CHAPTER 4. SHALLOW GROUNDWATER HYDROLOGY

4.1. INTRODUCTION

The surface water-groundwater interactions in the San Joaquin River corridor and the Tulare Lake basin were important in supporting the historical wetland and riparian habitats in the San Joaquin Valley. Additionally, the San Joaquin River and Tulare Lake basis was atypical compared to other Central Valley Rivers based on the periodic connectedness of surface flows between the two basins: (1) overflow from the San Joaquin River towards the Tulare Lake, (2) Kings River overflow into the San Joaquin River, and (3) Tulare Lake overflow into the San Joaquin River. Surface flows in the San Joaquin River and rivers draining into Tulare Lake provided substantial surface flows to the river during winter, spring, and early summer months, but the shallow groundwater table played a key role in supporting riparian vegetation, and providing baseflow augmentation to the mainstem rivers. Discontinuous semi-permeable clay lenses provided a semi-confined shallow groundwater aquifer, while a deeper clay layer provided a confined groundwater aquifer. In winter, spring, and early summer months, surface water percolated into these aquifers from the Sierra Nevada foothills, and the aquifers provided an important groundwater contribution to the San Joaquin River. The flood basins in Reaches 3, 4, and 5 remained inundated or moist enough to support extensive tule marshes. High groundwater tables and artesian springs allowed most reaches of the San Joaquin River to gain flow year round.

Since the late 1800s, groundwater pumping, has withdrawn large volumes of water from both the semi-confined shallow aquifer and the deeper confined aquifer. Dramatic decreases in groundwater elevation resulted, and many reaches were converted from “gaining” reaches (streamflows increasing from groundwater contribution) to “losing” reaches (streamflows decreasing due to infiltration into the bed of the stream).

These human-induced changes to the shallow groundwater table have impacted the riparian corridor in several ways, and will impair future restoration efforts on the San Joaquin River. Therefore, the goals of this chapter are to: 1) summarize historical and contemporary groundwater conditions in the San Joaquin Valley, 2) discuss how the regional groundwater system has changed, and 3) analyze the implications of this change to restoration efforts. Groundwater conditions in the San Joaquin Valley as a whole must be considered because they influence local groundwater conditions along the study area of the San Joaquin River. To accomplish these goals, available groundwater literature for the San Joaquin Valley will be reviewed to gain insight into how the shallow groundwater system may influence restoration opportunities and constraints on riparian vegetation and fishery habitat in the San Joaquin River corridor.

4.2. STUDY AREA

To describe the overall groundwater hydrology, the study area would need to be the entire San Joaquin Valley. With our emphasis on the shallow groundwater system adjacent to the San Joaquin River, our study area is from Friant Dam downstream to the Merced River (Figure 4-1), and within the approximate pre-Friant Dam 100-year floodway. Because quantitative data on the shallow groundwater system are limited, studies of groundwater conditions downstream of the Merced River were included in this evaluation because this downstream reach displays similar geologic and hydrogeologic conditions to the study area upstream of the Merced River, particularly Reaches 2 through 5.

4.3. OBJECTIVES

The primary objectives of this chapter, derived from the April 2000 scope of work, are to:

- Describe the geology and hydrogeology of the San Joaquin Valley.
- Describe how the San Joaquin Valley groundwater system has changed over time emphasizing the shallow unconfined groundwater aquifer.
- Identify how groundwater-pumping affects shallow groundwater flow and water quality.
- Identify "gaining" and "losing" reaches along the study reach.
- Discuss how the existing shallow groundwater system will affect riparian and fishery restoration efforts in the study area.

4.4. SAN JOAQUIN VALLEY GEOLOGY

The San Joaquin Valley is a large, asymmetrical basin aligned north-south, and is bordered on the east by crystalline rocks of the Sierra Nevada and on the west by folded and faulted marine sedimentary rocks of the Coast Ranges. The Tehachapi and San Emidio mountains mark the southern boundary of the San Joaquin Valley, while the delta of the San Joaquin and Sacramento Rivers lies to the north. The part of the valley trough with the deepest alluvial fill generally lies closer to the Coast Ranges than to the Sierra Nevada. The San Joaquin River and the Sacramento-San Joaquin River delta drain the northern half of the San Joaquin Valley. The Tulare Lake Basin occupies the southern half of the valley.

The San Joaquin Valley is filled with up to 32,000 feet of marine and continental sediments, the result of millions of years of inundation by the Pacific Ocean, and of erosion of the surrounding mountains (Planert and Williams 1995). Up to two to three million years ago, the Pacific Ocean had already deposited up to about 20,000 feet of marine deposits in the Central Valley (Planert and Williams 1995). These deposits are are mostly consolidated, and have minimal permeability (Figure 4-2 and Figure 4-3). A generalized stratigraphic section of the rocks and sediments underlying the San Joaquin Valley is summarized in Table 4-1 and described in more detail below.

The remaining upper (shallower) portion of the San Joaquin Valley is filled with alluvium eroded from the Coast Ranges and Sierra Nevada, lacustrine and marsh-deposits, dune sands, and river and flood-basin deposits. In the central part of the San Joaquin Valley, alluvium derived from the Coast Ranges intermingles with material derived from the Sierra Nevada (commonly referred to as Sierran Sand) (Belitz and Heimes 1987). Modern (in geologic time) alluvium is deposited along the outer margins of the San Joaquin Valley as alluvial fans and plains. San Joaquin River tributaries flow into the valley, most from the Sierra Nevada, and commonly bisect the alluvial fans and valley uplands. The valley deposits made from the Coast Range and Sierra Nevada alluvium form an important aquifer system within the valley. These deposits are interbedded and intermixed with clay and silt layers that settled in paleo-lake beds, which occupied local depressions on the valley floor. Some of the lacustrine clay and silt deposits are thick and laterally extensive. On average, fine-grained deposits make up 50 percent or more of the valley-fill sediments in the basin (Planert and Williams 1995, Page 1986). Generally, the alluvial deposits in the San Joaquin basin are a heterogeneous mixture of coarse- and fine-grained sediments that vary widely over short distances and depths.

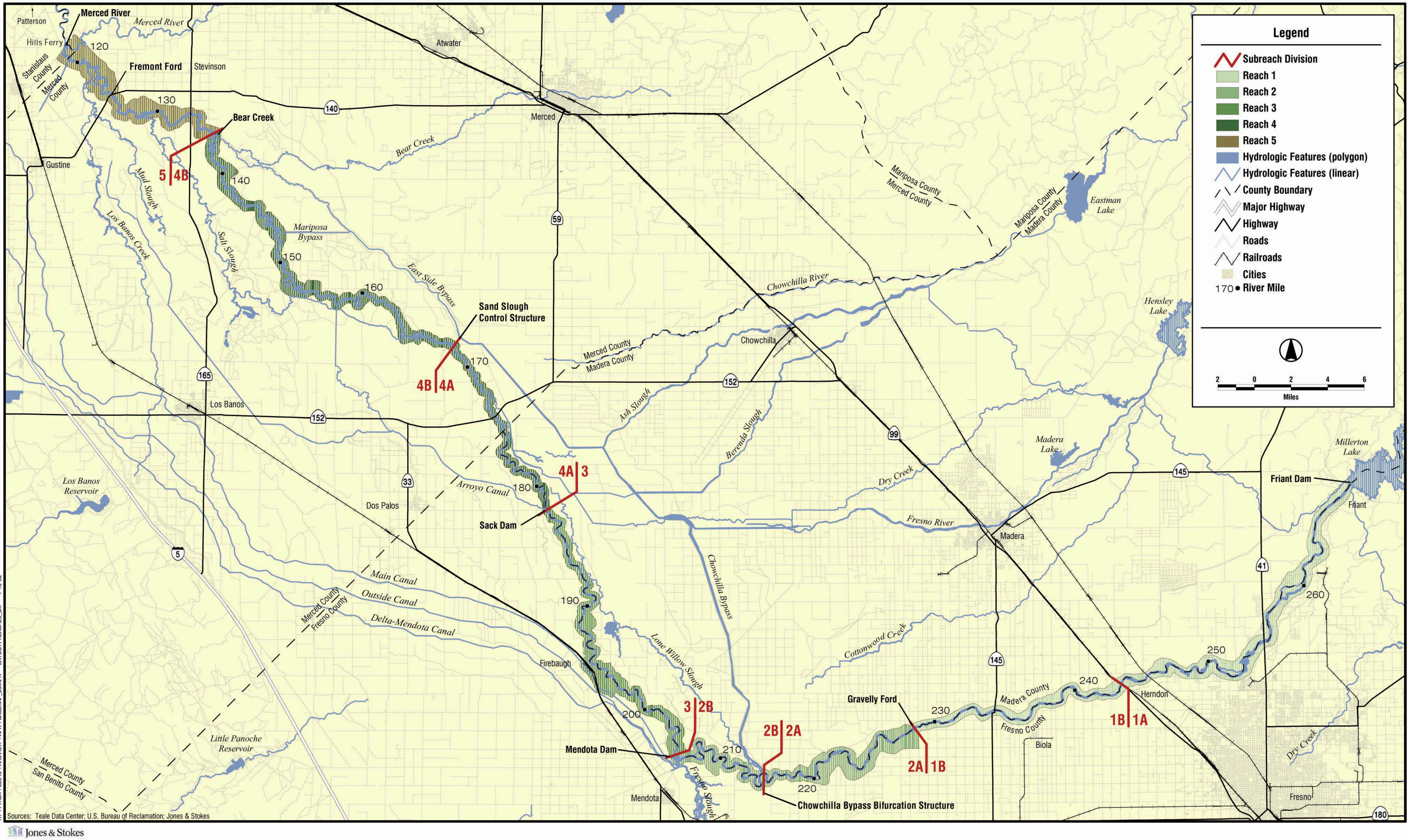
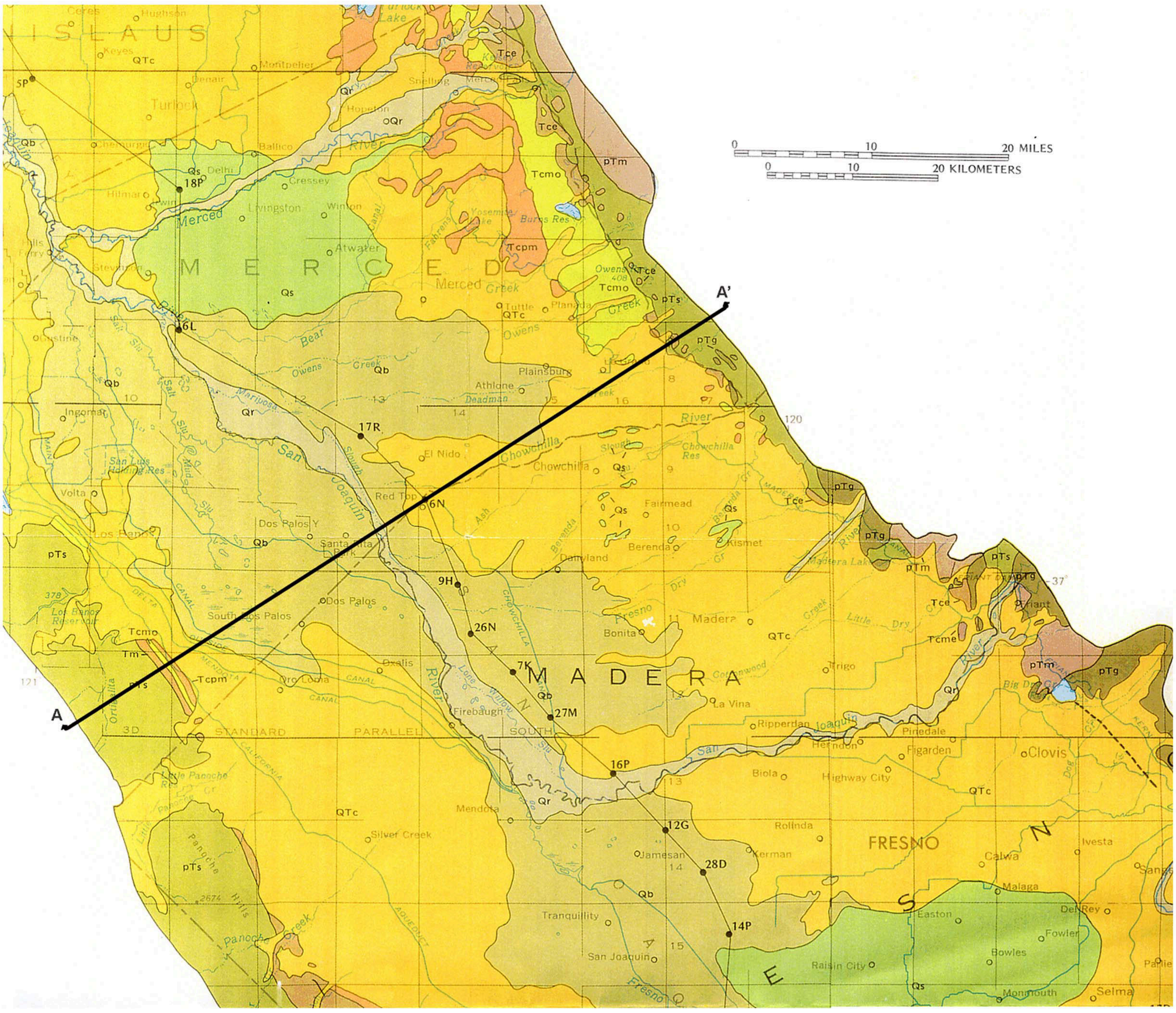


Figure 4-1. Project area of the San Joaquin River Restoration Study showing Reach and Subreach boundaries.



DESCRIPTION OF MAP UNITS

Qs **Sand dunes (Holocene)** Windblown sand and dune sand

Qb **Flood-basin deposits (Holocene)** Clay, silt, and some sand; near Stockton consist of muck, peat, and other organic soils. In places may include part of the Modesto Formation (Pleistocene)

Qr **River deposits (Holocene)** Gravel, sand, silt, and minor amounts of clay; deposited along channels, flood plains, and natural levees of main streams. In places may include part of Modesto Formation (Pleistocene)

QTl **Lacustrine and marsh deposits (Pliocene to Holocene)** Clay, silt, and some sand; in subsurface include three widespread clays: A clay (Pleistocene and Holocene?); C clay (Pleistocene); and modified E clay (Pleistocene), includes Corcoran Clay Member of Tulare and Turlock Lake Formations

QTc **Continental rocks and deposits (Miocene to Holocene)** Heterogeneous mix of generally poorly sorted clay, silt, sand, and gravel; some beds of claystone, siltstone, sandstone, and conglomerate. Include some informal units: younger alluvium (Holocene), older alluvium (Pleistocene and Holocene?) and continental deposits (Pliocene and Pleistocene); three formations of Pleistocene age: Modesto, Riverbank, and Turlock Lake; Tulare Formation (Pliocene and Pleistocene) on western side of valley, Laguna Formation (Pliocene) on eastern side, and Kern River Formation (Miocene to Pleistocene?) on southeastern part

Tvd **Volcanic rocks and deposits (Miocene and Pliocene)** Massive tuff with large fragments of vesicular basalt northwest of Tracy; tuff, and volcanic breccia at south end of valley

Tcpm **Continental rocks and deposits (Miocene and Pliocene)** Gravel, sand, silt, clay, conglomerate, sandstone, siltstone, and claystone, contain andesitic material. Principally Mehrten Formation (Miocene and Pliocene) on eastern side of valley; include continental equivalents of Etchegoin Formation (Miocene and Pliocene) on western side of valley, and Chanac Formation (Miocene) on southern part

Tcmd **Continental and marine rocks and deposits (Miocene and Pliocene)** Gravel, sand, silt, clay, silty sandstone, and siltstone. Include continental and marine equivalents of San Joaquin Formation (Pliocene) and Etchegoin Formation (Miocene and Pliocene)

Tm **Marine rocks and deposits (Eocene, Oligocene, Miocene, and Pliocene)** Sand, clay, silt, sandstone, shale, mudstone, and siltstone. On western side of valley include the San Joaquin and Etchegoin Formations, Temblor Formation (Oligocene and Miocene) and Kreyenhagen Formation (Eocene). On southeastern side include the Santa Margarita Formation of various authors, the Round Mountain Silt, the Olcese Sand, the Freeman Silt, and the Jewett Sand (including the Pyramid Hill Sand Member) (all Miocene), and the Vedder Sand (Oligocene)

Tcmo **Continental rocks and deposits (Oligocene and Miocene)** Gravel, conglomerate, sand, tuffaceous sand, clay, and sandy clay; contain rhyolitic material on eastern side of valley. Principally Valley Springs Formation (Oligocene and Miocene) on eastern side of valley; unnamed fanglomerates (Miocene) and Bena Gravel (Miocene) in the southern part

Tcme **Continental rocks and deposits (Eocene to Miocene)** Conglomerate, sandstone, consolidated fanglomerate, claystone, tuff and tuff breccia; near Fresno consist of tuffaceous sand and gravel. Near Bakersfield include the Bealville Fanglomerate (Oligocene and Miocene) and the Walker Formation (Eocene to Miocene)

Tce **Continental rocks and deposits (Eocene)** Conglomerate and sandstone; along eastern side of valley contain anauxite. Principally Ione Formation (Eocene) on eastern side of valley

Unconformity

pTs **Marine rocks (Pre-Tertiary)** Sandstone, shale, siltstone, and some limestone, chiefly on western side of valley; in places contain abundant secondary gypsum. Include Moreno Formation (Cretaceous and Paleocene) and Panoche Formation (Cretaceous)

pTg **Granitic rocks (Pre-Tertiary)** Chiefly granitic rocks on eastern side of valley, in places consists of mafic intrusive rocks

pTm **Metamorphic rocks (Pre-Tertiary)** Metasedimentary, metavolcanic and other metamorphic rocks on eastern side of valley

Figure 4-2. Geologic units of the San Joaquin Valley, and location of cross section shown in Figure 4-3. Modified from Bertoldi et al., 1991 and many others.

