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THE IMPACT OF DAM CONSTRUCTION ON LAND-COVER:
NEW MELONES DAM, 1972-2001

A Thesis
Presented to
The Faculty of the Department of Geography
San Jose State University

In Partial Fulfillment
of the Requirements for the Degree
Master of Arts

by
Christopher E. Soulard
August 2005

UMI Number: 1429450

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ABSTRACT

THE IMPACT OF DAM CONSTRUCTION ON LAND-COVER: NEW MELONES DAM, 1972-2001

By Christopher E. Soulard

Between 1972 and 2001, regional demand for raw materials such as water and mining byproducts has resulted in anthropogenic landscape change throughout the Lower Stanislaus Watershed. Land-use and land-cover change is primarily affiliated with the construction of New Melones Dam, which was completed in 1979. No multi-temporal landscape-change data currently exist for this stretch of the Stanislaus River watershed. This study utilizes a manual interpretation of land-cover using Landsat imagery and ancillary data for five dates (1972, 1980, 1986, 1992, and 2001). Statistical metrics have been developed to document and describe the rates of land-cover change and how these conversions vary spatially, thematically, and temporally. The most prevalent change throughout the study period was a change from natural vegetation to water, exclusively due to reservoir water inundation upstream of New Melones Dam. This change, along with the remainder of change in the watershed, is driven by demographic and economic forces.

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Introduction

Nearly every river in the conterminous United States is now regulated by dams, with over 75,000 damming projects in all. However, the construction of large dams is a relatively recent phenomenon, hitting its quickest stride between 1935 and 1965. According to the National Atlas of the United States (2005), around 7,700 major dams are currently in operation in the United States. This abundance of regulated rivers has benefited society by providing hydroelectricity, irrigation water, flood control, recreation, navigation, and emergency water storage.

Despite the obvious benefits provided by dams, research indicates that river regulation alters the ecological and physical properties of riparian areas, thus degrading previously pristine ecosystems. Direct detrimental reservoir effects are extensive and vary tremendously from dam to dam: elimination of natural flooding and sediment transport mechanisms, upstream habitat inundation, downstream habitat erosion, channel sediment erosion, and other effects (see Table 1). Although the rate of ecological change may be minimal in certain instances, even minor landscape change may have widespread consequences on vegetation communities, wildlife, and human populations.

Potential Change	**Consequence of Change**
Cause: Dams	
Reduced flood flows lead to reduced rate of channel migration	Reduced habitat diversity
Reduced flood flows eliminate frequent scour of active channel	Riparian vegetation encroachment into active channel
Increased base flows and raised alluvial water table	Waterlogging of vegetation
Base flows reduced or eliminated	Riparian vegetation stress and/or death
Trapping of bedload sediments behind dame, release of sediment starved water, channel incision	Alluvial water table drops and overbank flooding is less frequent due to channel incision
Reservoirs drown existing vegetation, fluctuating water levels may limit establishment of new vegetation along margins	Interruption of longitudinal continuity of riparian corridor
Cause: Hydroelectric Generation	
Rivers and streams dammed and diverted through canals	Water stress in dewatered reaches, riparian vegetation establishes along canals and ditches
Hydroelectric dams and associated canals, penstocks, powerhouses, and access road constructed within riparian zone	Riparian vegetation removed and replaced with road and structures
Flow fluctuates rapidly to generate peak hydroelectric power	Rapid stage changes can lead to increased bank erosion
Cause: Irrigation	
Water diverted from streams	Water stress in dewatered reaches, riparian vegetation establishes along canals and ditches
Irrigation water may infiltrate and recharge groundwater	Excess irrigation water may support vegetation

Table 1. Summary of consequences of dam-related activities. Modified from Kondolf et al. (1996).

Since the adoption of the National Environmental Policy Act in 1970, many site-specific studies have been conducted to assess the environmental impacts of dam construction (Taylor 1983; Harris et al. 1987; Kondolf et al. 1987; Smith et al. 1989; Nachlinger et al. 1989; Leighton and Risser 1989; Hicks 1995). However, many of these studies reflect a single study date, which disregards the validity of ecological inferences. Long-term measurement is necessary to capture gradual dam-induced landscape change because most dam-related landscape change occurs during the first decade or two after dam closure (Leopold 1990; Williams 1994). A few studies have attempted to capture multi-temporal change along riparian corridors using remotely sensed data and field observations, but these efforts have been isolated in Mono Basin and Lake Tahoe, major watersheds with clear economic implications (Manley 1995). In an attempt to study a wide variety of river systems across the Sierra Nevada ecoregion, the Sierra Nevada Ecosystem Project (SNEP) and its partners conducted an assessment of riparian corridors on a sample of river systems using aerial photography (Sierra Nevada Ecosystem Project 1996). However, this study merely infers the effects of human activities upon riparian areas "from the extent of human activities known to affect the extent or functioning of riparian vegetation (SNEP 1996, 1010)." In order to minimize the inferences and assumptions associated with sampling strategies, application of a wall-to-wall remote sensing interpretation to a contiguous stretch of river and the adjacent basin is necessary.

The primary objective of this study is to use satellite imagery to determine the rate and type of land-cover change surrounding New Melones Dam. Furthermore, this study intends to ascertain the causes of the landscape change, to determine whether these causes can be attributed to natural ecosystem cycles or human induced change, and to speculate how these mechanisms interact with the environment to cause the change itself. The final purpose of using satellite imagery to map land-cover change is to determine the consequences of dam induced change. The change in landscape caused by the construction of New Melones Dam may not only have ecological risks, but may also have social implications and long-term economic impacts.

Dam selection criteria

Many factors must be considered before performing digital change detection with remotely sensed data. The first series of considerations are the extent of the study area, identification of features to study, and the temporal characteristics of the analysis. In an ideal situation, these factors can be determined independently of project limitations such as funding or data access, but this project's dam site selection process is dependent upon data cost and availability. In this instance, the United States Geological Survey (USGS) provided low cost Landsat imagery that is near anniversary dated, radiometrically corrected, and geometrically registered (see Table 2). Furthermore, these available scenes provided relatively consistent temporal snapshots, with intervals ranging from 6 to 9 years (1972, 1980, 1986, 1992, and 2001). In terms of digital change detection, these core dates match the temporal framework for satellite data outlined by Loveland et al. (2002).

