digital aquifer models could begin to compete with the analog models. By 1980 digital computer models had replaced the analog models, even at the USGS. The models of the 1980s have now grown to include solute transport, pre- and postprocessors, and automatic parameter estimation. By far the vast majority of ground water flow problems are simulated using the USGS code MODFOW; there is a new version MODFLOW 2000.

The ground water model is a tool with which to investigate the dynamics of realistic aquifer systems. As suggested previously, it is only through the study and understanding of aquifer dynamics that one can determine the impact of an imposed stress on an aquifer system.

Dynamics of a Basin and Range Aquifer

To illustrate the dynamic response of aquifers, I will use closed basin aquifers such as those in the Basin and Range of Nevada as the prototypes. The aquifer geometry is illustrated in plan view in Figure 2. The basin is approximately 50 miles in length by 25 miles in width. At the upper end of the valley, two streams emerge from the nearby mountains and recharge the aquifer at an average combined rate of 100 cfs; approximately 70,000 acre-feet annually. At the lower end of the valley, an area of phreatophyte vegetation discharges ground water as ET at an average rate of 100 cfs. The system before development is in balance; 100 cfs is being recharged, and 100 cfs is being discharged by ET.

Table 1
Aquifer Properties for Our Hypothetical Basin and Range Aquifers

Basin size	50×25 miles (Figure 2)
Cell dimensions	1×1 mile
Hydraulic conductivity	0.0005 and 0.00025 ft/sec
Saturated thickness	2000 ft
transmissivity	1.0 and 0.5 ft^2/sec (approximately 90,000 and 40,000 ft^2/day—both highly transmissive)
Storage coefficient	0.1%–10% specific yield
Phreatophyte area	170 mi^2
Average consumption	100 cfs
Wellfield area	30 mi^2
Average pumping	100 cfs
Recharge	100 cfs

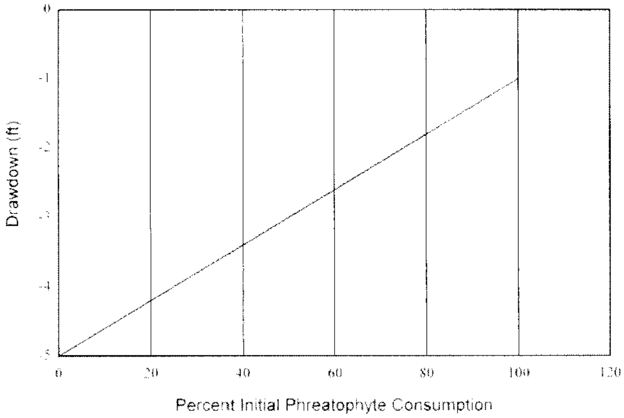

Figure 3. Linear function relating phreatophyte use to drawdown in the aquifer.

To simulate a well development in this aquifer, I will make the size of the development equal to the recharge (and the discharge) 100 cfs. We consider two locations for our wellfield, shown as Case I and Case II in Figure 2. The Case II wellfield is closer to the area of phreatophyte vegetation. To simulate the system, we need aquifer properties; the aquifer properties are specified in Table 1.

In our hypothetical system, we will eliminate phreatophyte ground water consumption as the pumping lowers the water table in the area containing phreatopyhtes. I deliberately created a ground water system in which capture of ET can occur. A linear function is used to cut off the phreatophyte consumption. As the water table drops from 1 to 5 feet, we linearly reduce the phreatophyte use of ground water—the function is shown in Figure 3. The reduction in phreatophyte use does not start until the ground water declines 1 foot; by the time the water table drops 5 feet, the phreatophyte use is eliminated in that cell. The phreatopyhte reduction function is applied cell by cell in the model.

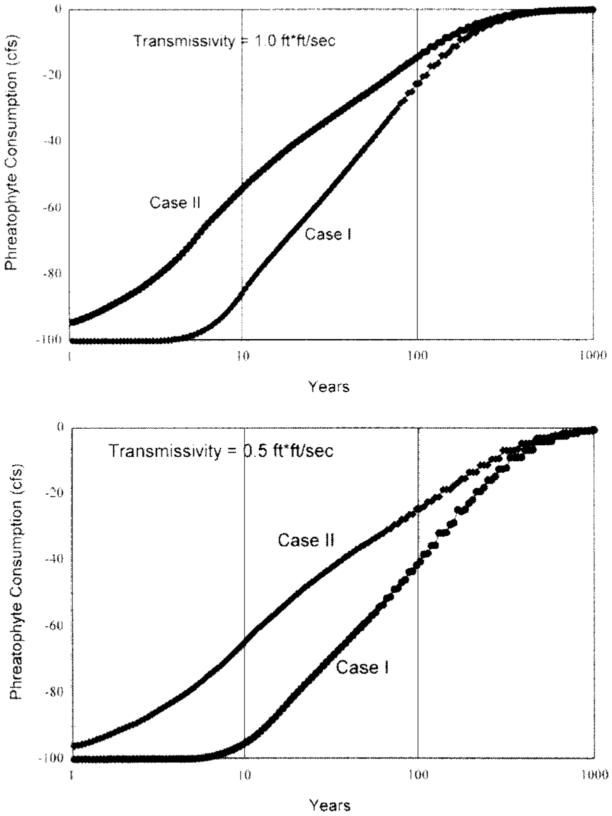

Figure 4. Plots of phreatophyte use vs. time.

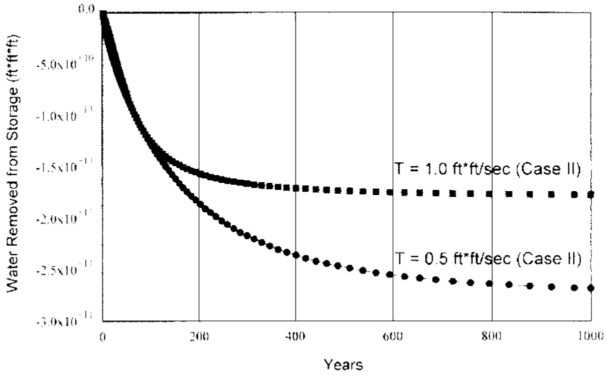

Figure 5. Plots of the change in storage vs. time.

For this system to reach a new state of sustainable yield, the phreatophyte consumption must be eliminated entirely. Using the model, we can examine the phreatophyte use as a function of time. Figure 4 is a plot of the phreatophyte use in our system versus time since pumping was initiated. I have considered two transmissivities for the hypothetical system (1.0 and 0.5 ft^2/sec); both are high transmissivities. In the higher transmissivity aquifer, the phreatophyte consumption is very small after 400 years; in other words, the system has reached a new steady state in approximately 400 years. The new steady state is a sustainable development. In the lower transmissivity case, it takes approximately 900 to 1000 years for the phreatophyte consumption to be become very small.

In both aquifers, the phreatophytes are impacted faster where the pumping is closer to the phreatopytes (Case II). The point of considering Cases I and II is to show that the location of the pumping makes a difference in the dynamic response of the system. Most individuals, even trained hydrogeologists, are surprised at how slowly a water-table ground water system, like both the two systems simulated, responds to development.

We can look at the output from the model another way by examining the total amount of water removed from storage in our aquifers (Figure 5). In the high transmissivity aquifer, the amount of water removed from storage stabilizes in ~400 to 500 years, indicating we have reached a new steady state. Figure 5 shows that something of the order of 10^{11} cubic feet (approximately 3 million acre-feet) of water has been permanently removed from storage as the system changed to reach this new steady-state condition. This illustrates the important point that water must be removed from storage to reach a new steady state (sustainable) condition. In the lower transmissivity aquifer, water is still being removed from storage at 1000 years, and we have not yet reached a new steady state. In the lower transmissivity aquifer, ~5.7 million acre-feet of water have been removed from storage in 1000 years of pumping. Figure 5 again illustrates how slowly a water table aquifer responds.