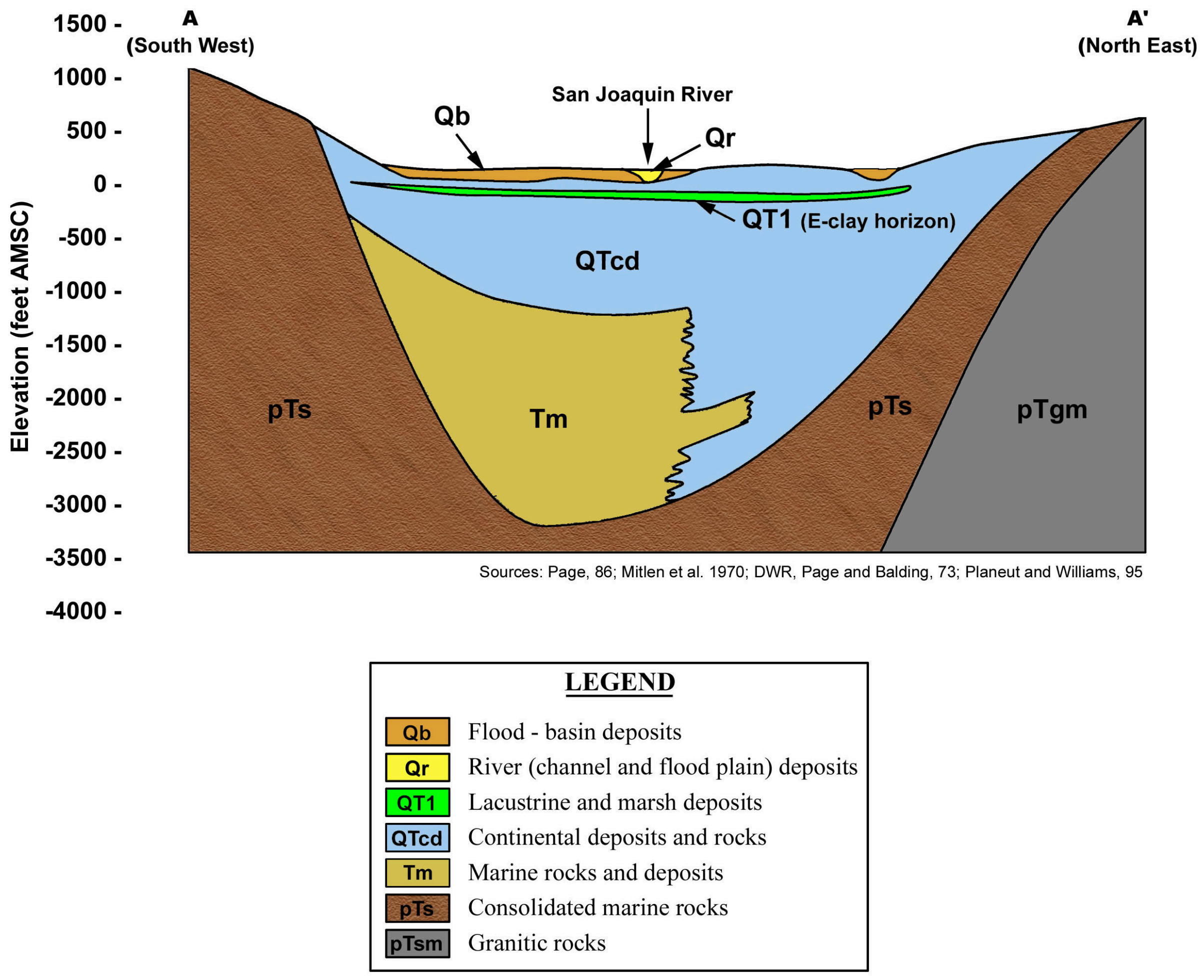


Figure 4-3. Diagrammatic geologic cross section A – A' through the San Joaquin Valley showing underlying rocks and valley fill material. Modified from Bertoldi et al., 1991 and many others.

The San Joaquin Valley surface along the river corridor is covered by a thin veneer of sediments, described by Page (1986), Page and Balding (1973), Mitten et al. (1970), Phillips et al. (1991), and Belitz and Heimes (1987). The sediment veneer is river, flood-basin, and/or dune sand deposits (Figure 4-2). Page (1986) indicates that river deposits consist of both river channel and flood plain deposits. The river deposits still accumulate except in areas where human activity intervenes (e.g., during on- and off-stream gravel mining, or sediment trapping behind dams). In the absence in these human interventions, these accumulations would still be occurring. River deposits are dominated by sand and gravel, and range in width from a few feet to nearly 1,000 feet (Page 1986). The flood plain deposits are finer grained than the channel deposits and consist of interbedded and discontinuous layers of fine sand and silt. The band of flood plain deposits paralleling the San Joaquin River range in width from a few hundred feet to three miles. Although difficult to determine from boring logs, the estimated thickness of the river deposits are between 50- and 115-feet (Mitten et al. 1970 and Page 1986).

Table 4-1. Generalized stratigraphy of San Joaquin Valley (from Planert and Williams 1995).

System and Series		Map Unit	Geologic Unit	Description	Maximum Thickness (feet)	Comments
QUATERNARY	Holocene	Qs	Sand dunes	Dune sand	140	Generally lie above saturated zone but are highly permeable.
		Qb	Flood-basin deposits	Clay, silt, and fine sand with locally organic rich zones.	100	Low permeability with low yields to wells.
		Qr	River deposits	Gravel, sand and silt with minor amounts of clay.	100+	Among most permeable deposits in Valley; include both channel and flood plain deposits; generally, few, if any, wells completed in this unconfined unit.
TERTIARY AND QUATERNARY	Pleistocene	QT1	Lacustrine and marsh deposits	Clay, silt and some sand	100	Deposited in lakes and marshes; thickest sections beneath Tulare Lake Bed. Includes widespread E-clay horizon or “Corcoran clay” member as well as A- and C-clays of Tulare Lake basin.
	Eocene through Pleistocene	QTcd	Continental deposits and rocks	Upper layers of unconsolidated and interbedded gravel, sand, silt and clay; deeper layers of interbedded consolidated sandstone, conglomerate, tuff, siltstone, shale, and claystone.	1,000-3,000+	Upper unconsolidated units have low to high permeabilities; grade from unconfined to confined conditions with depth. Sierran sand deposits on east side of basin are coarser grained and generally have higher permeability and better water quality than Coast Range alluvial deposits. Deeper consolidated units have low to moderate permeabilities and wide range of salinity.
		Tm	Marine rocks and deposits	Sand, clay, silt, sandstone, shale, mudsone, and siltstone	2,000+	Mix of continental and marine sediments deposited as Ocean advanced and retreated. Locally yield large quantities of fresh water to wells.
PRETERTIARY		pTs	Consolidated Marine rocks	Sandstone, shale, siltstone, and some limestone.	20,000+	Outcrops appear primarily on western side of valley. Low yields of poor quality water to wells.
		PTgm	Granitic rocks	Chiefly granitic rocks with mafic intrusions in places.	n/a	Outcrops appear primarily on eastern side of valley. Yield low quantities of good quality water to wells where fractured.

Flood-basin deposits in the low-lying basins of the San Joaquin Valley were mapped and described by Page (1986) and Mitten et al. (1970) (Figure 4-2). These deposits were created by floods in recent (Holocene) times and consist of fine sand, fine silt, clay, and organic matter. The flood-basin deposits average between 5 and 35 feet thick (Phillips et al. 1991, and Gronberg and Belitz 1992) but may be as much as 100 feet thick (Page 1986, and Mitten et al. 1970).

A large area of dune sand deposits is exposed along the south side of the Merced River in the north central part of the study area (Figure 4-2). These sand deposits range in thickness from 0 to 140 feet and consist of layers of well-sorted fine to coarse-grained sand and silt. Page (1986) indicates that, in most places, the dune sands lie above the saturated zone and do not serve as aquifers. However, the dune sands have high permeability and readily permit recharge of runoff, direct precipitation, and irrigation water.

4.5. SAN JOAQUIN HYDROGEOLOGY

Bordering and underlying the San Joaquin Valley, the consolidated marine sediments of the Coast Ranges and crystalline bedrock of the Sierra Nevada are virtually impermeable; groundwater flow through these units is insignificant. The marine and consolidated continental deposits that fill and occupy the deeper portions of the valley (Figure 4-3) are also less important aquifers because they commonly contain saline water and/or are of low permeability. The younger and shallower continental rocks and alluvial deposits contain most of the fresh groundwater in the basin. Because of its fine-grained nature, chemical components of the soil, and quality of recharge water, the Coast Range alluvium produces poor quality groundwater, particularly in the upper 50 feet. The Sierran Sand is coarser and more permeable. Where Sierran Sand exceeds a thickness over 200 feet, groundwater is preferentially pumped because of the high permeability of the sand (Gronberg and Belitz 1992, Groundwater Management Technical Committee 1999).

On a regional scale, early San Joaquin Valley studies suggested a simple groundwater conceptual model of an unconfined to semiconfined aquifer in the unconsolidated deposits, located above a laterally extensive impermeable clay layer, with a confined aquifer below this clay layer (top of Figure 4-4). The E-clay was thought to be a single laterally extensive and relatively thick zone of clay layers deposited as part of a thick sequence of lacustrine and marsh deposits underlying Pleistocene-era Tulare Lake. More recent studies have identified additional, less extensive clay layers in the valley (bottom of Figure 4-4). Within the Tulare Lake Basin, six clay layers were designated from youngest to oldest (shallowest to deepest) by the letters A through F. The Quaternary age A, C, and E clays were designated as extensive, with the E-clay being the most extensive, underlying most of the San Joaquin Valley. The E-clay is considered equivalent to the Corcoran Clay member of the Tulare Formation (Mitten et al. 1970). The top of the E-clay was defined at about 80 feet deep near Chowchilla and deepens to the southwest (Mitten et al. 1970). The A- and C-clay layers are confined to the Tulare Lake Basin and do not appear to extend further north than the southern city limits of Fresno, based on data presented by Page (1986). However, if present beneath the area, the A-clay horizon may act to create perched unconfined groundwater conditions very close to the ground surface.

Recent studies suggest that, because the basin sediments are so heterogeneous, the aquifer contains water under unconfined conditions at shallow depths and then grades through semiconfined and confined aquifer conditions as depth increases. The confined aquifer conditions result from numerous overlapping and discontinuous lenses of clay. Detailed analyses of wells logs indicate that the E-clay is not a single homogeneous unit, but is better characterized as a zone of multiple clay layers interbedded with more permeable units (Groundwater Management Technical Committee 1999). In addition, differences in hydraulic head measured directly above and below the E-clay are relatively

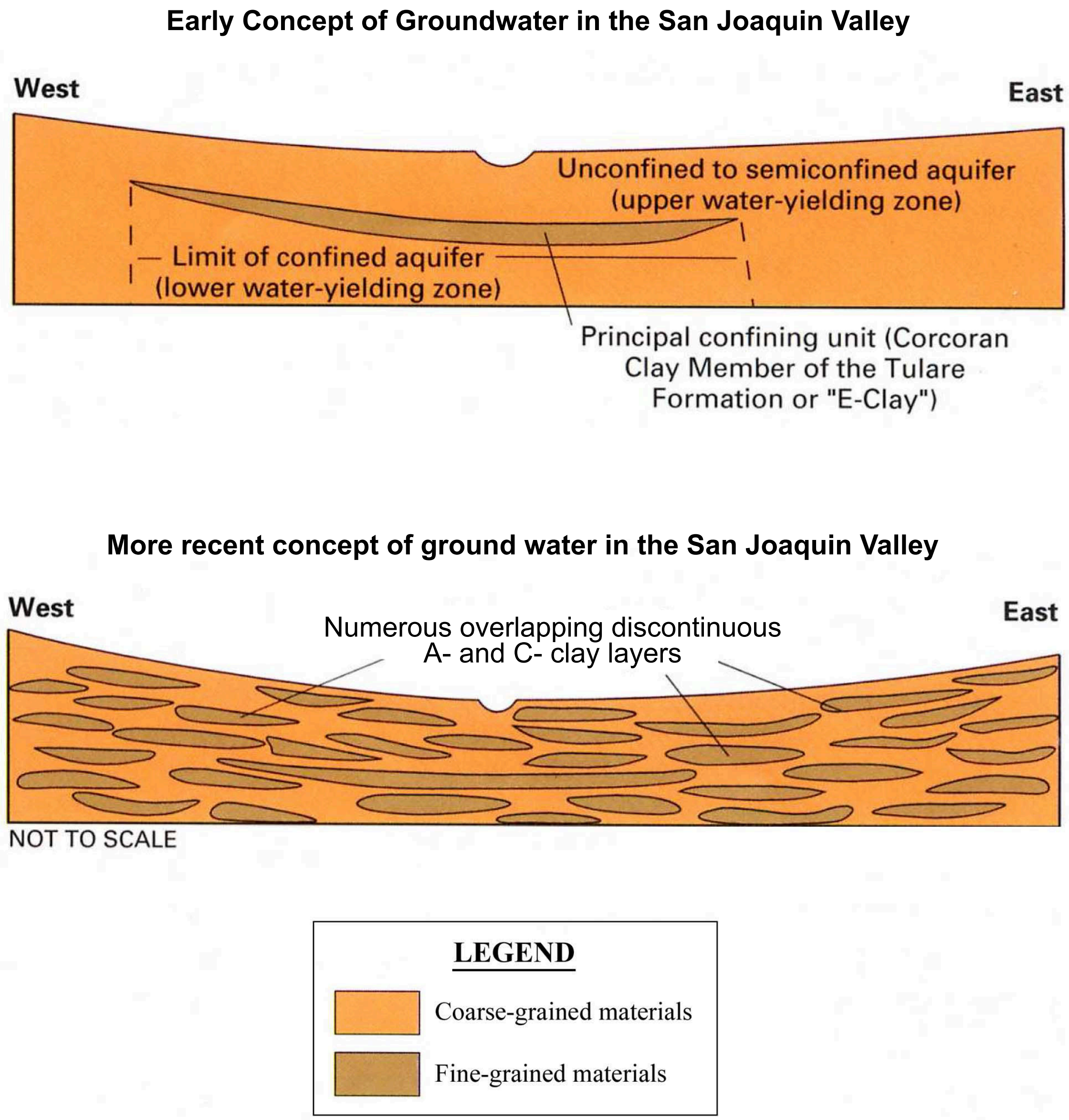


Figure 4-4. Diagrammatic cross sections showing aquifers of the San Joaquin Valley. According to early concepts of the aquifer system (upper figure), it was generally considered to be confined under the Corcoran Clay Member of the Tulare Formation ("E-clay"); however, recent studies suggest that the entire aquifer system is a single heterogeneous system in which vertically and horizontally scattered lenses of fine-grained materials provide increasing aquifer confinement with increasing depth. Modified from Bertoldi et al., 1991 and many others.

small, when compared to head differentials observed in wells monitoring shallow and deep portions of the aquifer system (Planert and Williams 1995). The pre-Euro-American settlement and current groundwater flow conditions in the regional unconfined and confined groundwater systems are described in Sections 4.6.1 and 4.6.2. The net implications to historical shallow groundwater conditions along the San Joaquin River of the two conceptual models is that (1) while the more complicated model is technically more correct, the simple model adequately explains the processes that created the artesian springs along the axis of the valley, and (2) the more complicated model helps explain the heterogeneity of artesian springs along the valley.

River deposits are the most permeable deposits in the San Joaquin Valley, and they appear to be hydraulically connected to adjacent stream channels and flood plain deposits (Page 1986). River deposits are also hydraulically connected with deeper portions of the unconfined aquifer zone. However, because of their fine-grained nature, flood-basin deposits yields are low and these deposits tend to impede the downward vertical movement of water.

4.6. EVOLUTION OF GROUNDWATER FLOW CONDITIONS

This section examines historical and post-development groundwater supply conditions. Important components include groundwater use pre- and post-development, land subsidence, and water quality.

4.6.1. Pre-groundwater development conditions (approx. pre-1860)

Prior to development and extensive pumping, groundwater flowed from the high elevations of the valley margins towards the San Joaquin Valley trough. Water originating from mountain rain and snowmelt entered the valley aquifer system and recharged the shallow unconfined aquifer along the valley margins (Figure 4-5). As a result, at the valley margins, the unconfined aquifer had a higher hydraulic head than that of the deeper confined aquifer. Belitz and Heimes (1987) report that early geologic surveys indicate marshland along most of the valley trough, and numerous early explorers describe expansive tule marshes along much of the river, from present-day Firebaugh to the Merced River confluence (summarized in Fox, 1987). In the valley trough, however, hydraulic head in the unconfined aquifer was less than that in the confined aquifer. The head differential in the valley trough created an upward pressure gradient (artesian condition), allowing groundwater to discharge to the river and valley marshes (Figure 4-5). This groundwater contribution process was also noted in early engineering surveys. For example, Hall (1886) mapped the approximate zone of artesian potential and the approximate boundaries of swamp and overflowed lands throughout the Sacramento, San Joaquin, and Tulare Lake basins (Figure 4-6). During periods of low surface flow, the shallow unconfined aquifer of the valley trough would contribute significant baseflows to the San Joaquin River (Figure 4-7); therefore, much of the river in the valley trough was a “gaining” reach (Figure 4-8). Marshlands and artesian conditions at this time confirm that the valley trough was a discharge area under predevelopment conditions. These groundwater conditions were applicable to Reaches 3, 4, and 5, and portions of Reach 2. Reach 1 was upslope from the confined aquifer (in the recharge area), thus spring flows were likely gravity flow and not artesian.

The San Joaquin River and Tulare Lake basins were periodically connected during periods of high river flow and/or high lake levels (see Chapter 2). During high flows on the Kings River, a portion of the flow would empty into Tulare Lake, but a portion would also flow north, joining the San Joaquin River via Fresno Slough at the present-day location of Mendota. During high flows on the San Joaquin River, flows would spill out on the southern bank and flow south into the Fresno Slough. From that point, the flow appears to have flowed back to the north via Fresno Slough re-joining the San Joaquin River at Mendota. There is also some suggestions that during periods of

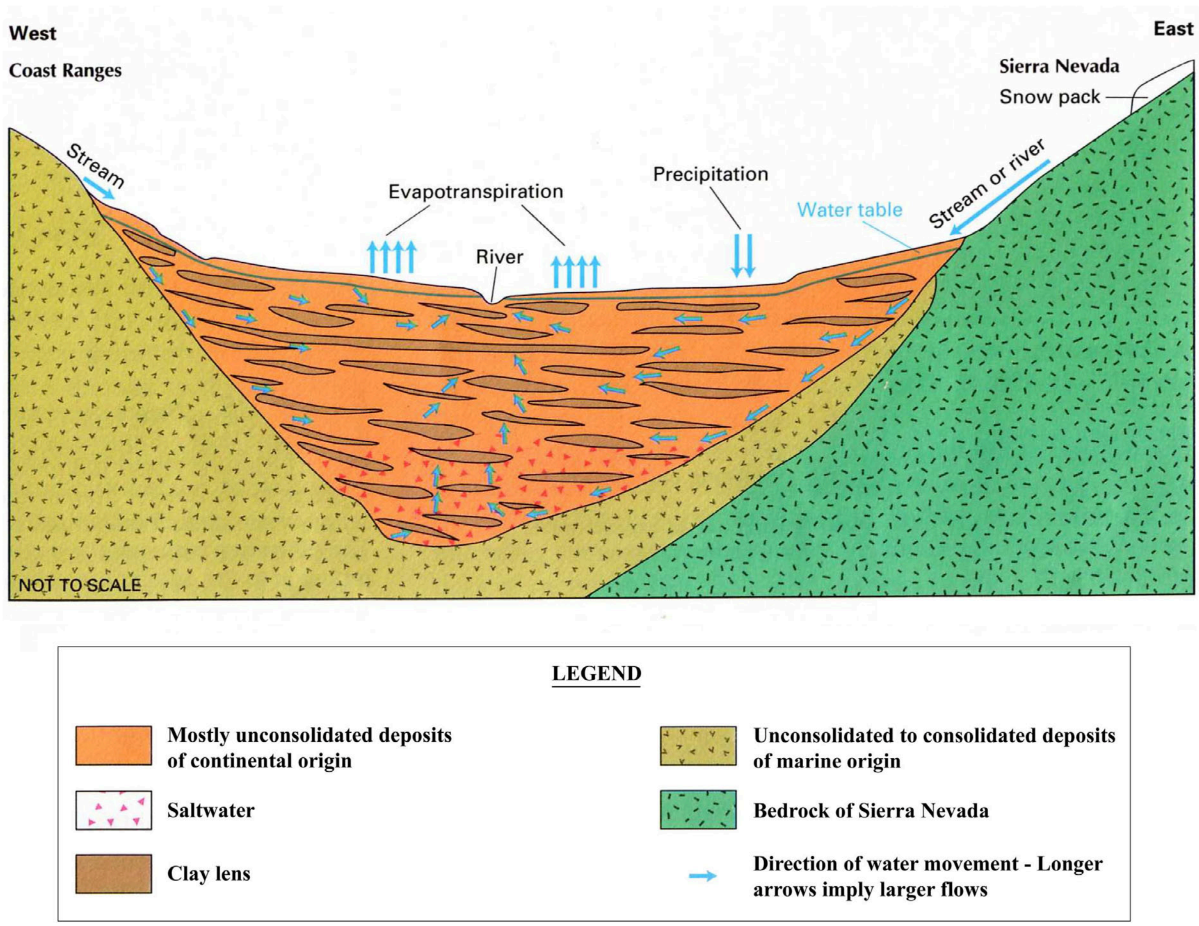


Figure 4-5. Diagrammatic hydrogeologic section showing that before development: 1) surface water recharged the aquifer at the valley margins, 2) moved downward and laterally into the aquifer system, and 3) then moved upward to discharge at rivers and marshes at the valley axis. Modified from Bertoldi et al., 1991 and many others.

high water elevations in Tulare Lake, that surface water would flow from the lake to the San Joaquin River via Fresno Slough. Additionally, there has been some statements that there was a groundwater contribution from Tulare Lake to the San Joaquin River. Fox (1987) summarized a statement from Anonymous (1873) that “the San Joaquin receives an important accession of volume from underground storage – probably from the Tulare Lake drainage”. This assumption is discounted by later surveyors (e.g., Mendenhall et al. 1916). This “accession of volume” described by Anonymous (1873) may have been the shallow groundwater and artesian contribution from the San Joaquin River aquifer rather than the Tulare Lake aquifer.

