Hydrology and Sedimentation 4

The Laguna de Santa Rosa watershed, set in a Mediterranean climate, has a complex and variable hydrology. The watershed includes numerous tributary streams, the majority of which drain west from the Sonoma Mountains across the Santa Rosa Plain towards the northwest trending Laguna wetland ecosystem (see figure 4-1). The uplands are drained by high-gradient, high-energy, coarse-bedded mountain channels, which flow down the hillsides to the broad, flat, vernal pool-dotted Santa Rosa Plain. The main stem Laguna is a slow-moving channel that has a unique character, which was once described as: "neither river, nor pools, nor floodplain, nor marsh, nor vernal pool – but with the characteristics of all, plus other characteristics, and a distinct type of watercourse related to physical feature, but a rare one" (LAC, 1988).

The character of Laguna watershed channels reflects underlying geological structures. The Santa Rosa Plain is surrounded by two actively uplifting ranges: The Santa Rosa block in the east (underlying the Mayacamas and the Sonoma Mountains) and the Sebastopol block in the west (underlying the Gold Ridge). The boundary between these two blocks is the western edge of the Laguna floodplain, near Sebastopol. The blocks are oriented on roughly a northwest-southeast axis, and both tilt towards the Laguna (Hitchcock and Kelson, 1998). The Santa Rosa block has a major laterally displaced slip-strike fault system (the Mayacamas-Rodgers Creek faults) that forms the topographic boundary between the gently sloping Santa Rosa valley and the steep slopes of the Mayacamas and Sonoma Mountains. As these blocks have tilted and uplifted erosion has acted on the exposed surfaces, washing sediment into the syncline occupied by the Laguna in the form of an alluvial fan. This configuration of basin, ranges and alluvial fans is very common in the American west. On the east side of the Laguna, the main tributaries (Windsor Creek, Mark West Creek, Santa Rosa Creek, etc.) have eroded valleys into the block or range, transporting sediment downstream. There is a marked break of slope that forms a distinct topographic boundary between the eroding block and its depositional apron, along the line of the Healdsburg and Rodgers Creek faults. In the Laguna watershed this line is broadly defined by Calistoga Road and Yulupa Avenue in the north and by Petaluma Hill Road in the south of the watershed. On the west side, the headwaters of Blucher Creek are eroding into the rising center of the Sebastopol block in a similar fashion. Channels cut in rapidly uplifting blocks tend to have characteristic 'V' shaped incised valleys, and experience rapid erosion as they attempt to stay in equilibrium with their surroundings. In addition to channel erosion, such fluvial systems often have steep and landslide-prone valley sides, as the channel cuts slopes steeper than their angle of limiting stability. Therefore naturally high levels of sediment transport from the hills on both east and west sides of the Laguna watershed.

The Laguna watershed has been significantly altered by anthropogenic processes since European settlement in the 1840s. Key stages in the basin land use history include the following:

- 1837 - Start of intensive ranching. The Santa Rosa Plain was converted to cattle grazing. We anticipate that this led to changes in vegetation from perennial bunch grasses and annual forbs to Mediterranean grasses, with soil compaction and increased runoff and erosion, and the clearance of some woodland.
- 1853 - Conversion of some grazing to wheat farms. This land use change led to the start of large-scale land drainage to convert wetland areas to productive farmland. In addition the first large scale oak wood clearance began around this time. It has been suggested that this land use conversion released large amounts of sediment from the hillsides to the lower Laguna.
- 1940s - Start of rapid urbanization. From the 1940s onwards agricultural land was converted to urban as population increased exponentially. At the same time the type of agriculture varied, with dairy farming peaking in the early 20th century, orchards and row crops peaking in the 1950s, while irrigated farming has expanded since its introduction in the 1960s.
- Current trends. Growth in urban and vineyard area, with decline in crops and grassland. The current trend is for greater urbanization/suburbanization, mostly at the expense of cropland and especially pasture. At the same time agricultural land is being converted to vineyards.

This landscape evolution has had several general effects on hydrologic and sediment processes:

- Reduced canopy interception and evapotranspiration leading to more and flashier runoff, and therefore, greater erosivity of runoff and increased sediment transport capacity;
- Increased impermeable area, decreased permeability, and extended drainage channel network leading to greater volume and flashier channel flows, increasing erosion potential and sediment transport capacity;
- Increased area of disturbed and bare earth leading to greater soil erodibility and sediment yield;
- Increased storage of sediment; and
- Morphologic and topographic changes;

Thus more sediment is generated from the ground surface, and the drainage system is generally more effective at transporting the sediment. Within this broad picture there have been some more subtle changes, however. The initial conversion of the landscape to grazing is likely to have had a dramatic effect, releasing large volumes of fine sediment from the alluvial fan surface as grazing compacted the ground surface, reducing infiltration capacity and increasing surface erosion. Subsequent conversion to row crops is expected to have reduced erosion where it involved the same land surface area (though not to pre-disturbance levels) by increasing surface roughness and infiltration capacity compared with grazing.

On the other hand woodland clearance associated with large-scale farming released large amounts of additional sediment, especially on the hillsides. Assuming it followed the patterns observed elsewhere in northern California, development will have increased erosion in the channel network, and temporarily increased sediment yield from construction plots, while permanently increasing yield through the development of bare earth ditches and unpaved roads. Conversion of grazing and arable land to vineyards is likely to have increased sediment yield due to soil erosion, especially where rows are orientated downslope.

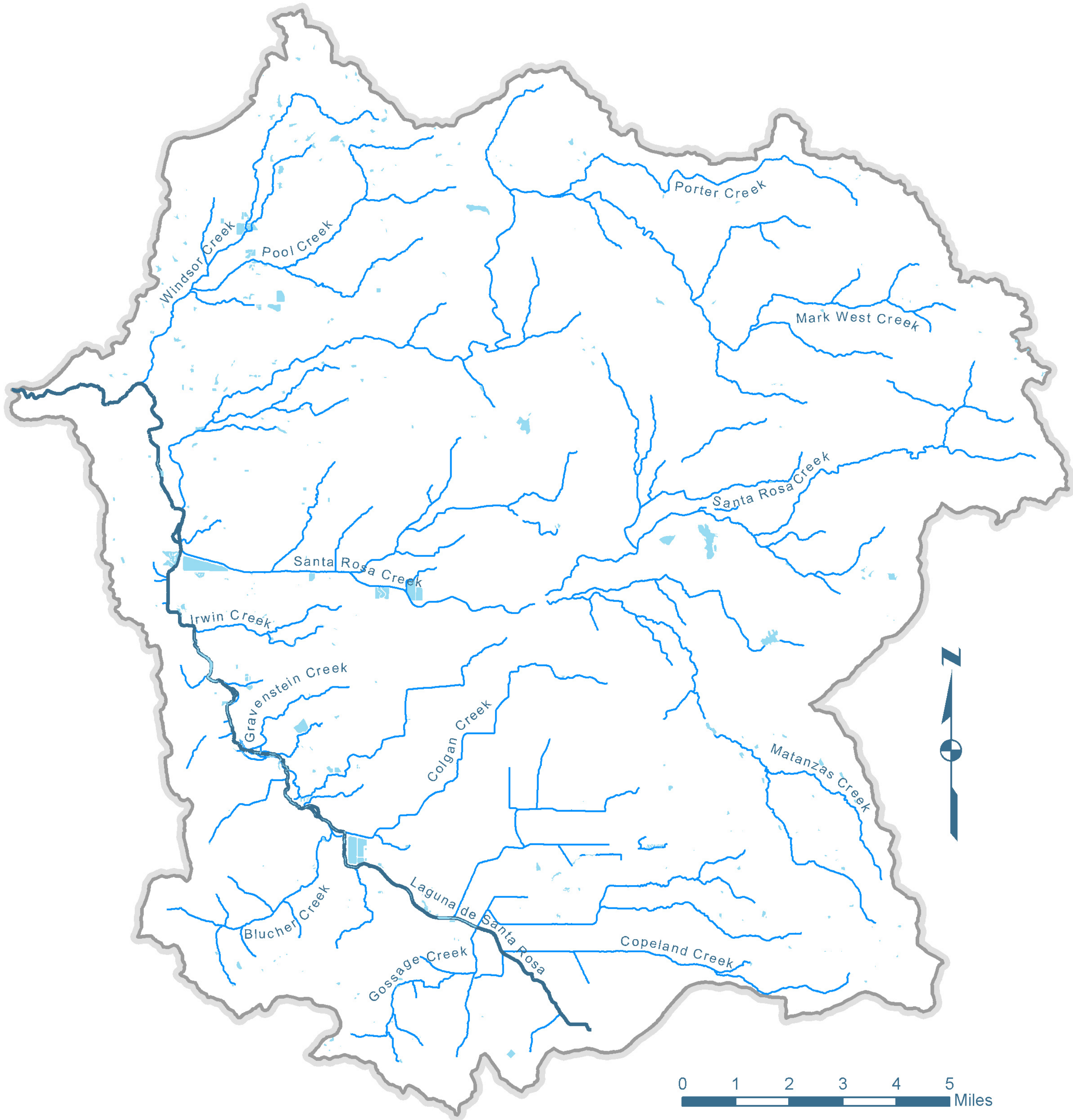

Figure 4-1 Laguna watershed and tributaries

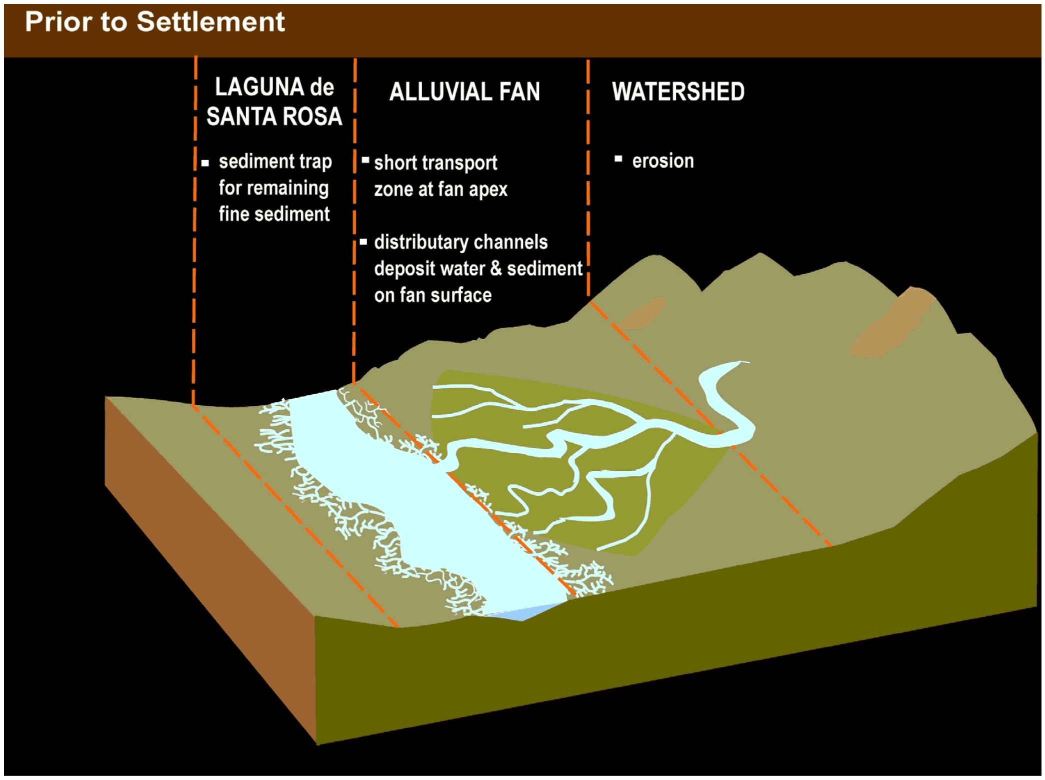

Figure 4-2 (a) Conceptual model of physical processes affecting the Laguna prior to settlement

In addition to watershed land use changes, natural stream channels in the watershed were progressively replaced with larger, straighter channels that were designed to make the alluvial fan more habitable and productive for farming and that are better suited for efficient flood conveyance. Channel modifications have essentially moved the focus of sediment deposition away from the fan surface and towards the Laguna. By eliminating overbank flows and channel avulsions and by connecting distributary channels to the Laguna, the modified drainage network has had three effects:

- Sediment that would previously have traveled down dispersed distributary channels and been deposited on the fan surface is now either concentrated in drainage channels or transmitted to the Laguna.
- When channels work effectively to transport flood flows in-channel (typically hydraulically smooth channels during large flow events) sediment that would previously have been carried out of bank and deposited on the alluvial fan is now transported to the Laguna and either deposited there or washed out to the Russian River.
- When channels do not work efficiently (typically vegetated, hydraulically rough channels or channels that are oversized for small events) sediment is deposited in-channel, eventually requiring removal to preserve flood conveyance capability.

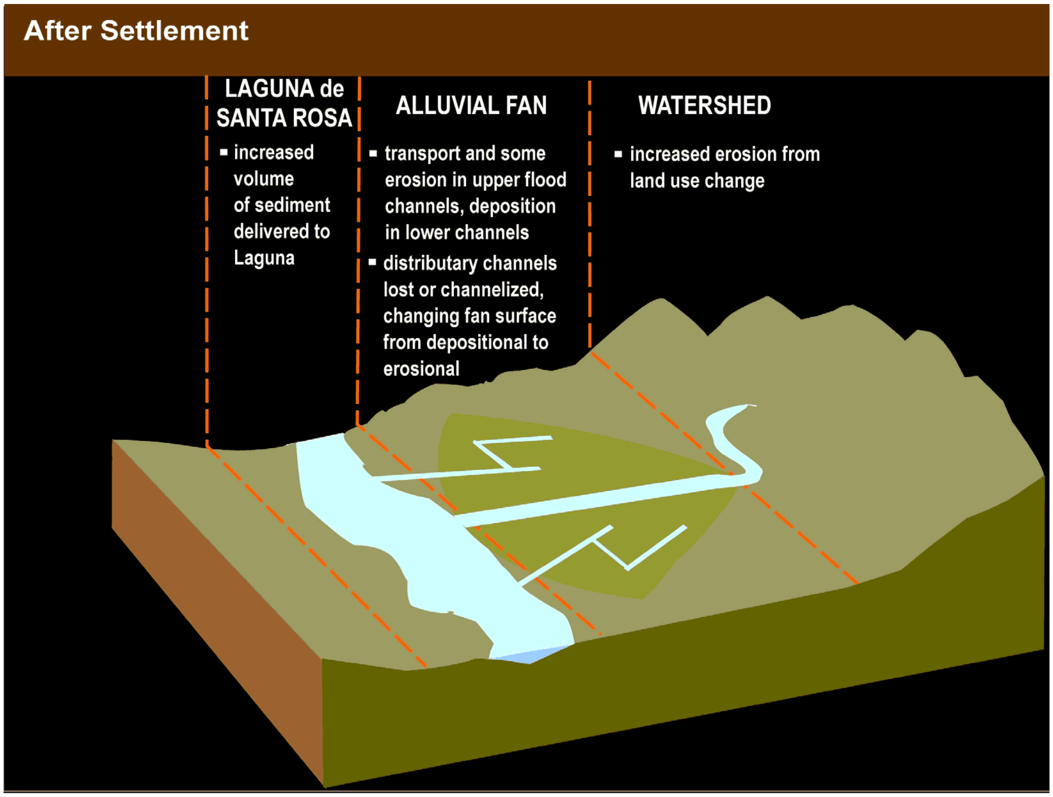

Figure 4-2 (b) Conceptual model of physical processes affecting the Laguna after settlement

Thus channel modification has reduced sediment deposition on the fan and concentrated it in the channel network and in the Laguna. In addition, some of the modified channels have themselves become sources of sediment due to accelerated erosion. Straight, hydraulically effective channels with low width to depth ratios and little bank vegetation have in some cases suffered bank and bed erosion, contributing sediment into the Laguna.

The combined effect of these processes has been to increase sediment generation and transport capacity to the Laguna, resulting in increased potential for deposition.

Figure 4-2, a simple conceptual model for sediment processes in the Laguna, presents a conceptual model that describes key changes in the main hydrologic and sediment processes due to anthropogenic impacts.

4.1 Summary of recent and current studies

Results have been presented in five main recent or current studies on the hydrology and sedimentation in the Laguna system. The USGS is presently conducting a sixth study that will characterize flow and sedimentation processes within the study area. The study includes development of a conceptual model of floodplain processes and sedimentation, a sediment budget, measurement of floodplain sedimentation and inundation, and extrapolation of the results throughout the basin in GIS in order to evaluate the changes in flood storage capacity over time. A 1-D calibrated hydrodynamic model will be developed for an approximately 1.5 mile stretch of the Laguna for sediment transport simulations. Another study presently being conducted by the USGS is focused on groundwater hydrology within the Santa Rosa Plain, the main aquifer underlying the Laguna watershed. No findings from that study have yet been released, but its goals are described below in the section describing groundwater conditions.