It is important to notice that, even though the two developments (Case I and Case II) are equal in size, the aquifer responds differently depending on where the developments are sited. This again emphasizes the importance of studying the dynamics of the aquifer response: the response is different depending on where the development is located.

This example of our rather simple basin and range aquifer illustrates the importance of understanding the dynamics of aquifer systems. Again, while this is a simple example, the principles illustrated apply to aquifers everywhere. It is the rate at which the phreatopyte consumption can be captured that determines how this system reaches sustainability; this is a dynamic process. Capture always entails the dynamics of the aquifer system.

Conclusions

The idea that knowing the recharge (by which one generally means the virgin rate of recharge) is important in determining the size of a sustainable ground water development is a myth. This idea has no basis in fact.

The important entity in determining how a ground water system reaches a new equilibrium is capture. How capture occurs in an aquifer system is a dynamic process. For this reason, hydrologists are occupied in studying aquifer dynamics. The principal tool for these investigations is the ground water model.

These ideas are not new; Theis spelled them out in 1940. Somehow the ground water community seems to lose sight of these fundamental principles.

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Appendix

Conversion of Relevant Units—English versus Metric

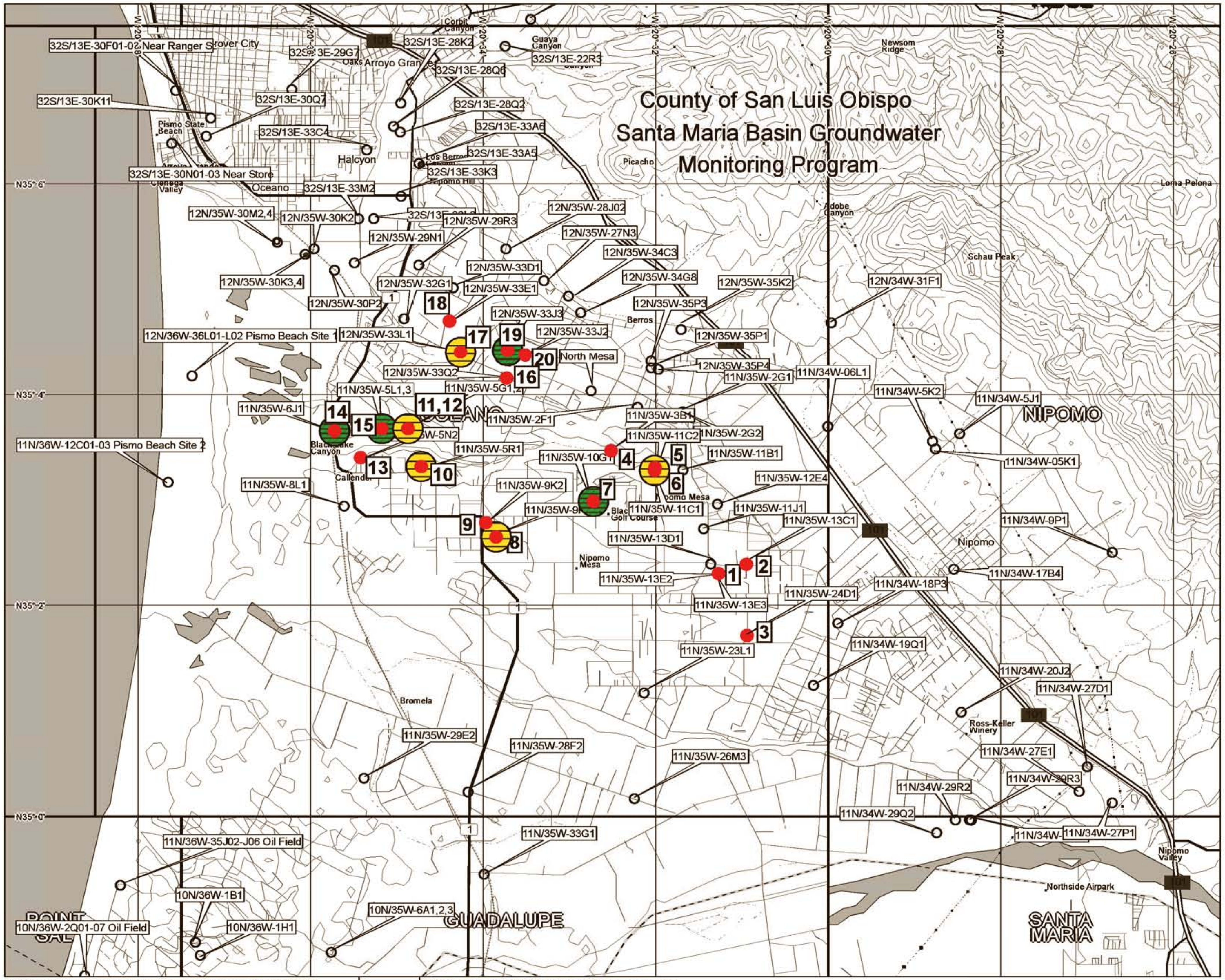
1 foot = 0.305 m
1 mile = 1.61 km
1 square foot = 0.0929 m^2
1 square mile = 2.59 km^2
1 acre-foot = 1234 m^3
1 cubic foot per second (cfs) = 0.0283 m^3/sec

Appendix C

Hydrographs for Nipomo Mesa Area

Nipomo Mesa Groundwater Resource Capacity Study
San Luis Obispo County, California

The County’s Santa Maria Basin Groundwater Monitoring Program Database is the source of data for the hydrographs.



3-D TopoQuads Copyright © 1999 DeLorme Yarmouth, ME 04096 3500 ft Scale: 1 : 87,500 Detail: 11-2 Datum: NAD27

Legend:

● Hydrograph provided herein

🟡 0ft to 10 ft MSL

🟢 Below sea level

Notes:

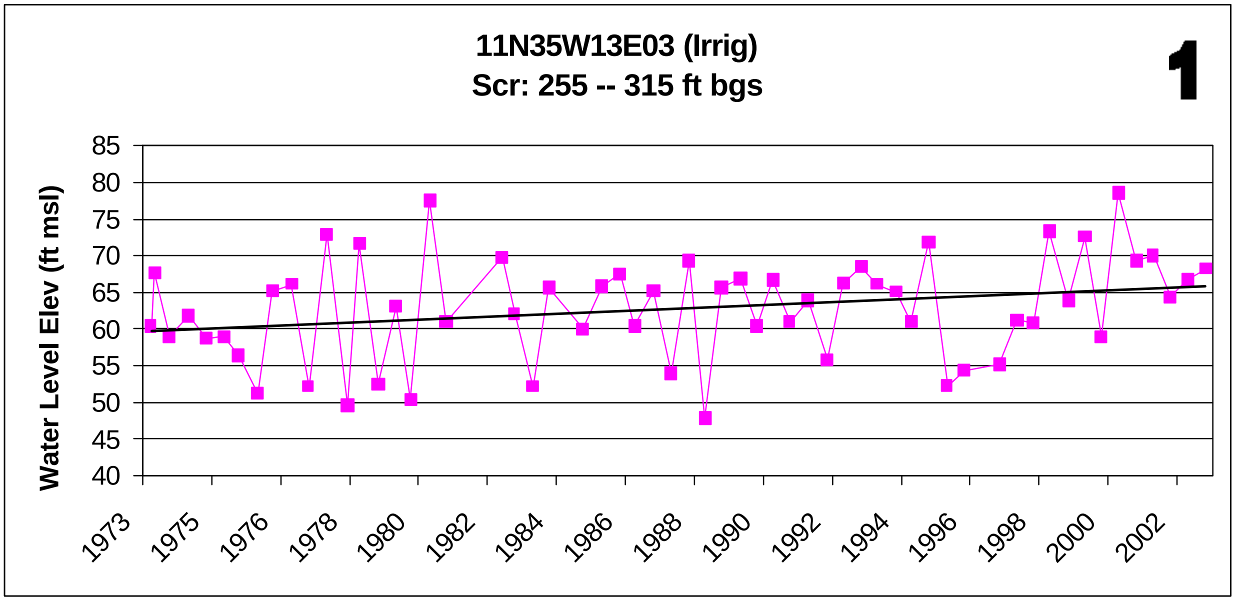
14) Non-pumping level -20 ft msl
Pumping level -30 ft msl