Path/Row (WRS-2)	Satellite	Scene ID/Ordering ID	Acquisition Date	Notes
043-034	Landsat 1 MSS	1046034007220790	07/25/1972	NALC
043-034	Landsat 2 MSS	2046034008019290	07/10/1980	NLAPS
043-034	Landsat 4 MSS	5043034008521490	08/07/1986	NALC
043-034	Landsat 5 TM	0430340720199200	07/20/1992	MRLC
043-034	Landsat 7 ETM+	7043034000125050	09/07/2001	N/A

Table 2. Landsat scenes used in this study. NALC data are part of the USGS North American Landscape Characterization. NLAPS data are from the USGS National Land Archive Production System. MRLC data are part of the USGS Multi-Resolution Land Characteristics Project.

Currently, most of the studies on dams that have been conducted address the effects of dams along large dam projects. Moreover, these dam studies are isolated to rivers in the Southwest and Midwest, such as the Colorado River (Collier 2000; Turner 1980). With this in mind, the initial goal of this thesis was to ascertain whether or not the land-cover change associated with dams applies to smaller dam projects in California.

The age criterion is also an important element, particularly because Landsat data have only been available since 1972. According to the USGS, most dam-related landscape change occurs during the first decade or two after dam closure (Williams 1994). Therefore, the selection of a dam constructed prior to this period does not enable the analyst to assess the landscape prior to human disturbance or may capture an incomplete account of dam-induced land-cover change.

The size criterion is also an important element to consider before a study can commence. In a remote sensing interpretation, the appropriate dam size criterion will vary depending on whether the platform has a high, medium, or coarse spatial resolution. In this instance, the resolution of Landsat satellite systems provides a level of detail optimal for Level III (Biome) or Level IV (Regional) interpretations.

New Melones Dam is the optimal selection for this study not only because it is located in Calaveras County, California, but also because it has massive dimensions (1560 feet x 40 feet x 625 feet) and construction was completed in 1979 (see Figure 1). New Melones Dam was originally approved as part of the Central Valley Project to supply irrigation water to farmers in California's Central Valley, but now also caters to recreationists, provides flood control, and includes hydroelectric power functionality.

New Melones is one of the largest damming projects in existence in the Sierra Nevada Mountain Range and has the distinction of being the second largest fill dam in California (next to Oroville Dam). The entire project covers 10,927 hectares, which tends to suggest that the potential for landscape change is far reaching.

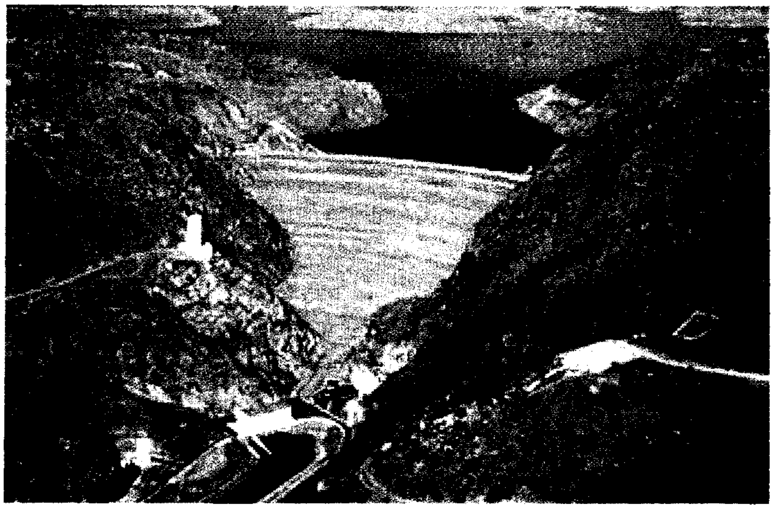


Figure 1. New Melones Dam and Reservoir. Image provided courtesy of United States Bureau of Reclamation (12/8/04).

The massive extent of the New Melones Unit presents an issue regarding the delineation of an appropriate study area that encompasses the majority of dam-related landscape change, while minimizing external variables that may influence land-cover in the vicinity. Moreover, the dimensions of the study area should be manageable and appropriate for a timely interpretation. Potential delineation methods for the study area include drawing an arbitrary polygon around the New Melones Unit, delineating a buffer distance around the reservoir and main channel of the Stanislaus River, utilizing the service basin outlined in the Environmental Impact Statement (EIS) (see Figure 2), or distinguishing the watershed as the study area (US Army Corps of Engineers 1973). The first two possible delineation methods incorporate a biased estimate of local impact, while the third possibility encompasses a massive spatial extent. Using the entire watershed also presents a manageability problem, but selecting a contiguous group of sub-watersheds resolves this problem. In the end, the area for this study was delineated by selecting the lowest 14 of 25 sub-basins composing the Lower Stanislaus Watershed (California Spatial Information Library [CalWater 2.2.1]). This study area acknowledges any possible backwater effects from downstream dams by including Tulloch Reservoir, and includes an adequate sample of developed and agricultural lands directly impacted by dams within the watershed (see Figure 3).