The Army Corps of Engineers conducted two studies developing hydrologic models for the Santa Rosa Creek and Laguna de Santa Rosa watersheds. There is a draft report summarizing the results of the former study. However, the results of the Laguna de Santa Rosa hydrology assessment have not been formally reported. Three additional studies have recently produced hydrology and sedimentation findings with respect to the Laguna de Santa Rosa. PWA (2004) summarized the results of a 5-year long study on the hydrologic and sedimentation characteristics of the Laguna. Another study by the NASA AMES is currently investigating key hydrological and sediment yield characteristics of the Laguna de Santa Rosa watershed. Results of these studies have not yet been published. However, brief summaries of their findings as presented in the State of the Laguna Conference are included below (Santa Rosa, March 29 to April 1, 2007).

4.1.1 PWA 2004 study on the sedimentation, rate, and fate in the Laguna

PWA estimated the rate and effect of sedimentation processes in the Laguna watershed and articulated on the implications of these processes on flood conveyance through the Laguna and in flood channels. PWA investigated sediment delivery to the Laguna calculating sedimentation rates using several lines of evidence, including a field-based geomorphic assessment, empirical models of soil erosion to predict sediment yield (Pacific Southwest Interagency Committee [PSIAC] and the Modified Universal Soil Loss Equation [MUSLE]), aerial photographic interpretation, and comparison of historic and current floodplain cross section surveys. PWA supported these results with data from reservoir surveys and a network of three continuous suspended sediment monitors that were installed along the main stem Laguna (2 stations) and Santa Rosa Creek (1 station) for the runoff season of 2002-2003. The study identified the main sediment source areas, sediment yield, and the rate at which the Laguna is filling. The study found that the Laguna has filled an average of approximately 1.5 feet between 1956 and 2002, representing a loss of flood storage of 54 acre feet (ac-ft) per year. The study estimated that the current sediment yield in the watershed is approximately 153 ac-ft per year, of which approximately 50 percent is stored in the watershed, 25 percent settles out in the Laguna, and 25 percent is delivered to the Russian River. The study found that most sediment is contributed by Santa Rosa Creek (42 percent of the total Laguna yield), followed by the upper Laguna tributaries upstream of Llano Road, near Cotati (24 percent), Mark West Creek (18 percent), Windsor Creek (9 percent), Blucher Creek (4 percent), and Colgan Creek (3 percent). The study also estimated the historic sediment yield rate before European settlement of the watershed and future rates based on hypothetical built-out conditions informed by the county general plan. Historic sediment yield rate was estimated as approximately one quarter of the current rate. Based on assumptions of a 20 percent growth in urban area and vineyard production over the next 50 years, an increase in sediment yield to approximately 200 acre feet per year was predicted. At this rate, the flood storage capacity of the Laguna would be reduced by approximately 50 to 60 acre feet per year (4 percent of the current storage volume of the Laguna over 50 years) and result in 2.5 to 3.0 feet of increased flood elevation in the Laguna over 50 years.

4.1.2 USGS study of the 2006 New Year's flood

The USGS is studying the 2006 New Year's flood in the Laguna floodplain. The objectives of the study are to measure and map the inundation extent of the New Year's flood of 2006 on the Laguna de Santa Rosa and analyze the precipitation intensities causing these high peak flows. This study also investigates the conditions under which the floodplain deposition occurred during and after the flood and developed a deposition potential map of the area for this precipitation event to provide an upper boundary for floodplain sedimentation conditions.

On December 31, 2005 and January 1, 2006, the lower Laguna experienced flooding with peak flows of over 6,500 cfs based on the USGS streamflow gage near Sebastopol (#11465750), (see photograph below). Median flows at this location are typically less than 500 cfs. The high peak flows resulted in overbank flows at many channel locations for several periods of time between December 12 and January 6.

Hourly precipitation data for the December 29 to December 31 storm period were spatially distributed using regression equations and a digital elevation model (DEM) to map total accumulation amounts through the storm. Field observations of inundation levels as evidenced by debris lines on hillslopes, trees, vegetation, buildings, and fences were made. Elevation measurements were extrapolated on the basis of contours of the DEM. The study found that maximum flood inundation approached the 100-year flood elevation boundary in the downstream reaches of the Laguna (Figure 4-4). It also revealed that although this storm was approximately equivalent to a 20- or 30-year event, inundation elevations in the eastern uplands were not significant.

Figure 4-4 is a map of elevation for the Laguna de Santa Rosa floodplain, between the Russian River and State Highway 12. The map illustrates the estimated inundation levels reached during the 2006 New Year's flood, identified by the red line. Points on the map illustrate the observation locations.

Figure 4-3 Laguna in flood

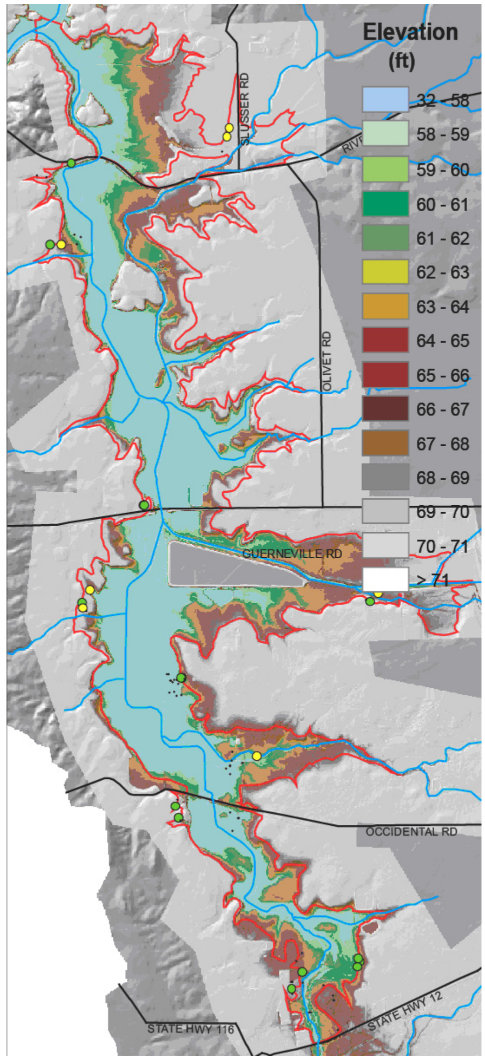

Figure 4-4 Laguna floodplain elevation map

4.1.3 NASA/AMES study

The NASA/AMES is modeling non-point source nutrient input to the Laguna incorporating sediment yield assessment from different land uses. The study is developing a SWAT model (USDA's Surface Water Assessment Tool) to address the role of certain land use practices or changes such as agriculture, woodland conversions, and (sub)urban runoff sources in water quality, flood frequency, soil erosion, and sedimentation of the Laguna floodplain. The study produced an updated land cover map of the Laguna watershed. The map merged the USGS 30-meter resolution National Land Cover Dataset with the California Department of Water Resources crop type polygons and the Sonoma County Assessor's parcel descriptions. National Agricultural Imagery Program's digital orthographic imagery data were used to confirm the merged land cover product in key areas of uncertainty. The study also updated climate station records to 2007 and added data from precipitation stations at Graton, Windsor, and Sonoma. This study is still on-going and no report has yet been published. The findings reported here are derived from personal communication with Chris Potter (NASA/AMES) or from Laguna Conference and Science Symposium proceedings.

The NASA/AMES SWAT model was calibrated using gage data along Santa Rosa Creek. The model required minimal (re)calibration to match daily and monthly measured gage discharge rates ($r^2 > 0.9$; for years 2001-2006). Laguna de Santa Rosa discharge rate predictions explained 85 percent of the measured discharges. The SWAT model also estimated sediment yield in the Laguna watershed using MUSLE. Sediment yield estimates were not presented at the Laguna Symposium. However, preliminary results indicate that the estimates are within 5 percent of PWA's PSIAC estimates, which are estimated to represent sediment yield in the Laguna watershed (PWA, 2004; pers. comm. Chris Potter).

4.1.4 USACE Santa Rosa Creek basin hydrology assessment

The Army Corps of Engineers conducted a hydrologic modeling study of the Santa Rosa Creek watershed and published a draft report (USACE, 2002). The study was conducted using the Hydrologic Modeling System, HMS, to simulate precipitation versus runoff process in the Santa Rosa Creek watershed. The only other hydrology study for the Santa Rosa Creek watershed was done by the NRCS for their Central Sonoma Watershed Study (1960).

The study used 12 precipitation stations and divided the watershed into 29 subbasins. There is little data on streamflows in the watershed. The USGS has operated three stream gages in the watershed since 1940 but for short periods of time only. Two stations in the watershed had only been recently activated. Since there are only scattered streamgaging records available, a curve of peak discharge versus frequency was developed using a synthetic unit-hydrograph approach.

Since most flood-producing storms in the region last from one to two days, the study used a storm duration of 24 hours. Time distribution of rainfall was based on an actual 24-hour event during the historic storm of 3 to 5 January 1982. The maximum discharge at the outlet from a storm over the Santa Rosa Creek watershed usually occurs within a few hours following the most intense period of rainfall.

Peak flows for the one-percent chance flood event computed by the HMS model for existing watershed conditions are presented in Table 4-1.

Table 4-1
Discharges during 1-percent (100-year) flood event

Location	Drainage Area (sq-mi)	Peak Discharge (cfs)
Above Diversion	20.8	8,250
Below Diversion	20.8	3,030
Below Spring Lake Outlet	22.4	4,280
Below Brush Creek	33.2	8,300
Below Matanzas Creek	55.7	13,400
Below Piner Creek	71.1	17,900
At Mouth	78.5	19,600

The study concluded that the one-percent peak flow at the Santa Rosa Creek outlet as well as other key locations throughout the watershed has increased significantly. Results also suggested that the four major flood control reservoirs in the watershed will experience significant spilling during the 100-year flood event. Assuming that the Santa Rosa Creek flood control channel is adequately maintained, it appeared to offer protection for a 25- to 50- year flood with the design freeboard. Proposed development in the watershed by the year 2020 according to the General Plan is unlikely to increase runoff significantly. Currently approximately 50 percent of the total watershed (mostly in the upstream areas) is undeveloped and unanticipated significant development in the upper watershed could significantly increase runoff. The study recommended that any major improvements should look beyond the General Plan time frame (beyond 2020).

4.1.5 USACE Laguna de Santa Rosa basin hydrology assessment

The Army Corps of Engineers San Francisco District (USACE) conducted a basin hydrology assessment of the Laguna de Santa Rosa watershed (2003). This study has not yet been published. PWA's 2004 sedimentation analysis relied on draft results of this assessment for sediment yield analysis. The summary of the basin hydrology assessment presented here is derived from our communication with the USACE in 2002 through 2004 and from spreadsheets depicting the peak flows and volumes of simulated events that were provided to PWA.

- The study developed flood hydrographs of various flow-frequencies at the following locations:
- Windsor Creek at the confluence with Pool Creek
- Mark West Creek at the Old Redwood Highway
- Blucher Creek at Highway 116
- Colgan Creek at Llano Road
- Santa Rosa Creek at Willowside Road
- Laguna de Santa Rosa at Llano Road.

Flood hydrographs for the study were developed based on a synthetic unit-hydrograph approach that transforms excess rainfall directly into runoff. Unit hydrographs were derived from an S-curve hydrograph developed by the USACE. The HMS software, which was used in conjunction with Geospatial Hydrologic Modeling Extension (Geo-HMS), simulated the precipitation-runoff process for the Laguna de Santa Rosa watershed. The unpublished results of flood frequency analysis are presented below in Table 4-2 and Table 4-3. The hydrographs for the simulated events are illustrated in Figure 4-5 through Figure 4-9.

Table 4-2
Estimated peak runoff rates during several events

Location	Drainage Area (sq mi)	Peak Flow Rates in cfs				
		2-year	10-year	25-year	50-year	100-year
Laguna de Santa Rosa at Llano Road	44.12	4,590	8,400	10,290	11,570	12,810
Blucher Creek at Highway 116	7.40	940	1,700	2,070	2,320	2,570
Colgan Creek at Llano Road	6.84	710	1,300	1,600	1,800	1,990
Santa Rosa Creek at Willowside Road	75.83	7,560	13,220	15,550	17,330	19,160
Mark West Creek at Old Redwood Highway	42.75	3,900	8,040	10,300	11,820	13,270
Windsor Creek at Pool Creek confluence	17.32	2,020	3,980	5,020	5,730	6,420

Table 4-3
Estimated runoff volumes during several events

	Runoff Volumes in ac-ft				
	2-year	10-year	25-year	50-year	100-year
Laguna de Santa Rosa at Llano Road	3,456	6,857	8,592	9,750	10,883
Blucher Creek at Highway 116	583	1,155	1,447	1,643	1,833
Colgan Creek at Llano Road	480	975	1,229	1,397	1,586
Santa Rosa Creek at Willowside Road	8,352	16,147	19,179	22,007	25,516
Mark West Creek at Old Redwood Highway	4,644	9,995	13,019	15,008	16,926
Windsor Creek at Pool Creek confluence	1,746	3,647	4,725	5,453	6,160

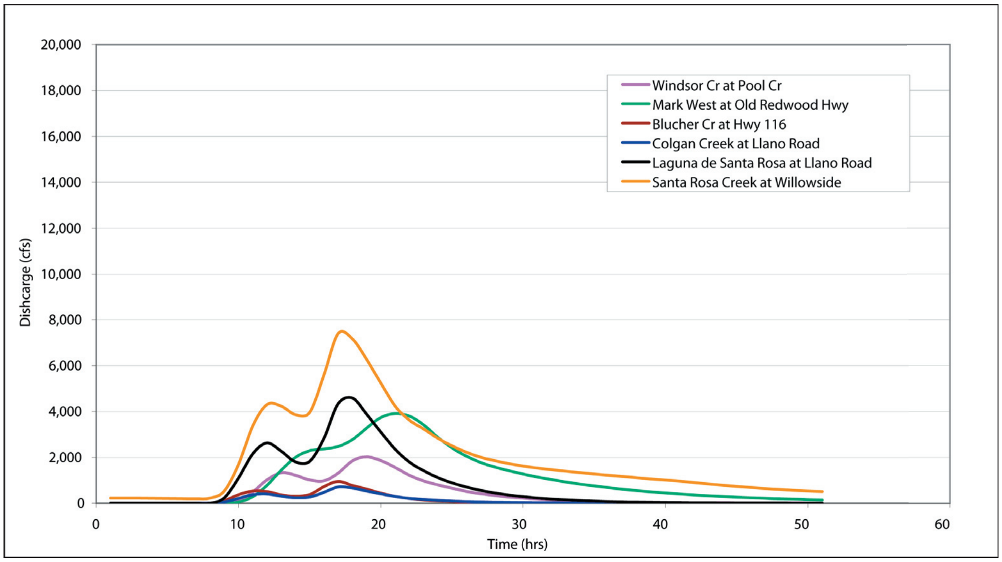

Figure 4-5 Laguna de Santa Rosa 2-year flow hydrographs
(Source: USACE. 2003. Draft Laguna de Santa Rosa Basin Hydrology Assessment. Unpublished Report)

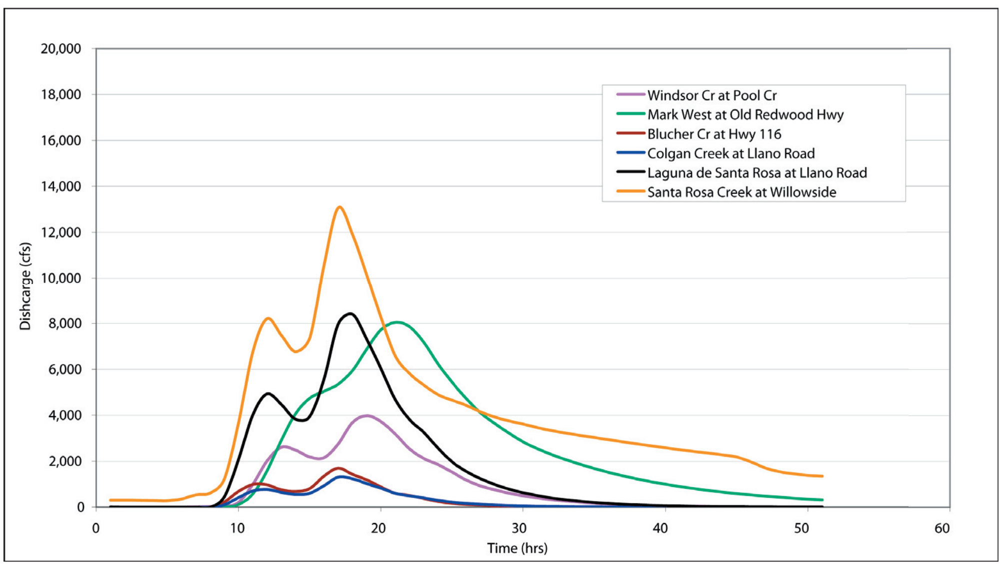

Figure 4-6 Laguna de Santa Rosa 10-year flow hydrographs
(Source: USACE. 2003. Draft Laguna de Santa Rosa Basin Hydrology Assessment. Unpublished Report)