15) Non-pumping level -10 ft msl
Pumping level -40 ft msl

Σ²Π

LOCATIONS OF SELECTED HYDROGRAPHS
COUNTY MONITORING WELL LOCATIONS
Nipomo Mesa Water Resource Capacity Study
San Luis Obispo County, California

Figure C-1



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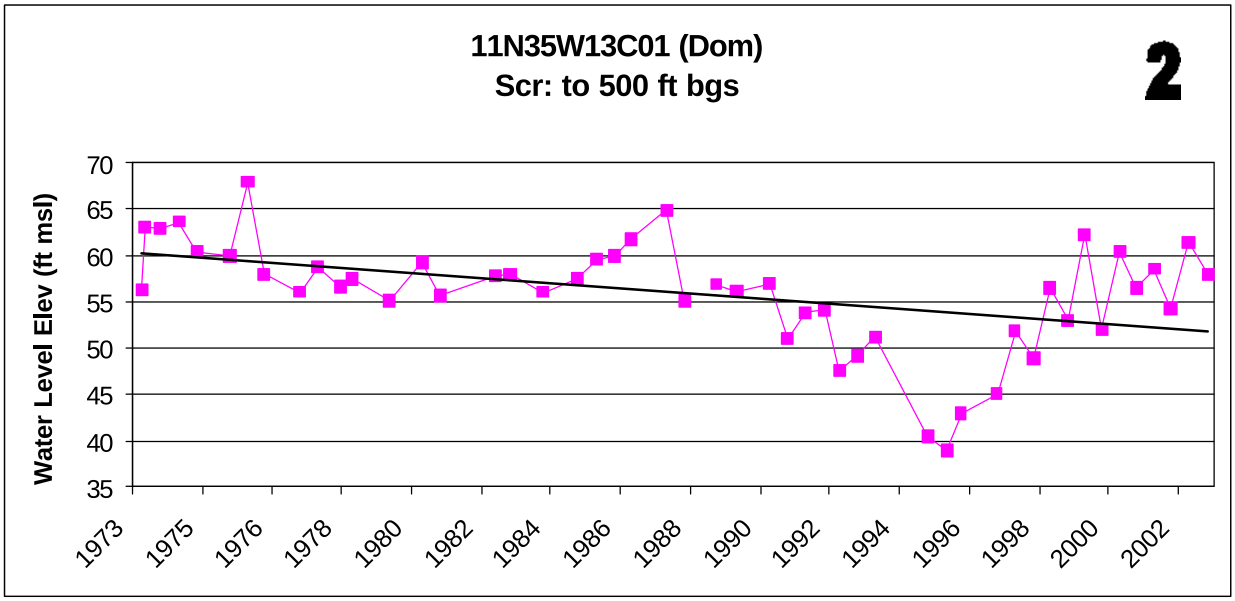
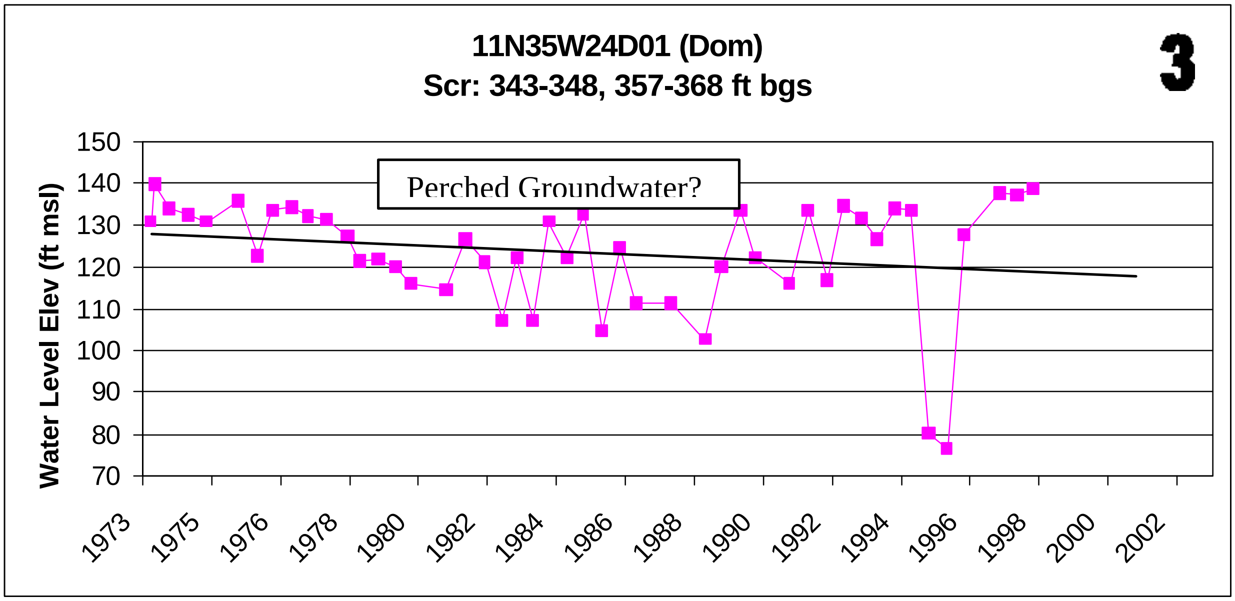