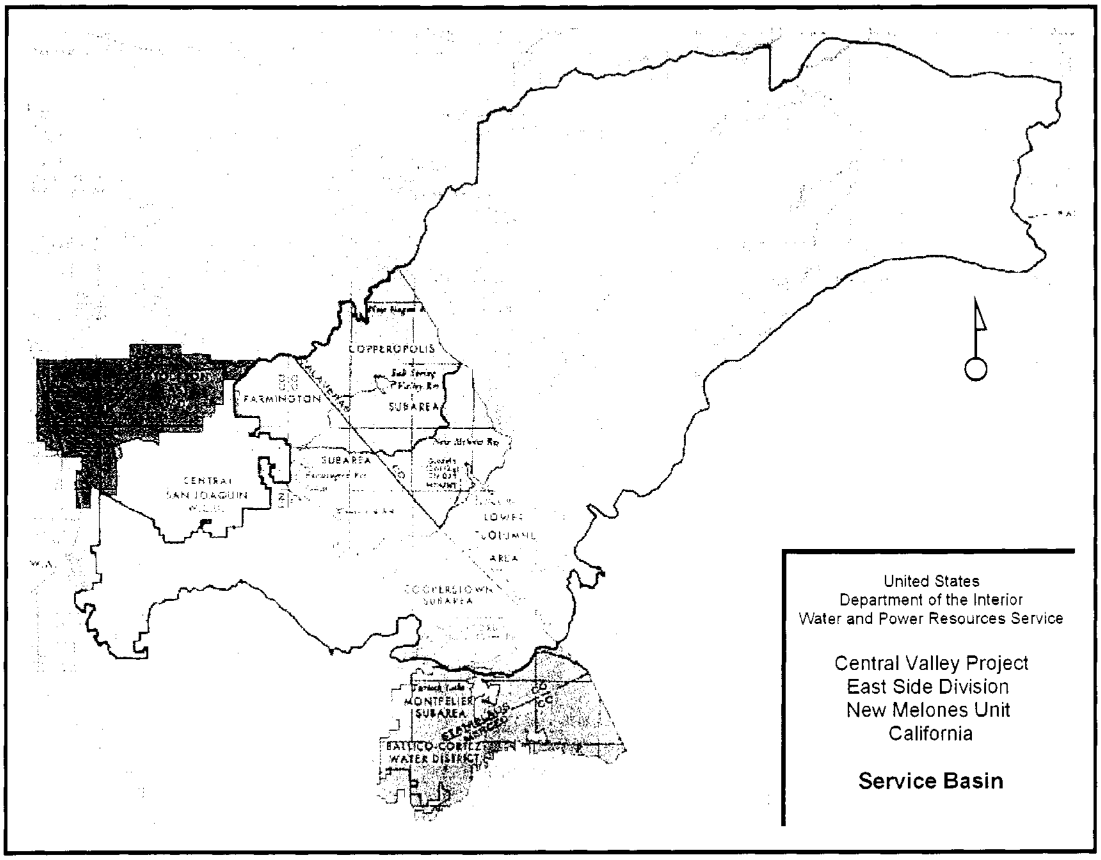
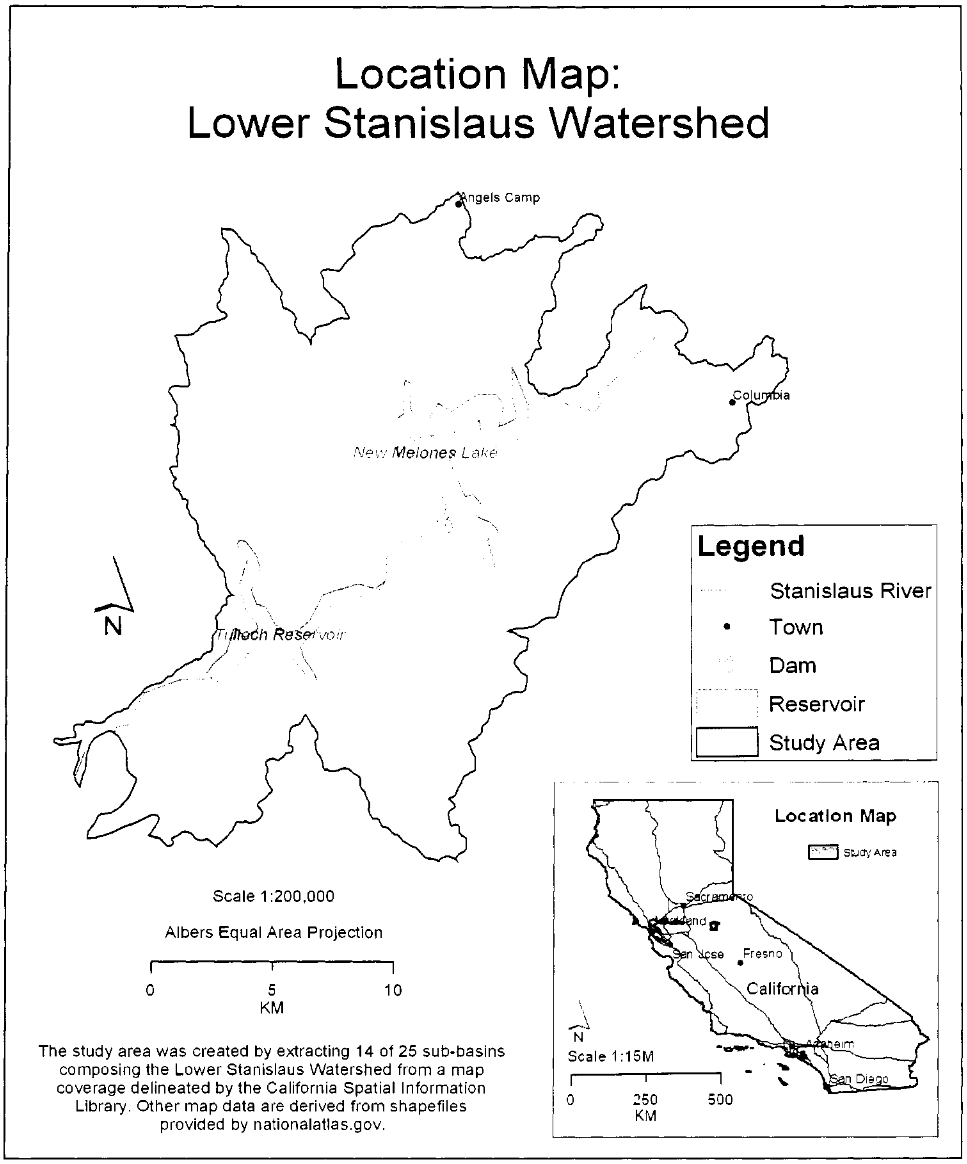


Figure 2. New Melones Unit planned service basin. Bold black line defines the service basin boundary (US Army Corps of Engineers 1973).



The study area was created by extracting 14 of 25 sub-basins composing the Lower Stanislaus Watershed from a map coverage delineated by the California Spatial Information Library. Other map data are derived from shapefiles provided by nationalatlas.gov.

Figure 3. Map of study area. New Melones Dam at 120°31' 37°57'.