To substantiate historical accounts of the shallow unconfined aquifer being close to ground surface, contour maps of pre-development groundwater surface and ground surface were compared. Pre-development shallow groundwater contours were estimated by Williamson et al. (1989). The existing ground surface was generated from the most recent USGS 30 meter grid Digital Elevation Model for 7.5-minute quadrangles along the river (Figure 4-9). The USGS data were used to create a Digital Terrain Model (DTM), and 10 ft contours were generated from the DTM. The existing ground surface

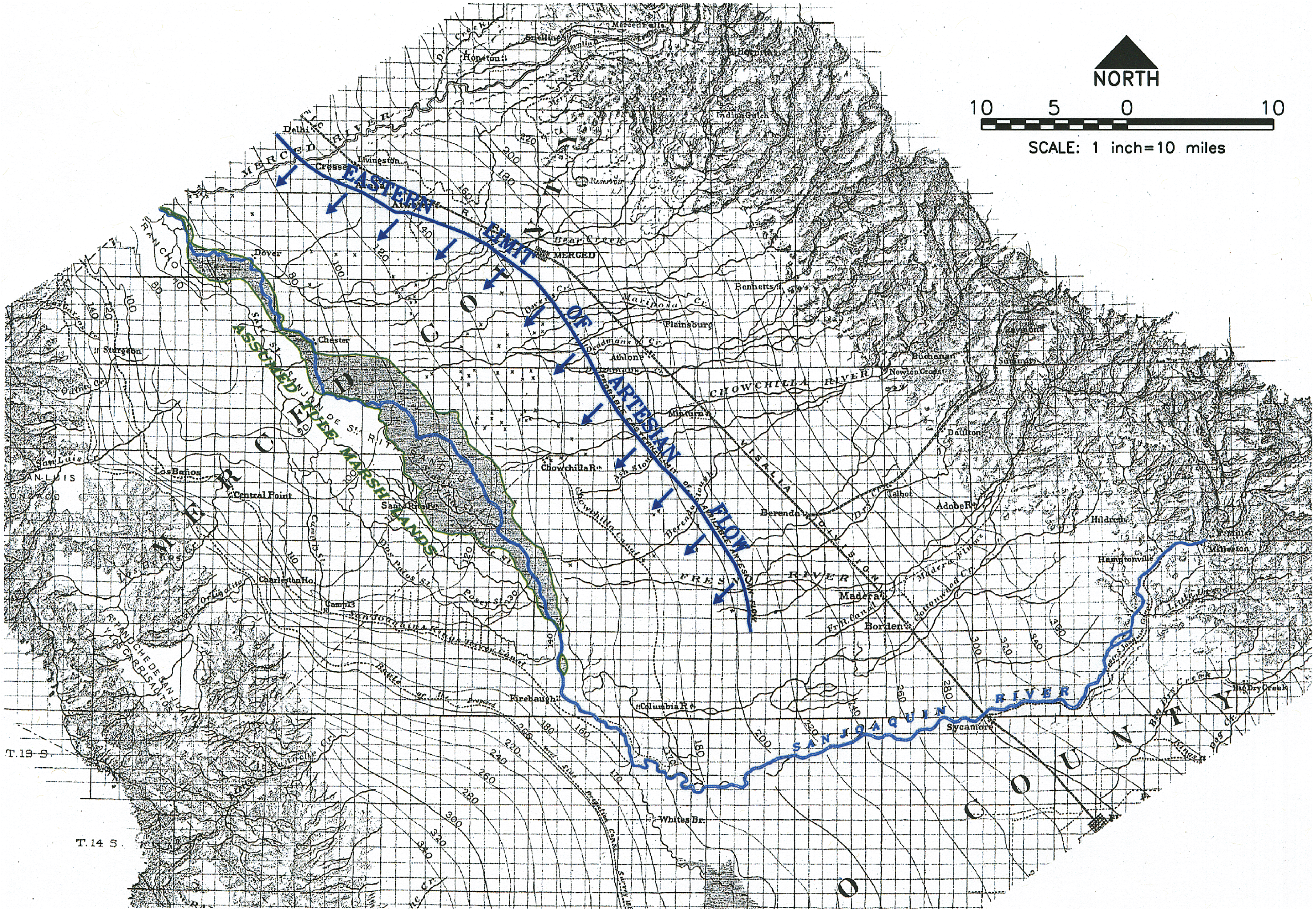


Figure 4-6. Approximate artesian zone and tule marshland based on W.H. Hall map (1886). Artesian potential was between this line and the San Joaquin River, but artesian springs were most likely closer to the river than to the line drawn by Hall.

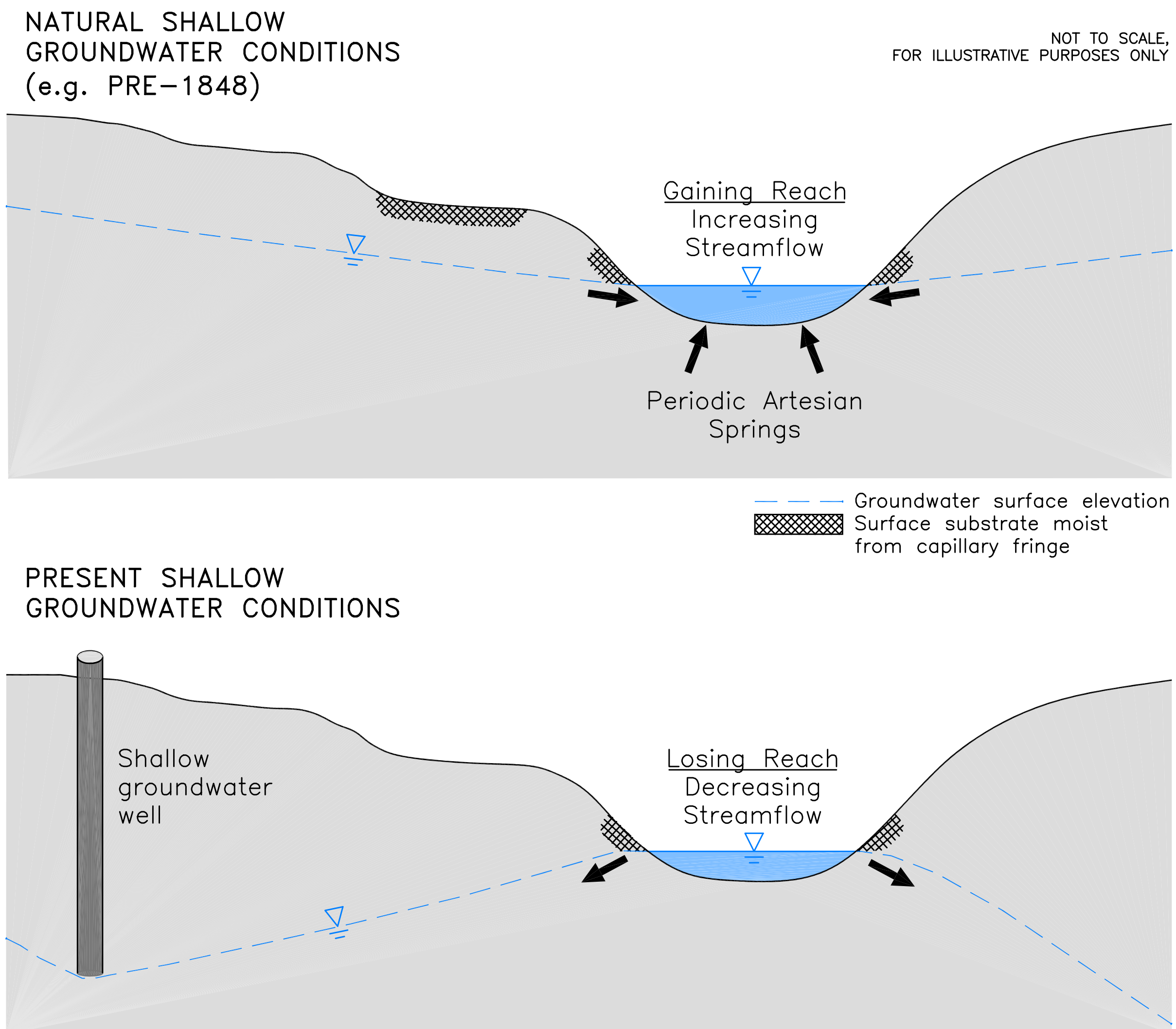


Figure 4-7. Diagrammatic cross section of the relationship of the shallow groundwater table to the San Joaquin River under historical conditions, as well as current conditions with significant shallow groundwater pumping adjacent to the river.

DTM does not accommodate recent subsidence-induced changes in ground surface elevations. Pre-development groundwater contours were used to create another DTM, and the two DTM's were used to generate "cut/fill" contours between the existing ground and pre-development water table. These contours represent "depth to groundwater surface" from ground surface, for pre-development conditions (Figure 4-10).

These contours show that the pre-development groundwater elevations were virtually the same elevations as the river downstream of SR 99 (RM 245), and were close to the ground surface elevations of adjacent lands downstream of RM 230. These contours corroborate historical accounts of the shallow groundwater being very close or above the river surface; however, this coarse scale of mapping does not incorporate finer scale seasonal trends that certainly occurred between winter and summer periods, as well as local topographical and groundwater table variability.

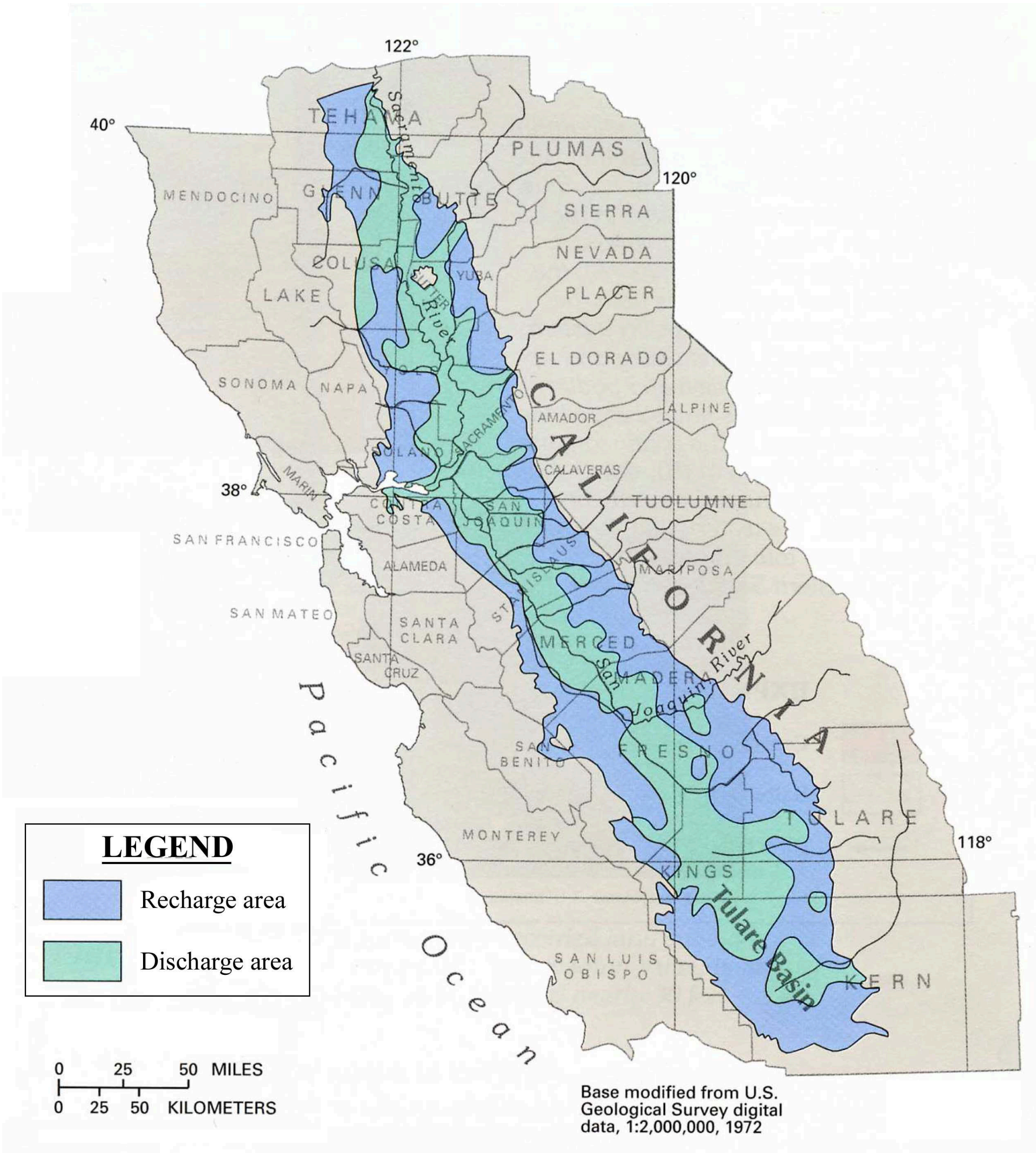


Figure 4-8. Zones of groundwater recharge and discharge in the Central Valley. Before groundwater pumping and surface water diversions, most of the recharge to the Central Valley aquifer system was from rain and snowmelt in the mountains at the valley margins, and discharge was to rivers and marshes near the valley axis. Modified from Williamson et al. (1989).

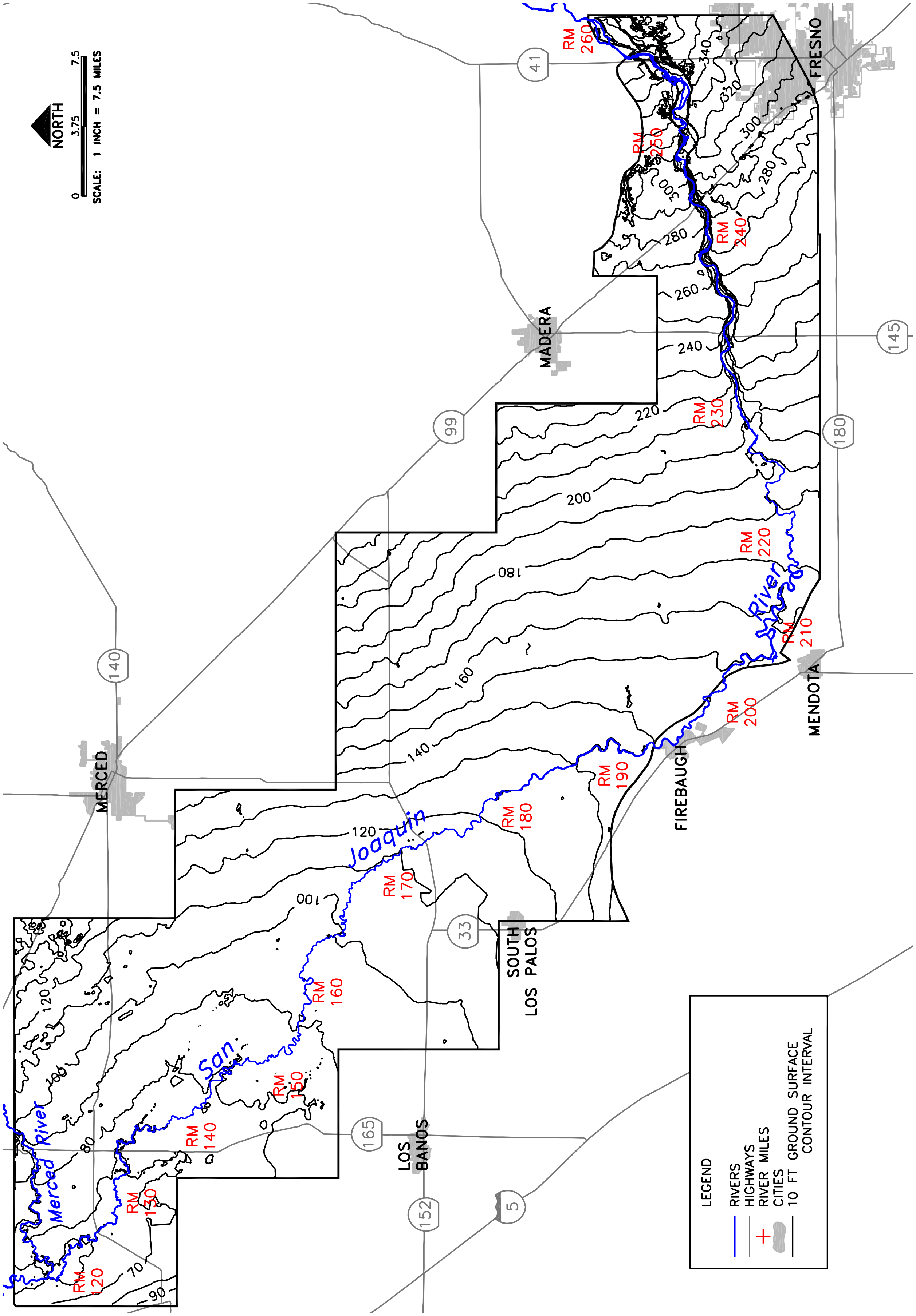


Figure 4-9. Existing ground topography from USGS 30 Meter grid digital elevation models. Not corrected for present-day subsidence.