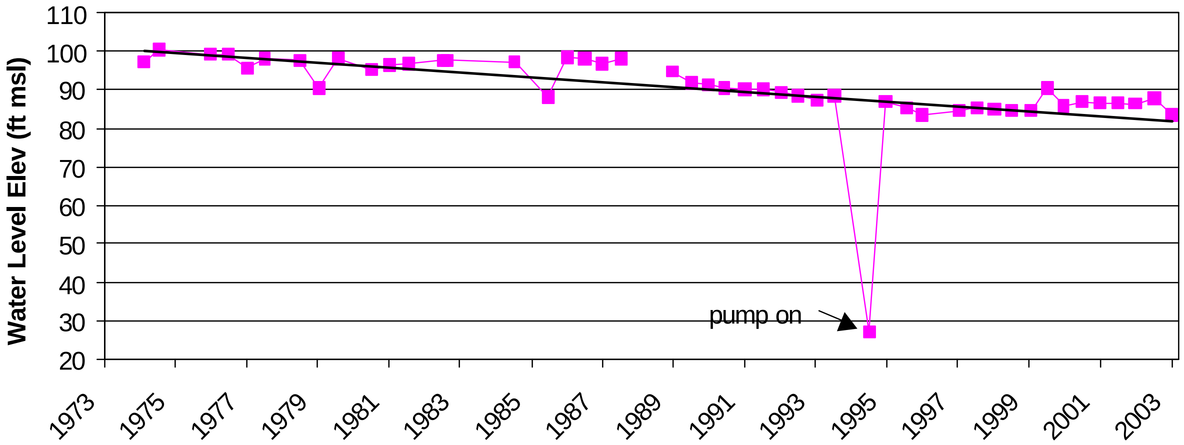
11N35W13C01 (Dom)
Scr: to 500 ft bgs



11N35W24D01 (Dom)
Scr: 343-348, 357-368 ft bgs

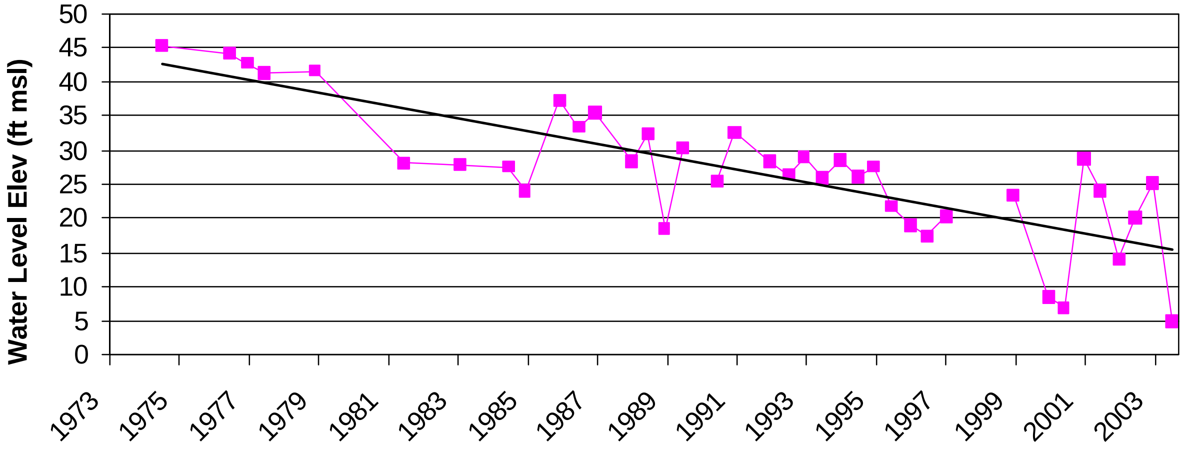
11N35W03B01 (Dom)
Scr:290-310 ft bgs

4



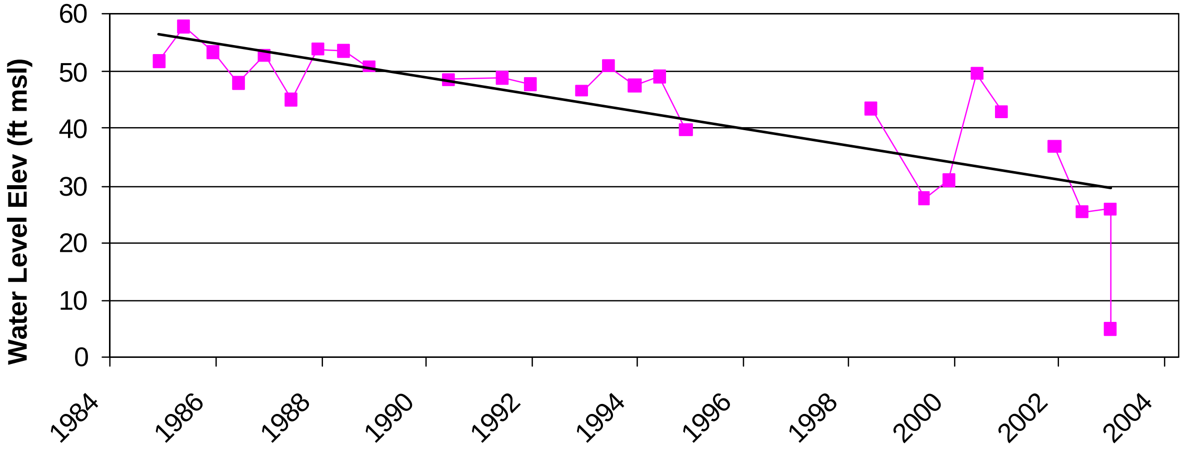
11N35W11C01 (Irrig)
Scr: 210-233/320-324 ft bgs