Background

Construction history

The New Melones Dam expansion is a controversial project that began in December 1944, following the ratification of the federally mandated Flood Control Act. The initial plan authorized the U.S. Army Corps of Engineers to replace the existing Melones Dam in an attempt to improve flood control along the Stanislaus River. The preliminary design of the New Melones Unit included construction of a 355-foot-high concrete arch dam and continued use of the existing powerplant facility; however, revision of the Flood Control Act in October 1962 led to a complete overhaul of this dam design. The new design not only authorized the construction of a 625 foot-high earth and rockfill dam (California's second largest earthfill dam) and new powerplant structure, but also modified the objectives of the New Melones Unit. The new project plan established a multipurpose agenda including flood control, irrigation, municipal and industrial water supply, power generation, and recreation.

The construction phase of the New Melones unit commenced in July 1966. The initial work consisted of building access and haul roads, resident engineer and administration facilities, and a public overlook area (see Figure 4). These activities were centralized just downstream of the old dam structure. Much of this work was completed by 1978. According the U.S. Bureau of Reclamation (USBR), which took over operation of New Melones Dam in 1979, secondary construction consisted of contracts for a diversion and outlet tunnel, a spillway cut northwest of the dam facility, linking access roads, and the excavation and placing of the dam itself (Simonds 1994). The spillway, 5,945 feet long and 200 feet wide, was completed in 1979. Material excavated from the area surrounding the spillway was utilized as earthfill in the New Melones Dam embankment, which was also completed in 1979.

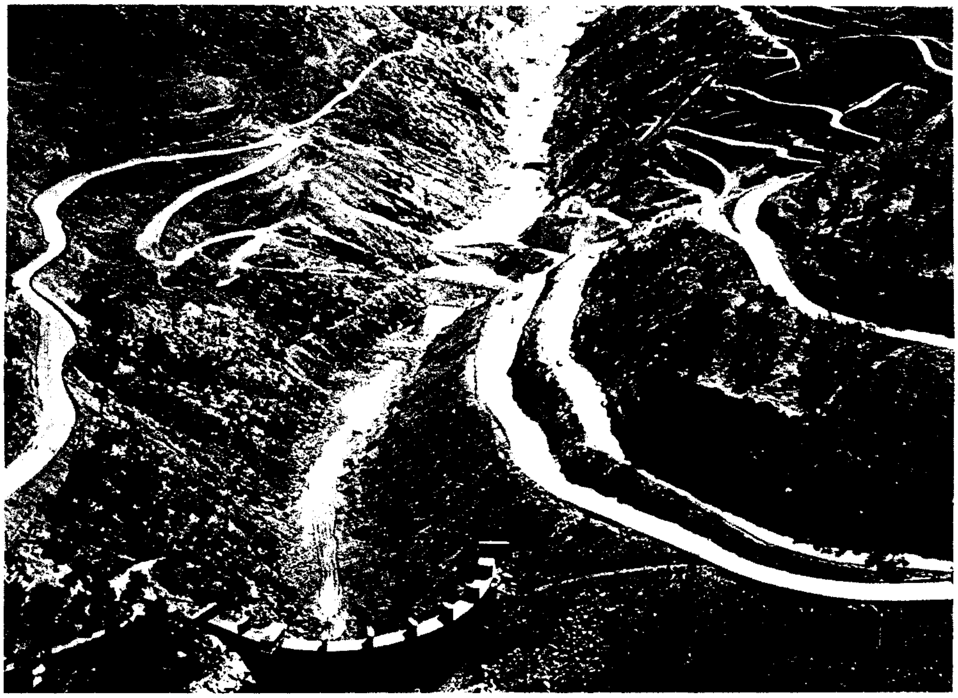


Figure 4. New Melones Dam construction phase. Photo illustrates access roads around the original Melones Dam (US Army Corps of Engineers 1973).

General description of location

This study is geographically centered on the New Melones dam site, and it is delineated by the lowest 14 of 25 sub-basins that compose the Lower Stanislaus River Basin. The Stanislaus River runs about 60 miles below New Melones Dam, past Tulloch Dam and Goodwin Dam, before its confluence with the San Joaquin River. The Stanislaus River drains an area of 900 square miles above the dam site, beginning at an elevation above 10,000 feet at the Sierra Nevada crest. Many damming projects scatter the three forks of the Stanislaus River between its origin and New Melones, but most of these small projects are located below 2,300 feet. New Melones is typical of damming projects in California in the sense that massive downstream reservoirs in the foothills dwarf upstream projects. In this instance, the 40 upstream dams only account for 16 percent of the total reservoir capacity along the Stanislaus River, while New Melones accounts for 84 percent (see Figure 5) (Kondolf and Matthews 1993). New Melones, which is about three quarters of a mile downstream of Old Melones Dam, is also typical of Sierran foothill reservoirs since many of the dams built in the early 20th century were enlarged in the 1960s and 1970s to meet increased and multi-purpose demands.