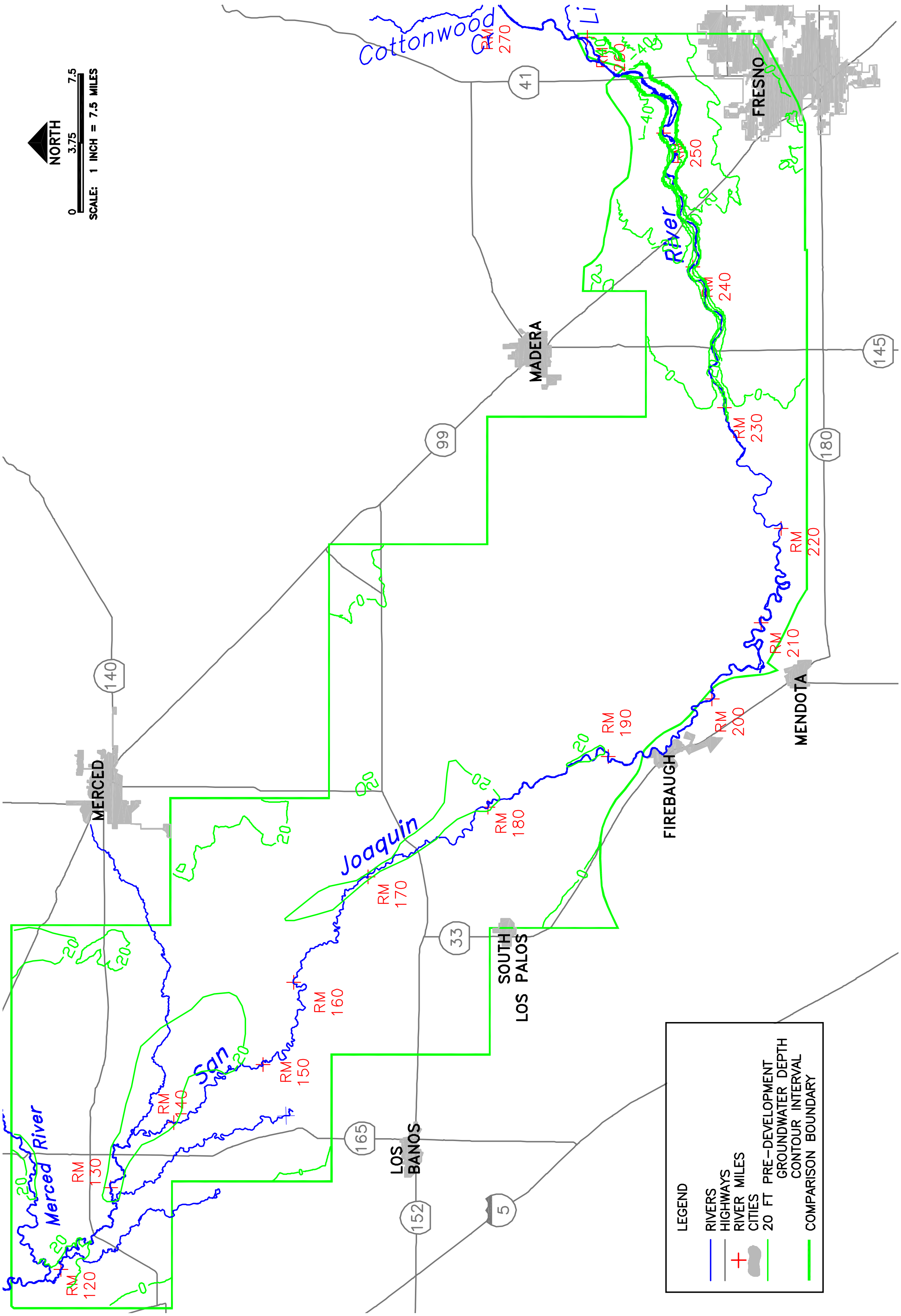


Figure 4-10. Estimated pre-development groundwater contours from Williamson et al. (1989), shown as a depth from the existing ground surface (from Figure 4-9).

4.6.2. Post-development conditions

Use of groundwater resources began in the 1870s when wells were dug by hand or by steam powered drill rigs. Deeper wells extended through the Concoran Clay layer, and took advantage of the hydraulic head of the artesian zone to avoid any need for pumps. By 1885, these artesian wells lost pressure due to overdraft, and by 1900, many of the former artesian wells required pumps (Mendenhall, 1908). Significant groundwater withdrawals began in the mid-1910s and increased steadily through the early 1940s. After World War II, groundwater withdrawals escalated dramatically in the San Joaquin Valley (Belitz and Heimes, 1987). Most pumping occurred in the lower confined aquifer, but pumping also occurred in the upper unconfined zone. By the mid-1960s, groundwater pumping had significantly decreased hydraulic head, increased depth to groundwater, and altered groundwater flow directions (Figure 4-11). While most springs in the study reach have disappeared, there are supposedly a few remaining springs in the Los Banos area (Wolfe, personal communication).

Similarly, increases in depth to groundwater in the unconfined aquifer in the San Joaquin Valley currently exist, in areas of intense groundwater pumping. Shallow groundwater contours for 1953 and 1996 illustrate the trend in increasing depth to groundwater. Similar to the process for the obtaining a pre-development conditions map, the 1953 and 1996 groundwater elevation contour maps were converted to "depth to groundwater" contour maps (Figures 4-12 and 4-13). Differences between Figure 4-10, Figure 4-12, and Figure 4-13 document that the first stage of significant increase in depth to groundwater (1953) was minor (zero to 40 ft), downstream of RM 215. By 1996, increase in depth to groundwater was much more severe closer to the river between Friant Dam (RM 267) and RM 170. Figure 4-13 demonstrates a linear trough of depressed groundwater elevations east of and parallel to the San Joaquin River, extending from approximately El Nido on the north to Mendota to the south. Groundwater elevations are also depressed in Chowchilla and at a groundwater pumping center located southeast of Madera Lake.

In both the unconfined and confined aquifer zones, groundwater overdraft has changed flow direction from toward the San Joaquin River (Figure 4-5) to away from the San Joaquin River towards pumping/withdrawal centers (Figure 4-7, Figure 4-14). In the southern portion of the study area, the altered groundwater flow direction is likely a result of intense groundwater pumping from the unconfined zone, along the east side of the river (Figures 4-12 and 4-13). Belitz and Heimes (1987), and Phillips et al. (1991), report that due to groundwater pumping from this region, there is now a strong component of horizontal flow from west to east across the valley trough and under the San Joaquin River (Figure 4-14). There is a substantial volume of surface water contributed to the San Joaquin River from agricultural return flows; in addition to the surface flow contribution, a portion of the total water applied to adjacent agricultural lands flows to the San Joaquin River as a shallow groundwater contribution.

In the confined aquifer, overdraft has also caused a decrease in the regional hydraulic head of the confined aquifer, reversing the vertical gradient over much of the San Joaquin Valley. Vertical groundwater flow is now preferentially downward, from the upper unconfined zone of the aquifer system through the confining beds towards the lower confined portion of the aquifer system (Figure 4-14). A factor compounding this reversal in the vertical gradient is the completion of thousands of wells that are screened over both the unconfined and confined aquifer zones. Many of these cross-connected wells allow virtually unrestricted flow between zones. Although surface-water imports increased in the 1940s and 1960s, as of 1996, groundwater flow patterns in the San Joaquin Valley were the same as those described for the 1960s (Planert and Williams 1995). The implication of excessive overdraft is clear: water in the upper unconfined zone that once flowed towards the river and marshlands under predevelopment conditions, now flows vertically downward and away from the river and marshlands, eliminating natural discharge of shallow groundwater to the San Joaquin River over many reaches (Figure 4-7).

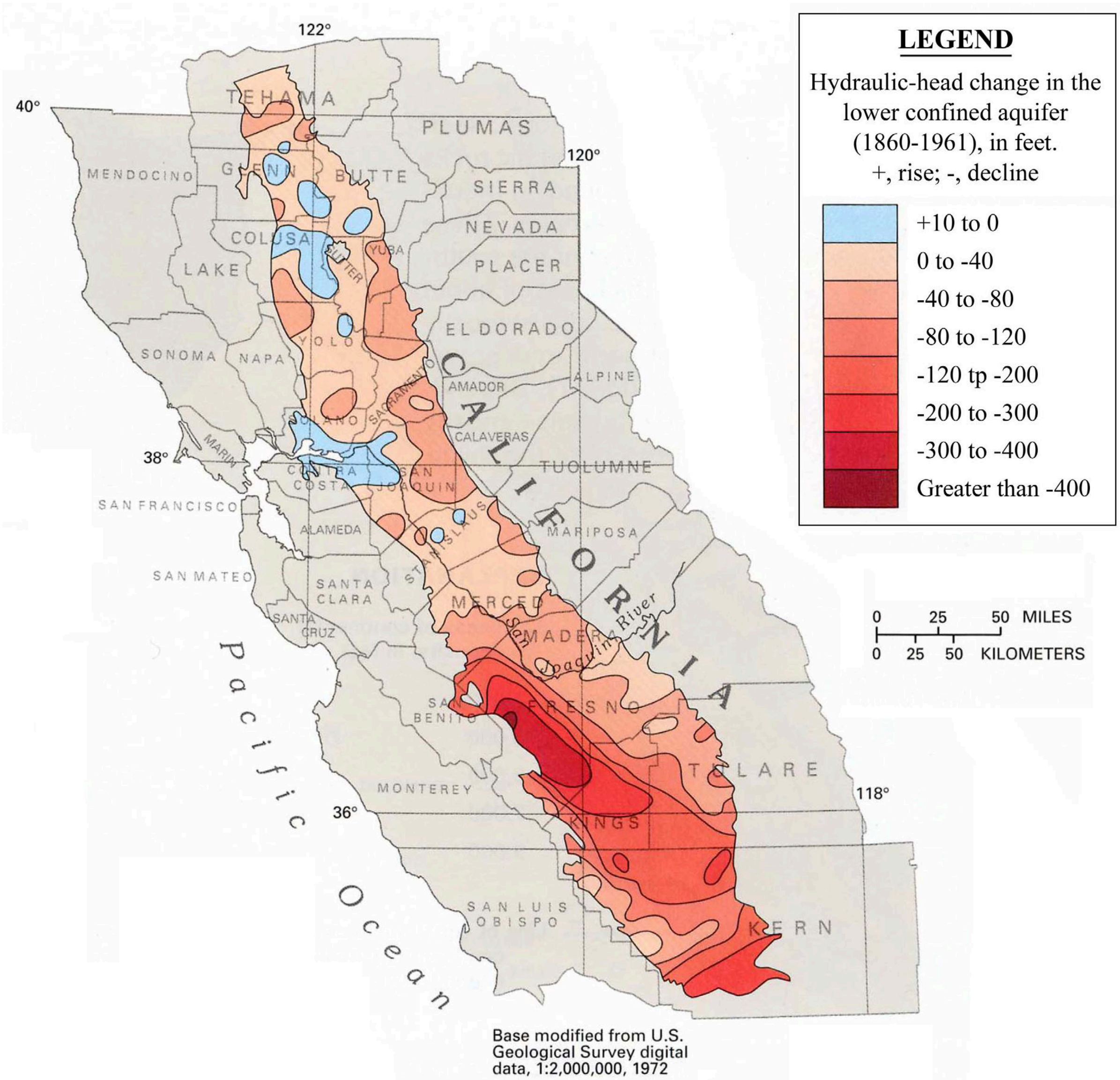


Figure 4-11. Zones of hydraulic head changes between 1860 and 1961 due to groundwater pumping and surface water regulation. Ground-water withdrawals from 1860 to the 1960's caused water levels in the confined part of the aquifer system to decline over most of the Central Valley, in some areas more than 400 feet. Modified from Williamson et al. (1989).

Long-term periods of dry weather reduce natural recharge of the aquifer system, and correspondingly tend to reduce surface water deliveries for irrigation from the CVP. When imported surface water deliveries for irrigation are limited, more groundwater is pumped to make up the shortfall. During the drought of the late 1980s and early 1990s, surface water deliveries were drastically reduced to most water districts in the San Joaquin Valley, resulting in increased groundwater pumping from the entire (confined and unconfined zones) aquifer system (Groundwater Management Technical Committee 1999). A regional response to drought in the San Joaquin Valley is a notable decrease in groundwater elevations due to increased pumping, followed by a regional rise in groundwater elevations once wetter precipitation years resume (Figure 4-15).

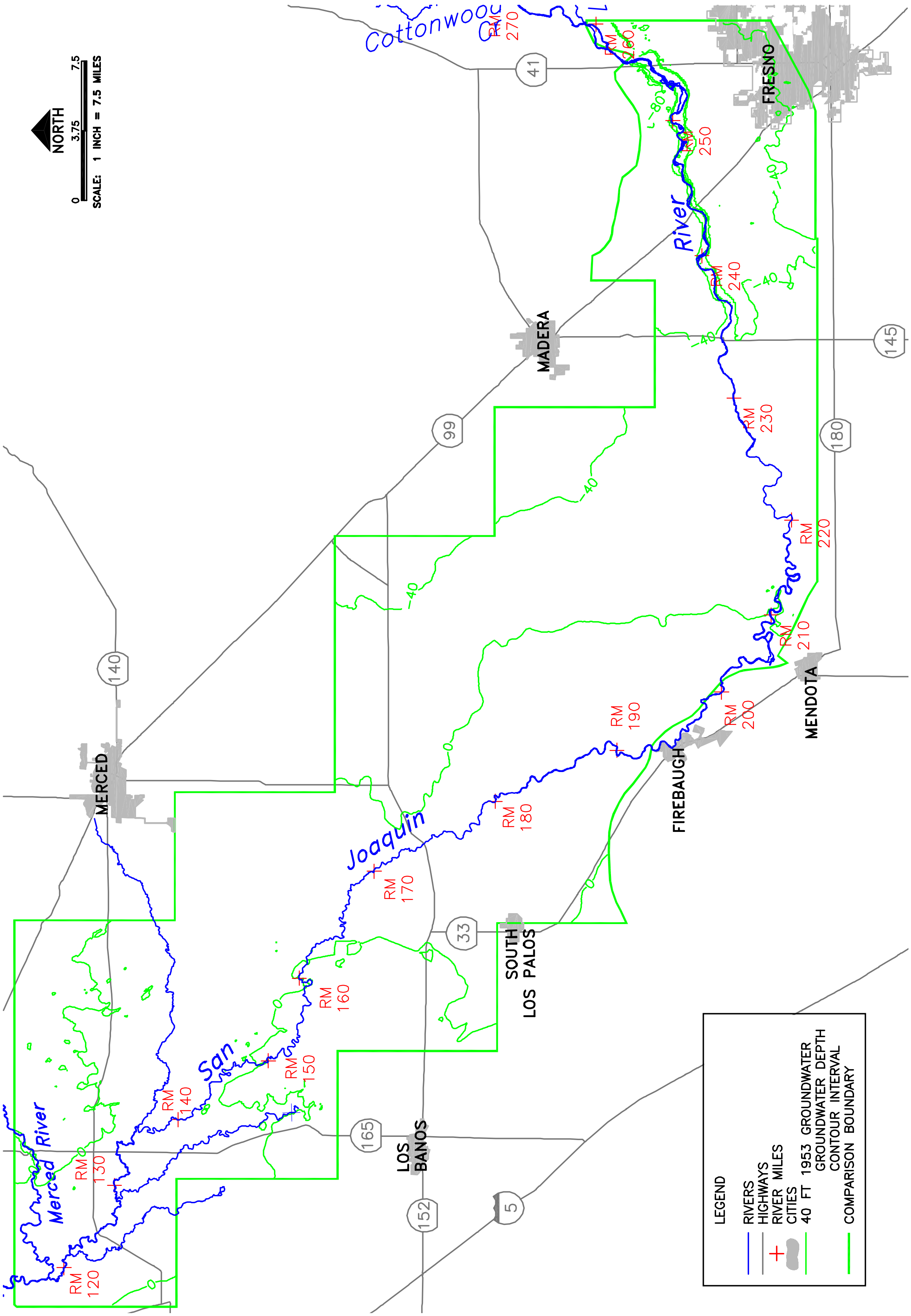


Figure 4-12. Estimated 1953 groundwater contours from Williamson et al. (1989), shown as a depth from the existing ground surface (from Figure 4-9).

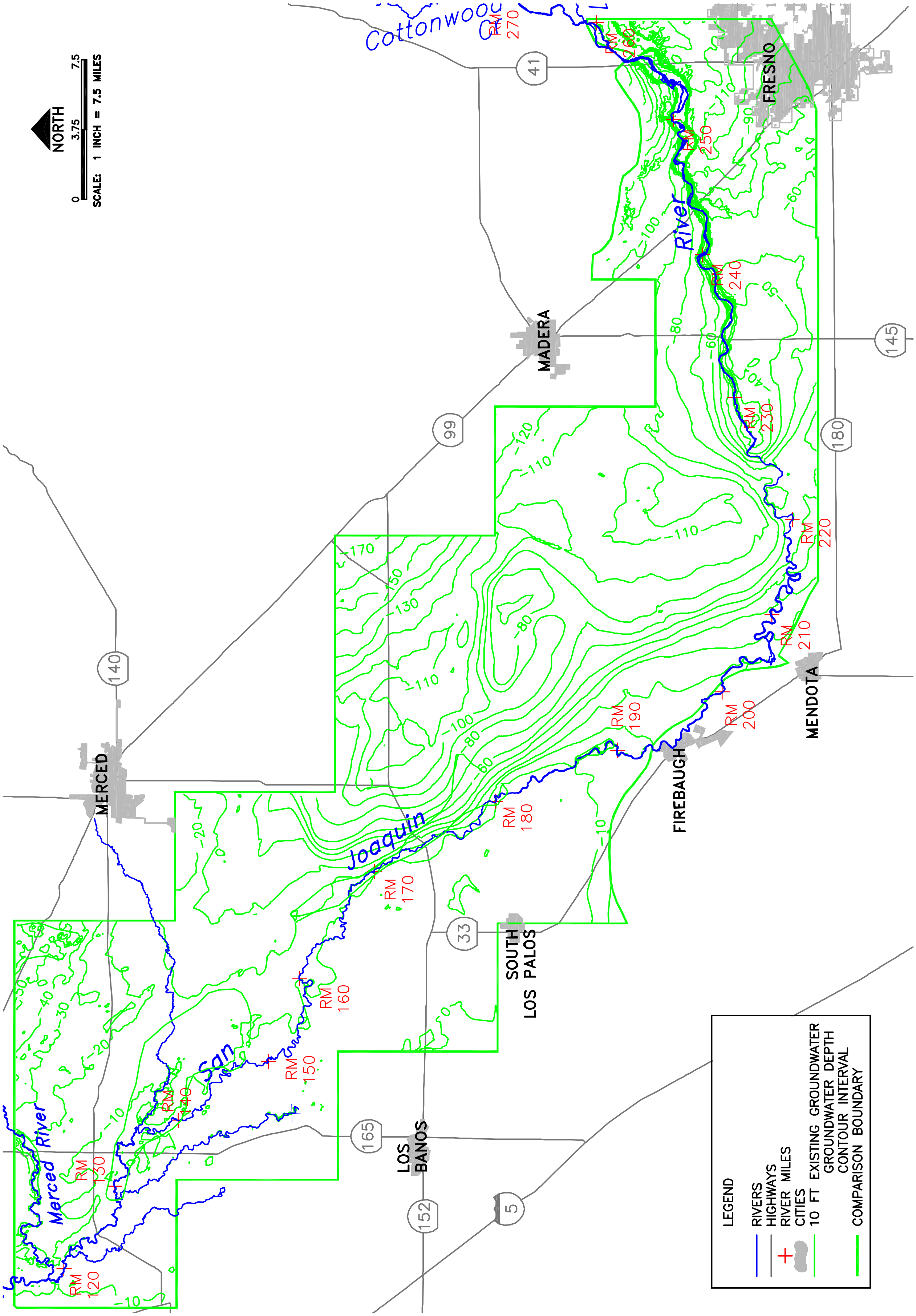


Figure 4-13. Estimated 1996 groundwater contours from Williamson et al. (1989), shown as a depth from the existing ground surface (from Figure 4-9).