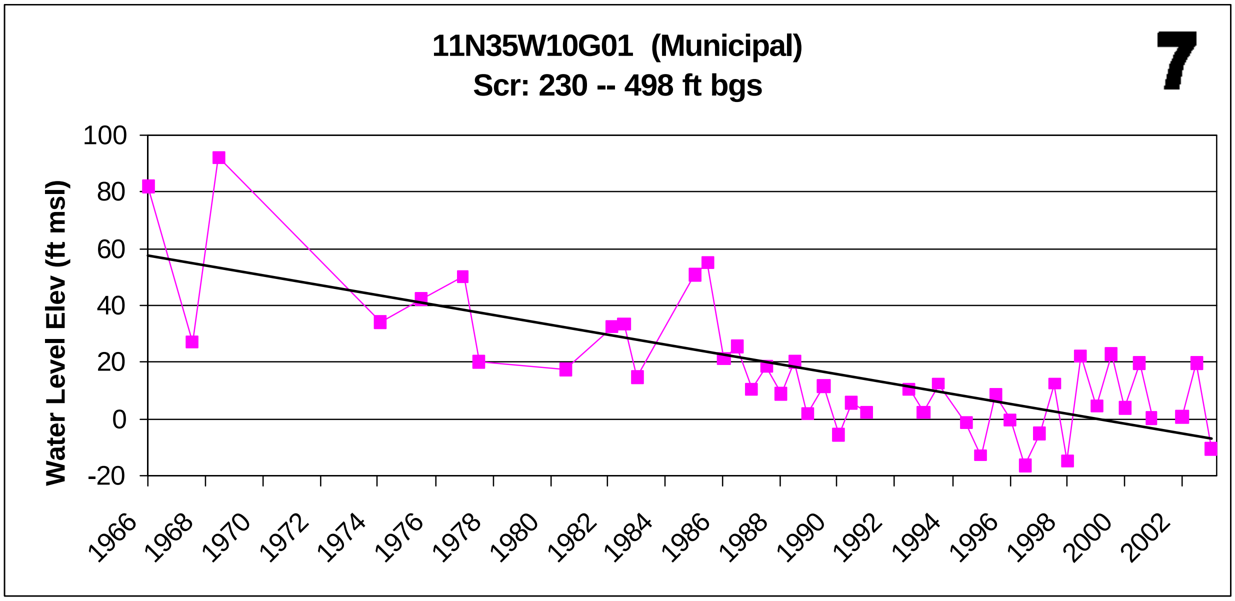
5



11N35W11C02 (Dom)
Scr: 232-312 ft bgs

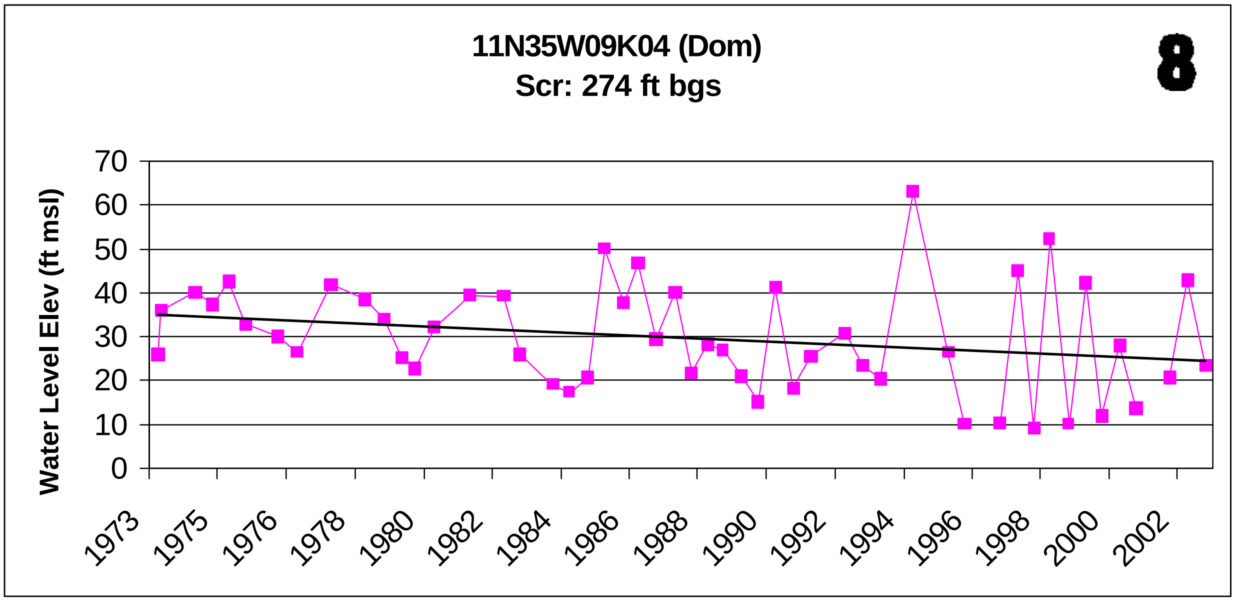
6





7

11N35W10G01 (Municipal)
Scr: 230 -- 498 ft bgs



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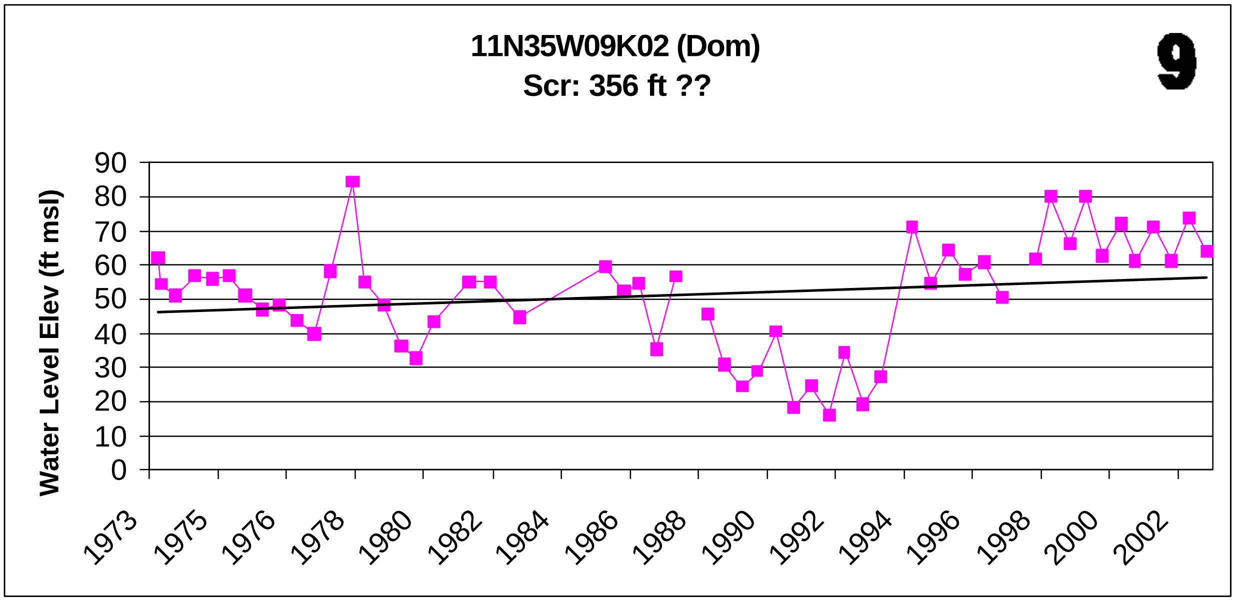
11N35W09K04 (Dom)
Scr: 274 ft bgs

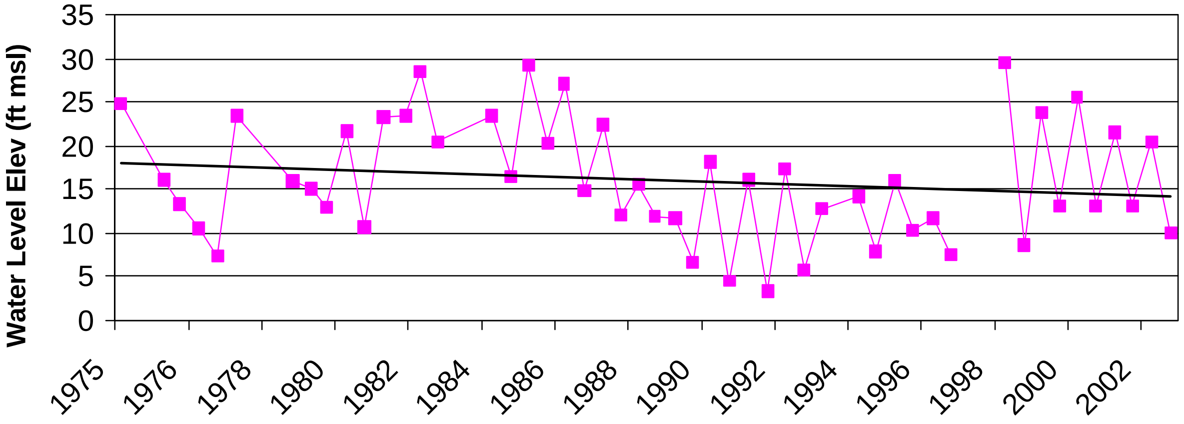


9

11N35W09K02 (Dom)
Scr: 356 ft ??

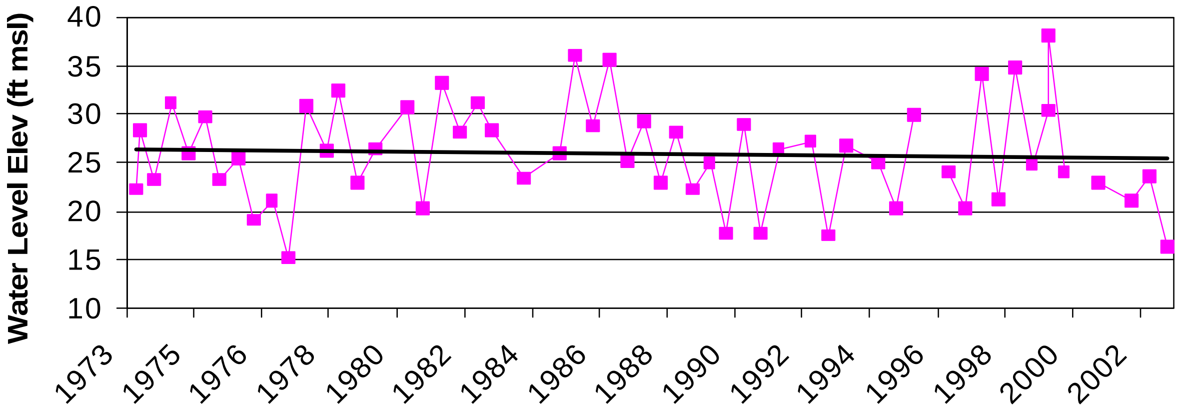
11N35W05R01 (Dom)
Scr: 220-240 ft bgs

10



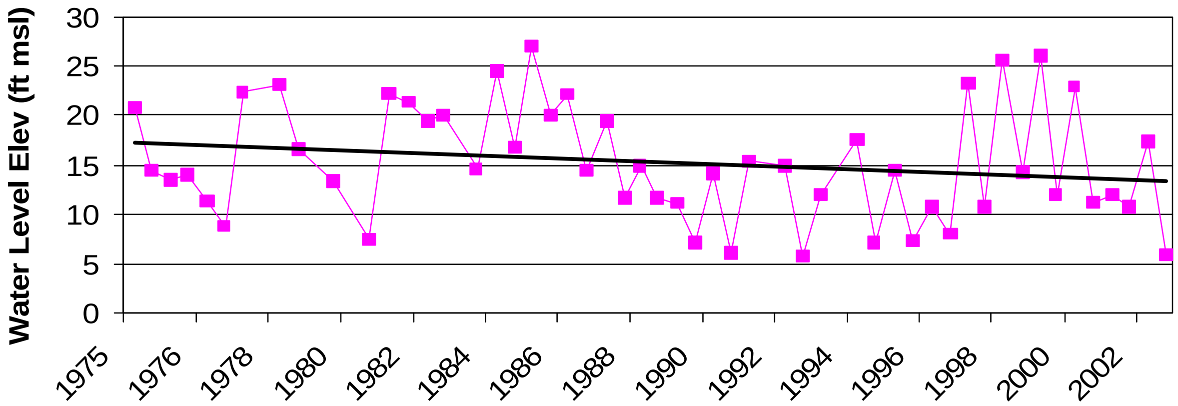
11N35W05G01 (Stock)
Scr 250-265, 165?