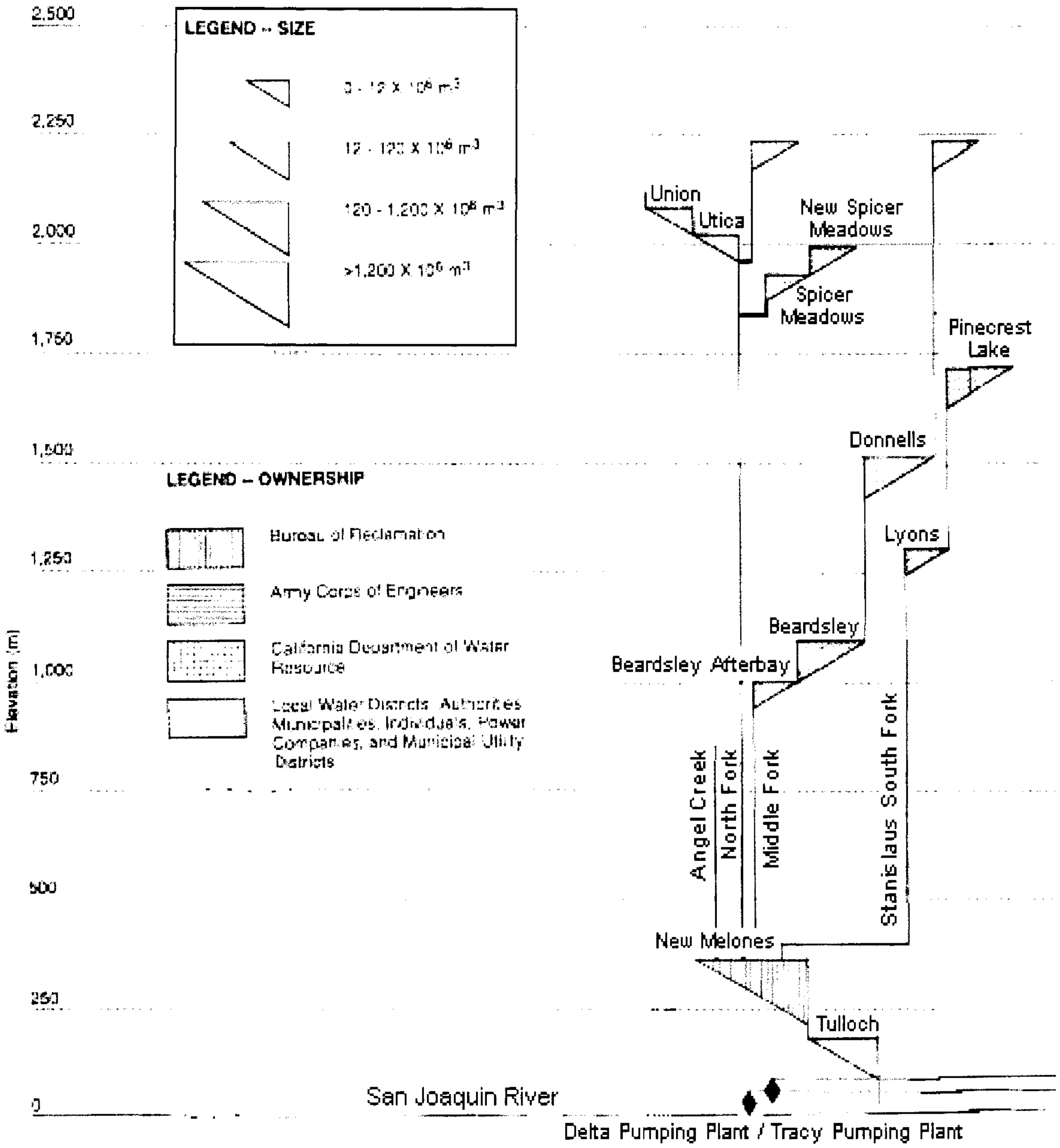


Figure 5. Map of reservoirs along the Stanislaus River, plotted by elevation. Reservoir ownership and size is also depicted. Modified from Kondolf et al. (1993).

Climate

The temperate, semi-arid Mediterranean climate of the Lower Stanislaus River Basin is characterized by hot, dry summers and cool, wet winters. Yearly temperatures typically range from 83 degrees Fahrenheit in the summer to 50 degrees in the winter, but temperatures at the dam site have reached a high of 113 degrees to a low of 14 degrees (see Table 3) (US Army Corps of Engineers 1972). The movement of moisture-bearing storms from the Pacific Ocean to the east accounts for the main source of precipitation, which primarily falls as rain in the foothills and snow in the mountains above 4,000 feet. Orographic uplift causes the majority of precipitation to fall at higher elevations, which explains why annual precipitation averages 65 inches in the upper part of the basin and 27 inches at New Melones. The entire Lower Stanislaus watershed averages 47 inches of precipitation per year, with approximately 90 percent of rainfall occurring between November and April.

Temp °F	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Mean	**50**	**53**	**57**	**62**	**68**	**76**	**83**	**81**	**74**	**65**	**57**	**51**

Table 3. Average air temperature from Sonora, California (US Army Corps of Engineers 1972).

Streamflow

Flows to and from New Melones Dam are highly dependent on precipitation in the watershed. Moreover, basin topography, geology, and groundwater characteristics determine how precipitation is channeled into the Stanislaus River above and below New Melones Dam. Steep, rocky canyons characterize most of the upstream tributaries that lead to New Melones Dam. A significant portion of these steep-sided canyons is composed of impervious limestone, which is utilized by the mining industry to manufacture cement. Over 70 limestone caves are known to exist in the area, most notably Moaning Cave, which has been operated commercially since 1922. The area immediately surrounding the reservoir levels off to flat ridges, where the pre-dam floodplain likely originated. One of these flat-topped ridges is Table Mountain, which separates the Lower Stanislaus basin from the adjacent watershed. This sinuous volcanic flow is the sole igneous feature in the study area. According to the EIS, the entire "reservoir area is underlain by metamorphic rocks, chiefly greenstone, quartzite, and slaty rocks (US Army Corps of Engineers 1972, 26)." Minimal drainage to groundwater occurs in joint fractures, but direct groundwater drainage through the generally impervious geologic substrate is negligible across the study area.

Streamflow is also extremely dependent on anthropogenic variables, such as releases from dams along the river, agricultural diversions, and return flows. All of these variables fluctuate significantly over time. Average monthly flows below the New Melones Dam site are illustrated in Figure 12 (USGS California Water Science Center [11299200]). Overall, New Melones outflows have been greatly reduced compared to pre-dam conditions. Releases are dependent on rainfall inflows, resource demand, and flood prevention. Additionally, the USBR attempts to simulate natural streamflow conditions in an attempt to maintain riparian habitat. For example, high summer releases are intended to simulate natural flooding and prevent vegetation encroachment into the stream channel (Kattelmann 1996). The USBR also tries to alleviate thermal water pollution and enhance fish spawning by keeping the reservoir above 350,000 acre-feet (Simonds 1994). Two other gauging stations exist along the lower reach of the Stanislaus River, at Knights Ferry and Ripon. Flows below Knights Ferry are non-existent for most of the year due to upstream diversions, while flows measured at Ripon reflect irrigation return flows from agricultural lands in the San Joaquin Valley; however, neither of these gauging stations is located within the study area. Ultimately, very little of the rainfall precipitating in the Sierra Nevada mountains reaches the valley floor via the Stanislaus River.