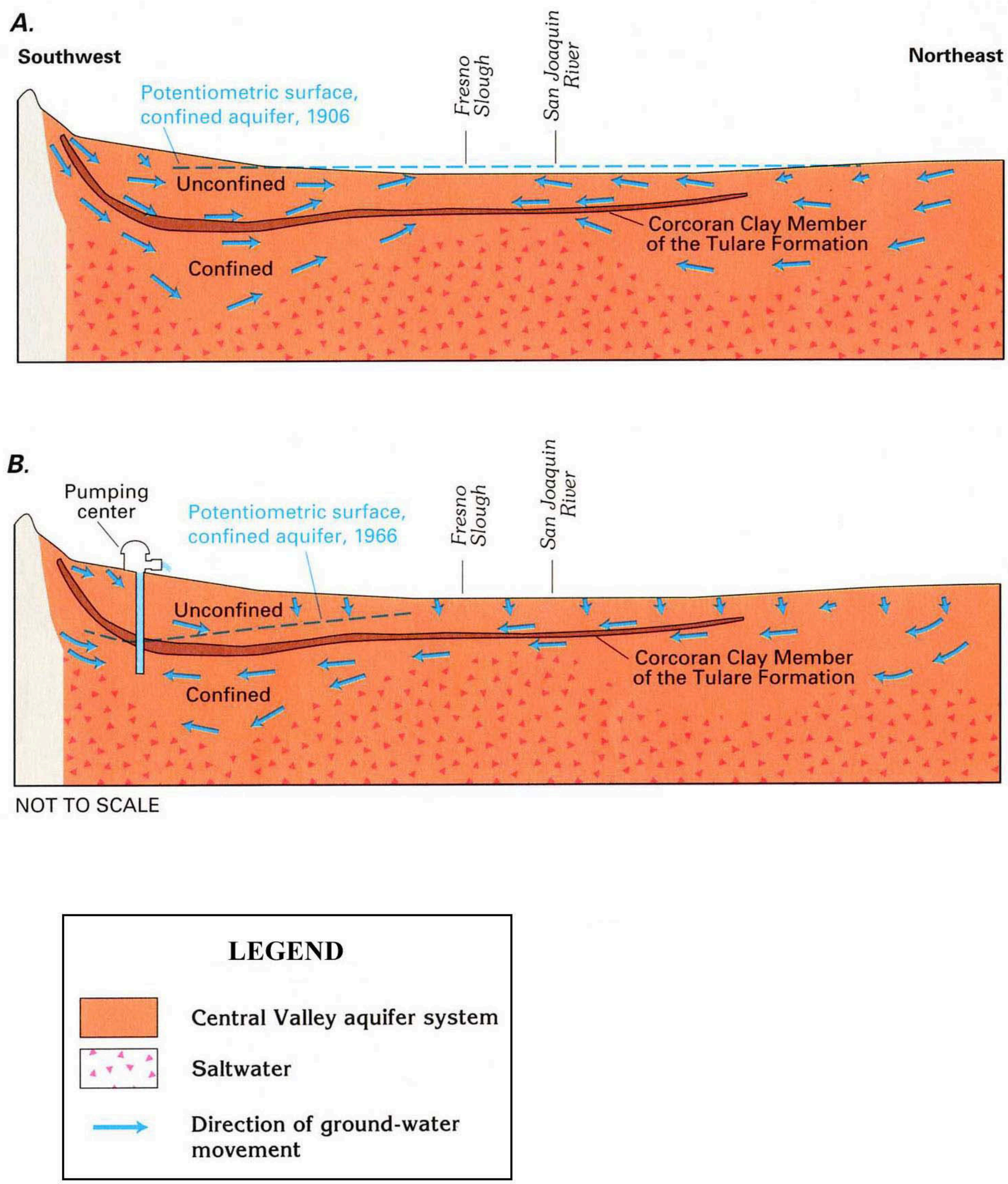


Figure 4-14. Diagrammatic cross section of the San Joaquin Valley showing pre-development groundwater conditions, and impact of pumping on present-day groundwater conditions.

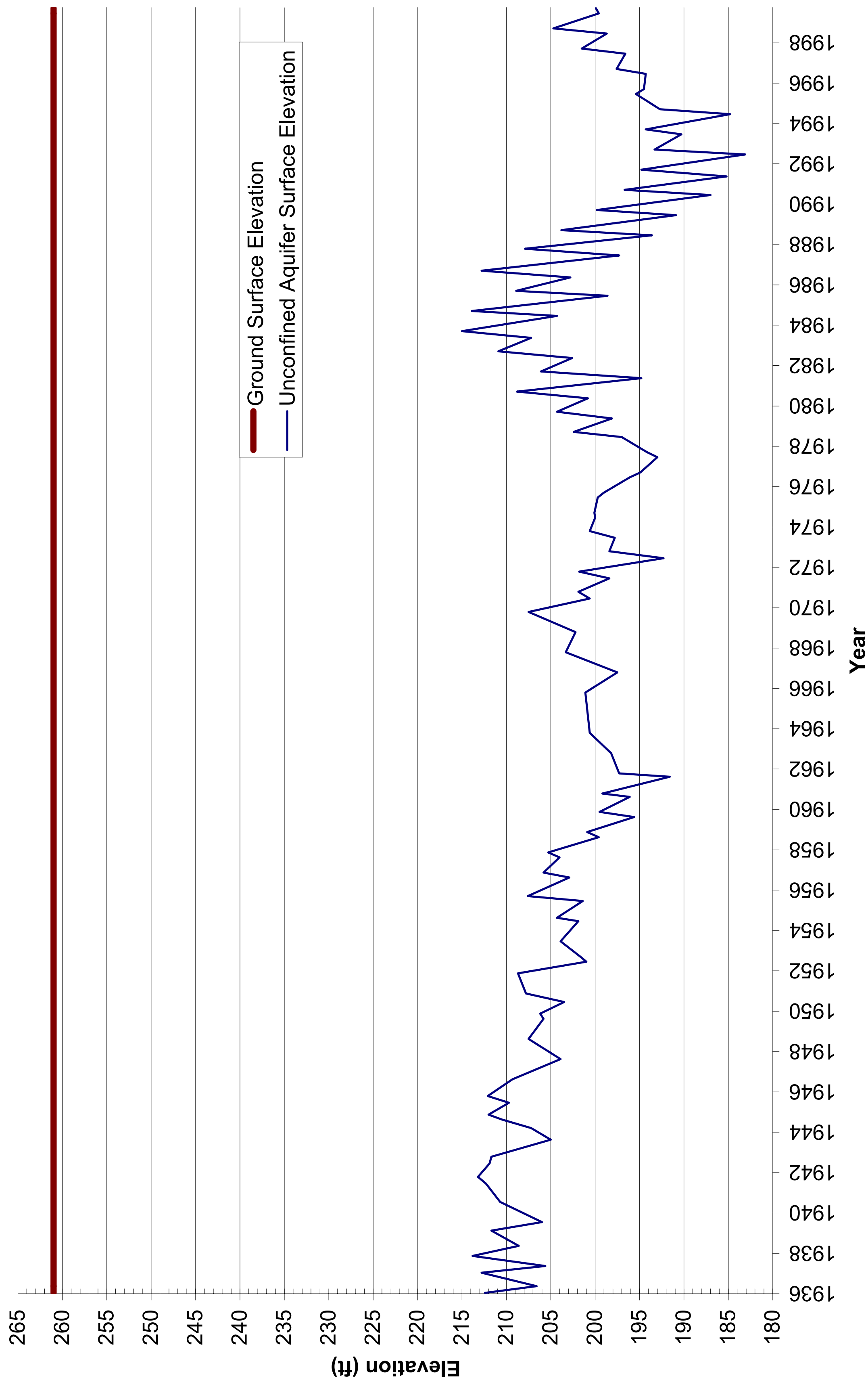


Figure 4-15. Example well showing drought and wet-year fluctuations in water table elevation within a general decline of water table caused by pumping overdraft. Well location is on north side of San Joaquin River at River Mile 237 (T.13S., R.18E., Section 4), downstream of Herndon.

In addition to groundwater pumping, application of irrigation water for agricultural practices may have locally significant effects on shallow groundwater levels within the study area. Irrigation is the primary source of groundwater recharge in the San Joaquin Valley. Although most irrigation recharge is located at distance from the San Joaquin River (e.g., eastern and western San Joaquin Valley), irrigation of cultivated fields and pasture near the river occurs within the study area. Phillips et al. (1991) observed localized and seasonal rises in shallow groundwater table elevations along the river during their study of shallow groundwater conditions. In both June and July 1989, although there were pumping-induced drops in groundwater elevations in intermediate and deep wells at one monitoring location, they observed a corresponding rise in the shallow water table associated with recharge of irrigation water. In spite of these spatially and temporal increases in shallow groundwater elevations due to irrigation, the net result in shallow groundwater table elevations has been a decline over time.

There is a considerable amount of data on shallow groundwater in the study reach, although much of the data is not immediately adjacent to the river. Maps of DWR well locations can be found at: http://well.water.ca.gov/gw/gw_data/hyd/Rpt_Bas_Well_AllCal.asp. Clicking to finer scaled maps at this site will eventually lead to the individual well locations, and selecting a certain well will download all water elevation measurements over the period of record. Recent groundwater elevation contour maps are at: http://www.dpla.water.ca.gov/sjd/groundwater/basinlst.html. For a large number of wells, long-term trends of groundwater elevations are available (Figure 4-15), some of which is available on-line at the above web sites. However, because of the severe overdraft of the shallow groundwater aquifer, many of these wells have been extended into deeper aquifers, and thus are not as useful for evaluating potential ramifications to restoration efforts along the San Joaquin River. More pertinent data is available from the San Joaquin River Pilot Projects monitoring efforts in Reach 2 and the lower portion of Reach 1B (see Section 4.6.5). Additional data may be available in the shallower private wells along the river, but this data may be more difficult to obtain.

4.6.3. Land Subsidence

Land subsidence is another impact of intense groundwater development in the San Joaquin Valley. From 1961 to 1977, the rate of groundwater withdrawal from the aquifer system was greater than the net recharge from all sources (Planert and Williams 1995). Some of the loss in groundwater storage is permanent because pumping of deep wells dewatered clay beds; once drained, the clay beds become compacted. Dewatering the clay layers reduces the clay's pore pressure and the weight of the overlying sediments compact the clay. Loss in porosity of the clay layers is permanent and causes irreversible land subsidence.

Significant subsidence due to groundwater withdrawals began in the San Joaquin Valley in the 1920's. By 1977, approximately half of the valley subsided at least a foot, with the most severely affected areas located in the southern and western parts of the valley, outside of the study area (Figure 4-16). Some areas south of Mendota had subsided by nearly 30 feet (Figure 4-17).

4.6.4. Groundwater-Surface Water Interaction

Since the 1950s, San Joaquin River flows have been controlled by Friant Dam, located upstream of Fresno, and by dams on tributary streams. Much of the water stored in Millerton Reservoir is diverted through the Friant-Kern and Madera canals. As described in Chapter 2, streamflows in the San Joaquin River have been greatly reduced, and the channel is perennially dry in Reach 2 and Reach 4B in most years. Downstream of Reach 4B, river flows are replenished by irrigation return flows, local runoff, and groundwater inflow (Groundwater Management Technical Committee 1999).

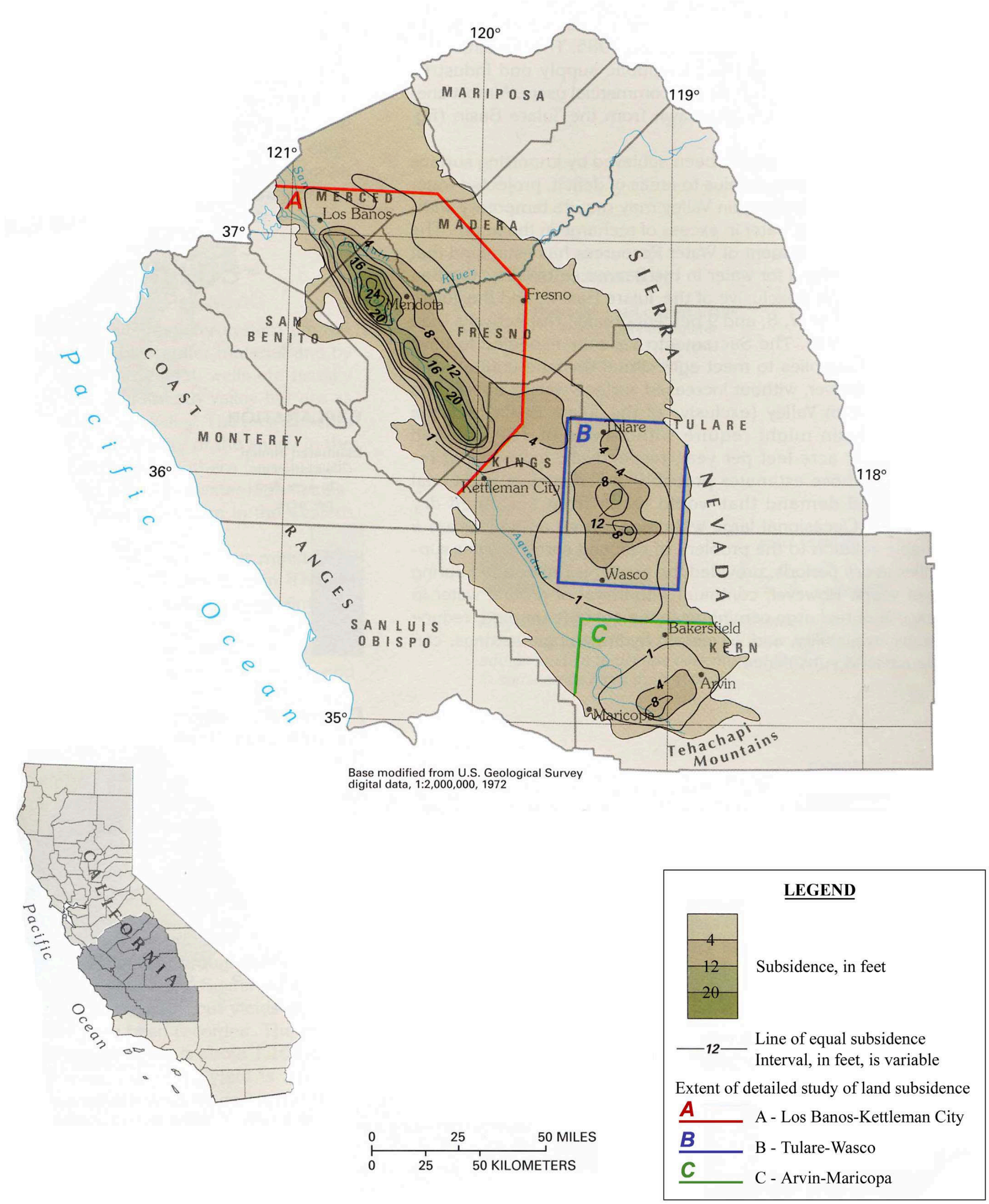


Figure 4-16. Zones of land subsidence in the San Joaquin Valley due to groundwater pumping. Land subsidence is most severe in the southern portion of the San Joaquin River corridor and Tulare Lake basin between Los Banos and Kettleman City. Modified from Ireland (1986).

A limited number of studies have evaluated groundwater and surface water interaction within the study reach. Generally, under present day conditions, groundwater elevations are significantly lower than the San Joaquin River channel and tributary channel elevations (e.g., Fresno, Chowchilla, Merced Rivers) in Reach 1 and 2, and moderately lower in Reach 3. The hydraulic head differential between stream water elevations and the underlying groundwater elevations induces seepage losses from the stream (Figure 4-7). This type of river reach is termed a “losing reach” or “losing stream”. Conversely, in the river reaches flowing through the lower valley trough, shallow groundwater levels at or above the elevation of adjacent stream channels will induce groundwater accretion into the river channels. Stream reaches that receive groundwater inflow are termed “gaining reaches” or “gaining streams”.

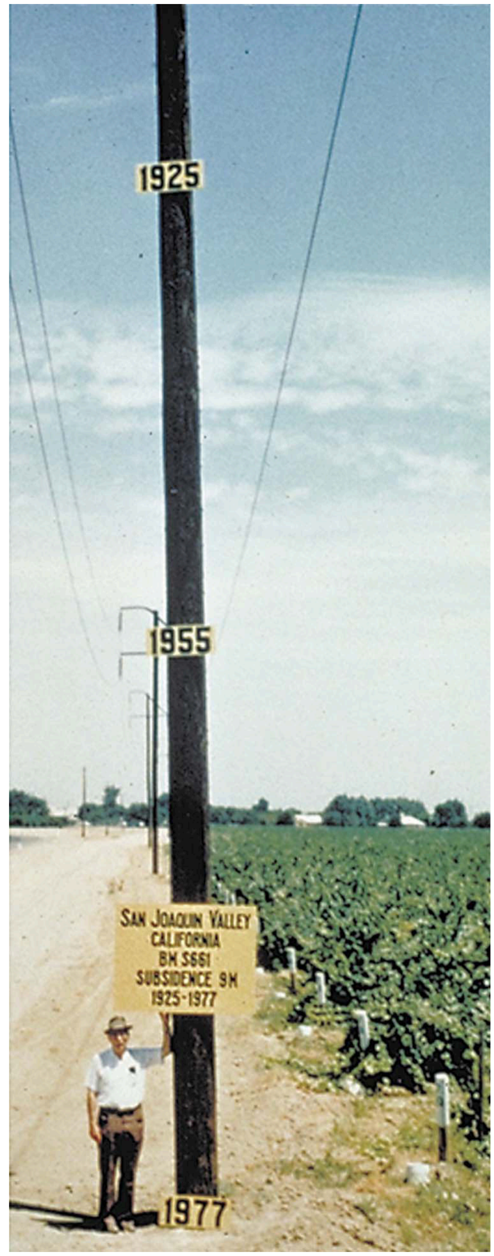


Figure 4-17. Illustration of maximum subsidence at a site 10 miles southwest of Mendota, showing 29.6 feet of subsidence between 1925 and 1977.

Historically, most of the San Joaquin River was a gaining reach (Figure 4-8); however, the significant decrease in groundwater elevations has reversed this condition, so most reaches are now losing reaches. However, some localized gaining reaches still remain on the lower river. The 1998 thalweg elevation of the San Joaquin River (developed from topographic data gathered by the Corps of Engineers Comprehensive Study) was compared to the 1996 groundwater elevations. Reaches where the 1996 shallow groundwater elevations were greater than the 1998 thalweg (lowest portion of river bed) elevation of the stream were considered to be potentially gaining reaches (Figure 4-18). The most pronounced potentially gaining reaches occurs in the reach between RM 195 (Firebaugh) and RM 165, and the reach between RM 148 (Mariposa Bypass) and RM 118 (Merced River confluence). Another potentially gaining reach occurs between RM 243 (Herndon) and RM 234 (SR 145), although the elevation difference was not as great as the two other reaches; plus the reach between RM 243 and RM 234 is a reach identified by DWR as a likely losing reach.

Based on synoptic streamflow monitoring conducted during the San Joaquin River Pilot Projects between 1999 and 2001 (JSA and MEI 2002, FWUA and NRDC 2002), seepage and riparian diversion losses were estimated for Reach 1 and 2. Between the Friant gaging station and Gravelly Ford (approximately 38 river miles), a minimum flow of 105 cfs is needed at the Friant gage to obtain a measurable flow at the Gravelly Ford gage, suggesting that the minimum seepage loss outside the irrigation season is 105 cfs (2.8 cfs/mile). Flow losses increase during the irrigation season as riparian diversions are utilized. Flow losses increase to approximately 130 cfs (3.42 cfs/mile) to 250 cfs (6.6 cfs/mile) during the summer and fall irrigation season.

Between the Gravelly Ford gaging station and Above Chowchilla Bifurcation Structure gaging station (approximately 13 river miles), a minimum of 75 cfs is needed at the Gravelly Ford gage to get a measurable flow at the Above Chowchilla Bifurcation Structure gage, suggesting that the minimum seepage loss outside the irrigation season is 75 cfs (5.8 cfs/mile). This reach has had the greatest depletion in shallow groundwater aquifer due to overdraft, which is likely reflected in the larger unit-length seepage loss rate. There do not appear to be as significant seasonal pattern to flow losses between the irrigation season and winter season (as occurred between Friant and Gravelly Ford). Maximum flow losses are approximately 250 cfs (6.6 cfs/mile), likely due to varying degrees of riparian withdrawals in the reach during those times when there are flows in the river. One other important relationship is the effect of Mendota Pool on the shallow groundwater table in Reach 2B. Because water is imported into Mendota Pool by the Delta-Mendota Canal, Mendota Pool is nearly always filled and locally recharges the shallow groundwater table in much of Reach 2B.

The location and rate of water exchange between gaining and losing reaches may be highly variable, due to pumping induced groundwater fluctuations. Fluctuating groundwater elevations may cause the net flow between stream channel and adjacent aquifer to change direction seasonally or over multiple years. When seasonal or annual fluctuations occur, river gains and losses will vary correspondingly. Seasonal and long-term droughts will also cause large groundwater elevation fluctuations in the river-aquifer system; droughts compound the variability in surface and groundwater interactions. Therefore, an important question is: in the San Joaquin Valley aquifer system, to what degree does pumping in either the upper unconfined or deeper confined zones affect the shallow groundwater elevations in the adjacent floodplain deposits?