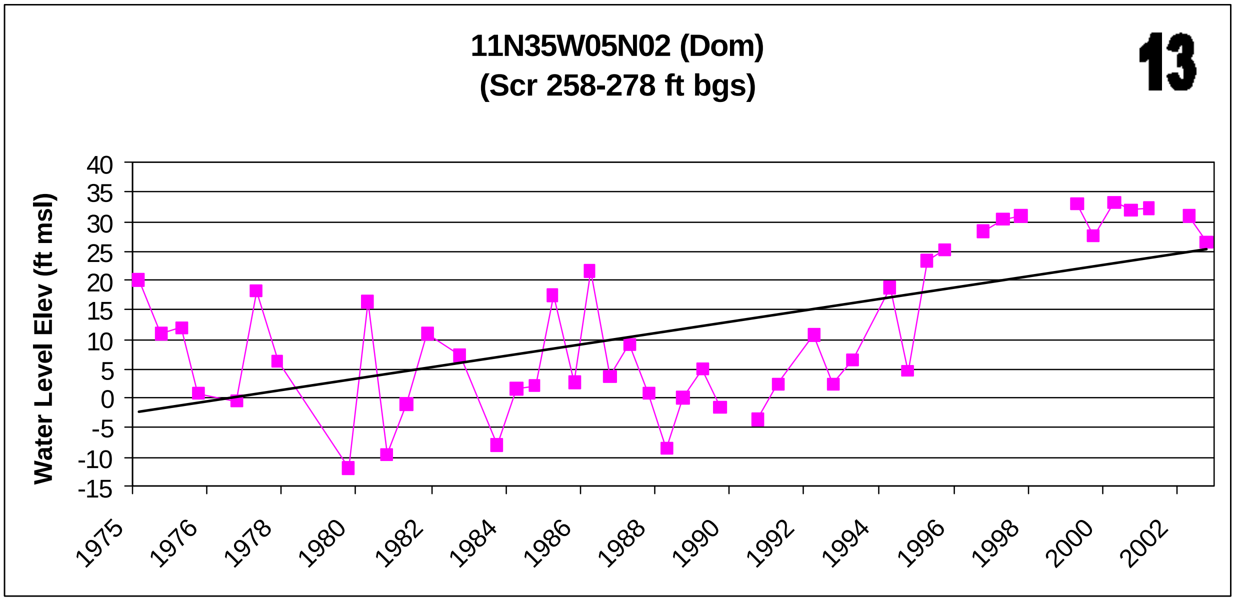
11

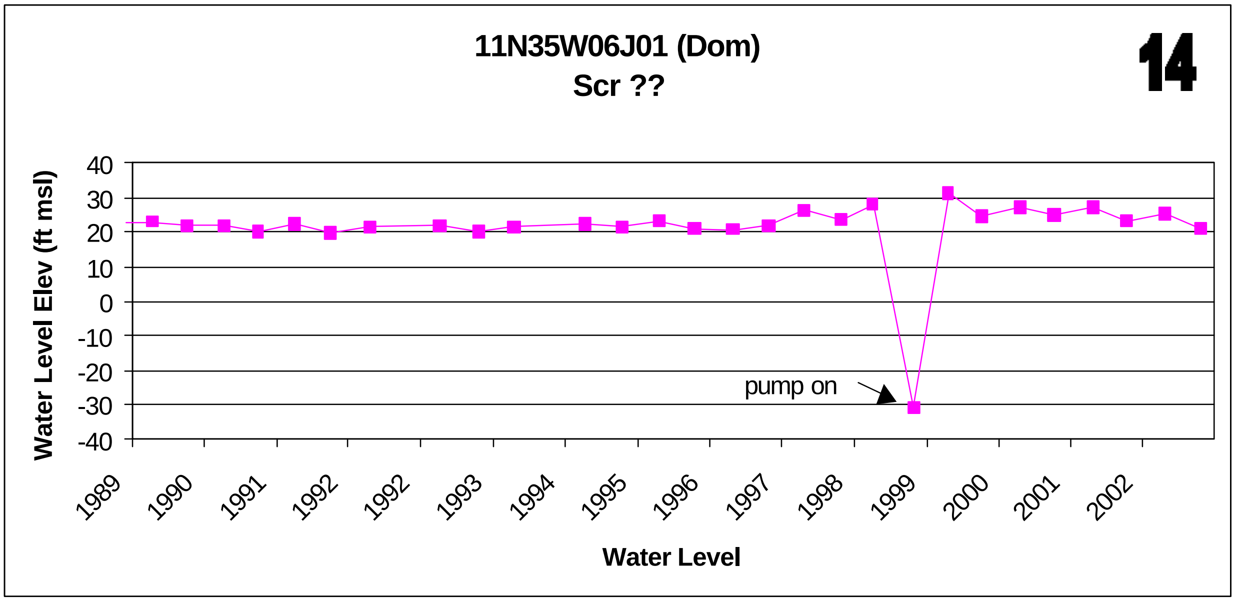


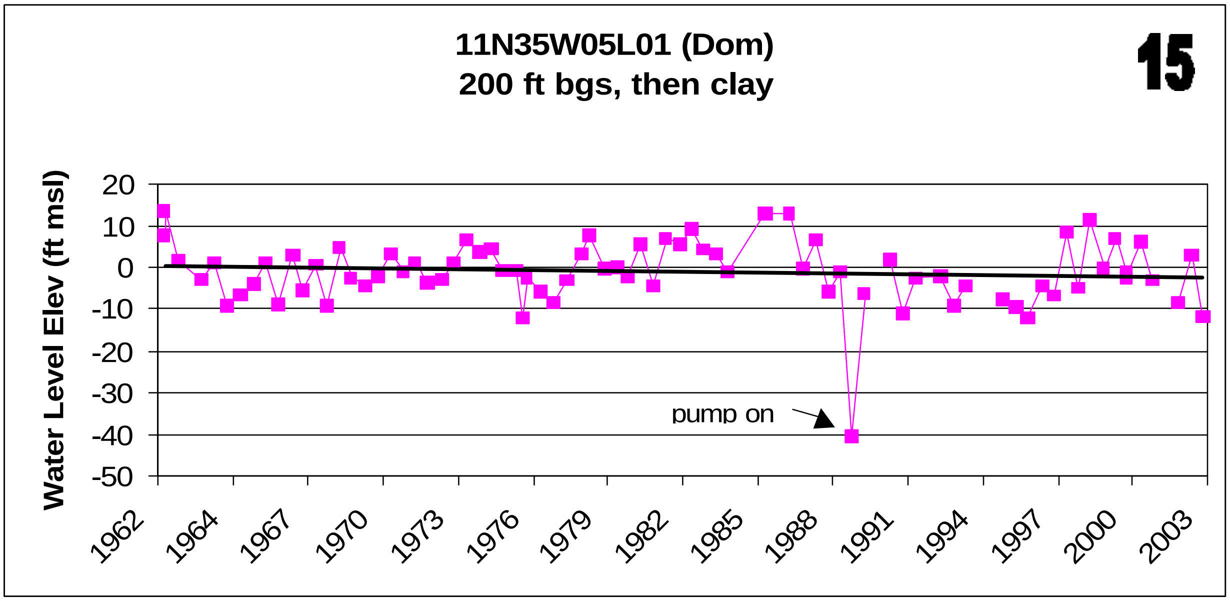
11N35W05G02 (Dom)
Scr 140+ ft bgs

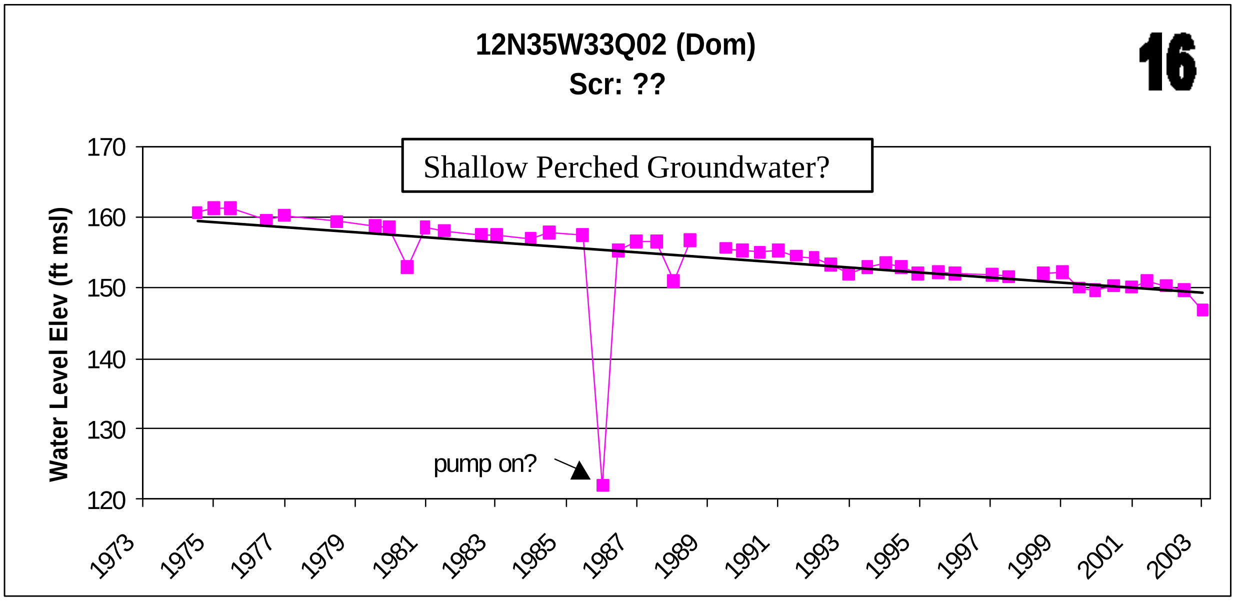
12