Vegetation

Vegetation patterns in the Lower Stanislaus basin are quite complex, particularly because of varying elevation, slope, exposure, lithology, and available moisture. The vegetation of rugged upstream canyon differs significantly from the flatter area around New Melones. The rugged terrain of the upper basin, characterized by steep slopes and poor soil development, is dominated by drought-tolerant chaparral plant communities, primarily chamise, manzanita, and ceonothus. This transition zone from the Sierra Nevada to the Central Valley is also distinguished by black oak and mixed conifer woodlands also present at higher elevations: yellow pine, Jeffrey pine, lodgepole pine, silver pine, white bark pine, Douglas fir, and red fir. Alders and willows characterize the prevalent riparian flora along the river upstream of New Melones reservoir.

On the other hand, the area at and around the reservoir is nearly void of riparian vegetation. This area primarily lies in the foothill woodland plant community, which has an abundance of large digger pines, live oaks, blue oaks, valley oaks, and California bays.

Few stands of toyon and chamise chaparral exist, but the moist, well-developed soils favor a grass and forb understory. A survey conducted by the U.S. Fish and Wildlife Service (USFWS) identified a list of rare floral species endangered, either directly or indirectly, by the construction of New Melones Dam (US Army Corps of Engineers 1973). Of the 12 rare plants investigated, the species determined by the USFWS to be at risk include Chinese Camp Brodiaea, Red Hills Soaproot, Colusa Grass, San Joaquin Valley Orcutt Grass, Greene's Orcuttia, and Pilose Orcuttia.

Wildlife

The Lower Stanislaus watershed contains a diverse array of mammals, birds, and fish species, particularly because the basin is located in an ecological transition zone between the Sierra Nevada and Central Valley ecoregions. However, commensalist species that derive a benefit from human habitats tend to thrive more in this region because they are more tolerant of human development. Mammalian wildlife in the Lower Stanislaus watershed is dominated by black-tailed deer, California mule deer, striped skunk, raccoon, fox, opossum, beechy ground squirrel, brush mouse, Botta pocket gopher, and many rabbit species. Typical Sierran predators, such as coyotes and bobcats, are rare in the reservoir area.

Predatory birds are ubiquitous in the study area: turkey vultures, red-tailed hawks, and Swainson's hawks. They thrive on small mammals, as well as smaller game birds including California quail, mourning doves, mountain quail, and pheasant. Pheasants are an introduced species considered the most important game bird in the region. Other non-native birds found in the study area are waterfowl species (ruddy, ring-necked ducks, mallard ducks, grebes, and coots) that have found a habitat niche in and around the basin's reservoirs.

Many of these predatory and game animals depend on riverine ecosystems to one degree or another, but these species comprise only a small percentage of faunal life inhabiting riparian and instream aquatic communities. Terrestrial species that inhabit the riparian areas upstream of the New Melones dam site include the water ouzel (dipper), the yellow warbler, and the northern water shrew, while downstream areas are dominated by killdeer, blackbirds, and herons. Aquatic fish life is characterized by sport fish species such as largemouth bass, smallmouth bass, sunfish, catfish, rainbow trout, and brown trout, along with native fish such as Sacramento squawfish, hardheads, hitch, Sacramento suckers, and cottids. Seasonal species consist of King salmon and steelhead trout, which traditionally move up the Stanislaus River between December and April to spawn. The biological assessment conducted by the USFWS concluded that no endangered species would be threatened by anthropogenic change in the basin (US Army Corps of Engineers 1973).

Historic land-use and development

Scattered prehistoric evidence such as village sites, mortars, middens, and petroglyphs indicate that sedentary human populations occupied the Stanislaus River Basin as far back as 4000 years ago. Additionally, significant historic evidence exists concerning the historic occupation of the Central Sierra Miwok and Yokut Indians in the Lower Stanislaus Watershed prior to westward Anglo migration.

Early development in the study area commenced during the gold rush of the late 1840s, including prospect claims and small-scale water diversion projects to aid in gold extraction and to irrigate farms growing hay and grain to raise cattle for miners. However, human development rapidly increased leading into the 20th century, as utility companies began generating hydroelectric power along the Stanislaus River and diverting water for more specialized agriculture. Significant hydroelectric power production expanded within the study area in 1926, with the construction of the Melones Dam and powerplant facility. But hydroelectric development did not halt with the construction of Melones Dam.

The 1950s ushered in an era of rapid dam construction along the Stanislaus River, which included construction of Tulloch Dam and Goodwin Dam (Goodwin is just south of the study area, and likely has upstream effects). Human development, either in the form of the agriculture or urban lands, also progressed during the hydroelectric expansion period.

Socioeconomic conditions

The service basin that pertains to the dams of the Lower Stanislaus watershed includes four counties: Calaveras, Tuolumne, San Joaquin, and Stanislaus. Agriculture is the dominant economic activity in the service basin, and is generally most intense in Stanislaus and San Joaquin counties. The predominant crops in these counties are alfalfa, fruit and nut trees, and vineyards. Irrigated pasturelands for livestock and milk production are also prominent. On the other hand, farming in Calaveras and Tuolumne counties can be characterized by low-intensity livestock grazing and dry-farmed crops.

Most of the agricultural area captured in this study resembles the low-intensity farming of the upper service basin.

Other major employers in the service basin are food processing, manufacturing, retail trade, services, and public administration, although most of these activities are centralized in urban areas. Non-urban industries that provide principal sources of income to the area are the mining and recreational sectors of the economy. Regional mining activities include extractive activities such as gravel mining, marble quarrying, limestone quarrying, and asbestos mining. Secondary mining activities such as cement manufacturing also exist. Most of the service basin that is captured in this study provides an adequate representation of regional mining and recreational lands, whereas the amount and intensity of urban development captured by this study severely under represents that of the service basin.

This study is located in the upper part of the service basin, which can be characterized by a mildly rugged terrain and scattered population. In 1976, only 7.5 percent of the population within the service basin resided in the upper basin. However, the EIS reports that this area experienced a 3.1 annual growth rate, which is significantly higher than the 1.6 percent growth within the lower basin valley. Despite the sparse population, the California Department of Finance projected a 91 percent population increase between 1976 and 2020, which translates to a population of 88,000 in the upper basin and an overall population of 1,100,000 in the service basin by 2020 (US Army Corps of Engineers 1973).