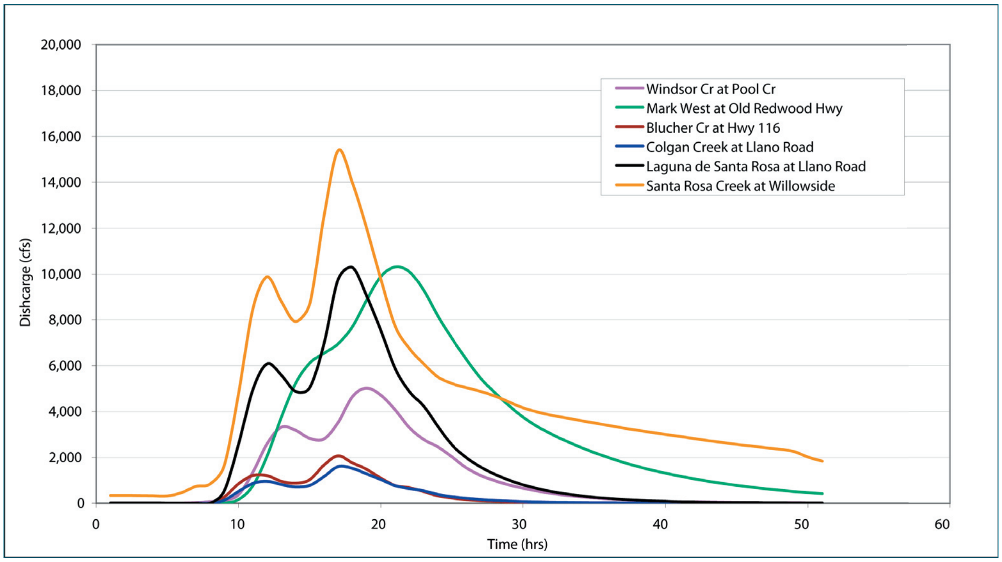

Figure 4-7 Laguna de Santa Rosa 25-year flow hydrographs
(Source: USACE. 2003. Draft Laguna de Santa Rosa Basin Hydrology Assessment. Unpublished Report)

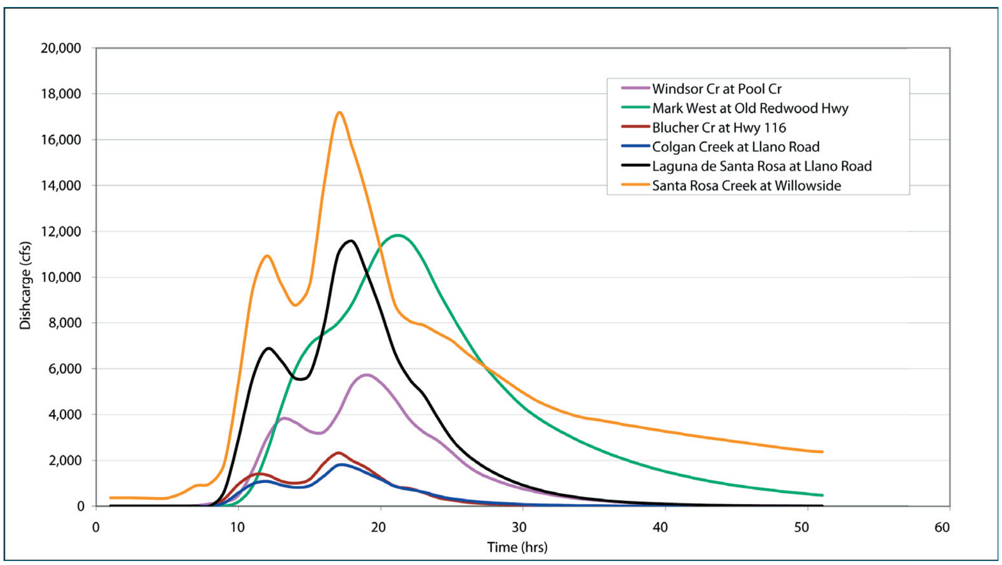

Figure 4-8 Laguna de Santa Rosa 50-year flow hydrographs
(Source: USACE. 2003. Draft Laguna de Santa Rosa Basin Hydrology Assessment. Unpublished Report)

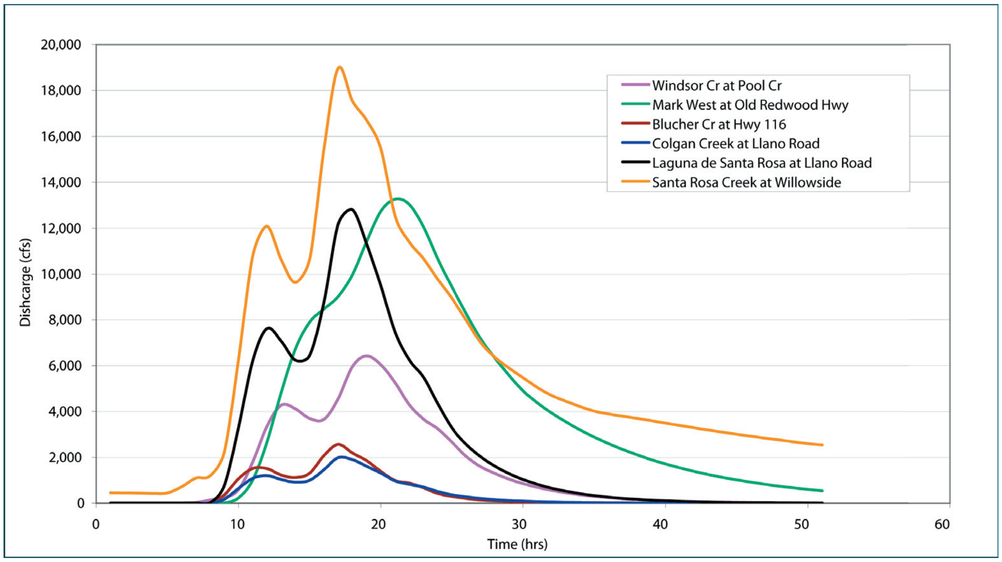

Figure 4-9 Laguna de Santa Rosa 100-year flow hydrographs
(Source: USACE. 2003. Draft Laguna de Santa Rosa Basin Hydrology Assessment. Unpublished Report)

4.2 Data analysis: characterization of sedimentation and hydrology

There is scarce data on water flows and sediment movement through the Laguna de Santa Rosa watershed. The USGS has, over the years, operated peak flow, real time, and daily flow stations at approximately twenty locations. The data from these stations were used to develop hydrologic conceptual models for the current effort. In terms of sediment processes in the Laguna watershed, a recent study on sediment transport, rate, and fate in the Laguna (PWA, 2004) constituted the basis of conceptual models of sediment transport and deposition.

4.2.1 Hydrologic data

Understanding water input and movement through the Laguna can be achieved through analysis of precipitation and flow gage data. We compiled available records from one precipitation gage operated by CIMIS and one operated by Sonoma County and from approximately fifteen flow gages operated by the USGS. Available records from precipitation and flow gages were analyzed and used to quantify, where possible, key hydrologic processes included in the conceptual models.

Precipitation

There are several precipitation gages within and in the vicinity of the Laguna de Santa Rosa watershed (Figure 4-6). Precipitation records of one station were compiled to inform the hydrologic budget we prepared as part of our conceptual model development: CIMIS Station ID 83. The CIMIS station in the watershed is located between Llano Road and Laguna de Santa Rosa, south of Highway 12. The station was activated on January 1, 1990 and has an elevation of 80 feet.

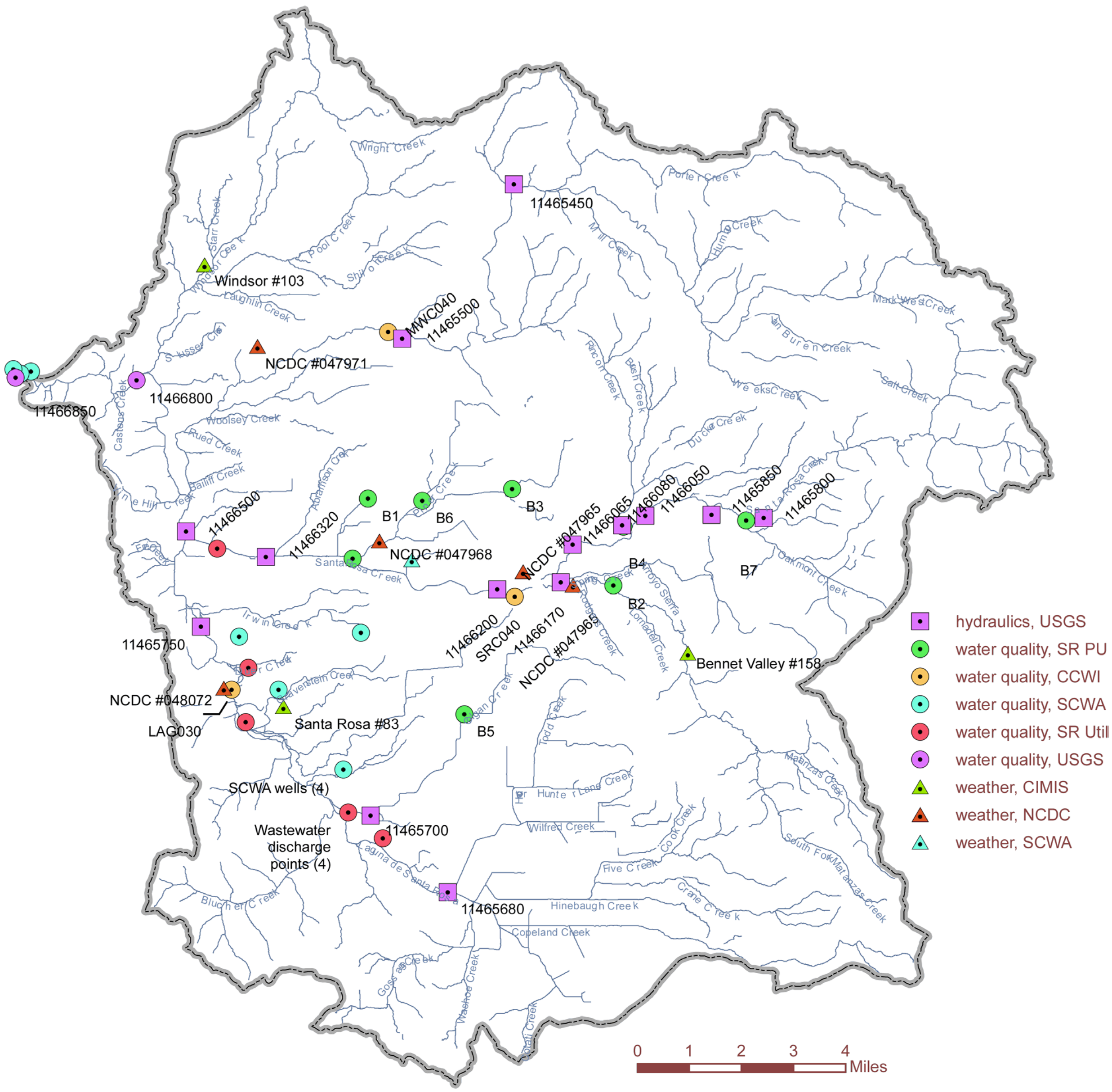

Figure 4-10 Weather and water gaging stations

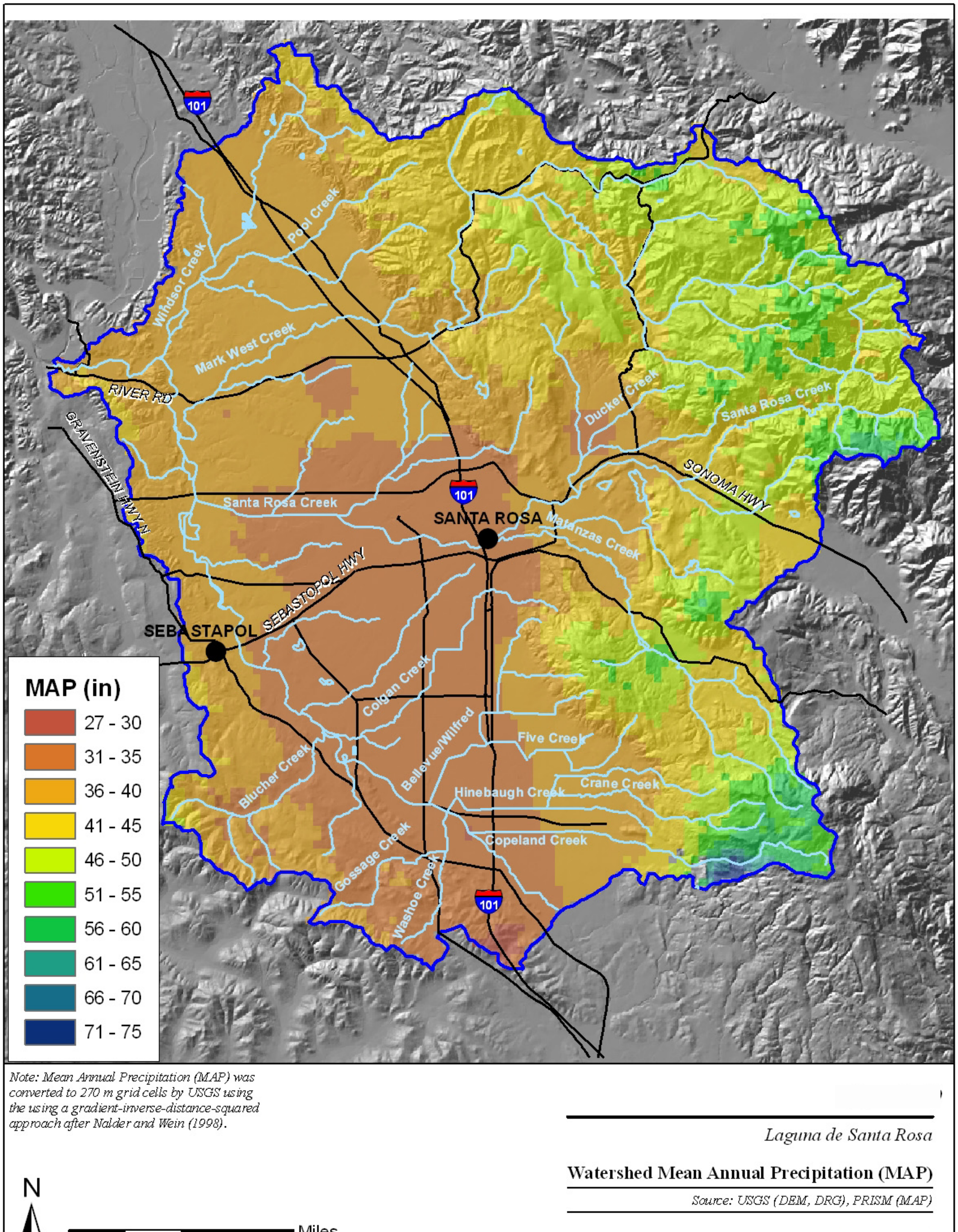

Figure 4-11 Watershed mean annual precipitation

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The mean annual precipitation is strongly affected by elevation and varies considerably in the watershed. A mean annual precipitation for the watershed was created using the 4-kilometer PRISM data (average of 1970-2004) that has been downscaled to 270-meter using a gradient-inverse-distance squared approach (PRISM data and analysis from L. Flint, USGS). The mean annual precipitation in the Laguna watershed ranges from a low of approximately 30 inches in the lowlands near the Laguna to a high of 60 inches in the higher elevations of Mayacamas Mountains (Figure 4-11). Average annual precipitation in the Laguna watershed is 39 inches based on the PRISM data for the Laguna watershed.

Surface water hydrology

One major constraint with hydrological analysis of the Laguna de Santa Rosa is the lack of long-term flow gaging in the watershed. The paucity of the hydrological records for the Laguna have been partially addressed through the installation, in late 1998, of four USGS gages recording 15-minute stage data, that is converted to discharge estimates. Two of these gages are on the Laguna de Santa Rosa (at Stony Point Road [11465680] and Occidental Road ["near Sebastopol" 11465750]); one is on Santa Rosa Creek at Willowside Road (11466320) and one on Colgan Creek (11465700) (Figure 2-8). In addition, there are two daily streamflow gages on the Russian River, upstream and downstream of the Laguna confluence: near Healdsburg (11464000) and near Guerneville (11467000), respectively. These stations constitute the most functional records to quantify hydrologic processes in the Laguna watershed. There are a dozen additional USGS gages within the Laguna watershed that only report water surface elevations or peak flows or have been discontinued. Table 4-4 below details all the gaging stations and their period of record.