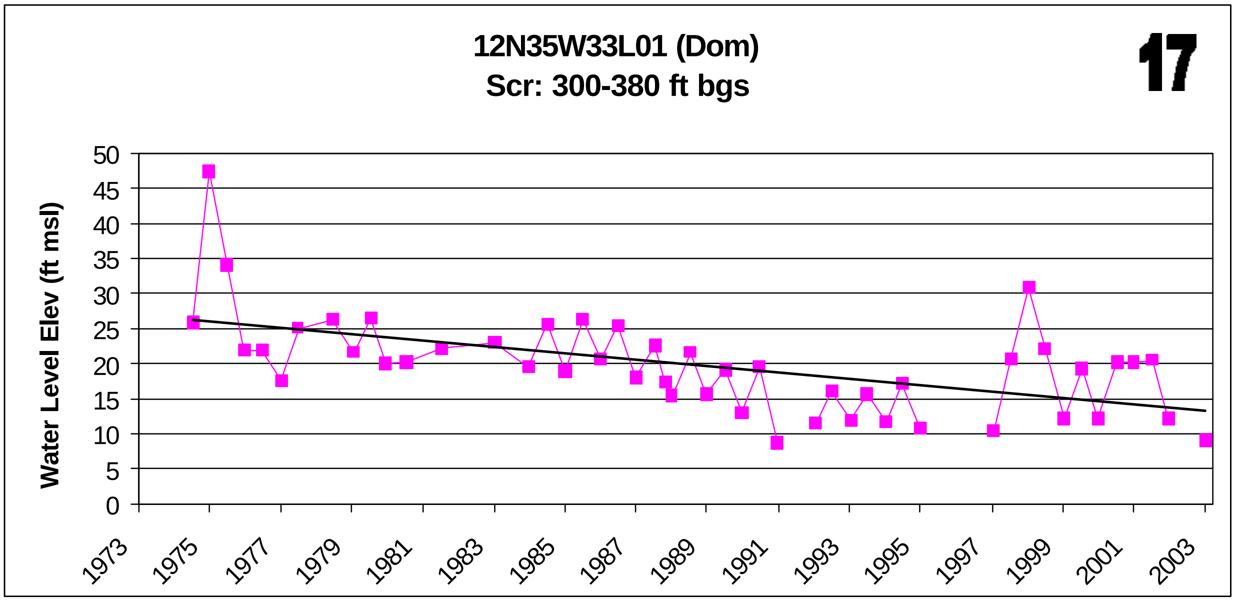


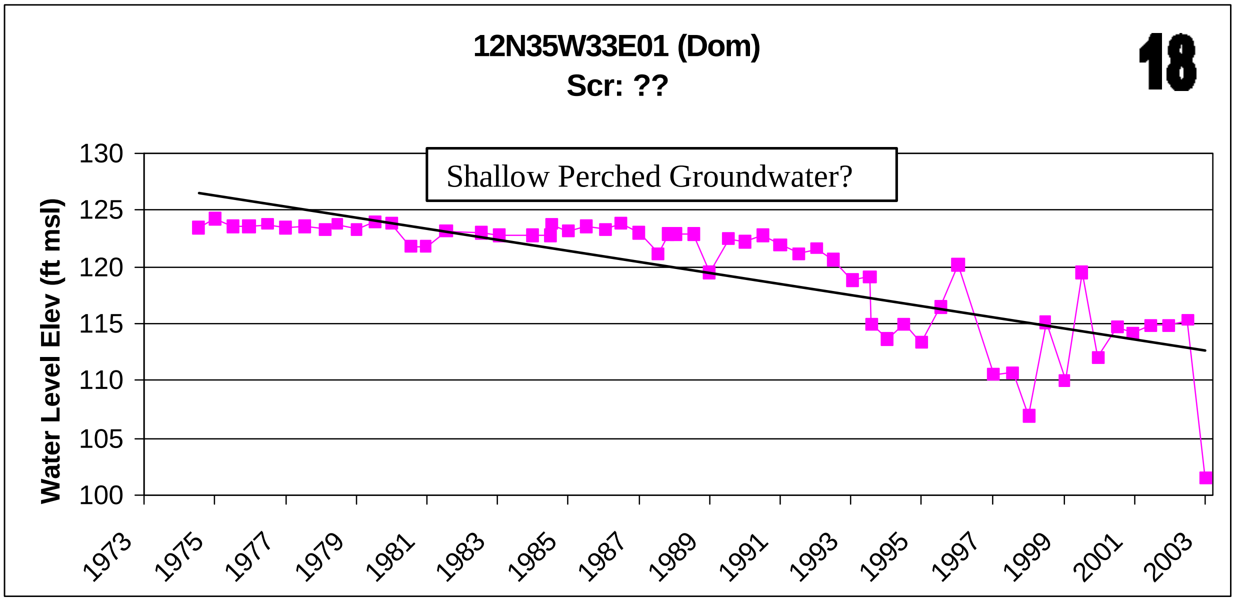

11N35W05N02 (Dom)
(Scr 258-278 ft bgs)
13
Water Level Elev (ft msl)
40
35
30
25
20
15
10
5
0
-5
-10
-15
1975
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002