Methods

Considering the medium resolution of the Landsat imaging platforms (Multi-Spectral Scanner has a 60-meter spatial resolution, while Thematic Mapper and Enhanced Thematic Mapper both have a 30-meter spatial resolution) and the large spatial extent of the project, this project adheres to the general Level I-Anderson classification scheme, with slight modifications to account for land disturbance, agricultural distinctions, and natural vegetation density (see Figure 6) (Anderson et al. 1976; Loveland et al. 2002). Natural land-cover classes include forest/woodland, shrubland/grassland, wetland, natural barren, and water, while other classes include transitional mechanical disturbance, developed, agriculture, mining, and water (in the case of manmade reservoirs).

Urban – Areas with much of the land covered with structures (e.g., high density residential, commercial, industrial, transportation, mining, confined livestock operations), or less intensive uses where the land-cover matrix includes both vegetation and structures (e.g., low density residential, recreational facilities, cemeteries, etc.). Includes any land functionally attached to the urban activity.

Agriculture – Includes cropland and livestock pasture. Land in either a vegetated or unvegetated state used for the production of food and fiber.

Forests and Woodlands – Tree-covered land where the tree cover density is greater than 20%.

Shrubland/Grassland – Land predominately covered with grasses, forbs, or shrubs. The vegetated cover must comprise at least 20% of the area.

Wetland – Lands where water saturation is the determining factor in soil characteristics, vegetation types, and animal communities. Wetlands are comprised of water and vegetated cover.

Water Bodies – Areas persistently covered with water, such as streams, canals, lakes, reservoirs, bays, or oceans.

Natural Barren – Land comprised of natural occurrences of soils, sand, or rocks where less than 20% of the area is vegetated.

Mechanical Disturbance – Land in an altered state that is in transition from one cover type to another. Note that mechanical disturbed land does not include disturbances from natural hazards.

Figure 6. Land-use/land-cover class definitions. Modified from Anderson et al. (1976) and Loveland et al. (2002).

A manual interpretation method was implemented in this project, primarily due to shortcomings in automated algorithm methods and the difficulty of incorporating ancillary information into a fully automated interpretation procedure. Automated methods may be more time and cost-effective than a manual interpretation, but many automated methods only use color, tone, and brightness elements in the classification process. On the other hand, a manual interpretation can incorporate color, tone, brightness, size, shape, texture, pattern, site, and association into the decision making process.

Manual interpretation can be supplemented with ancillary information to improve the classification. Topographic maps and Digital Orthophoto Quadrangles (DOQs) provided by the USGS were primarily utilized to identify manmade features on the landscape. Moreover, since each of these sources provides a snapshot of a particular moment in time, these snapshots can be used to aid in the change detection between each time interval.

Other ancillary data employed during this interpretation include the USGS National Land Cover Dataset (NLCD), USFS National Wetland Inventory maps, Principal Component Analysis (PCA) images, and images created with automated unsupervised classification techniques. The NLCD thematic raster layers were beneficial because they provided a starting point for interpretation of the 1992 image. The choice to start with the 1992 image as the base layer in this study was decided due to the abundance of ancillary information produced around 1992, but particularly because the 1992 scene used in this study was the same scene used to create the USGS NLCD product. This temporal consistency made NLCD a great reference for the base interpretation. Additionally, NLCD has a known classification accuracy (an overall accuracy of 85 to 90 percent for a Level I generalization) (Loveland et al. 2002). However, NLCD's 21-category classification scheme was not completely analogous to classes within the study area, and the regional scale of the NLCD assessment neglected to capture some local landscape characteristics. The PCA was also beneficial, particularly in identifying and isolating developed land-use in the Landsat TM imagery. PCA was able to accomplish this by separating relevant data from atmospheric or illumination noise. The unsupervised classification was not especially useful for identifying developed areas, but provided significant insight into subtle classification breaks between forest and grassland. Spectral signature profile tools were used in conjunction with the unsupervised classification clusters to provide additional insights into vegetation class breaks (see Figure 7). Considering that the manual interpretation was the fundamental interpretation technique employed in this project, each of these ancillary sources was exclusively used to identify borders between classes that warranted additional investigation.

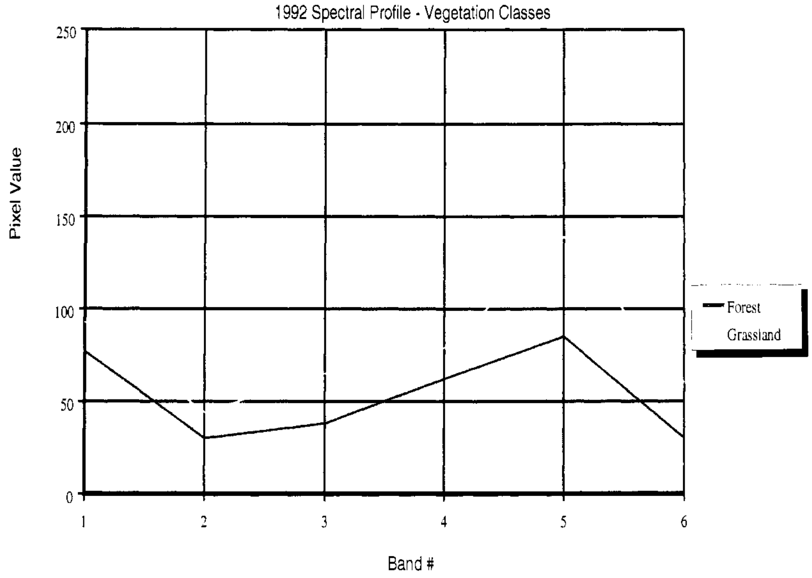


Figure 7. The spectral profile tool plots the spectral signature of user-defined pixels, thus aiding in the differentiation between vegetation classes.

Once the 1992 scene date was classified using the manual interpretation and the ancillary data mentioned above, the post classification comparison was utilized to determine change for each temporal interval (see Figure 8). Other change detection methods exist, such as write-function memory insertion or image algebra, but these techniques fail to provide change classes with quantitative ‘from-to’ information. The post classification method was advantageous because it provides this information. Another benefit afforded by this method was that change from date to date was manually interpreted, which reduces errors of omission and commission that may arise by independently creating land-cover maps for each date (Jensen 1996).