Table 4-4
USGS gaging stations withinor near the Laguna watershed

Station No	Station Name	Available Data
11465680	Laguna de Santa Rosa at Stony Point Rd.	Daily Streamflow Values for 11/6/98-9/30/05 Unpublished Streamflow Data for 10/1/05 - 5/18/07
11465750	Laguna de Santa Rosa near Sebastopol	Daily Streamflow Values for 11/18/98-9/30/05 Unpublished Streamflow Data for 10/1/05 - 5/18/07
11465700	Colgan Creek near Sebastopol	Daily Streamflow Values for 11/7/98-9/30/05 Unpublished Streamflow Data for 10/1/05-5/18/07
11466320	Santa Rosa Creek at Willowside Rd	Daily Streamflow Values for 12/9/98-9/30/05 Unpublished Streamflow Data for 10/1/05-5/18/07
11466500	Laguna de Santa Rosa near Graton	Elevation above sea level, recorded only above 55.0 ft Published data for 2/40-9/49 and 10/64 to 2005
11466050	Santa Rosa Creek at Mission Boulevard, at Santa Rosa	Elevation above sea level, from October 1 to May 31 Published data for 11/97 to 2005

11466080	Santa Rosa Creek at Alderbrook Drive, at Santa Rosa	Elevation above sea level, from October 1 to May 31 Published data for 10/97 to 2005
11465850	Spring Lake at Santa Rosa	Elevation above sea level, recorded only above 291.50 ft, from October 1 to May 31 Published Data for 10/97 to 2005
11466200	Santa Rosa Creek at Santa Rosa	Elevation above sea level, from October 1 to May 31 Published Data for 12/39-9/41 and 10/01 to 2005
11466065	Brush Creek at Santa Rosa	Elevation above sea level, from October 1 to May 31 Published Data for 11/02 to 2005
11466170	Matanzas Creek at Santa Rosa	Elevation above sea level, from October 1 to May 31 Published Data for 11/02 to 2005
11467000	Russian River near Guerneville	Daily Streamflow Values for 10/1/39-9/30/05 Unpublished Streamflow Data for 10/1/05-5/18/07
11464000	Russian River near Healdsburg	Daily Streamflow Values for 10/1/39-9/30/05 Unpublished Streamflow Data for 10/1/05-5/18/07
11465200	Dry Creek near Geyserville	Daily Streamflow Values for 10/1/59-9/30/05 Unpublished Streamflow Data for 10/1/05-5/18/07
11465359	Dry Creek near mouth, near Healdsburg	Daily Low Flow Values, recorded only below 200 cfs Published Data for 11/80 to 2005
11465450	Mark West Creek at Mark West Springs	Peak Flows Between 1958-1962
11465500	Mark West Creek near Windsor	Real-time Site
11466800	Mark West Creek near Mirabel Heights	Real-time Site

Two issues constrain the use of these data sources. First, many of the gages have not yet undergone sufficient calibration to allow high confidence in the readings. The lake-like conditions in high stage on the Laguna make the calibration of stage and discharge at many of the Laguna-area gages uncertain. The two daily flow stations along the Laguna were rated "poor" by the USGS due to its lake-like behavior during high-flows and frequent overbank conditions, resulting in poor stage-discharge rating curves. The Santa Rosa Creek station (11466320) is the only station that was rated as "fair". Second, the gage records are not yet of long enough standing to allow construction of meaningful flood-frequency relationships. The only available flood-frequency relationships from a finalized study are reported in the FEMA Flood Insurance Study (1997) and are detailed in Table 4-5 below.

Flood flows in the Laguna de Santa Rosa are strongly influenced by the backwater effect of coincident high flows from the Russian River. FEMA (1997) notes that "the maximum stage on Laguna de Santa Rosa has a high correlation with the maximum stage of the Russian River downstream from its confluence with the Laguna de Santa Rosa. As a result of completion of Warm Springs Dam on Dry Creek, the 100-year flood stage on Laguna de

Santa Rosa has been reduced to an elevation 75 feet NGVD." Flood levels for the 100-year flow are given as a constant from the confluence with the Russian River to Slusser Road on Mark West Creek (38,600 feet upstream of the Russian River confluence) and to Blucher Creek on Laguna de Santa Rosa (46,000 feet upstream of the Mark West confluence). The 10-year flood elevation is reported as 67.5 feet and is level upstream to the railroad tracks east of Sebastopol. The 1986 flood on Laguna de Santa Rosa (slightly influenced by Russian River flooding) plots at slightly over 74 feet (FEMA, 1997). The peak stage reported by USGS for the Laguna at Guerneville Road (11465750) in the 2005-6 New Year's Eve Flood was 72.6 feet.

The ability of the lower Laguna de Santa Rosa-Mark West system to provide flood storage both of its own waters and those incoming from the Russian River is recognized. It is estimated that without the Laguna-Mark West system's flood storage in the 1964-65 flood, levels in Guerneville may have been up to 14 feet higher, and that the Laguna detention reduced Russian River flows by a maximum of 40,000 cfs (SCFCWCD, 1965). Flood inundation extent during the 1964-5 floods was estimated at 7,400 acres (SCFCWCD, 1965), although the total flooded area recorded by individual streams is estimated at 8,080 acres (Laguna = 5,600 acres, Mark West Creek = 1,430 acres, Santa Rosa Creek, 1,050 acres).

SCWA (1997) estimate the storage capacity provided by flood inundation at various flows using staff gage readings from February 7, 1940 – April 15, 1941, near Graton. The Laguna basin is expected to provide 79,000 acre-feet of water storage at the 100-year (75 feet NGVD29) flood level.

Table 4-5
Flow details from Sonoma County unincorporated areas flood insurance study
(Source: FEMA 1997)

		Drainage Area (sq mi)	Peak Discharges (cfs) 10-yr	50-yr	100-yr	500-yr
Laguna de Santa Rosa	Upstream of confluence with Mark West Creek	170.0	21,100	30,300	35,100	44,900
	Downstream of confluence with Santa Rosa FCC	166.0	16,800	23,900	28,000	35,700
	Upstream of confluence with Santa Rosa FCC	87.4	14,000	20,100	23,300	30,800
	Upstream of confluence with Colgan Cr	n/d	7,710	11,200	12,850	17,100
	At Stony Point Rd	n/d	7,170	10,400	11,950	15,900
	Upstream of confluence with Copeland Cr	n/d	977	1,410	1,630	2,120
	Upstream of confluence with Hinebaugh Cr	n/d	2,280	3,250	3,800	5,000
	Downstream of confluence with Hinebaugh Cr	n/d	5,550	7,900	9,250	12,000
Mark West Creek	Upstream of confluence with Windsor Cr	227 *	29,602	42,248	47,900	62,318
	Upstream of confluence with Laguna de Santa Rosa	52.1	8,172	11,000	12,085	15,000
Santa Rosa Flood Control Channel	Upstream of confluence with Laguna de Santa Rosa	78.6	9,900	14,500	16,500	22,000

* estimated
n/d = not determined

To support PWA's sedimentation study, the Army Corps of Engineers prepared a draft basin hydrology assessment for the Laguna de Santa Rosa watershed (USACE, 2003) as well as having completed a separate draft hydrologic analysis of the Santa Rosa Creek watershed (USACE, 2002). Neither study has been finalized by the USACE and should not be used for any hydrologic or sediment-related processes without the USACE's permission. The runoff volumes and peak discharge rates for 2-, 10-, 25-, 50-, and 100-year flows at six locations throughout the watershed were provided by the USACE and are presented in Table 4-2 and Table 4-3. Notably, the estimated 100-year peak flow for Santa Rosa Creek at the mouth is approximately 16% higher and for the Laguna at Llano Road is approximately 10% higher than the rate reported in FEMA (1997).

Dames and Moore (1988, in CH2MHill, 1989) estimated average monthly flows for the Laguna de Santa Rosa at Guerneville Road. Flows were assembled using rainfall statistics (a weighted average of daily precipitation at the National Weather Service (NWS) gage near St Helena (NWS station 047643) and SCWA Santa Rosa gage 1014) and calibrated against 11 years of daily streamflow data (August 1959 – September 1970; 134 months) for USGS streamflow gage station 11465800 on Santa Rosa Creek near Santa Rosa. Potential evaporation (PE) estimates were generated using pan evaporation data from the Santa Rosa Wastewater Treatment Plant (West College). Monthly values were converted to 6-hour precipitation values and daily PE values with simulated-to-observed differences of less than 6 percent. A synthetic unit hydrograph was calculated via HEC-1, the earlier version of the HMS software developed by the USACE. Flows were compared to flows recorded at the Guerneville gage from January 1958 – December 1987. Table 2-6 shows the flows thus estimated.

Table 4-6
Average monthly Laguna de Santa Rosa flows at Guerneville Road

Month	Average Monthly Streamflow (cfs)
October	20
November	117
December	352
January	645
February	657
March	368
April	173
May	32
June	11
July	4
August	4
September	5

4.2.2 Sediment data

There is very little data on sediment movement through the Laguna system and very few reports dedicated to quantify sediment production, transport, or deposition processes across the watershed. We summarized existing studies on the sediment processes in Section 4-1. This section will present the detailed results of sediment yield estimates of PWA's previous study. It will summarize the selected estimates by subwatershed and by time scale to quantify key processes included in the hydrologic and sediment conceptual models. It should be noted that all the recent studies have addressed sediment production and delivery in the Laguna watershed; no analysis of sediment transport conditions through the system is available to incorporate into the conceptual models.

Sediment yield estimates from empirical models

PWA used the Pacific Southwest Interagency Committee (PSIAC) and the Modified Universal Soil Loss Equation (MUSLE) methods to estimate the average annual sediment yield and event sediment yield due to sheet and rill erosion, respectively. MUSLE was also used to provide an estimate of annual sediment yield by taking the weighted average of soil loss from individual events.

The sediment yields estimated using these two methods represent the total amount of sediment delivered to stream channels at the selected outlets. The sediment yields within the Laguna de Santa Rosa system were estimated at the following locations:

- Windsor Creek below confluence with Pool Creek
- Mark West Creek at Old Redwood Highway
- Santa Rosa Creek at Willowside Road
- Laguna de Santa Rosa at Llano Road
- Colgan Creek at Llano Road
- Blucher Creek at Highway 116

The PSIAC method provides sediment yield estimates in acre feet per square mile per year (ac-ft/sq-mi/yr). A unit weight of 90 pounds per cubic feet (lb/ft^3) (approximately 1,400 kilogram per cubic meter) was used to convert the results to tons/sq-mi/yr. The sediment yield estimates for the above subwatersheds using the PSIAC methodology are provided in Table 4-7.

The total annual load to the mainstem Laguna system from all subwatersheds is approximately 153 ac-ft/yr or 272,916 tons/yr. This estimate does not take into account Matanzas Reservoir, the largest reservoir in the watershed, as well as several smaller reservoirs such as those along Paulin Creek and Brush Creek. Therefore the sediment yield estimate also includes the volume of sediment that would be trapped by the reservoir.

Table 4-7
Annual sediment yield estimates by PSIAC

	Annual Sediment Yield (ac-ft/sq-mi/yr)	Annual Sediment Yield (ton/sq-mi/yr)
Laguna at Llano Road	0.84	1,495
Blucher at Hwy 116	0.78	1,388
Colgan at Llano Road	0.61	1,089
Santa Rosa at Willowside Road	0.85	1,513
Mark West at Old Redwood Highway	0.66	1,182
Windsor at Pool Creek confluence	0.78	1,385

The event sediment yields calculated by MUSLE for 2-, 10-, 25-, 50-, and 100-year flows are given in Table 4-8.

Table 4-8
Event-based sediment yields estimated by MUSLE

	Drainage Area (mi^2)	2-year ($tons/mi^2$)	10-year ($tons/mi^2$)	25-year ($tons/mi^2$)	50-year ($tons/mi^2$)	100-year ($tons/mi^2$)
Laguna at Llano Road	44.1	557	1,146	1,457	1,670	1,880
Blucher Creek at Hwy116	7.4	1,134	2,317	2,935	3,359	3,783
Colgan Creek at Llano Road	6.8	174	363	465	533	600
Santa Rosa Creek at Willowside Road	75.8	1,609	3,182	3,837	4,404	5,061
Mark West Creek at Old Redwood Hwy	42.8	1,701	3,919	5,220	6,106	6,968
Windsor Creek at Pool Creek confluence	17.3	1,196	2,642	3,478	4,058	4,631

Event sediment yields can be weighted according to their incremental probability, resulting in a weighted storm average. To compute the annual yield, the weighted storm yield is multiplied by the ratio of annual water yield to an incremental probability-weighted water yield. The results of annual sediment yield estimates thus computed are provided in Table 4-9.

Table 4-9
Mean annual sediment yield estimated by MUSLE

	Mean Annual Runoff (in)	Mean Annual Runoff (ac-ft)	Annual Sediment Yield (ac-ft/sq-mi/yr)	Annual Sediment Yield (ton/sq-mi/yr)
Laguna at Llano Road	10	23,531	2.23	3,857
Blucher Creek at Hwy116	10	3,947	4.51	7,789
Colgan Creek at Llano Road	12	4,378	0.93	1,610
Santa Rosa Creek at Willowside Road	14	56,620	6.38	11,017
Mark West Creek at Old Redwood Hwy	18	41,040	9.01	15,551
Windsor Creek at Pool Creek confluence	18	16,627	6.77	11,698

2002-2003 turbidity measurements

PWA collected water surface and turbidity measurements at three locations along the Laguna de Santa Rosa and Santa Rosa Creek suitable for developing sediment rating curves. The monitoring locations along the Laguna de Santa Rosa and Santa Rosa Creek that are currently gaged for stage and streamflow by the USGS were chosen for monitoring turbidity/suspended sediment. The monitoring locations included:

- Santa Rosa Creek at the Willowside Road Bridge
- Laguna de Santa Rosa at the Occidental Road Bridge
- Laguna de Santa Rosa at the Stony Point Road Bridge

Sediment loading (lbs/sec) was computed from the sediment concentration data and discharge data (Figure 4-12 through Figure 4-14). Sediment loading and cumulative sediment yield computations at the Willowside Road monitoring location on Santa Rosa Creek and at the Stony Point Road monitoring location on the Laguna de Santa Rosa do not include the major storm events that occurred during mid-December. Rating curves relating sediment loading and discharge for each monitoring location indicate that suspended sediment concentration is dependent on several parameters and partially a function of discharge.

Our turbidity records for Santa Rosa Creek during 2002-2003 (a relatively average year in terms of rainfall and runoff) show a load of 96,993 tons, compared with a PSIAC-estimated yield of 114,722 tons. The measured load missed the first large event of the season, but by comparing the Santa Rosa Creek and Laguna at Occidental Road loads we can estimate that Santa Rosa Creek delivered approximately 40-50,000 tons of sediment during this storm, giving a total yield for the year of approximately 150,000 tons. For 2002-2003 (all storms) the measured suspended sediment load for the Laguna de Santa Rosa at Occidental Road was 385,297 tons (compared with a PSIAC-estimated yield of 222,000 tons). The rating curve for the Laguna de Santa Rosa at Occidental Road is considered 'poor,' while Santa Rosa Creek is considered 'fair'; discharge estimates were used in our computation of suspended load. In both comparisons of values presented, estimated sediment yield was compared with calculated suspended sediment load. Sediment yield would be expected the to be higher than the suspended sediment load since there will be additional load carried as bedload (especially in Santa Rosa Creek) and some sediment yield that does not reach the channel (especially in Laguna de Santa Rosa).

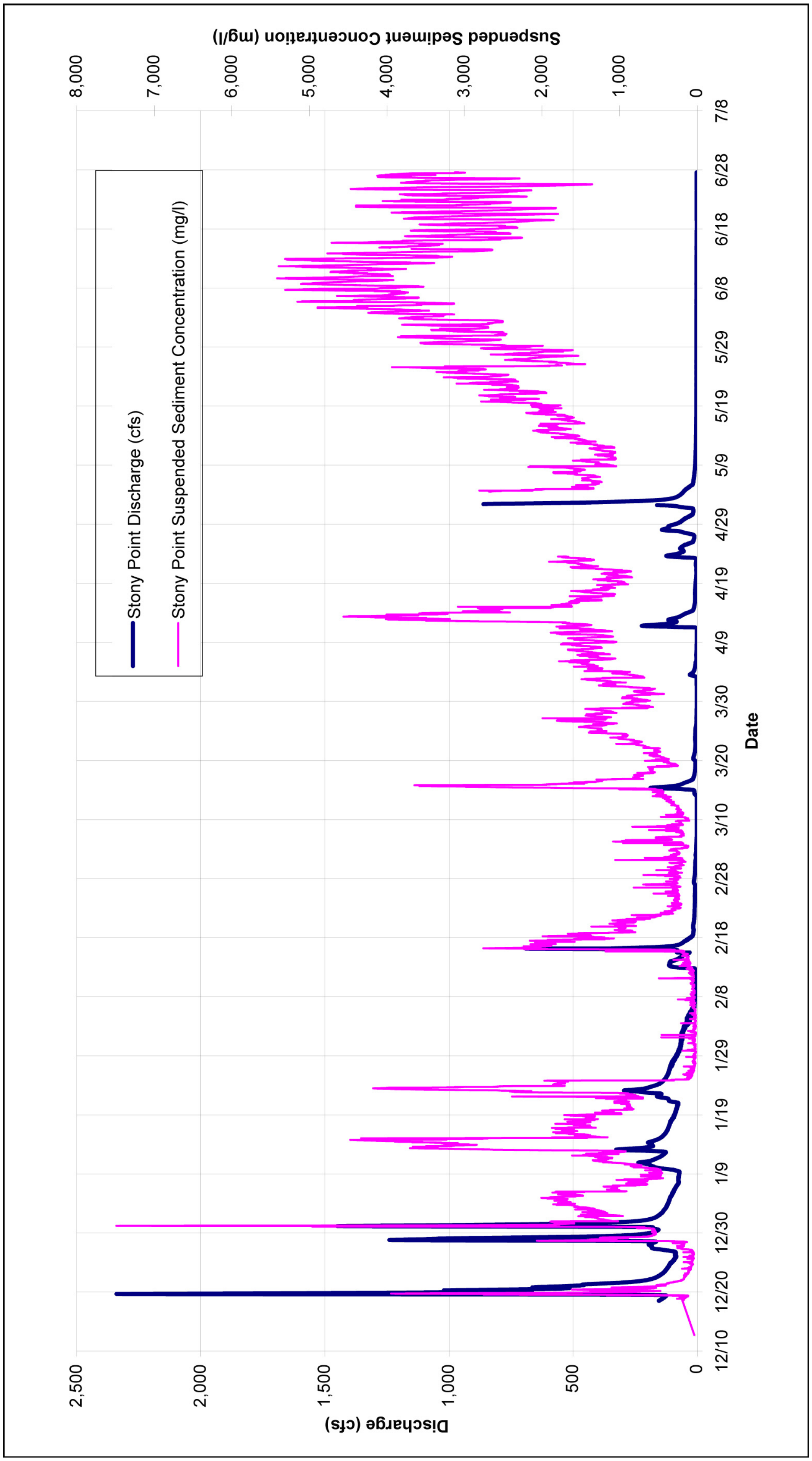


Figure 4-12
Laguna de Santa Rosa at Stony Point Road discharge and suspended sediment concentration 2002–03