DWR developed reach-specific water budgets that quantified major inflows (e.g., groundwater supplied in a gaining reach) and outflows (e.g., channel outflow, diversions) for data available from 1970 to 1977, to quantify the long-term accretion and seepage rates to/from selected river reaches in the San Joaquin Valley (Table 4-2) (DWR 1985). The seepage estimates derived from the Pilot Projects (using 1999 to 2001 data), as well as the Phillips et al. (1991) estimates, are based on only three years of data (Table 4-2). DWR's seven-year seepage/accretion rates indicate that the San Joaquin River was a losing river from the Friant gage downstream to at least Dos Palos gage, and the river was a gaining river downstream of the Dos Palos gage. These conditions are in general agreement with qualitative and quantitative estimates of gains and losses to/from the River presented by Mitten et al. (1970).

The seepage estimates estimated by the Pilot Projects and other studies helped develop the San Joaquin River water budget flow model described in Chapter 2. Seepage rate estimates were based on USGS, USBR, and Pilot Project stream flow measurements, and thus the records represent a combination of seepage loss due to recharge of the shallow groundwater table and cumulative riparian diversions. Therefore, the seepage rates determined from the pilot projects may not be directly comparable to DWR's seepage estimates.

Two aquifer tests were conducted by K.D. Schmidt & Associates near Mendota to determine the extent of hydraulic connection between the shallow fine grained deposits (approximate 10 feet) and the underlying coarse-grained deposits (located at 20 and 50 feet below ground surface). One pump test documented that pumping groundwater from the deeper coarse-grained deposits caused substantial and relatively rapid groundwater drawdown in piezometers monitoring the shallow fine-grained deposits (one foot of drawdown in a piezometer located several hundred feet from the pumping well), indicating good hydraulic communication between the two units. In the second aquifer test, a large capacity well screened from 122 to 244 feet below the ground surface was pumped and monitored. Responses in two nearby observation wells that were screened to monitor the

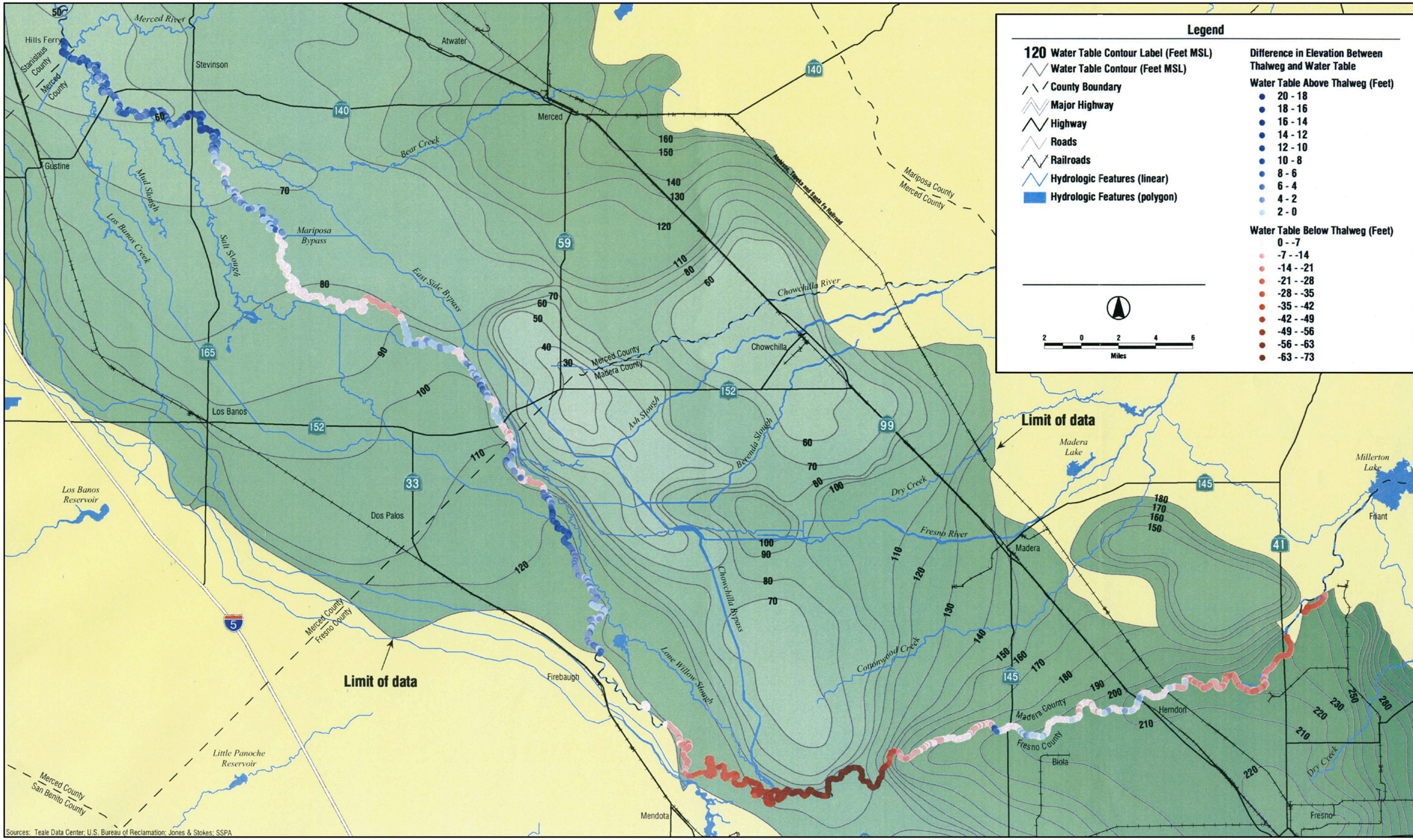


Figure 4-18. Potentially gaining and losing reaches based on Spring 1996 water table conditions and 1998 channel thalweg conditions. From JSA (2000).

Table 4-2. Estimated rates of seepage and accretion to select river reaches.

San Joaquin River Reach	Reach Length (miles)	1970-77 Gain/Loss (cfs/mi.)**	1999-2001 Gain/Loss (cfs/mi.) **	1986-89 Gain/Loss (cfs/mi.) **
Friant Dam to Gravelly Ford	38	-0.58	-2.8*	n/a
Gravelly Ford to Chowchilla Bifurcation Structure	13	-2.07	-5.8*	n/a
Mendota to Dos Palos (Sack Dam)	23	-0.43	n/a	n/a
Dos Palos (Sack Dam) to Fremont Ford	56	+0.38	n/a	n/a
Fremont Ford to Newman	7	+13.93	n/a	n/a
Newman to Patterson	19	n/a	n/a	+3.2 to +6.7
Data Source		DWR 1985	FWUA and NRDC 2002; JSA and MEI 2002	Phillips et al. 1991

Notes:
*minimum seepage rates used to better approximate losses under equilibrium conditions and to reduce effects of riparian diversions in loss computations
**negative numbers indicate seepage out of river and positive numbers indicate groundwater accretion into the river.

deeper aquifer zone, and in eight piezometers, each screened to approximately 12-feet below ground surface, were documented. The test results indicated that pumping from the deeper Sierran sands could cause shallow groundwater elevations to decrease. Groundwater drawdown was approximately one foot in the shallow zone, due to downward, pumping-induced leakage. These results are likely conservative because canal seepage, a significant recharge source to the shallow groundwater zone, was observed during the pumping test. In summary, pumping from the deeper Sierran sands can cause decreases in the shallow groundwater elevations, which, in turn, can impact the water availability to adjacent river and to riparian habitat.

Phillips et al. (1991) also analyzed the hydrogeologic characteristics of the groundwater flow in 22 wells screened from unconfined (11.5 feet below ground surface) through confined deep (107.5 feet below ground surface) zones adjacent to and beneath the San Joaquin River, along a 19-mile stretch between Newman and Patterson. Boring logs indicate that deposits of Sierran sands were above the E-clay, and overlying the Sierran sands were 10 to 30 feet of flood-basin deposits. Although the Phillips et al. study reach (downstream of the confluence with the Merced River) is downstream of our study area, the findings are applicable to reaches with similar deposits. The shallow flood basin deposits within the Newman to Patterson portion of Phillips et al. study area consist of interbedded sand, silt, and clay; its permeability is highly variable. Within the flood-basin deposits, individual layers could not be correlated between boring/well locations, however, interbedded clay and sand layers of variable thickness were documented at each boring/well location. Phillips et al. (1991) concluded that the consistent occurrences of finer grained, lower permeability layers are probably are the key controls over the groundwater flow system near the river. Significant findings of the Phillips et al. study include:

- The water elevation hydrographs and hydraulic gradients indicate that groundwater pumping, even from deeper zones, has a significant effect on the groundwater system near the San Joaquin River. The component of groundwater flowing from west to east underneath the San Joaquin River is significant; this flow would have naturally discharged to the River. The cause for this flow pattern is groundwater overdraft and a large cone of depression developed in the unconfined zone northeast of the study reach (Figure 4-13).
- Irrigation from surface water delivery is the primary source of groundwater recharge. It supplements some of the historical infiltration recharge from surface sources (streams, precipitation), but at a lower rate, such that decreasing shallow groundwater elevations are the net effect.
- The effects of irrigation and groundwater overdraft can be observed in the regional groundwater elevations (e.g., Figure 4-13) and in elevations recorded in shallow observation wells (e.g., Figure 4-15).
- At the time of the Phillips et al. (1991) study, groundwater inflow was a substantial component to the net gain in stream flow in the reach from Newman to Patterson. Seasonally, water contributions to the reach were greatest from spring and summer irrigation return flows. Simulated average water inflow rates to the San Joaquin River in the Phillips' study reach ranged from 3.2 to 6.7 cfs/mile (Table 4-2).
- Groundwater elevations show a seasonal variation to some degree, with decreasing elevations in the late summer and early autumn, and increasing elevations in the late winter and early spring.
- In general, horizontal hydraulic gradients between the unconfined aquifer wells and the San Joaquin River are toward the river and they generally do not have a strong seasonal trend. Exceptions include: 1) localized groundwater recharge and mounding adjacent to an irrigation ditch, where the horizontal gradient increases rapidly during the late spring and summer irrigation periods, and 2) short term reversals on both sides of the river, when river stage height increases sharply. Short-term bank storage and release is associated with the rise and fall of a flood peak.

S.S. Papadopulos & Associates (2000) provides insight into the variables that affect water levels in the shallow San Joaquin River-aquifer and riparian zone system. They performed a groundwater model sensitivity analysis to evaluate the impact of different hydrologic, hydrogeologic, and land-use variables over simulated shallow groundwater elevations. The Papadopulos groundwater model extended from Friant Dam to the Merced River. Water elevations and flow directions varied depending on factors such as: starting boundary conditions (water elevation), evapotranspiration, characteristics of certain crop types, regional and local irrigation-soil moisture contents, regional and local groundwater pumping rates, river flow rates, seasonal and long-term variability in rainfall and evapotranspiration, and soil permeability. The Papadopulos model provides a coarse level evaluation of the shallow groundwater surface elevations along the study reach.

4.6.5. San Joaquin River Riparian Pilot Projects

Recent monitoring efforts in Reaches 1B, 2A and 2B of experimental flow releases have also provided data for evaluating surface flow and unconfined groundwater flow interactions adjacent to the river. This monitoring effort was conducted as part of the San Joaquin River Pilot Projects between 1999 and 2001, and the monitoring effort established ground-surveyed cross sections, monitored water surface elevations in the San Joaquin River and in off-channel wells and piezometers, and documented riparian seedling initiation on different surfaces of the cross sections (FWUA and NRDC 1999, JSA and MEI 2002, and SAIC 2002). Particularly important is concurrently tracking surface water elevations in the river and adjacent shallow groundwater elevations, which illustrates correlations between the two under present-day groundwater conditoins. Because many reaches of the San Joaquin River are losing reaches, surface flows and subsequent lateral seepage determine the depth to groundwater. This relationship is important for future natural riparian regeneration and estimation of seepage losses (needed for consideration in restoring future flow continuity).

In the 1999 pilot project, the goal of the flow releases from Friant Dam were to establish riparian vegetation on upper sand bar surfaces, primarily in Reach 2. Monitoring focused on evaluating whether managed flow releases promoted riparian tree growth along those subreaches that had very limited riparian vegetation due to long periods of dewatered conditions in the river, and at what locations vegetation established. In 2000, the goal of the pilot project flow release was primarily to maintain vegetation that had initiated during the previous years' pilot project release. In 2001, the goal of the pilot project flow releases was primarily vegetation maintenance and evaluation of hydrologic routing and shallow groundwater characteristics. The primary objectives of the monitoring was to evaluate vegetation at the beginning and end of the growing season, to determine the response of vegetation to augmented flows released into the San Joaquin River during the summer and fall of 1999-2001 (JSA and MEI, 2002), and to evaluate and calibrate hydraulic and flow routing models. In order to satisfy the monitoring objectives, groundwater wells and piezometers were installed to document seasonal fluctuations in the shallow groundwater table along the floodway, as well as to evaluate the relationships between surface water flows in the San Joaquin River and the shallow groundwater table on potential riparian recruitment surfaces on floodplains and bars.

The first set of transects was established during September 1–5, 1999 (FWUA and NRDC 2002). These transects were resurveyed in November 1999 and April 2000. During 2000, additional permanently marked transects were established, for a total of 13 sites and 24 transects between River Miles 212 and 234.4 (Figure 4-19) (JSA and MEI 2002). Monitoring methods were also greatly revised in 2000 in order to better quantify vegetation changes. Transects were perpendicular to the channel and of varied length. They were monitored in 1999, 2000, and 2001 (JSA and MEI 2002, SAIC 2002). At each study site, the following data was collected:

- Cross section geometry
- Water surface elevation in the channel
- Shallow groundwater surface elevation at one or more locations on each cross section
- Presence of riparian vegetation, plant numbers, plant size (size class), species, and cover class.

Hydrology was monitored with a variety of techniques. Streamflow was estimated at the Gravelly Ford gaging station, discharge measurements were made at the Gravelly Ford gaging station, and spot discharge measurements were made at various locations in Reach 2 to evaluate gains and losses. Water surface elevations at cross sections were manually observed from staff gages, and shallow groundwater elevations were monitored by hand measurements in alluvial groundwater wells and instream and floodplain piezometers through 2002; pressure transducers and continuous water stage recorders monitored shallow groundwater elevations thereafter.

A brief summary of results is presented that focus on the 2001 monitoring season, as some of the more interesting observations were made during this monitoring season. Readers are directed to FWUA and NRDC (2002), SAIC (2002), and JSA and MEI (2002), for more details on monitoring methods and results of 1999, 2000, and 2001 pilot projects.

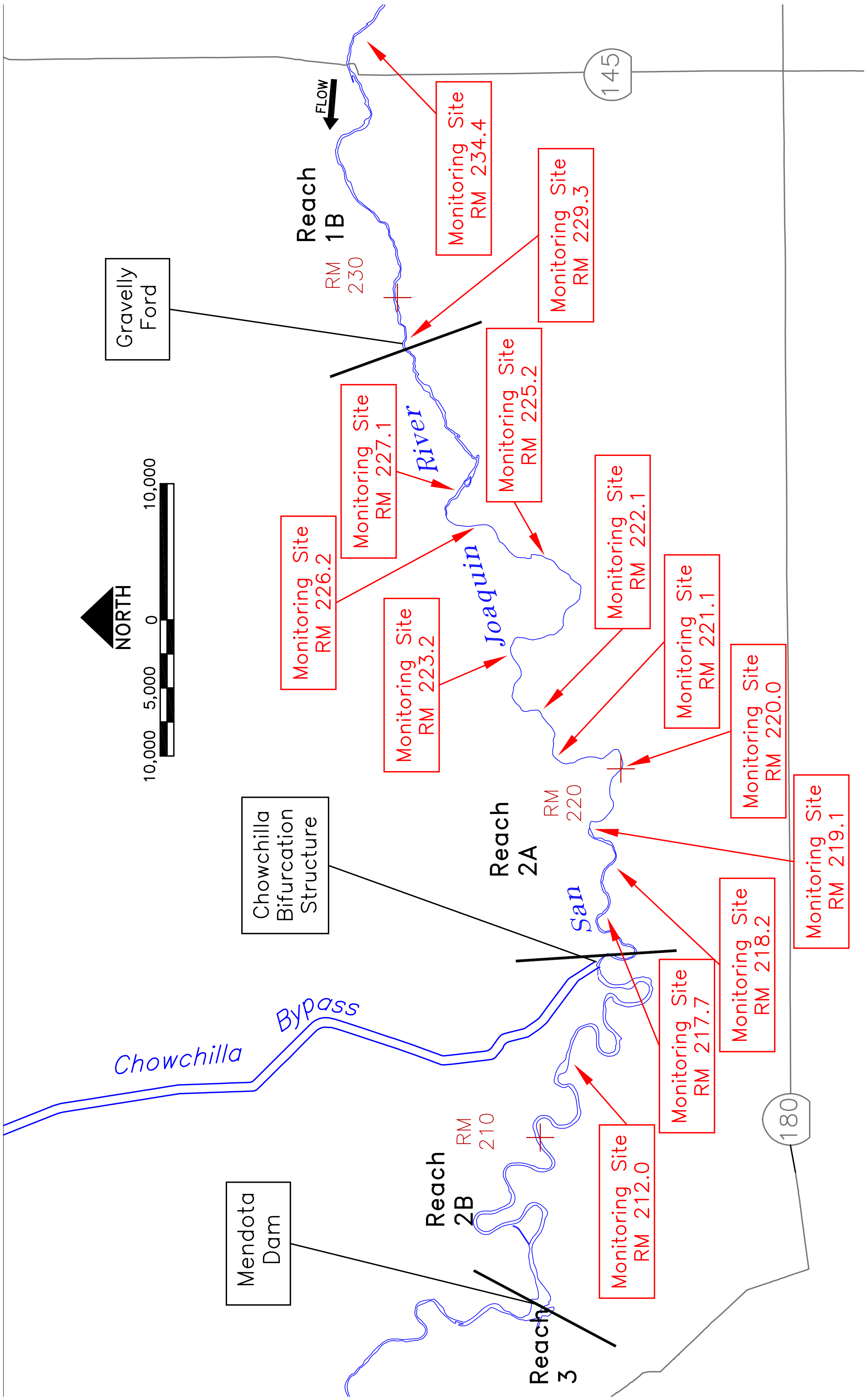


Figure 4-19. Location of 1999-2001 San Joaquin River Riparian Habitat Restoration Program Pilot Project study sites.

4.6.5.1. Results of pilot projects

Flows were released from Friant Dam during the summers of 1999-2001 for the respective pilot projects (Table 4-3). Because the one of the primary objectives of the 1999 and 2001 pilot projects was hydrologic routing and groundwater response, the following discussion focuses on results from the those two monitoring efforts.

Table 4-3. Summary of hydrology during 1999-2001 releases for pilot projects.