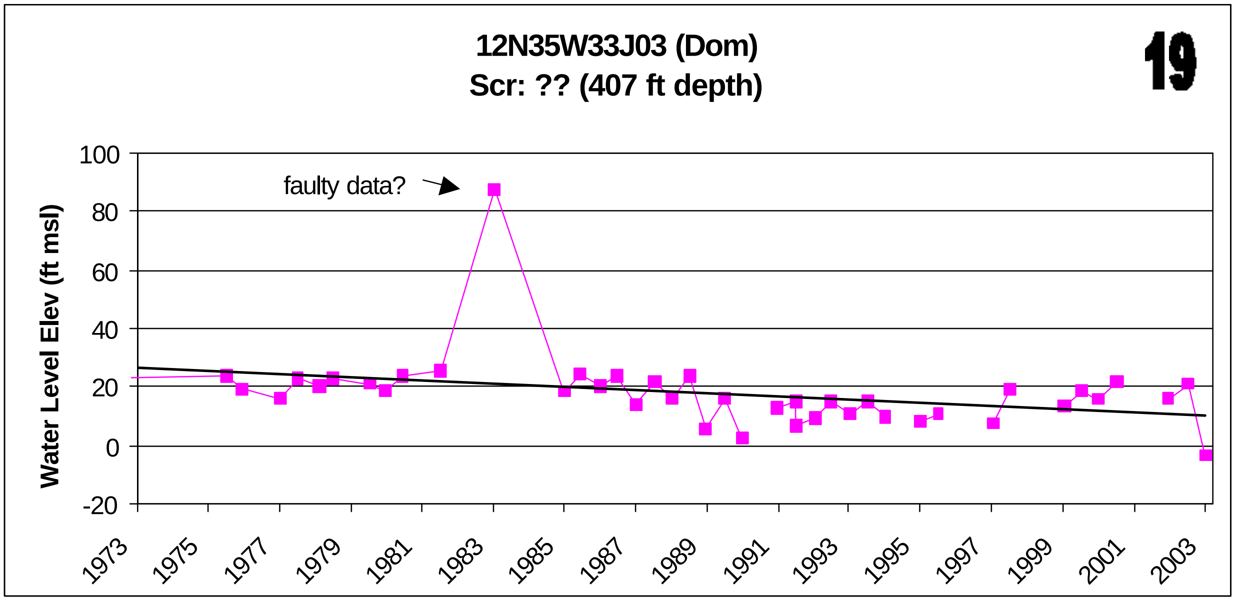

11N35W06J01 (Dom)
Scr ??
14
Water Level Elev (ft msl)
40
30
20
10
0
-10
-20
-30
-40
pump on
1989
1990
1991
1992
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
Water Level


11N35W05L01 (Dom)
200 ft bgs, then clay
15
Water Level Elev (ft msl)
20
10
0
-10
-20
-30
-40
-50
pump on
1962
1964
1967
1970
1973
1976
1979
1982
1985
1988
1991
1994
1997
2000
2003


12N35W33Q02 (Dom)
Scr: ??
16
Shallow Perched Groundwater?
pump on?
Water Level Elev (ft msl)
170
160
150
140
130
120
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003

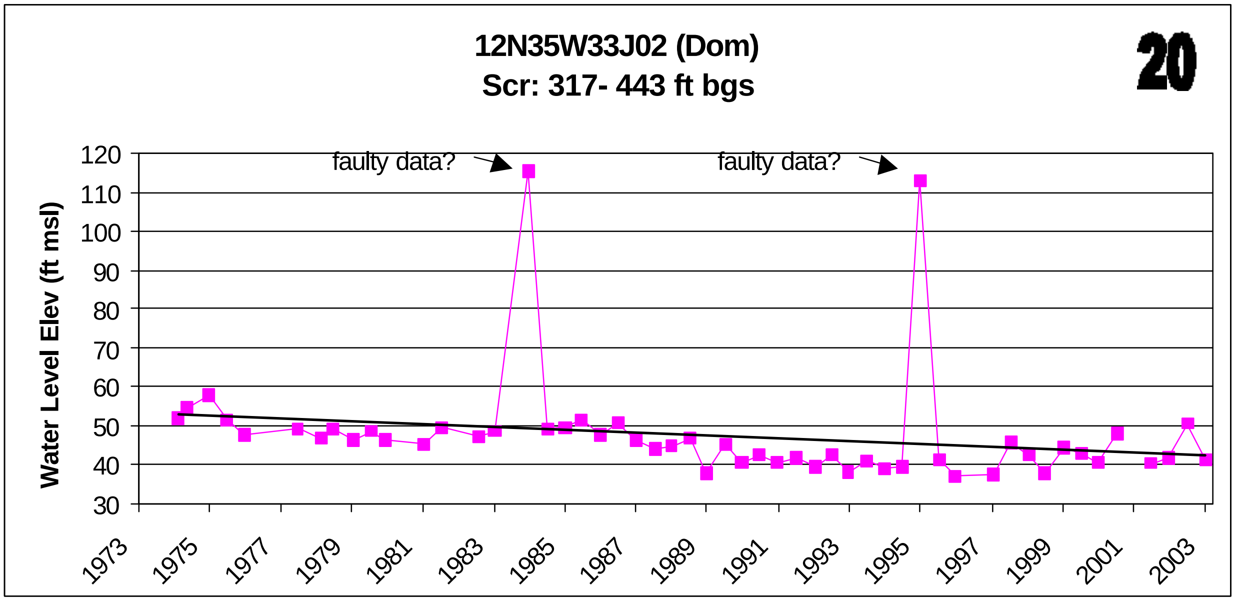

12N35W33L01 (Dom)
Scr: 300-380 ft bgs
17
Water Level Elev (ft msl)
50
45
40
35
30
25
20
15
10
5
0
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003


12N35W33E01 (Dom)
Scr: ??
18
Shallow Perched Groundwater?
Water Level Elev (ft msl)
130
125
120
115
110
105
100
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003



12N35W33J03 (Dom)
Scr: ?? (407 ft depth)

19



12N35W33J02 (Dom)
Scr: 317- 443 ft bgs

20

Appendix D

Summary Documentation of Modeling to Evaluate Saltwater Intrusion

Nipomo Mesa Groundwater Resource Capacity Study
San Luis Obispo County, California

Appendix D
Summary Description of Groundwater Models

MODLOW/MT3D Model

Modeling was conducted using MODFLOW (McDonald and Harbaugh, 1988) and MT3D (Zheng, 1990, 1999) to represent a cross-section of the coastal aquifer perpendicular coastal margin. The model cross-section is 80,000 feet long, 1000 feet deep, and consists of one row, forty 2000-foot-wide columns, and thirteen layers most of which are approximately 60 feet thick. The coastal margin is at the center of the model (40,000 feet), and the offshore slope of the model aquifer is based on bathymetric contours on the San Luis Obispo 1:100,000 USGS topographic map.

Constant head is specified at the upgradient margin and at the top layer offshore of the coastal margin to produce a horizontal hydraulic gradient of 0.00125. Uniform horizontal and vertical hydraulic conductivity of 10 and 1 ft/d, respectively, was assigned to the aquifer, and extremely high conductivity of 100,000 ft/d is assigned to the represent the sea. Aqufier storage and specific yield were assigned as 0.001 and 0.25, respectively. Initial concentration of 19,000 mg/l was specified for the sea, initial concentration of 0 mg/l was specified for the aquifer.

Pumping was simulated a distance of 15,000 feet inland of the coastal margin from a well screened from –100 to –800 ft MSL. Change in head and concentration was monitored in the middle portion of the aquifer beneath the coastal margin. Results are discussed in Section 5.3 of the report.

SEWAT Model

Modeling was also conducted using SEAWAT (Guo and Langevin, 2002), which is a specialized version of MODFLOW/MT3D that also accounts for variable fluid density. Model design and assigned properties are similar to the MODFLOW/MT3D model described above, except for the SEWAT model the discretization is much finer.

The model represents a cross-section of the aquifer system perpendicular to the coastline. It is 60,000 feet long and 900 ft deep and consists of 629 columns and 60 layers. The shoreline is at the center 30,000 ft from both ends of the model. The slope of the seafloor is based on bathymetric contours from the USGS San Luis topographic quadrangle.

Model inflow includes constant head at upland margin and uniform recharge of 4 inches per year (25% of average rainfall). Regional horizontal hydraulic gradient is approximately 0.00125. Horizontal and vertical hydraulic conductivity was assigned is 10 and 1 ft/day, respectively. Dispersivity is 50 feet.

First, the model was run without any pumping to achieve an equilibrium position for the saltwater-freshwater interface. Then pumping was assigned 15,000 from the inland from the shore at a depth interval between 100 ft to 600 ft below the water table. Increase in salinity with time a various depths 3000 feet inland of the coastline was evaluated in response to pumping 15,000 feet inland. Results are discussed in Section 5.3 of the report.