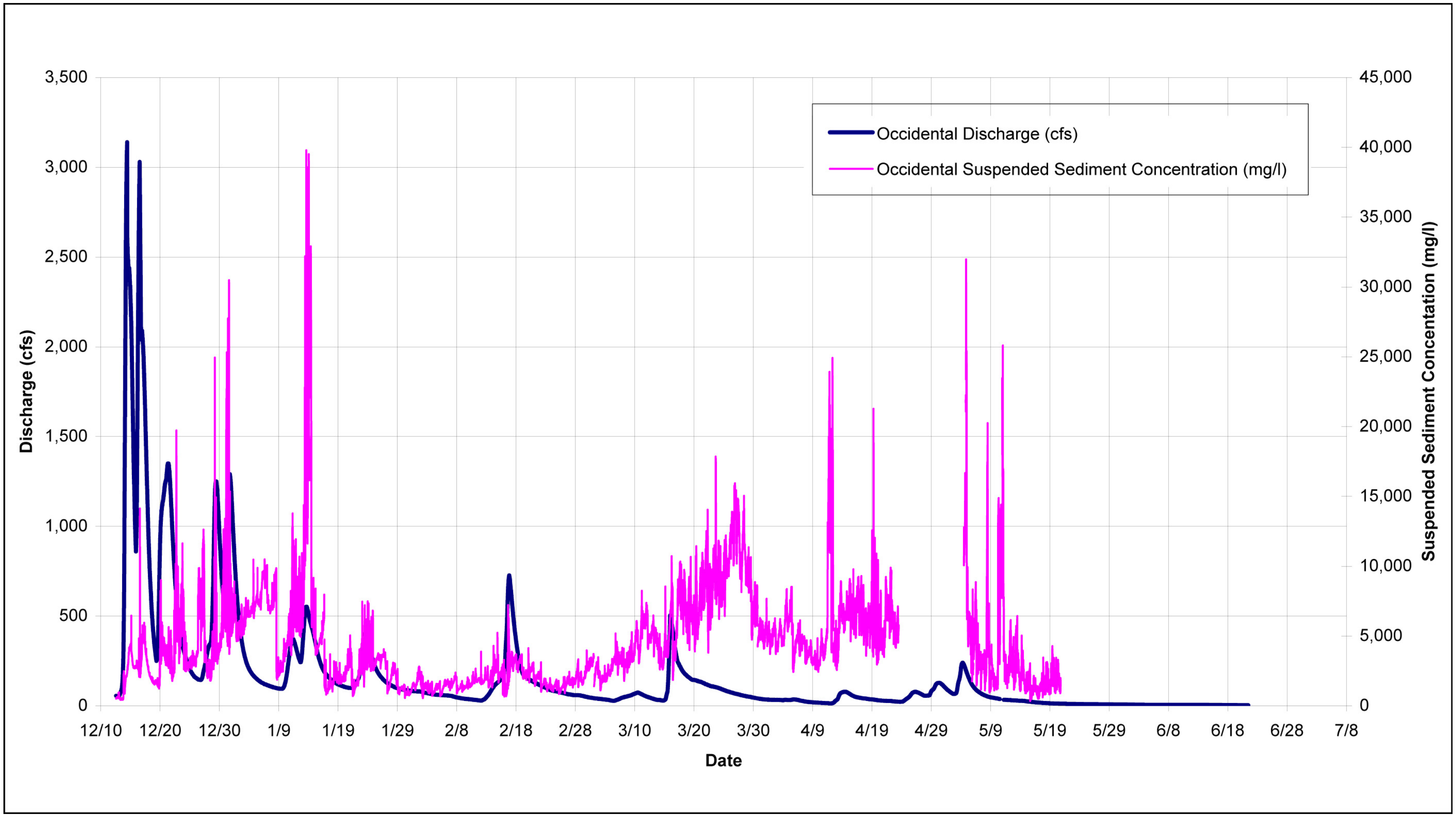


Figure 4-13
Laguna de Santa Rosa at Occidental Road discharge and suspended sediment concentration 2002-03

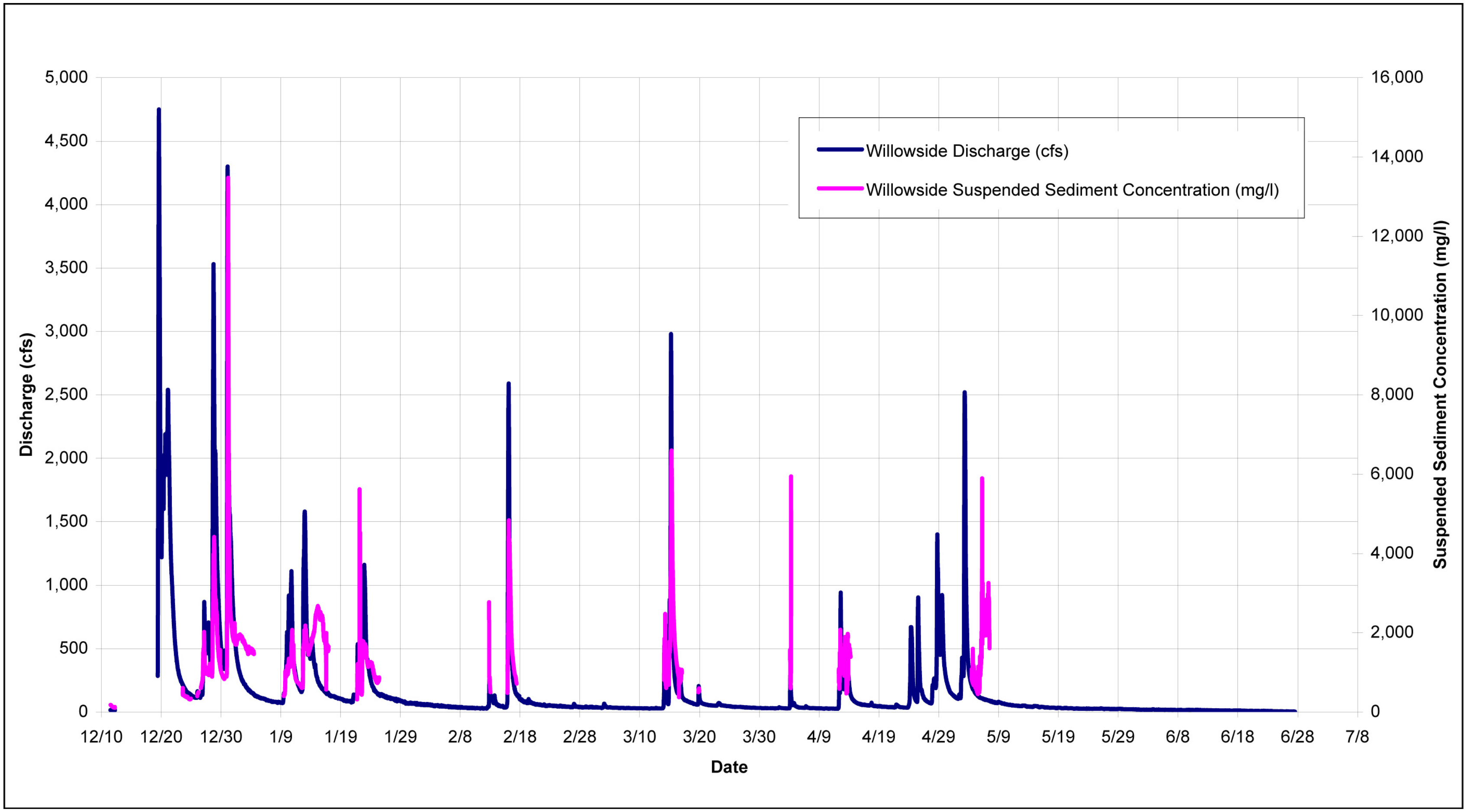


Figure 4-14
Santa Rosa Creek at Willowside Road discharge and suspended sediment concentration 2002-03

Reservoir sedimentation studies and sediment yields in nearby watersheds

Matanzas Creek is the southern tributary of the Santa Rosa Creek and drains an area of 11.5 mi^2. Matanzas Reservoir was built in the early 1960s as a part of the Central Sonoma Watershed Project. The Soil Conservation Service initially surveyed the reservoir in 1964, and then 1972 and 1982. The storage capacity reduction in the reservoir was reported for the two periods between the surveys, and an average annual sedimentation rate was estimated. Table 4-10 below presents the survey information and the annual sedimentation estimates.

Table 4-10
Loss of storage volume in Matanzas Reservoir, 1964-1982

Date of Survey	Period between surveys (years)	Storage Capacity (ac-ft)	Specific Weight	Average Annual Sedn (per sq-mi) Ac-ft Tons		Agency Supplying Data
Jun 1964	--	1,500	--	--	--	SCS
Mar 1972	7.8	1,411	90	1.0	1,960	Not specified
Aug 1982	10.4	1,324	90	0.7	1,423	Not specified

The loss of storage capacity shown above represents an average sediment volume of between 0.7 and 1.0 ac-ft/sq-mi/yr. The actual sediment yield of the watershed will be higher because not all generated sediment will be delivered to the channel network and the reservoir. However, because Matanzas Reservoir is close to the steep headwaters and forms a very effective sediment trap, we assume that these figures are relatively close to the actual sediment yield of the watershed. The Matanzas Creek watershed is very similar to the larger Santa Rosa Creek watershed in terms of soils, geology, land cover, and hillslope gradients. Therefore, the annual sediment yield estimates of between 1.0 and 0.7 ac-ft/sq-mi/yr derived from the reservoir surveys are believed to be representative of sediment yields in the Santa Rosa Creek watershed, albeit slight underestimations. In addition, due to the similarities of watershed characteristics draining the Sonoma Mountain range in the Laguna de Santa Rosa watershed, the estimates are expected to approximate sediment yields in other subwatersheds as well.

Milliman and Syvitski (1992) quoted a study by Janda and Nolan that estimated the annual sediment yield in the Russian River watershed. Their estimate was 680 $t/km^2/y$ or 1760 $t/mi^2/y$. Assuming a unit weight of 90 lb/ft^3 or approximately 1400 kg/m^3, the annual sediment yield in the Russian River watershed would be 1.02 ac-ft/sq-mi/yr, consistent with the estimates from Matanzas Reservoir. Ritter and Brown (1971) evaluated suspended sediment transport in the Russian River basin. For the years 1965 to 1968, Ritter and Brown found a suspended load of 1,150 to 14,000 tons/sq-mi/year, the highest being in the very wet 1965 year. Griggs and Hein (1980) estimated average erosion rates for a number of Northern California watersheds based on off-shore sedimentation studies. Their study suggested an erosion rate of approximately 1,600 tons/sq-mi/yr for the Russian River watershed. Sonoma Ecology Center has published a sediment budget of the Sonoma Creek watershed in which, an annual sediment yield of approximately 1,100 tons/sq-mi was estimated. California Geological Survey (CGS) prepared a technical memorandum that concluded that from a review of the literature and analysis of recent studies conducted by the CGS watersheds underlain by Franciscan mélange are likely to have natural/background sediment loads of approximately 1,000 tons/sq-mi/year or greater (Bedrossian and Custis, 2002).

Sediment inputs to the Laguna from the Russian River

In addition to sediment from within the watershed, the Laguna occasionally receives sediment-rich water from the Russian River. During flood events where the Russian River backs up into the Laguna, some fine sediment is carried upstream to the Laguna and would deposit especially where the water from both systems meet, around the Mark West Creek confluence. There are no estimates of the amount of sediment that is contributed by the Russian River. Good long-term flow records for the lower Laguna channel, including flow direction, and sediment and flow records for the Russian River around the Laguna confluence are required to estimate the amount of sediment contributed and deposited by the Russian River in the Laguna.

Grain size analysis

PWA collected 32 bulk samples from channel beds along the Laguna tributaries. The samples were collected by hand at strategic positions around the watershed. Each sample was collected from a riffle or riffle-equivalent position (in modified channels) and consisted of approximately 25-40 lbs of sediment from the near sub-surface layer of the channel bed. Efforts were made to ensure that the samples were collected from exposed bed sites, to clear obvious armor layer deposits and to minimize the loss of fine materials during collection, but it should be expected that each sample somewhat underestimates the fine sediment proportion. Particle size analysis was performed on all samples. Summary statistics for the bulk samples are provided in Table 4-11, organized by sample number.

Table 4-11
Particle size distribution of bed material samples in Laguna tributaries

Sample Location	Description	% Gravel	% Sand	% Fines
Mark West @ Porter Creek	Gray poorly- graded gravel with sand	56	39	5
Mark West @ Calistoga	Gray poorly- graded gravel with sand	51	47	2
Mark West @ MW Springs (Redwood Hill)	Gray poorly- graded gravel with sand	54	45	1
Mark West @ MW Springs	Gray well- graded gravel with sand	77	21	2
Mark West @ Old Redwood Hwy	Gray poorly- graded sand with gravel	48	51	1
Mark West @ Laughlin	Gray poorly- graded gravel with sand	50	49	1
Mark West @ Slusser	Gray well- graded gravel with sand	67	33	0

Sample Location	Description	% Gravel	% Sand	% Fines
Santa Rosa@ Wildwood	Gray poorly- graded gravel with sand	70	30	0
Santa Rosa @ Montgomery	Gray poorly- graded gravel with sand	62	38	0
Brush Cr. @ Hwy 12	Gray poorly- graded gravel with sand	64	35	1
Spring Cr. @ Park Trial	Brown well-graded gravel with silt and mud	64	28	8
Manzinitas CR. @ Yulupa	Gray well-graded gravel with sand	70	28	2
Santa Rosa @ Sonoma	Gray well-graded gravel with sand	72	28	0
Pauline Cr @ Lomitas	Gray well-graded gravel with sand	68	30	2
Santa Rosa @ Fulton	Gray poorly- graded gravel with sand	52	47	2
Piner Cr. @ Fulton	Gray poorly- graded gravel with sand	64	36	0
Santa Rosa @ Willowside	Gray brown well-graded gravel with sand	59	40	1
Colgan Cr. @ Victoria	Brown silty sand	0	62	38
Colgan Cr. @ Stony Point	Gray well-graded gravel with sand	55	44	2
Colgan Cr. @ Llano	Olive gray clay with trace sand	4	10	86
Blucher @ Canfield	Gray sand with clay	2	87	11
Blucher @ Lone Pine (Hwy 116)	Gray sand with clay	1	93	6
Bellevue/Wilfred @ Petaluma Hill	Gray brown well-graded gravel with sand	58	38	4
Bellevue/Wilfred @ Todd	Gray well-graded sand with gravel	42	56	2
Bellevue/Wilfred @ Wilfred	Dark grayish brown silt with sand	2	19	79
Crane Cr. @ headwaters	Light brown silty gravel with sand	66	21	13
Crane Cr. @ Petaluma Hill	Gray poorly graded gravel with sand	60	38	2
Hinebaugh Cr. @ Petaluma Hill	Dark brown & gray poorly-graded sand with silt and gravel	28	61	11

Sample Location	Description	% Gravel	% Sand	% Fines
Hinebaugh Cr. @ Redwood	Gray poorly-graded sand with silt and gravel	19	75	6
Copeland Cr. @ Lichau	Gray brown well-graded gravel with sand	70	28	2
Copeland Cr. @ Snider	Gray well-graded gravel with sand	64	36	0
Copeland Cr. @ trailer park	Gray well-graded sand with silt	3	87	10
Pool Cr @ Windsor Road	Brown poorly- graded gravel with sand	62.5	35.8	-
Windsor Cr @ Windsor Road	Brown well- graded gravel with sand	58.1	40.9	-
Pool Cr @ Pleasant Ave	Brown poorly- graded sand with gravel	34.2	63.9	-
Windsor Cr @ Arata Ln	Brown well- graded gravel with sand	56.6	41.1	-
Windsor Cr @ Brooks Rd N	Brown poorly- graded sand with gravel	43.7	53.6	-
Windsor Cr @ Conde Ln	Brown poorly- graded sand with gravel	48.4	50.1	-
Pool Cr @ Conde Ln	Brown well- graded gravel with sand	58.3	40.1	-
Pool Cr @ Leslie Rd	Brown well- graded sand with gravel	48.4	50.0	-
Windsor Cr @ MW Station Rd	Brown poorly- graded gravel with sand	52.2	46.6	-

4.3 Conceptual models

Development of conceptual models of complex ecological systems such as Laguna de Santa Rosa is fundamentally important to define the scope of problems being considered and to describe the causes, interactions, and effects underlying environmental change (National Research Council, 1995). Conceptual models also serve as the foundation of a comprehensive modeling effort and subsequent restoration program. Our conceptual models are developed to explain a general state of understanding about the Laguna system and its physical and ecological processes and to present the rationale for selecting and developing subsequent modeling studies. The conceptual models of hydrologic, sediment, water quality, and ecologic processes will be coupled to provide the linkages between these different parts of the system and to provide the basic structure for future computational models.