Water Year	Dates of pilot project flows	Date of peak Friant Dam release	Peak release from Friant Dam (cfs)	Peak flow at Gravelly Ford (RM 227.5) (cfs)	Peak flow at Chowchilla Bifurcation Structure (RM 216.1) (cfs)
1999	July 3 – Oct 6	June 4-6	813[1]	550[1]	434[1]
2000	June 5-June 21	June 18	2,590	1,760	Not reported
2001	June 1-June 25	June 17-23	400[1]	181[1]	0[3]
2001	Aug 27-Sept 9	Sept 5-7	880[1]	640	0[4]

[1] Daily average flow, steady flow so roughly equal to instantaneous peak

[2] Daily average flow, short duration flow so less than instantaneous peak

[3] Flow extended downstream to at least RM 223.2 (SAIC 2002)

[4] Flow extended downstream to at least RM 217.7 (SAIC 2002)

In 1999, a single pulse release from Friant Dam was released, with a target flow of 800 cfs at Friant Dam and 600 cfs target at the Gravelly Ford gaging station (Figure 4-20). Although there were substantial flow attenuation and seepage losses, flow continued through the entire reach to Mendota Pool (434 cfs). Highlights from the 1999 hydrologic monitoring relevant to shallow groundwater issues include:

- Seepage losses in Reach 2A during the pulse (after the shallow groundwater was “primed”) were approximately 70 cfs when Friant Dam releases were less than 100 cfs, and approximately 100 cfs when Friant Dam releases exceeded 100 cfs. Initial seepage losses were considerably higher at the beginning of the pulse flow release.
- The shallow groundwater table in Reach 2A was strongly linked with surface flows in the San Joaquin River (Figure 4-21 and 4-22); when river flows increased, shallow groundwater table elevation rose to near the same elevation. A slight decrease in lateral gradient in the shallow groundwater table away from the river suggests that the river is “filling” the shallow groundwater table, which is corroborated in the seepage losses computed from longitudinal streamflow gaging. The shallow groundwater table in Reach 1B adjacent to the river may higher than the river water surface (Figure 4-23), resulting in Reach 1B being a gaining reach rather than a losing reach (as is Reach 2A). However, a single cross section leaves considerable uncertainty whether this site-specific trend is applicable to the rest of the reach.

In 2001, two pulse flows were released from Friant Dam (Figure 4-24): 1) a flow of 200 to 250 cfs between June 1 to June 24, with a short peak flow of approximately 400 cfs, 2) a shorter peak flow of 880 cfs between August 27 and September 9. The flow averaged approximately 40 cfs at Gravelly Ford between the two pulses, but flows approached zero during short periods of time (Figure 4-24). Continuous water stage recorders were installed in many of the piezometers, allowing more detailed evaluation of seasonal shallow groundwater table fluctuations in 2001. Highlights from the 2001 hydrologic monitoring relevant to shallow groundwater issues include:

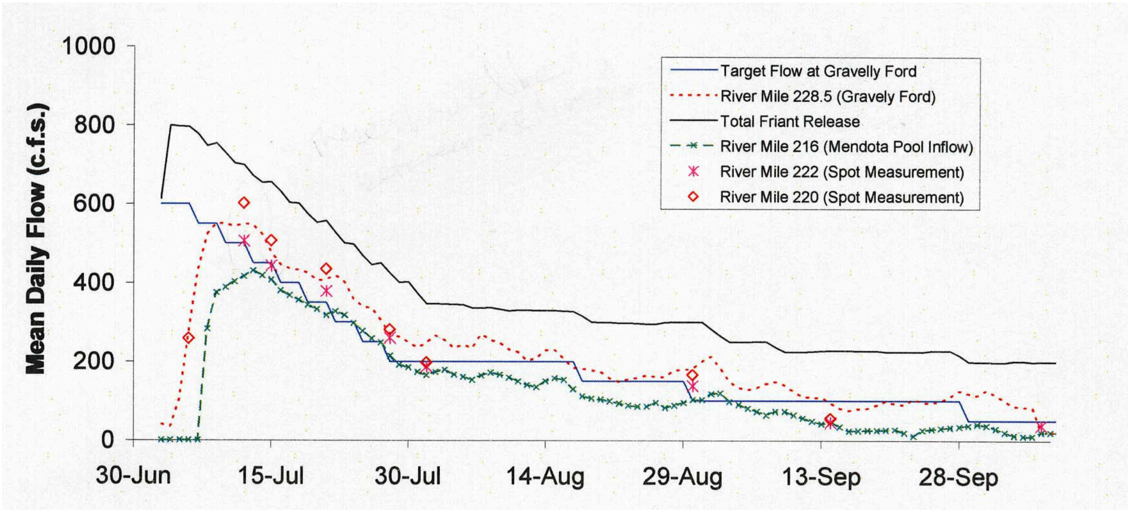


Figure 4-20. Friant Dam release (July to October 1999) and San Joaquin River discharge below Friant Dam and at the Gravelly Ford gage. From FWUA and NRDC (2002).

- There was a strong relationship between the river flows and shallow groundwater table within the floodway and the transition between floodway and agricultural lands. Monitoring wells were not installed at any significant distance beyond the floodway margins, so the relationship between river flows and regional shallow groundwater elevations cannot be quantified. The severe depletion in the regional shallow groundwater aquifer suggests that the groundwater flow gradient away from the river is strong, re-filling the depleted shallow groundwater aquifer. However, no data have been collected as part of the pilot project to confirm or reject this assumed gradient.
- Prior to the release, the river was dry downstream of the Gravelly Ford gaging station (RM 227.5). The limit of flowing water in the river extended five miles downstream to RM 223.2 during the June pulse flow (peak release = 400 cfs). The September pulse flow (peak release = 880 cfs) extended farther downstream, with flowing water ending between the RM 217.7 and the RM 212.0 sites. Therefore, surface flows did not necessarily reach the downstream-most transects.
- In-river water surface elevations increased between 1 and 3 feet during the pulse releases.
- Corresponding shallow groundwater fluctuations depended on location. At sites upstream of Gravelly Ford, the June pulse increased shallow groundwater elevations by 1 to 2 feet, while the September pulse increased elevations by 2 to 3 feet (Figure 4-25). Shallow groundwater elevations naturally tapered off after the peak streamflow occurred, within one month after the pulse. This plateau occurred because flow is perennial upstream of Gravelly Ford (i.e., the river supports the local shallow groundwater table).
- Downstream of Gravelly Ford, sites do not normally have river flows except during Pilot Project pulse flows and flood control releases. The groundwater response to the Pilot Project flows was different compared to the upstream study site with its perennial flows. Due to groundwater overdraft, groundwater elevations are far below the thalweg of the San Joaquin River downstream of Gravelly Ford. Therefore, when streamflows are released, the shallow groundwater aquifer rapidly fills up (up to 15 feet) as it is recharged (Figure 4-26 and 4-27).

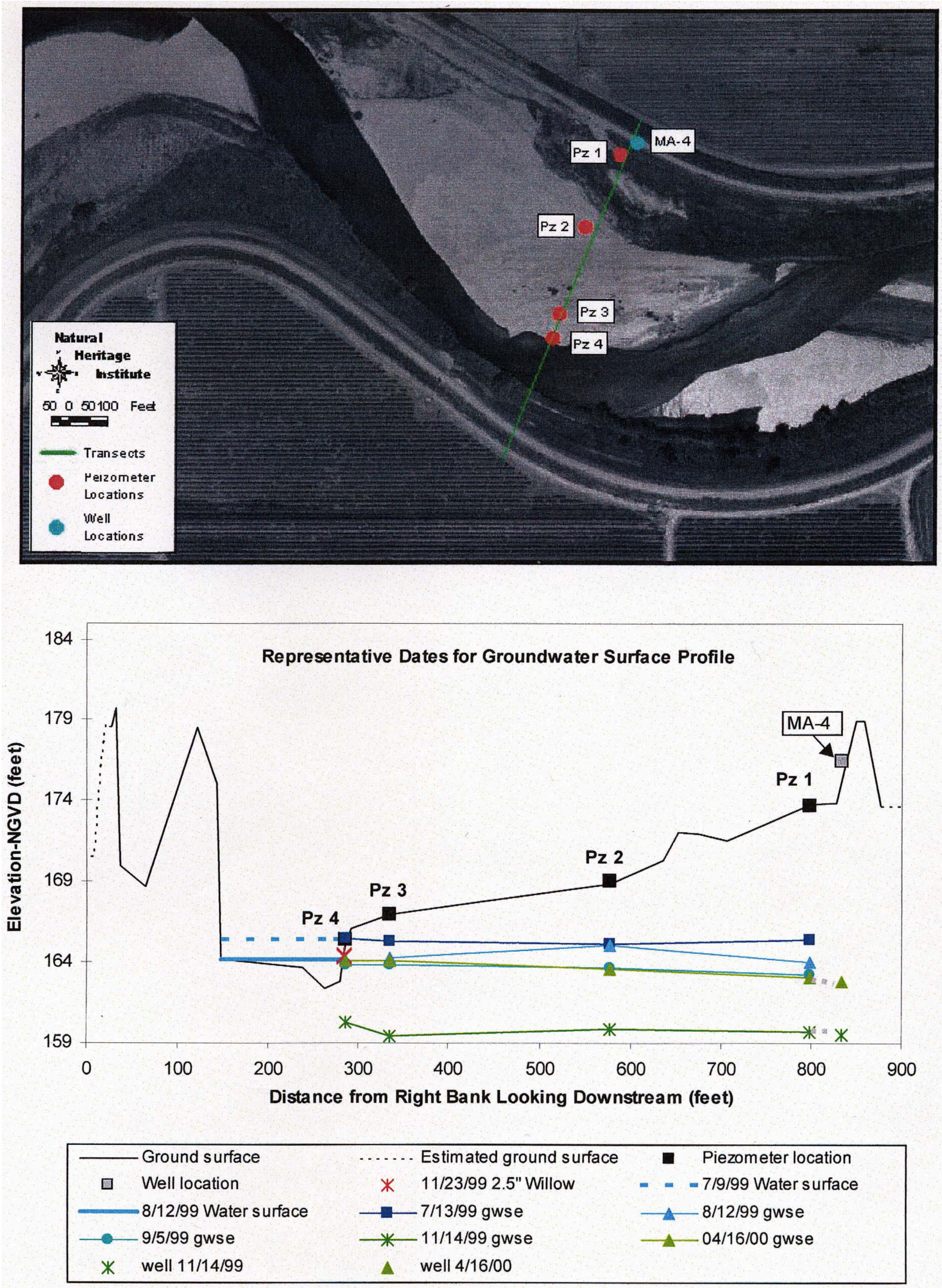


Figure 4-21. Aerial photograph and subset of 1999 groundwater measurements at the RM 217.7 monitoring site. From FWUA and NRDC (2002).

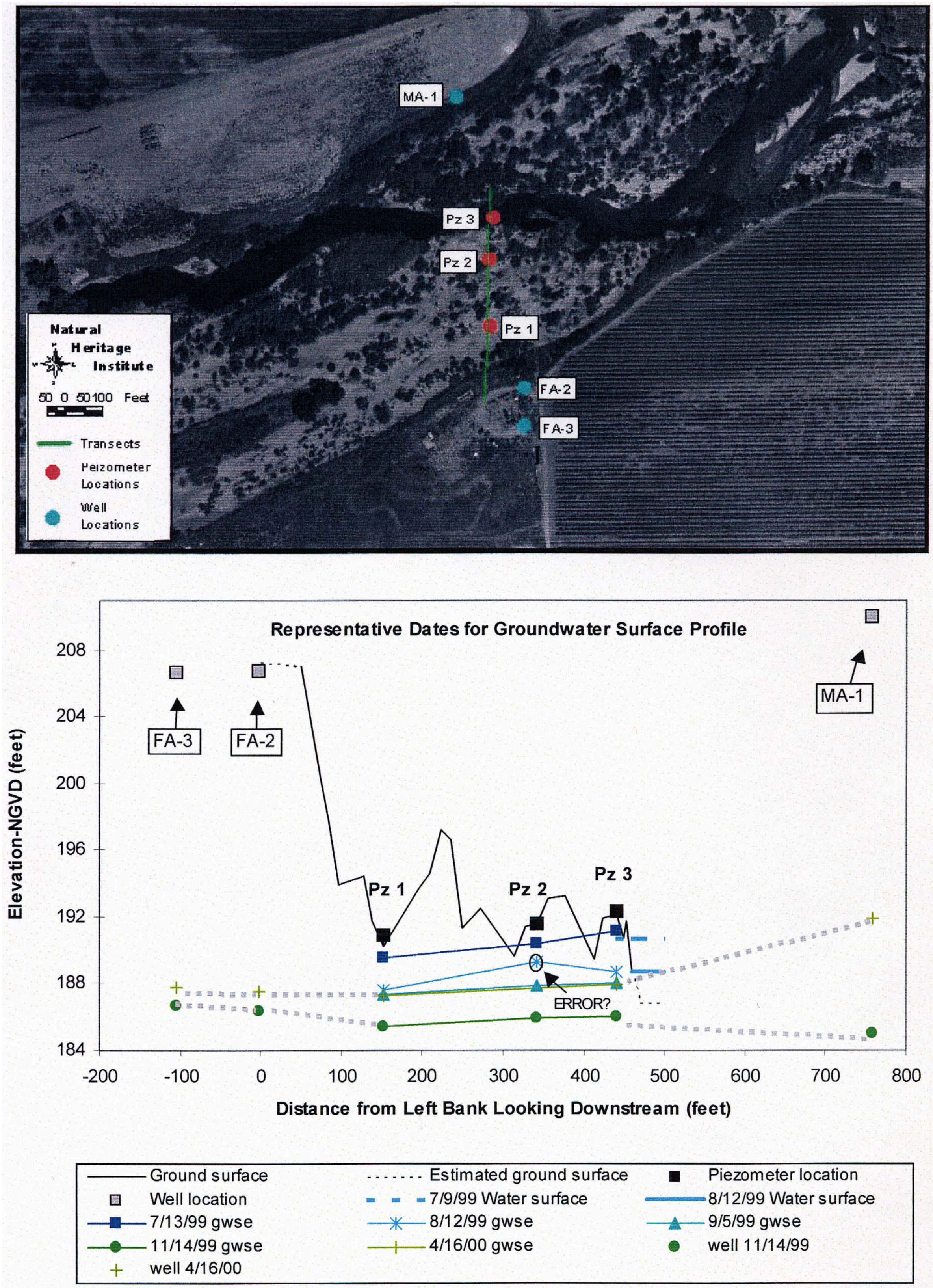


Figure 4-22. Aerial photograph and subset of 1999 groundwater measurements at the RM 229.3 monitoring site. From FWUA and NRDC (2002).

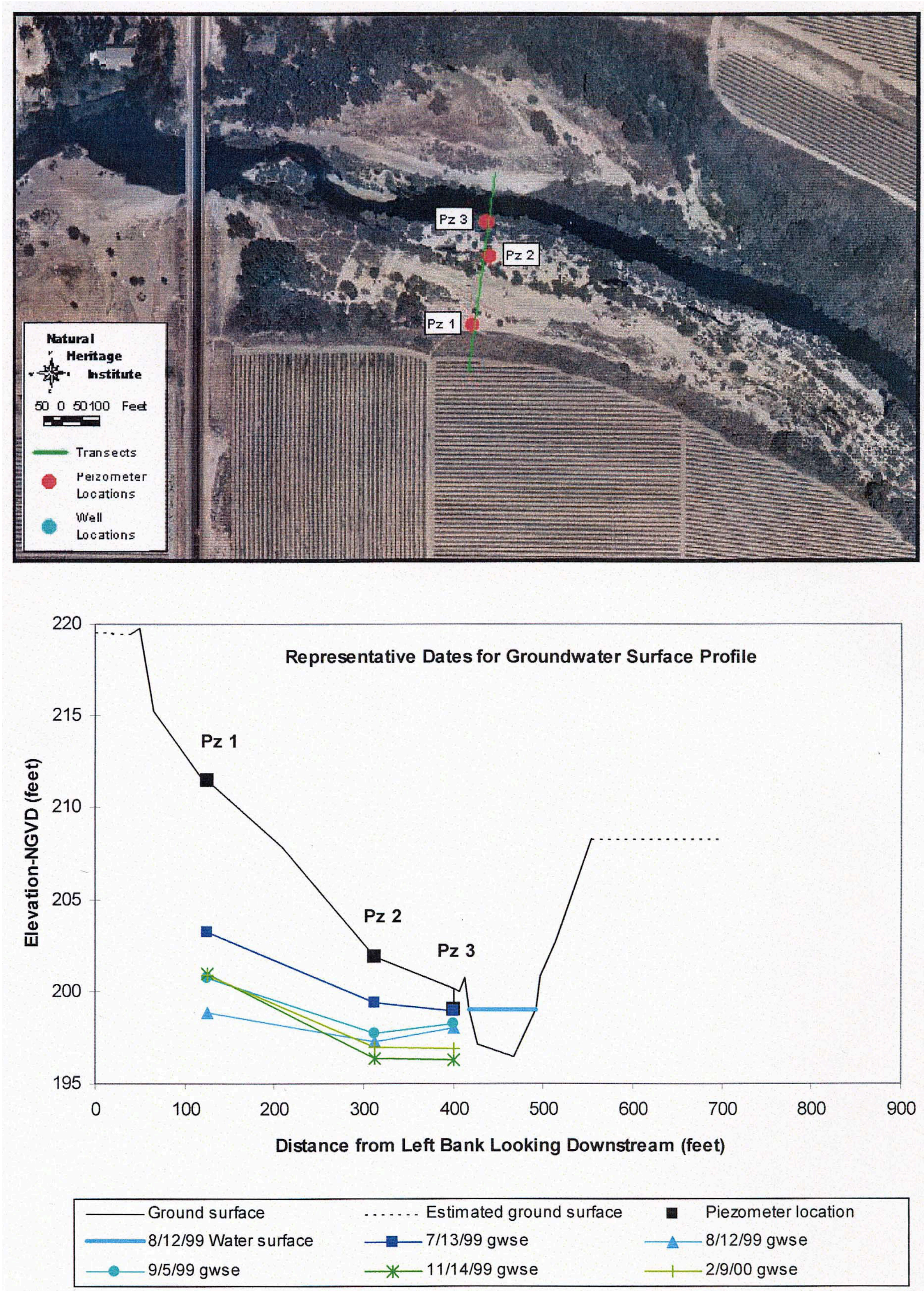


Figure 4-23. Aerial photograph and subset of 1999 groundwater measurements at the RM 234.3 monitoring site. From FWUA and NRDC (2002).

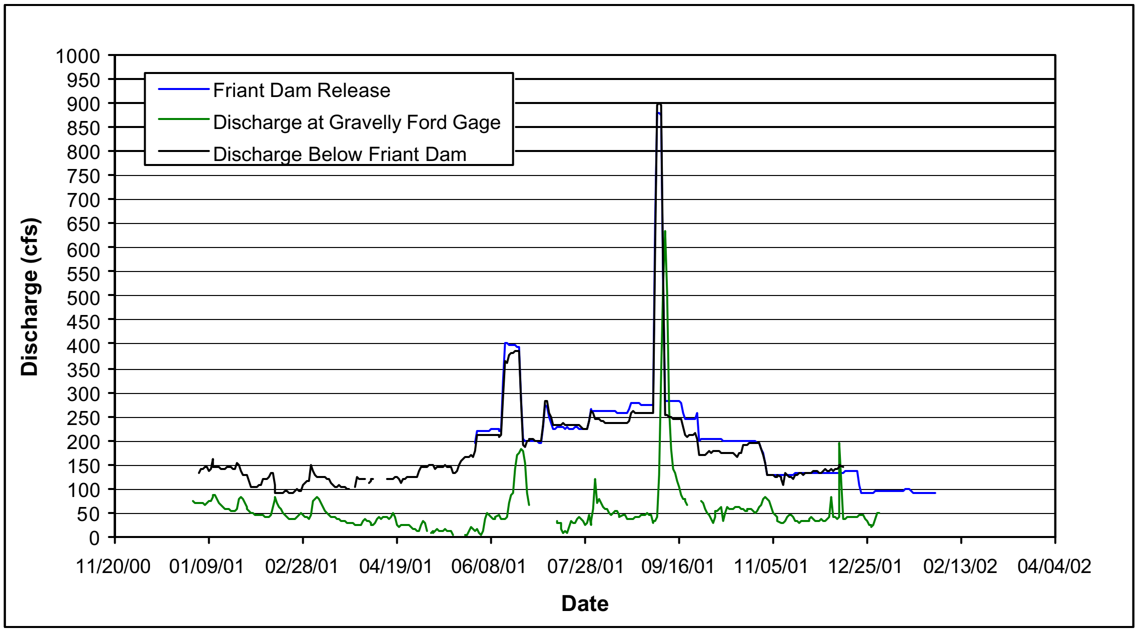


Figure 4-24. Friant Dam release (May to September 2001) and San Joaquin River discharge below Friant Dam and at the Gravelly Ford gage (January to December 2001). From SAIC (2002).