We explored the temporal and spatial variability of physical processes in the Laguna de Santa Rosa watershed in the previous section. Section 4.3.1 presents a temporal conceptual model on the Laguna and briefly summarizes time dependent equilibrium states of the system. We also developed two different types of spatial conceptual models to express our present state of understanding about hydrological and sediment processes in the Laguna de Santa Rosa watershed. These models are described in Sections 4.3.2 and 4.3.3. Our definition of conceptual model components is derived from CALFED's Delta Regional Ecosystem Restoration Implementation Plan (DRERIP) Framework (DRERIP, 2005).

The first type of conceptual model is an Operational Conceptual Model, or a model that clearly delineates the cause-effect relationship by identifying the key anthropogenic drivers, linkages, and outcomes in the Laguna ecosystem (DRERIP, 2005). These models were developed for two geomorphic domains in the watershed: the Lower Laguna Watershed and the Upper Laguna Watershed. Each domain is represented by a qualitative schematic that illustrates how drivers influence relationships among processes that lead to outcomes. In our conceptual models, an ecosystem element refers to a basic component or function and can be categorized as a process, habitat, stressor, or species. As specified in these models, a driver is a human-induced element with a known or hypothesized important effect on another element. In coupled models, a driver in a model can be the outcome from another model. A linkage is a cause-effect relationship among ecosystem elements. An outcome or intermediate outcome is a result, effect, or consequence (DRERIP, 2005). For each cause-effect linkage, the nature and direction of the effect is identified. A positive effect or a negative effect is represented by + or – sign, respectively. A response curve effect is represented by a bell-shaped curve and is an effect that is generated most strongly within a limited range of conditions.

The second type of conceptual model is a Budgetary Conceptual Model that summarizes the directions and known magnitudes of hydrologic and sediment delivery processes from subwatersheds to the Laguna de Santa Rosa. Data for Budgetary Conceptual Models have been derived from hydrologic information acquired from USGS gauging stations in the Laguna watershed and from PWA's previous analysis on sediment sources and rates in the Laguna (PWA, 2004).

4.3.1 Temporal variability

The Laguna de Santa Rosa and its watershed are part of an integrated physical system in which cascading arrangements of mass (i.e. sediment) pass through the morphological components of the system (i.e. landforms) over varied time scales. The components mutually adjust to changes in inputs of mass, frequently with negative feedback arrangements, which allow the system to be self-regulating. Self-regulation is usually directed toward an equilibrium state where the inputs of energy and mass are equal to the outputs from the system. There are several forms of equilibrium state including static, stable, unstable, metastable, steady-state and dynamic (Chorley and Kennedy, 1971). The time scale of interest strongly influences the view of system stability and the cause of any induced change.

In the short term (e.g., one to one hundred years), there may be unceasing adjustment between the system components. Variable conditions produce fluctuations about an average value (i.e., stable equilibrium). The long term (e.g., one hundred to several hundred years) can involve the establishment and maintenance of a characteristic set of landforms within a system that persist through time, although individual components will be evolving and the pattern and interrelationships of these features will be continuously changing (i.e., steady-state equilibrium). In the very long term (e.g., a thousand to several hundred thousand years), progressive or major episodic changes become more apparent (i.e., dynamic or metastable equilibrium, respectively).

The temporal variability of hydrologic and sediment delivery to the Laguna de Santa Rosa can be explored within two different contexts: before and after the European settlement of the area, approximately 150 years ago. Prior to European settlement, hydrologic and sediment delivery from tributary channels were likely in a state of dynamic equilibrium: variations year to year were driven by the natural processes of rainfall and stream flow and the production of sediment in the subwatersheds. Gradual progressive changes in sediment delivery would have resulted from tectonic processes. Since the European settlement of the Laguna de Santa Rosa watershed, there has been a series of land use changes in the watershed that have had significant impacts on sediment yield at an unprecedented rate. Specific land uses that influenced hydrologic and sediment delivery in the Laguna de Santa Rosa watershed are grazing, agriculture, urbanization/ suburbanization, drainage modifications and flood control projects. How a particular change may have affected sediment delivery to the Laguna over time cannot be specified due to insufficient historic data and the impacts that legacy land use features have on past, present, and future hydrologic and sediment dynamics. The Operational Conceptual Models were developed for the short term and represent a snapshot view of the processes for the present and near future conditions.

In the long term and the very long term, the Laguna de Santa Rosa watershed is subject to numerous external natural forces that affect its evolution. Sea level rise, a function of climate change, will alter the base level condition for Russian River, which in turn will decrease the overall slope and associated conveyance characteristics of Laguna. Sea level rise creates significant increases in the accommodation space, or volume available to act as a sediment sink as sea level rises further above the current base level. At the opposite ends of the watershed, tectonic uplift raises the upper watershed, increasing slopes and probably sediment delivery. In the lower reaches of the watersheds, subsidence – both tectonically and anthropogenically-induced – may alter slopes and increase accommodation space as land levels drop relative to sea level. Hydrologic change, a function of both climate change and anthropogenic influence, will also be reflected in the morphology and sediment budgets of the Laguna watershed. There are considerable uncertainties about precise impacts of climate change on California hydrology and water resources. Kiparsky and Gleick (2005) reviewed existing literature on the impacts of climate change on water resources in California. The following discussion provides a brief summary of their review as specifically related to the impact of climate change on precipitation and runoff. Several recent regional modeling efforts conducted for the western United States indicate that overall precipitation will increase (Giorgi et al. 1998; Kim et al. 2002; Snyder et al. 2002). Studies conducted by Giorgi et al. and Kim et al. reported that precipitation increases will be centered in Northern California and in winter months. Variability of the hydrologic cycle also increases when mean precipitation increases, possibly accompanied by more intense local storm and changes in runoff patterns (Noda and Tokiaka, 1989; Hennessy et al. 1997). Large-scale general circulation studies produce various results on storm volumes, but increased storm intensity is consistently forecast (Carnell and Senior, 1998; Hayden, 1999; Lambert, 1995), along with a shift in runoff toward earlier in the season. Estimates of changes in runoff due to climate change have also been produced for California. Such estimates are based on anticipated, hypothetical, or historical changes in temperature and precipitation (Kiparsky and Gelick, 2005). In addition to prediction models, several studies investigated precipitation and runoff trends in the last century. Karl and Knight (1998), updated by Groisman et al. (2001) analyzed long-term precipitation trends in the United States and determined that precipitation over the contiguous US has increased by approximately 10 percent since 1910 (with most of the increase in the highest annual one-day precipitation event), that the intensity of precipitation has only increased for very heavy and extreme precipitation days, and that the proportion of total precipitation from heavy events has increased at the expense of moderate precipitation events. To the extent that all of these external forcing functions occur, thereby triggering adjustments in the landscape, they will produce gradual but important changes in the subwatersheds of the Laguna de Santa Rosa.

4.3.2 Operational conceptual models

The geographic scope of our Operational Conceptual Model is twofold: the Upper Laguna Watershed and the Lower Laguna Watershed. These different geomorphic domains in the system are characterized by different drivers, linkages, and outcomes based on the dominant anthropogenic influences and consequent geomorphic processes in each domain. The temporal scope of the models is "ahistorical" and represents a snapshot view of the current Laguna watershed.

The Lower Laguna Watershed consists of the main channel of Laguna and its floodplain, including the lower reaches of the tributary channels and floodplains. The Lower Laguna Watershed represents the depositional zone in the Laguna system where stream channels act as sediment sinks and where sediment transported from the Upper Laguna Watershed is stored for different periods of time along the channels or the Laguna floodplain. The Operational Conceptual Model of Anthropogenic Influences on Sediment Processes and Surface Water Hydrology in the Lower Laguna Watershed is illustrated in Figure 4-15.

The Upper Laguna Watershed consists of headwater zones of tributary channels to the Laguna and the main stem tributary channels and represents sediment production and transport zones. This domain is the source for sediment through hillslope processes but also serves as the transport link between headwater zones and the Lower Laguna. Once sediment is delivered to the channels in the Upper Laguna Watershed, it moves downstream to the Laguna with reduced channel and valley bottom storage due to channel modification activities in the lower parts of tributary systems. The Operational Conceptual Model of Anthropogenic Influences on Sediment Processes and Surface Water Hydrology in the Upper Laguna Watershed is illustrated in Figure 4-16.

We identified the key anthropogenic drivers, linkages, and outcomes in the Laguna ecosystem and the nature and direction of the cause-effect relationships. The cause-effect relationships are brief summaries of the anticipated effects that watershed and flow characteristics have on sediment loads. Our approach to develop conceptual models was to first identify outcomes that have been recognized as key management concerns and referred to in the proposal development. These outcomes were identified in the Lower Laguna Watershed since this zone is the key area of concern from hydrologic, water quality, and habitat standpoints. The key drivers that would have an impact on these outcomes were then identified. The cause and effect linkages between these two groups that were termed "intermediate outcomes" were explored and described subsequently. Although presented here as fragmented geomorphic units, the Upper and Lower Laguna Watersheds are coupled: outcomes from the former are drivers for the latter. Therefore, once the drivers and outcomes for the Lower Laguna Watershed were recognized, the outcomes for the Upper Laguna Watershed were consequently identified. The process of exploring the drivers and linkages for the Upper Laguna Watershed was then pursued.

Lower Laguna watershed operational conceptual model

The Lower Laguna Watershed conceptual model of anthropogenic influences on sediment processes and surface water hydrology (see Figure 4-15) is derived from the following outcomes that signify key management concerns: water quality issues, flood hazard issues, and *Ludwigia*. These outcomes have arisen as critical components related to hydrology and sediment processes that need to be addressed by the on-going and planned efforts such as comprehensive watershed plan, restoration planning and TMDL development. Our model's structure is based on the understanding that urbanization, agricultural development, oversized channels, inflow hydrology, and sediment inflow affect the hydrology and sedimentation characteristics in the Lower Laguna.

Urbanization and suburbanization (referred to as (sub)urbanization) have had significant impacts on the hydrologic and sediment transport processes in both the Upper and Lower Laguna Watersheds. (Sub)urbanization is accompanied by increases in impervious surfaces, which reduce the area of infiltration, surface storage, and connectedness of drainage channels. These in turn impact the pathways and the timing of runoff and change the relative proportions of overland flow and groundwater flow to the channels. The natural storage of water in the watershed is reduced. In addition, irrigation and other outdoor uses of water in a (sub)urban area increase summer low flows in a semi-arid watershed where irrigation volumes are significant compared to the pre-urbanization dry season flows. These hydrologic modifications result in increased runoff volumes and peak flow rates and reduced time lags. Increased runoff volumes and rates result in increases in fine sediment and coarse sediment supply rates, respectively (explained below).

Agricultural development, which predominantly involves hay fields and row crops in the Lower Laguna Watershed, is typically accompanied by drainage reconfiguration, homogenization of land surface, vegetation removal, irrigation, water diversions, or channelization of streams and swales. The hydrologic effects of these modifications are decreases in infiltration rates, depression storage, and evapotranspiration, which in turn result in increases in peak flow rates and flashiness of flows. Similar to the impacts of (sub)urbanization, irrigation and water diversion practices typically lead to increased low flow conditions in summer. Physical removal of riparian and in-channel vegetation coupled with drainage reconfiguration reduces the extent of bank vegetation, which subsequently increases the amount of fine and coarse sediment supply to the channels.

Increased summer low flows raise the shallow water table elevations through recharge along the bed and increase the outflow of shallow ground water to streamflow. In Mediterranean climates where the stream ecology has adapted to a season cycle of water supply (that is typically dry conditions in summer), increased summer low flows enhance the emergence and survival of in-channel vegetation. Changes in the shallow water table have created condition favorable to a number of non-native species including *Ludwigia* (explained in more detail in Section 6).

As the population increased in the Laguna watershed, the urban extent and agricultural development increased. Floods became more damaging as development increased and resulted in the first efforts for flood control. To make the alluvial fan more habitable and productive for farming, natural channels were replaced with larger, straighter channels better suited for flood conveyance. Channelized streams are designed to increase conveyance capacity and efficiency. Therefore, they typically are large, straight channels with steep gradients. In addition to hydrologic changes, channel modifications moved the focus of sediment deposition away from the alluvial fan surface that characterizes the lowest part of the Upper Laguna region, at the margin of the Santa Rosa Plain, and towards the Laguna. By eliminating out-of-bank flows and channel avulsions and by connecting distributary channels to the Laguna, the new drainage network has reduced sediment deposition on the fan and concentrated it in the channel network and in the Laguna. In addition, some of the modified channels have themselves become sources of sediment due to accelerated erosion. Straight, hydraulically effective channels with low width to depth ratios and little bank vegetation have in some cases suffered bank and bed erosion, contributing sediment into the Laguna. The combined effect of these processes has been to increase sediment generation and transport capacity to the Laguna, resulting in increased potential for deposition.

Inflow hydrology is separated into two distinct components that have different impacts on different sediment processes: runoff volume and peak flow rate. The effect of inflow hydrology on the hydrology of the Lower Laguna is explicit: the latter is proportional to the former. Hydrologic modification due to anthropogenic impacts typically implies increased runoff volumes and peaks. Increased runoff volumes result in increases in fine sediment supply. Fine sediment transport is typically supply-limited: the magnitude of transport is constrained by the availability of sediment to the stream and not by the transport capacity of the stream. Moreover, since fine sediment is easily mobilized and initiation of transport is not primarily dependant on flow competence (flow necessary to mobilize sediment), volumes are more relevant than flow rates to fine sediment transport. On the other hand, coarse sediment transport is typically transport-limited: the ability of flow to entrain and transport sediment controls the magnitude of coarse sediment transport. Therefore, increased peak flow rates result in increases in velocities and shear stresses, which in turn lead to increased coarse sediment transport.

Due to these anthropogenic changes in physical processes in the Laguna watershed that have resulted in increases in the amount of fine and coarse sediment supply and in-channel vegetation, the magnitude and the geographic extent of fine and coarse sediment deposition have increased. In-channel deposition and associated reduction in channel capacity in turn lead to increases in potential flood hazards that are of paramount concern to watershed managers and all stakeholders. Deposition in the Lower Laguna channels also impact habitat conditions for *Ludwigia*. We hypothesize that deposition would have a threshold effect on *Ludwigia*: favorable conditions as deposition increases until an optimum substrate and water level elevation is reached. Subsequent increases in deposition and associated bed levels would negatively affect *Ludwigia* habitat.

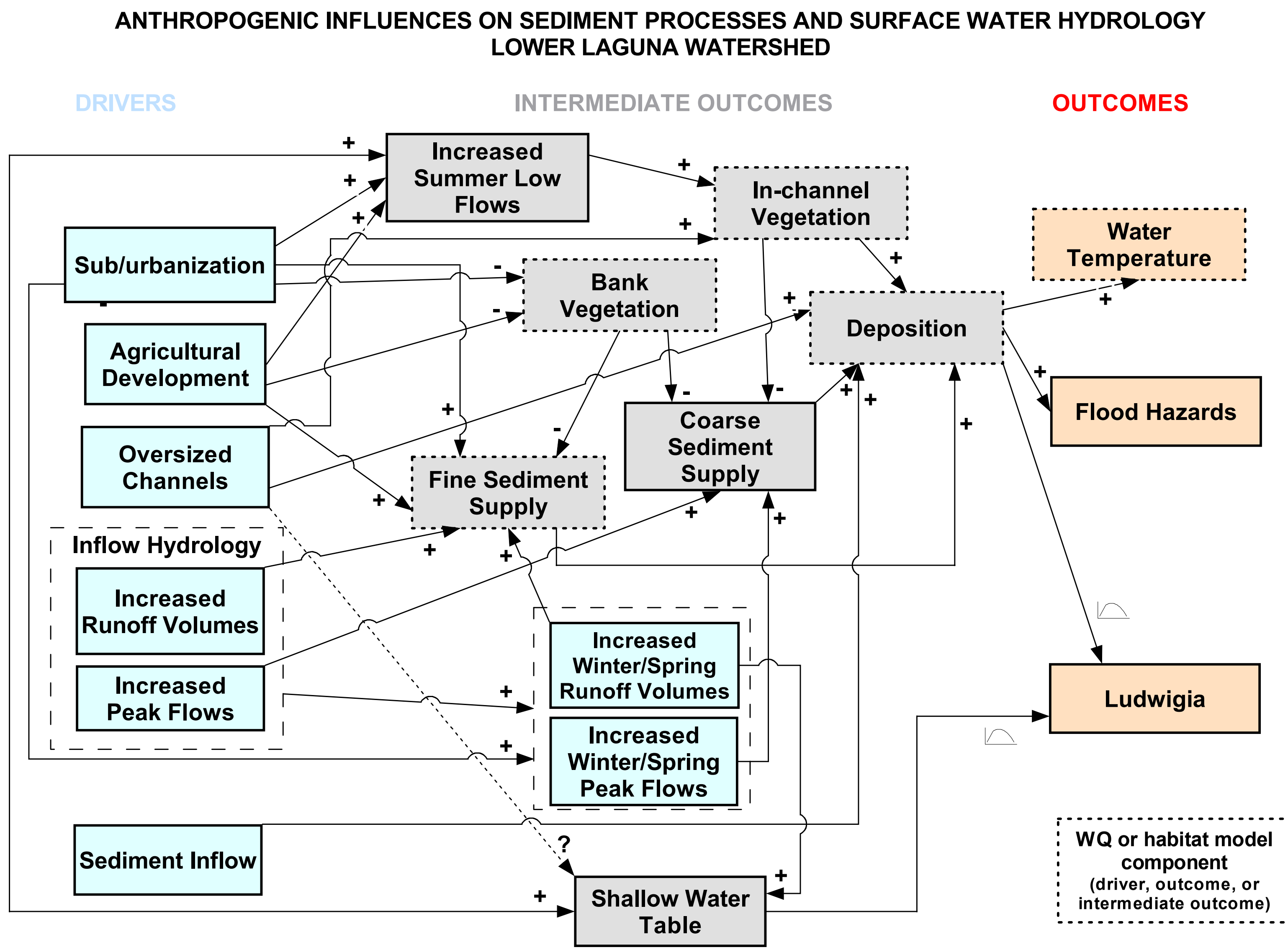


Figure 4-15
Anthropogenic influences on sediment processes and surface water hydrology in lower Laguna watershed

Upper Laguna watershed operational conceptual model

The Upper Laguna Watershed conceptual model of anthropogenic influences on sediment processes and surface water hydrology (see Figure 4-16) is coupled with the Lower Laguna model and controls the water and sediment inflow to the lower Laguna. Therefore, the outcomes from the Upper Laguna are outflow hydrology and sediment outflow.

We included physical watershed characteristics of the uplands as input to the Upper Laguna Model without articulating on their impacts on the drivers in this domain. Physical characteristics such as relief, precipitation, and geology inherent to the upland areas, where the main process is sediment production, have a direct impact on the Upper Laguna Watershed. These characteristics are not significantly modified due to anthropogenic impacts, and therefore are identified as upstream inputs.

Topography has a direct effect on hydrologic and sediment processes. Steeper slopes lead to faster delivery of runoff. Watersheds with a larger percentage of steeper slopes produce more sediment in transport-limited situations (Montgomery and Dietrich, 1994; Wohl et al., 1998). Steeper slopes initiate more frequent mass wasting events and contribute to the transport of loose particles on the hillslope and in the channel.

Precipitation is the main driver for all the hydrologic processes in any watershed. The magnitudes of all components of the hydrologic budget are directly proportional to precipitation. Sediment processes also depend on precipitation, which acts as a driver for natural erosion processes. Under otherwise equivalent conditions, higher rates of precipitation and higher precipitation variability result in higher rates of erosion from slopes, incision by streams into valley sides, and the transport of supplied sediment to the basin outlet (Hooke, 2000). Higher rainfall increases the likelihood of sediment-producing events, and therefore a higher sediment load. As a first approximation, mean annual precipitation is a measure of the differing amounts of rainfall throughout the Laguna watershed.

The effect of geology and soils on the hydrologic and sediment processes is evident. Impervious lithology and soils with low infiltration capacities would generate more runoff than permeable geology and soils that have higher infiltration capacities. Sediment yields from basins underlain by resistant rocks and compacted soils (such as clays) would be less than those underlain by weak rocks and loose, granular soils.

Similar to the Lower Laguna, the inflow hydrology, sediment inflow, (sub)urbanization, and agricultural development are identified as the main drivers in the Upper Laguna Watershed.

Hydrologic and sediment processes as drivers are directly proportional and linked to the outflow hydrology and sediment outflow as outcomes.

The hydrologic modification impacts of (sub)urbanization on winter/spring and summer flows are summarized in the preceding section. In addition, (sub)urbanization also lead to alteration of land cover and stream channels. Urban development brings about loss of tree cover and paving of land surface, resulting in the reduction of resistance to erosional forces and subsequent land degradation. (Sub)urbanization is typically accompanied by channelization, bank hardening, and drainage works. Straighter, larger channels are built to efficiently convey large floods. This results in elimination of overbank flows and channel avulsions and concentration of runoff in the stream channels, leading to in-channel and bank erosion. Sediment that would previously have traveled down dispersed distributary channels and been deposited on the alluvial fan surface is, with these changes, either con-

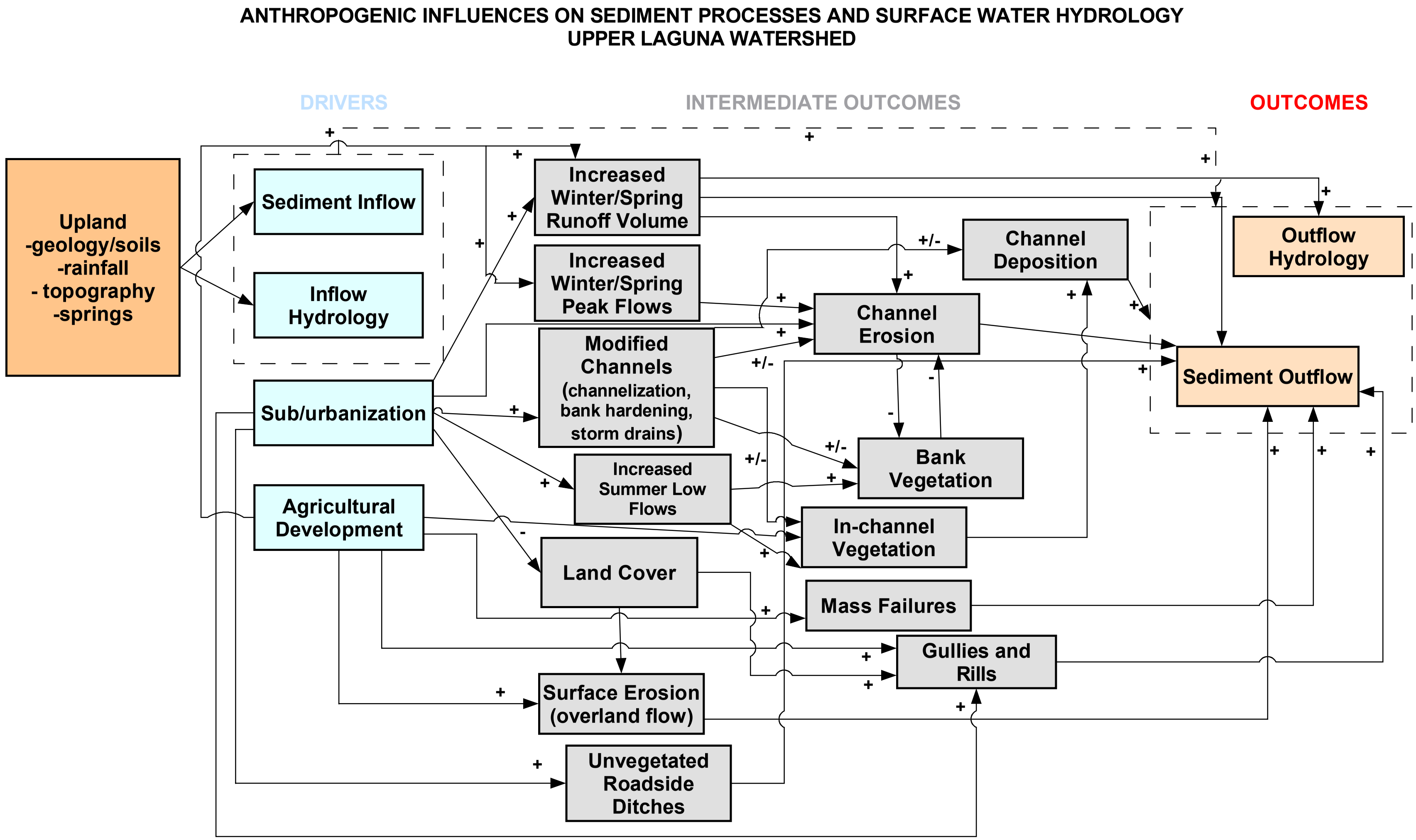


Figure 4-16
Anthropogenic influences on sediment processes and surface water hydrology in upper Laguna watershed

centrated in drainage channels or transmitted to the Laguna. When channels are oversized, they cannot efficiently carry their sediment load during low flows, resulting in sediment deposition after low flow events. To alleviate the impacts of hydrologic modification due to (sub)urbanization, channel bed or banks are typically hardened to reduce erosion. Urbanization also often involves putting entire channels, tributaries, or stream reaches into storm drains or box culverts. These systems are usually connected to impervious surfaces above ground that might supply negligible amounts of sediment, causing the downstream channel to become sediment-starved and prone to destabilization and erosion. (Sub)urbanization can also increase drainage density through the creation of road shoulders and ditches, making it easier for overland flow to reach stream channels in a short period of time. If such ditches are unvegetated, they are prone to erosion by clear overland flow, and thus contribute to increased sediment outflow from this geomorphic domain.

Vineyard and orchard development in the Upper Laguna Watershed have included direct physical impacts such as vegetation removal, tillage, compaction of land surface, and impacts on the hydrologic system such as drainage reconfiguration, water diversions, and irrigation. All of these processes either directly or indirectly affect the delivery of water to and interaction of ground water and surface water. The direct physical impacts of agriculture coupled with indirect impacts through hydrologic changes, result in increases in mass failures, and gullies and rills.

Intermediate outcomes of hydrologic and sediment processes in the Upper Laguna Watershed are increased channel erosion and altered depositional characteristics due to anthropogenic influences. These intermediate outcomes directly impact the outcomes from this domain: outflow hydrology and sediment outflow.

4.3.3 Budgetary conceptual models

The Budgetary Conceptual Models present the summary of information on the hydrologic and sediment budgets of the Laguna de Santa Rosa. A budget in this context is an accounting of the sources and disposition of water or sediment as it travels from its watershed of origin to its eventual exit from the Laguna. The hydrologic and sediment budget for the Laguna watershed is relatively incomplete due to the scarcity of data on flow and sediment.

We developed an annual hydrologic budget for the Laguna de Santa Rosa for Water Year 2005. Figure 4-17 presents a schematic illustrating hydrologic contributions from each subwatershed in the Laguna and annual runoff values for the period from October 2004 to September 2005. This period was chosen because 2005 annual flows are comparable to average conditions in this region. Annual runoff values for gaged subwatersheds were augmented by deriving runoff values from several ungaged subwatersheds using a network of monitored locations nearby. A list of USGS stations that were used to develop the hydrologic budget is presented below in Table 4-12.

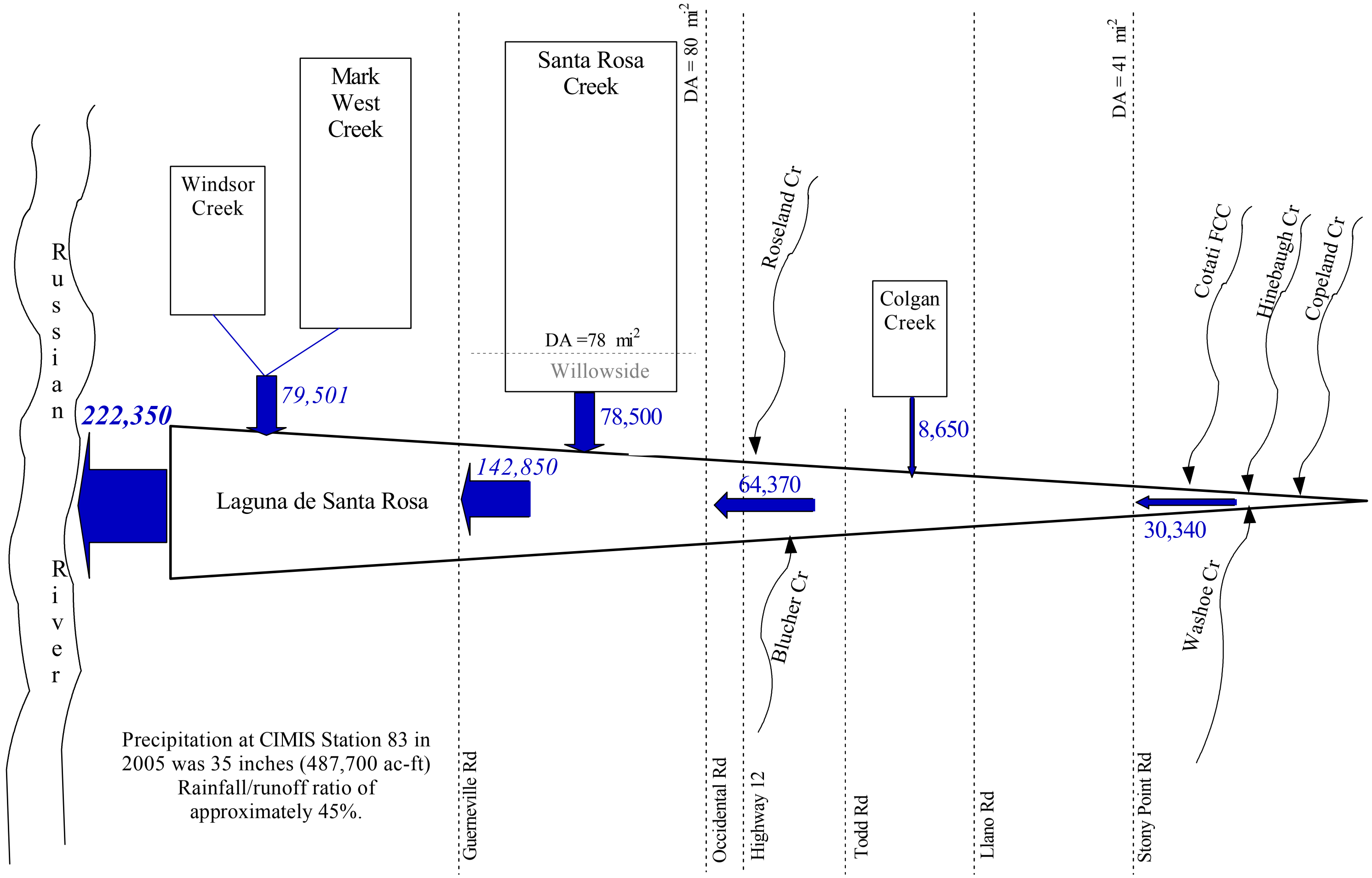
Table 4-12
Summary of USGS gauging stations in the Laguna de Santa Rosa watershed and vicinity

USGS Station Number	Station Number and Name	Record	Period of Record	WY 2005 Runoff (ac-ft)	Average Annual Runoff (ac-ft)
11465700	Colgan Creek near Sebastopol	Discharge	Nov 1998 to current year	8,640	6,780
11466200	Santa Rosa Creek At Santa Rosa	stage and discharge	Dec 1939 to Sep 1941 and Oct 2001 to May 2004 for discharge		
11466320	Santa Rosa Creek At Willowside Road near Santa Rosa	discharge	Dec 1998 to current year	78,480	69,170
11465750	Laguna De Santa Rosa near Sebastopol	discharge	Nov 1998 to current year	64,370	57,850
11465680	Laguna De Santa Rosa at Stony Point Road near Cotati	discharge	Nov 1998 to current year	30,340	23,210
11466500	Laguna De Santa Rosa near Graton	stage	Feb 1940 to Sep 1949, Oct 1964 to current year.		
11465500	Mark West Cr near Windsor	real time	?		
11466800	Mark West C near Mirabel Heights	real time	?		
11465200	Dry Creek near Geyserville	discharge	Oct 1959 to current year	196,900	211,000
11465350	Dry C Nr Mouth near Healdsburg	discharge	Oct 1981 to current year		
11467000	Russian River near Guerneville	discharge	Oct 1939 to current year	1,456,000	1,654,000
11464000	Russian River near Healdsburg	discharge	Oct 1939 to current year	969,900	1,035,000

The total precipitation in the Santa Rosa Plain based on the CIMIS station was approximately 35 inches for the year 2005. The CIMIS station precipitation totals do not represent precipitation conditions in the upland areas such as the Mayacamas Mountains, where the mean annual precipitation is expected to be much higher (see Figure 4-11). We assumed an annual precipitation total of approximately 488,000 ac-ft based on the CIMIS station record. This is an underestimate of the total precipitation amounts in the watershed. However, it is an adequate estimate to get a rough understanding of different components of the 2005 budget for surface water hydrology.