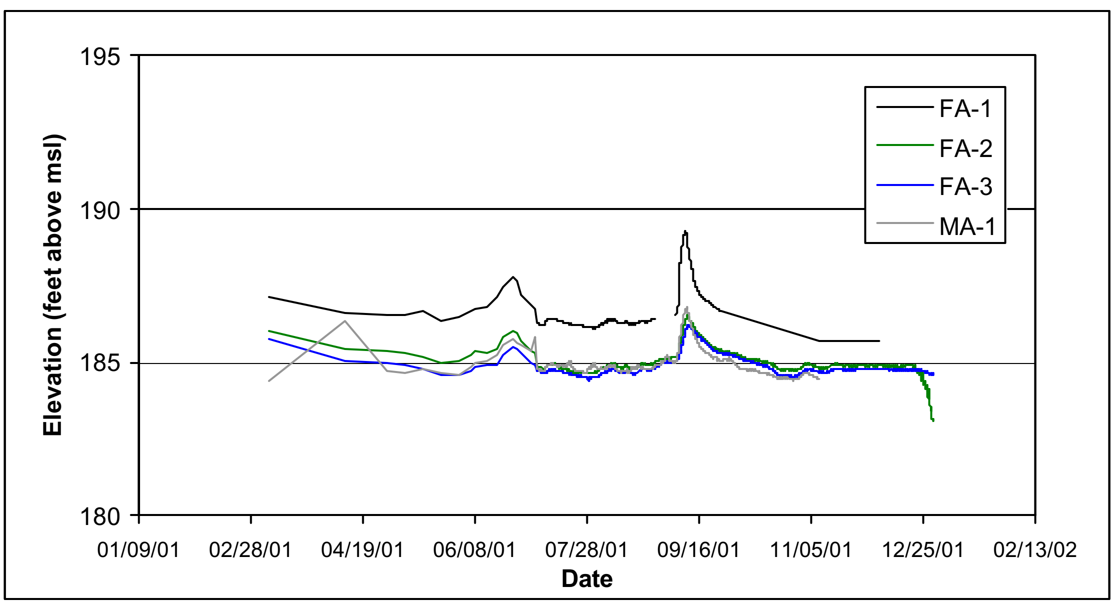


Figure 4-25. Summer 2001 Groundwater elevation trends from four alluvial wells at the RM 229.3 (Lake Avenue) study site (upstream of Gravelly Ford). Cross section thalweg elevation is 181.66 ft. From SAIC (2002).

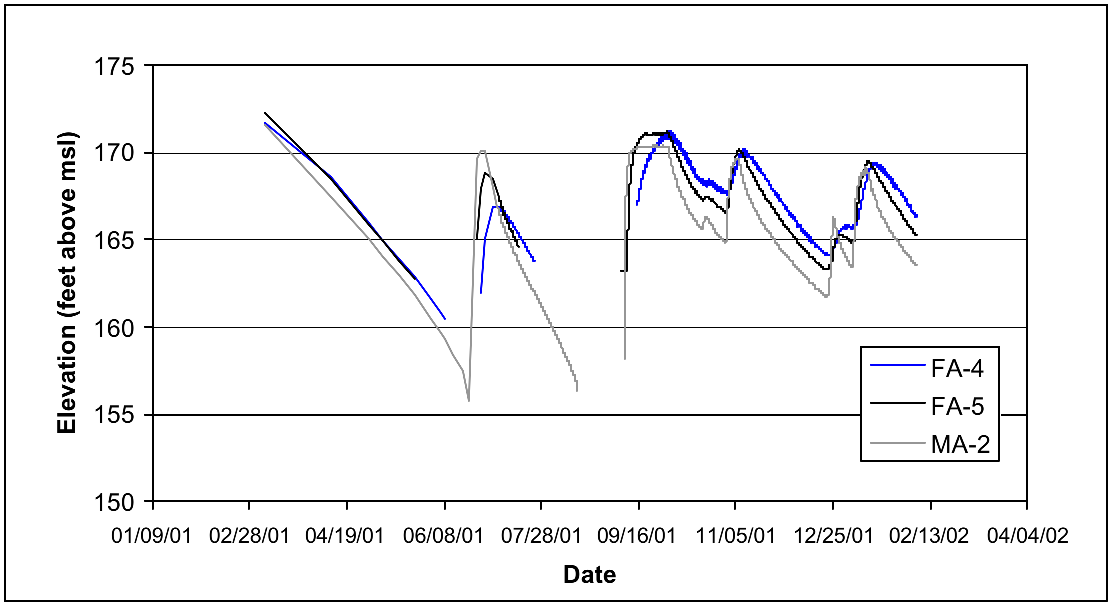


Figure 4-26. Summer 2001 Groundwater elevation trends from three alluvial wells at the RM 222.1 study site (downstream of Gravelly Ford). Cross section thalweg elevation is 171.33 ft. From SAIC (2002).

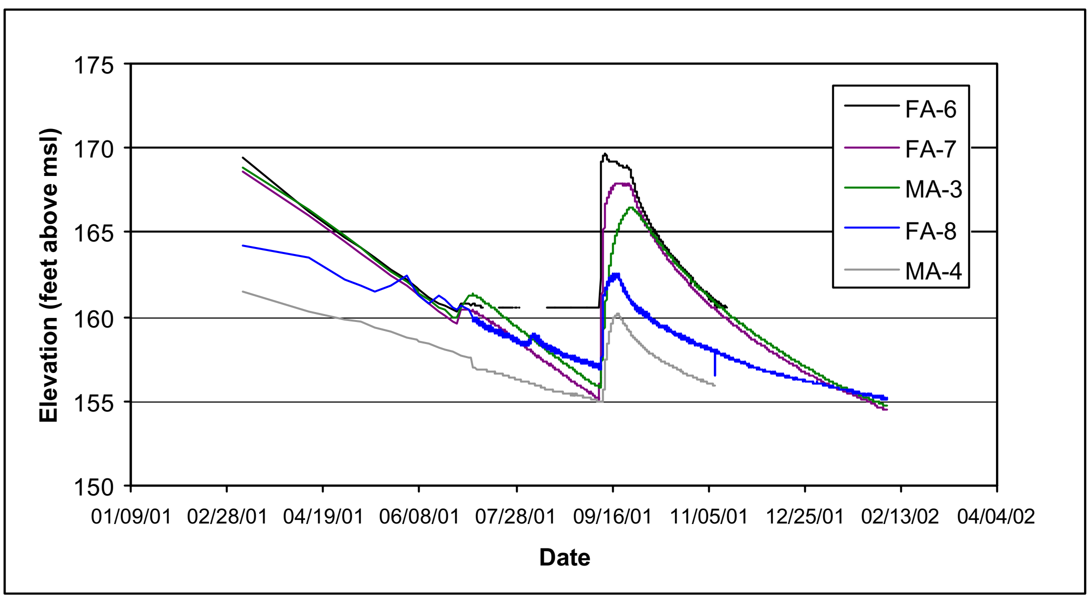


Figure 4-27. Summer 2001 Groundwater elevation trends from five alluvial wells at the RM 220.0, RM 218.2, and RM 217.7 study sites (downstream of Gravelly Ford). Cross section thalweg elevations are 168.83 ft (FA-6, FA-7, MA-3), 163.66 ft (FA-8), and 161.60 ft (MA-4). From SAIC (2002).

This likely results in significant flow attenuation and flow loss until this shallow groundwater "hole" is filled. The peak flow at the Gravelly Ford gaging station (RM 227.5) during the September pulse was approximately 630 cfs, but flow ended between RM 217.7 and 212.0, such that 630 cfs was "lost" to this hole in 11 to 16 river miles (Figure 4-24). Once the initial groundwater recharge occurs with surface flows, the steady-state seepage loss rate decreases to approximately 100 cfs in Reach 2A based on 1999 synoptic flow measurements described above. Recharging the shallow groundwater aquifer could require a substantial flow from the river, and the recharge effects could be hampered by shallow groundwater pumping nearby based on the response of shallow groundwater tables shown in Figure 4-26. Continued pumping of the adjacent shallow groundwater table will impair future flow restoration and continuity efforts through this reach.

- The shallow groundwater response to the June 2001 pulse was strong downstream to the RM 222.1 site, but the response was very small at the RM 220.0 site (Figure 4-27). Recalling that the surface flow during the June 2001 pulse ended at approximately RM 223, the small groundwater response observed at RM 220.0 suggests that the longitudinal groundwater response ended at approximately RM 220.
- Local influences on shallow groundwater elevations at the RM 222.1 site (Figure 4-26) are not apparent at the other sites during the Pilot Project flows (Figure 4-25). Shallow groundwater elevations rose in response to the June and September pulse flows, but there are other rises in the shallow groundwater table in November, December, and January that are not related to instream releases (Figure 4-26). Perhaps the groundwater elevation increases are due to cessation of local groundwater pumps, and/or irrigation with surface water that recharges the shallow groundwater aquifer. Regardless, in Reach 2, shallow groundwater monitoring results illustrate that shallow groundwater elevations fluctuate greatly through the year.

4.6.6. Groundwater Quality

The term "freshwater" is defined for this chapter as water with a total dissolved-solids (TDS) concentration of less than 1,000 milligrams per liter. Under pre-development, unimpaired conditions, the quality of freshwater in an aquifer was controlled by 1) the source of water recharging the aquifer system, and 2) the geochemistry of the sediments that comprise the aquifer system. For example, runoff from the granitic Sierra Nevada mountains, has much lower TDS concentrations than runoff from the Coast Ranges, which are primarily composed of marine sedimentary rocks. Thus, groundwater in the east side of the San Joaquin Valley generally has lower TDS concentrations (200 to 500 mg/l) than groundwater in the west side of the valley (500 to >1,500 mg/l) (Planert and Williams, 1995). In general, TDS concentrations increase with depth in the San Joaquin Valley, because the upper sediments are of continental origin.

Agriculture, irrigation, and import of water from the Delta have caused much of the shallow groundwater in the San Joaquin Valley to become more saline. This salinity first increases because much of the irrigation water now comes from the Delta. Compounding this, evaporation of irrigation water and evapotranspiration of soil moisture and shallow groundwater tends to concentrate salt in the soils and the shallow unconfined aquifer. Shallow irrigation wells worsen the problem by recirculating the increasingly more concentrated saline groundwater, which further concentrates dissolved solids. Thus, agricultural drainage return flows likely cause TDS concentrations to rise in the San Joaquin River. This phenomenon is further pronounced because flows into the San Joaquin River have been reduced during most seasons; thus, dilution is less likely to reduce TDS concentrations. Besides increasing TDS concentrations, irrigation has also increased the concentrations of selenium, boron, chromium, molybdenum, and mercury in the shallow unconfined aquifer in the western part of the San Joaquin Valley (Planert and Williams 1995; Phillips et al. 1991). These minerals and metals were leached from the soil and marine rocks which are found along the western margin of the aquifer. Poor quality shallow groundwater that originates from the western margin flows into the San Joaquin River, but at a higher than natural flow rate due to the existing regional west-to-east groundwater flow direction beneath the river (Belitz and Heimes 1987; Phillips et al. 1991). Phillips et al. (1991) estimated that average concentrations of groundwater inflow to a 19-mile reach of San Joaquin River, between Newman and Patterson (just downstream of the Merced River confluence), are 1,590 mg/l TDS, 1,321 micrograms per liter (ug/l) boron, 0.9 ug/l selenium, and 6.6 ug/l molybdenum. Excessive nitrate concentrations have also been sporadically recorded throughout the San Joaquin Valley, and are usually attributed to septic tanks, feed lots, and dairies (Planert and Williams 1995).

4.7. GROUNDWATER CONDITIONS' RELEVANCE TO BIOTA

Groundwater conditions (elevations, flow direction, water quality) are relevant to all wildlife and plants, through their dependence on the hydrologic cycle. Two biotic groups in particular, riparian and wetland vegetation, and fisheries, will be discussed below.

4.7.1. Riparian and Wetland Vegetation

The loss of artesian springs and the decline in shallow groundwater elevations have readily apparent implications to wetland vegetation, particularly to perennial wetland vegetation. Even if land use had not transformed to agriculture and residential uses, and if the conversion of vast tule swamps, sloughs, and oxbows had not occurred, the loss of artesian springs and the decrease in groundwater elevations would impair our ability to restore and sustain pre-development wetland communities in some areas without substantial water supplementation. These changes in groundwater regime are obvious constraints to wetland restoration. Opportunities for restoring perennial wetland vegetation arise primarily: 1) where the shallow unconfined groundwater surface remains at or above the river-bed (e.g., in gaining reaches in Reaches 4 and 5), or 2) where perennial river flow increases groundwater elevations at the riparian corridor margins (e.g., Reaches 1 and 3). Opportunities for restoring seasonal wetlands may not be as highly dependent on the shallow groundwater regime, but seasonal inundation from surface flows are likely very important, as is available space, land ownership, land use, supplemental flows, and soils.

Riparian vegetation is also impacted by the loss of artesian springs and the decline in groundwater elevations. Within the riparian corridor, the depth between potential seedbeds, the groundwater surface, and the capillary fringe is an important variable that will strongly influence whether riparian plants can regenerate naturally. Soils are also important factors, because the capillary fringe is a function of soil texture and groundwater elevation (Figure 4-7). Riparian vegetation dies when the groundwater table and capillary fringe are too far below the plant root zone. Drawdown or overdraft of the shallow groundwater reduces or eliminates water available to riparian vegetation in the absence of surface flows in the San Joaquin River. The depth to groundwater also affects the rate at which plants remove water from the system (transpiration rate). When the entire root zone contains freely available water, plants transpire efficiently and are less stressed. Gaining river reaches are more promising restoration candidates than are losing reaches because the shallower groundwater elevation should greatly increase riparian revegetation success. However, simply identifying gaining reaches is insufficient for restoration planning. Plant life histories and seasonal water needs of riparian vegetation must be matched to available shallow groundwater conditions, along priority reaches. Natural pattern of seasonal variability in groundwater elevations may be an important component for the long term viability of certain riparian plant species (see Chapter 8 for riparian plant life histories and water supply needs of key woody riparian species). Reach 2 is perhaps the most impacted reach, due to the combined loss of river surface flows and severe decline in shallow groundwater elevations. In Reach 4, riparian vegetation is less impacted by the dewatered sections because the shallow groundwater elevation has not decreased as dramatically as in Reach 2 (compare Figure 4-10 with Figure 4-13). Therefore, Reaches 1B and 2 present the greatest constraints to riparian and wetland restoration because these reaches have the greatest depth to groundwater. However, the results of the 1999 Pilot Project has shown that management of surface flows in the San Joaquin River can be used to successfully establish riparian vegetation if the surface flows are maintained. Reaches 4 and 5 represent areas with significant opportunity for riparian and wetland restoration, due to groundwater availability in the shallow unconfined aquifer.

4.7.2. Fish Habitat

The pre-groundwater development and unimpaired unconfined aquifer probably served several important functions for native fishes. First, during the late summer of drier water years, surface flows from the upper watershed would be fairly low (see Chapter 2), and so the unconfined aquifer and its artesian springs likely augmented stream flows in most reaches (Figure 4-8). These naturally augmented flows likely allowed year-round migration opportunities for all native species. Second, water from the artesian springs and seeps of the unconfined aquifer may have created numerous islands of thermal refugia for native cold-water fish species. These springs may have lasted far enough into the salmonid smolt outmigration period to extend their migration period into summer, as snowmelt hydrograph transitioned to summer baseflows. The springs may have also provided local opportunities for juvenile salmonids to over-summer in an otherwise inhospitable location (Reaches 1 through 5), where they could later outmigrate as yearlings. However, no historical literature has been found to support or reject this hypothesis.

Presently, large portions of Reaches 2 and 4 are completely dry most years. In Reaches 1 and 2, declines in the shallow unconfined groundwater have resulted in Reaches 1 and 2 becoming primarily losing reaches; therefore, flow releases from Friant Dam or Mendota Dam are required to create perennial flow through Reaches 1 through 4. In Reach 5, where agricultural return flows and groundwater seepage cause the river to gain flows, water quality is very poor (see Chapter 6), which further constrains future fish restoration efforts.

The opportunities provided, and constraints imposed, by the shallow unconfined aquifer are similar to those on riparian and wetland vegetation; opportunities exist in gaining reaches, and constraints exist in losing reaches. The contemporary groundwater elevations probably do not provide many opportunities to cold-water fish species, because any remaining shallow groundwater contributions are small volume, subject to rapid thermal warming, and of poorer water quality. Pre-development artesian springs and unconfined shallow groundwater originating from the valley's east side probably were cooler and had better water quality than today's available flow. Opportunities likely favor native, warm water fish species. Therefore, Reaches 3, 4, and 5 provide good opportunities for restoring native, warm water fishes because these gaining reaches can maintain or supplement any dam release provided for fishery habitat restoration.

4.8. SUMMARY

The available background literature and data clearly indicates that regional and localized groundwater uses in the San Joaquin Valley have had a significant impact on shallow, unconfined groundwater flow, and its interaction with the deeper, more confined zone and with the San Joaquin River. A summary of natural and anthropogenic factors influencing the shallow aquifer area summarized in Table 4-4.

Table 4-4. Factors influencing groundwater conditions in the shallow aquifer system adjacent to the San Joaquin River, California.

Natural Factors	Anthropogenic Factors
1. Seasonal variability in rainfall and runoff	1. Irrigation (local and regional)
2. Long-term drought	2. Groundwater pumping (local and regional)
3. Evapotranspiration	3. Changes in surface water flow regime (dams and diversions)
4. Variability in water bearing properties of aquifer material	4. Agricultural return flows
	5. Leakage from conveyance canals
	6. Surface water imports
	7. Changes in land-use and evapotranspiration rates
	8. Cross-connection from wells screened in both shallow and deep aquifer zones
	9. Land subsidence (loss of aquifer storage capacity)
	10. Changes in water quality

Of these factors, loss of the pre-development artesian hydraulic head, and the decrease in unconfined groundwater elevations, represent the most dramatic changes of groundwater contribution to flows in the San Joaquin River. Since the late 19th century, San Joaquin Valley groundwater elevations and surface water flow conditions have drastically reduced by large-scale pumping, storage, and diversions that supply agricultural and urban water demands. The San Joaquin River historically gained flow from the shallow groundwater aquifer and artesian springs over most of its length; groundwater use has converted much of the river to a losing reach, and probably greatly reduced the contribution from remaining gaining reaches in lower reaches of the river (e.g., Reach 3 through 5).

The shallow unconfined aquifer adjacent to the river is most important to fish and riparian uses due to its connectivity with the river. The groundwater elevation of this aquifer varies considerably along the river, and is largely correlated with long-term regional irrigation and pumping trends. The impacts of pumping on the groundwater elevation can be amplified by natural drought cycles because drought typically coincides with periods of increased groundwater pumping. Thus, although groundwater levels may partially rebound during wetter water years, they quickly lower during drier years. The lowering of groundwater elevations over most reaches within the study area have many biological implications that may constrain future restoration opportunities, particularly for native fish, riparian vegetation, and wetland vegetation. The pre-development, shallow groundwater conditions (including the artesian processes) cannot realistically be restored, so opportunities based on favorable groundwater conditions for fish, riparian vegetation, and wetland vegetation are broadly identified as those areas where the shallow groundwater elevations are near the existing river bed elevations (Reaches 3 through 5). Overdrafted groundwater, combined with coarse alluvial soils, in Reaches 1 and 2 present the most significant constraint.

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