We also developed a sediment budget for the Laguna de Santa Rosa (Figure 4-18). The sediment budget summarizes average annual sediment delivery volumes to the Laguna based on the Pacific Southwest Interagency Committee method (PSIAC) that were described in our previous report on sediment sources, *Rate and Fate in the Laguna de Santa*

SURFACE HYDROLOGY BUDGET FOR LAGUNA DE SANTA ROSA FOR WATER YEAR 2005 (~AVERAGE YEAR)



Annual runoff for Water Year 2005 (in acre feet). *Runoff values in italic are calculated based on monitored locations nearby.*

Arrow size ~ Total Discharge

Rectangle area ~ Watershed area

Figure 4-17
Surface hydrology budget for Laguna de Santa Rosa for water year 2005
(~Average Year)

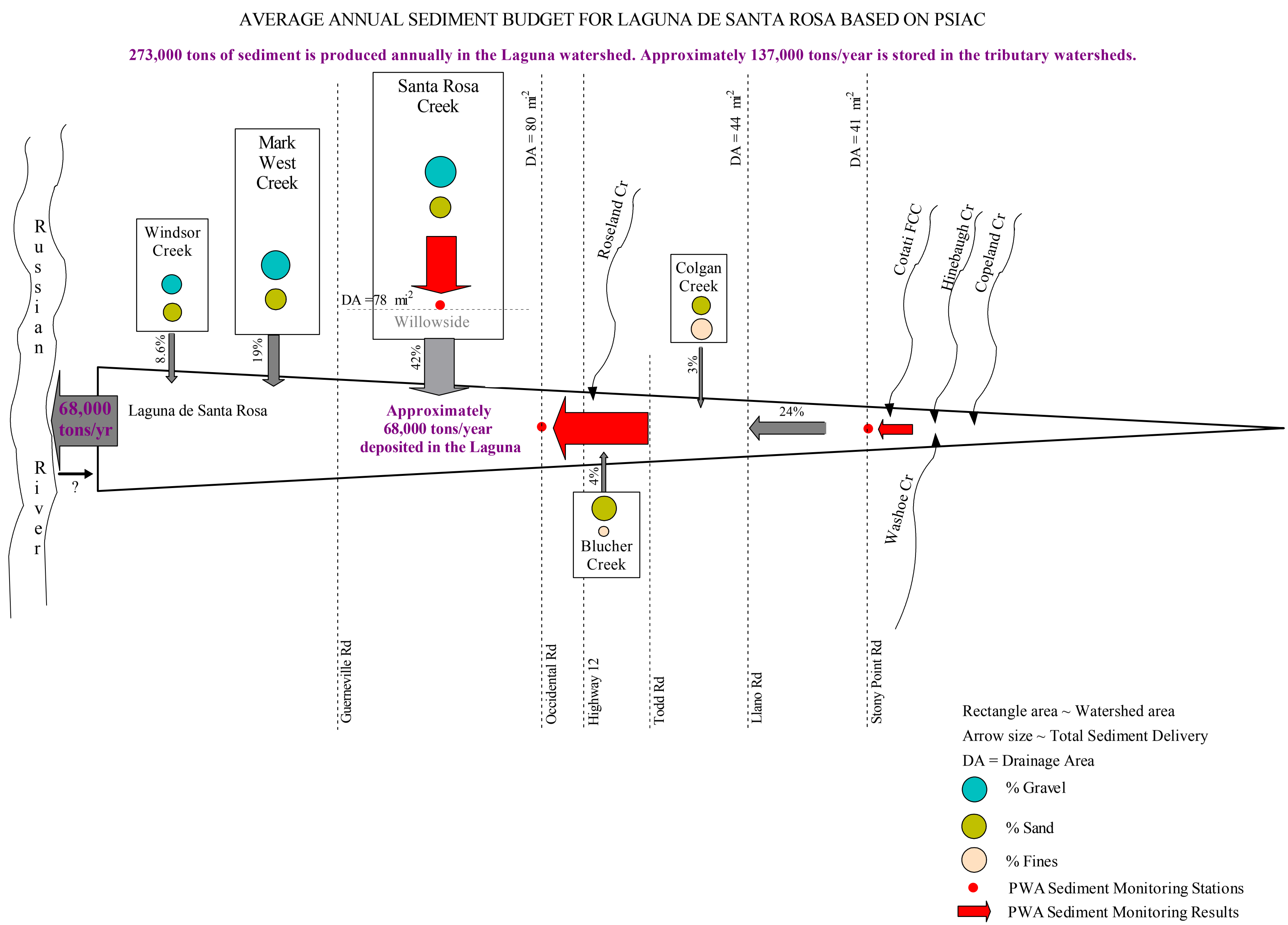


Figure 4-18 Average annual sediment budget for Laguna de Santa Rosa based on PSIAC

Rosa (PWA, 2004). PSIAC uses nine factors to determine the sediment yield classification for a watershed which then is assigned a range of sediment yield by class. These sediment yield estimates were based on qualitative rankings of physical characteristics for PSIAC and on USACE's draft hydrology analyses. The absolute amounts of sediment yield should be viewed as a rough estimate using the best available data and professional judgment. The relative contribution of sediment yield from each watershed, as predicted by PSIAC, would be expected to provide a relatively accurate understanding of the sediment budget of the Laguna.

In addition to empirical methods, PWA's sedimentation study (PWA, 2004) also used other lines of evidence to estimate sediment yield and deposition rates. These were comparison of historic and current floodplain cross sections along the Laguna, measured sediment deposition in Matanzas Reservoir, and discharge turbidity measurements for the 2002-2003 runoff season. The results of these analyses are presented in Table 4-13, as well as the results of analyses that have become available since that report was completed.

Table 4-13
Sediment yield estimates for the Laguna watershed and other watersheds nearby

Method	Annual Sediment Yield (in tons/mi2)	Total Annual Sediment Yield (in tons)
MUSLE	7,644	1,940,000
PSIAC	1,406	273,000
Turbidity Measurements (yielding SSC) at Santa Rosa Creek; Laguna at Occidental; and Laguna at Stony Point	1,250 4,850 840	96,993 385,297 34,241
Matanzas Reservoir sedimentation (1964-1982)	1,420 – 1,960	
Preliminary Matanzas Reservoir sedimentation (1988-2006) based on SCWA's planned dredging project	7,000	
Russian River Watershed	1,760	
Sonoma Creek Watershed	1,100	110,000

Perspective on sediment yield estimates

Table 4-13 illustrates the fact that estimates of sediment yield typically vary by orders of magnitude. This is especially true when the hydrologic conditions are above average, which was the case in 2006. Estimates of sediment yield for the same system made using different methods typically vary by up to an order of magnitude. Therefore, when estimates from several methods converge on a similar value, it is likely that these estimates are reliable. The PSIAC estimate for total sediment yield over the whole watershed is 153 ac-ft/yr or 272,916 tons/yr (using a specific weight of 90 lb/ft3). This corresponds to 0.8 ac-ft/sq-mi/yr or 1,400 tons/sq-mi/yr. These estimates have recently been supported by the results of the NASA AMES study, which indicated that the sediment yield results of their SWAT model are comparable to PWA's PSIAC analysis and are within 5 percent of our annual sediment loads (Chris Potter, pers. comm..). The PSIAC results are also close to the sediment yields measured for both the Matanzas Reservoir watershed (1,423 tons/sq-mi/yr) and the Russian River watershed (1,760 tons/sq-mi/y). In our previous study (2004), we concluded that MUSLE values were high, possibly due to high runoff peaks and volumes estimated by the USACE hydrology analyses.

An additional line of evidence supporting the use of the PSIAC estimate is the measured suspended sediment load from Santa Rosa Creek and the Laguna de Santa Rosa at Occidental Road during 2002-2003 season (a relatively average year in terms of rainfall and runoff). Our turbidity records for Santa Rosa Creek show a load of 96,993 tons, compared with a PSIAC estimated yield of 114,722 tons. The measured load missed the first large event of the season, but by comparing the Santa Rosa Creek and Laguna at Occidental Road loads we can assume that Santa Rosa Creek delivered approximately 40-50,000 tons of sediment during this storm, giving a total yield for the year of approximately 150,000 tons. The PSIAC estimate for the area of the Laguna upstream of Occidental Road is 221,949 tons/yr. For 2002-2003, measured suspended sediment load was 385,297 tons. It should be remembered that the rating curve for the Laguna de Santa Rosa at Occidental Road is considered 'poor,' while Santa Rosa Creek is considered 'fair'; discharge estimates were used in our computation of suspended load. For this reason, we attribute greater credibility to the estimate of measured suspended load from Santa Rosa Creek than the estimate for the Laguna at Occidental Road.

The two most recent studies on sediment yields in the Laguna watershed and the adjacent Sonoma watersheds corroborates our conclusion that the PSIAC estimates best represent sediment yields in the Laguna. The final report on the Sonoma Creek watershed yields (Trso, 2006) and the SWAT model results (on-going study by NASA/AMES) are within 20 and 5 percent of the PSIAC predicted yields, respectively.

On the basis of these multiple converging lines of evidence we believe we can tentatively accept the PSIAC figures as the best estimate for current sediment yield and infilling rate for the Laguna watershed, with the caveat that they probably represent a slight underestimation of sediment yield. Additional data to augment the record on suspended sediment delivery to the Laguna (such as continuous monitoring of turbidity data at the USGS gauges and monitoring or periodic sampling of sediment in other key tributaries) would further improve our understanding on sediment yields and trends in the watershed and would support future TMDL studies.

A recent newspaper article on the planned dredging of Matanzas Reservoir supported a substantially higher estimate of sediment deposition than previous periods, which are shown in Table 4-10. If this article is based on the actual sedimentation volume (as opposed to being in error or representing estimated excavated volume), further review of conditions during the sedimentation period and a potential update of our previous analysis and assumptions may be warranted.

4.3.4 Conceptual model of the groundwater hydrology within the Laguna de Santa Rosa watershed

This section broadly describes the role of groundwater hydrology within the Laguna de Santa Rosa watershed with respect to surface water hydrology and water supply. It is derived primarily from information contained within the 2005 Urban Water Management Plan published by the Sonoma County Water Agency (SCWA) in December 2006. A 5-year effort was initiated in December 2005 by the SCWA and the USGS to develop a refined conceptual model of the groundwater aquifer in the Santa Rosa Plain; this conceptual model will be used together with monitoring data to develop a numerical model (MODFLOW) of the groundwater hydrology of the basin.

The Laguna de Santa Rosa watershed overlays the majority of the groundwater basin identified as the Santa Rosa Valley Basin, including the component subbasins referenced as the Santa Rosa Plain, Rincon Valley, and Healdsburg Area. The Santa Rosa Plain is the largest subbasin in the County and in the Laguna watershed, and underlies its most populated areas as well as the Laguna itself. The Santa Rosa Plain Subbasin drains northwest toward the Russian River. To the south lies the Petaluma Valley Groundwater Basin; south of Rohnert Park, this basin drains to the southeast, towards San Francisco Bay.

For the Santa Rosa Plain Subbasin, average annual natural recharge from 1960 to 1975 was estimated to be 29,300 ac-ft (DWR, 2003). Natural recharge occurs east of Santa Rosa, primarily along stream beds, at the heads of alluvial fan areas, and in some parts of the Sonoma Volcanics. Recharge areas in the subbasin were evaluated and reported by DWR in 1982; these are shown in Figure 4-19. As part of the five-year study presently underway by the USGS, the location of significant recharge areas in the subbasin are again being evaluated; the results of this effort are anticipated to be available in 2010 or 2011 (Tracy Nishikawa, USGS, pers. com.).

General water level contour trends in the Santa Rosa Plain groundwater subbasin as reported in the last report published by DWR (1982) are generally declining to the west, following the land slope to the Laguna de Santa Rosa channel. A review of spring 2006 data from DWR (CDEC, 2007) shows that the typical depth of groundwater below the ground surface in the Santa Rosa Plain is approximately 25 feet, with a range of approximately 0-86 feet below ground surface. A 1982 California Department of Water Resources (DWR) study concluded that groundwater levels in the northeast part of the Santa Rosa Plain Subbasin had increased, while groundwater levels in the south had decreased (DWR, 1982). Groundwater storage capacity in the Santa Rosa Plain is estimated by the USGS to be 948,000 ac-ft (Cardwell, 1958, cited in DWR, 1982).

The following description of the geology of the Santa Rosa Plain is excerpted from the SCWA 2005 Urban Water Management Plan (SCWA 2006).

The geology of the Santa Rosa Plain Subbasin is complex and the stratigraphic relationships are the subject of recent and continuing studies, including mapping by the USGS and others (USGS, 2002). The subbasin is cut by many northwest-trending faults that influence groundwater flow. Most of the groundwater is unconfined, but in some locations can be confined where folding and faulting exists (DWR, 2003). The water-bearing deposits underlying the basin include the Wilson Grove Formation, the Glen Ellen Formation, and a younger and older alluvium (DWR, 2003). The Wilson Grove Formation is the major water-bearing unit in the western part of the basin and ranges in thickness from 300 feet to

1,500 feet (Winzler and Kelly, 2005; DWR, 2003). Deposited during the Pliocene, it is a marine deposit of fine sand and sandstone with thin interbeds of clay, silty-clay and some lenses of gravel. Interbedded and interfingered with the Wilson Grove Formation are Sonoma Volcanic sediments in the eastern basin separating the water-bearing units. Aquifer continuity and water quality are generally good according to Cardwell, 1958, which is still the most detailed reference on the hydrogeology.

The Glen Ellen Formation overlies the Wilson Grove Formation in most places and is Pliocene to Pleistocene in age (DWR, 2003). At some locations, the two formations are continuous and form the principal water-bearing deposits in the basin (Cardwell, 1958). The Glen Ellen consists of partially cemented beds and lenses of poorly sorted gravel, sand, silt, and clay that vary widely in thickness and extent (Cardwell, 1958; DWR, 1982). The formation is used for domestic supply and some irrigation (DWR, 2003). The Pliocene Petaluma Formation is exposed at various localities in Sonoma County, from Sears Point northward nearly to Santa Rosa. The formation consists of folded continental and brackish water deposits of clay, shale, sandstone, with lesser amounts of conglomerate and nodular limestone and occasional thick beds of diatomite are present. The Petaluma Formation has been defined as being contemporaneous in part and interfingering with the Merced Formation. The Petaluma Formation is noted for its low well yields.

Quaternary deposits include stream-deposited alluvium, alluvial fan deposits, and basin deposits (Todd Engineering, 2004). The younger alluvium (Late Pleistocene to Holocene age) overlies the older alluvium (Late Pleistocene age). The alluvium deposits consist of poorly sorted sand and gravel and moderately sorted silt, fine sand, and clay. The upper and mid-portion of the alluvial fan deposits are on the eastern side of the Santa Rosa Plain and are permeable and provide recharge to the basin. The basin deposits overlie the alluvial fan materials and have a lower permeability (Todd Engineering, 2004; Cardwell, 1958).

Vertical connections from the ground surface and shallow groundwater aquifer to intermediate and deeper groundwater aquifers vary significantly across the subbasin due to geologic variability. The 1982 DWR report on groundwater conditions in the Santa Rosa Plain indicated that water quality testing of surface and groundwaters suggested the presence of vertical connectivity in the vicinity of the confluence of Santa Rosa Creek and the Laguna de Santa Rosa. There was little suggestion of vertical connectivity in other locations within the subbasin from similar testing.

Groundwater extraction in the Santa Rosa Plain subbasin occurs at wells with depths ranging from shallow (less than 100 feet below ground surface) to deep (more than 400 feet below ground surface). Wells are owned and operated by both private and public entities, and serve such varied uses as individual residences, agricultural operations, and municipal water supplies. Average annual pumping during the period 1960 to 1975 has been estimated at 29,700 ac-ft. Well yields range from 100 to 1,500 gallons per minute (DWR, 1975).

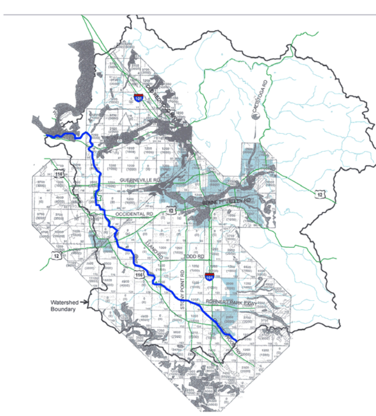


Figure 4-19
Available storage capacity and areas of natural recharge
(see full-sized inset)

In recent years, the SCWA has obtained 3 to 9 percent of its annual supply from wells it operates near Sebastopol within the Santa Rosa Plain Subbasin. Future extractions by the SCWA are anticipated to represent just under 4,000 acre-feet annually, presently representing about 5% of its total water supply. Other SCWA contractors, such as the Cities of Rohnert Park, Santa Rosa, and Cotati also pump water from the subbasin. Including the North Marin Water District, which draws on supplies outside of the subbasin, total groundwater and local surface water supplies (including recycled water) provided by these contractors are presently close to 7,500 acre-feet per year and projected to rise to nearly 10,000 acre-feet in 2015 before declining to a projected rate of less than 3,000 acre-feet annually by 2030 (SCWA 2006).

As described in the 2005 Urban Water Management Plan (SCWA 2006), recent investigations of groundwater elevations have reached different conclusions as to whether groundwater levels are generally increasing or decreasing over time. Increasing demand for groundwater led to declining groundwater levels at least until the importation of additional surface water began in about 1990. However, numerical modeling simulations completed as part of one study found that storage would continue to decline under current conditions; other studies indicated an expected increase in groundwater storage that is more consistent with the stable to slightly increasing groundwater level trends observed in area wells.

In 1958, USGS analysis of water levels in creeks in the Santa Rosa Plain were generally lower than levels in nearby wells, suggesting the groundwater was flowing to the creeks. But as of 1982, DWR reported that insufficient recent data was available to allow a similar comparison (DWR 1982). The USGS study currently underway will help to establish the nature of stream-aquifer interaction that exists and will exist under various management scenarios.