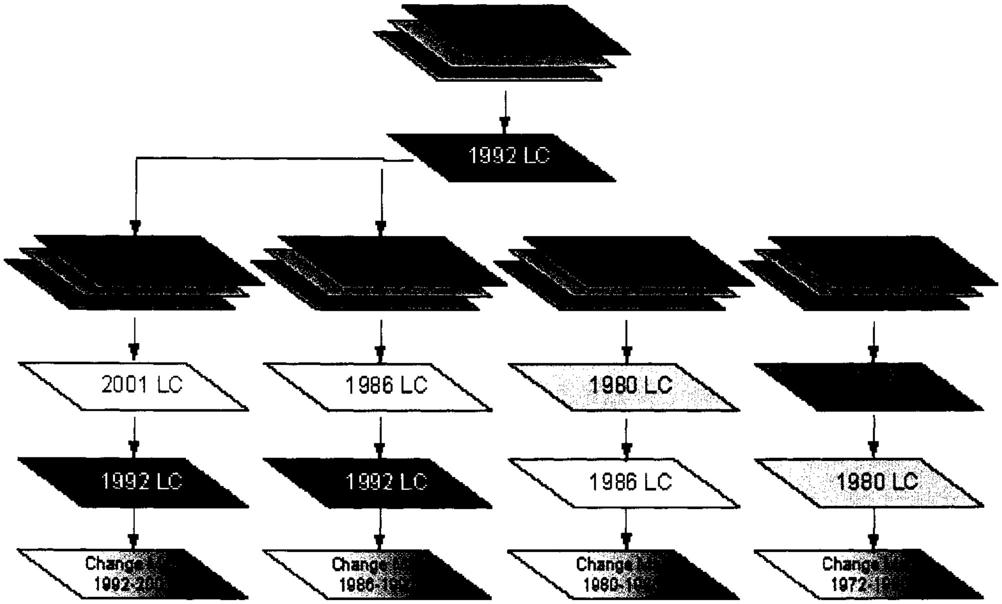


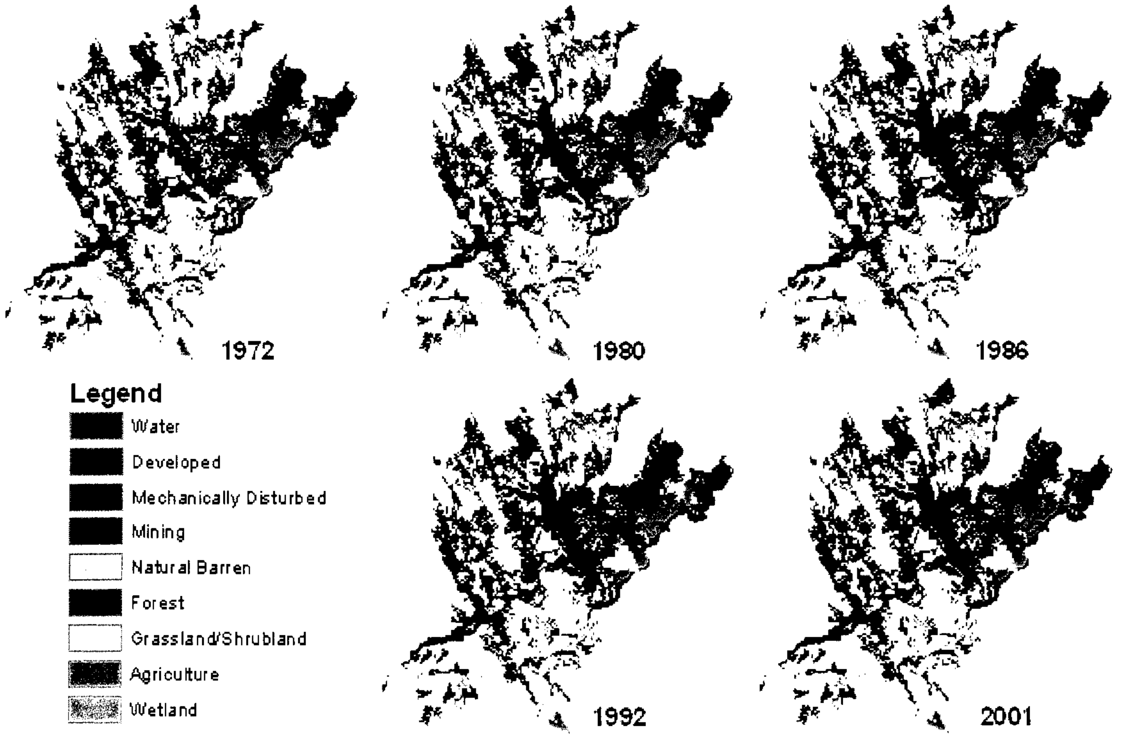
Figure 8. Example of the post-classification method as it pertains to this project.

Landscape changes were classified by comparing the land-cover images for two dates. Changes were forward classified for the 2001 scene using the 1992 scene as a template, and back-classified for the 1972, 1980, and 1986 periods using adjacent scenes (the finer resolution afforded by the 1992 Landsat TM data reduce the amount of classification errors that will occur during the forward and back-classification). The end result of this change detection was land-cover images for the 5 core dates (1972, 1980, 1986, 1992, and 2001), a multiple change image illustrating the frequency of change per pixel over the study period, and a statistical matrix describing land-cover change statistics for the 5 dates and 4 time intervals (1972-1980, 1980-1986, 1986-1992, and 1992-2001).

The statistical matrix does not include a standard accuracy assessment, particularly because standard accuracy assessment techniques for single-date land-cover classifications can be problematic in multi-temporal change analyses (Dobson et al. 1994). Whereas an accuracy assessment could be conducted for the 1992 thematic layer due to the sheer abundance of ancillary data sources, other dates lack sufficient historical references. The manual interpretation method inherently has a high level of accuracy due to qualitative comparisons on a pixel by pixel basis between imagery and ancillary references. These are the same sources that would otherwise be used in a quantitative correlation approach, thus making an accuracy assessment redundant.

Results

The entire study area comprises 420.8 square kilometers (116,894 60m x 60m pixels), which is equivalent to 109,986 acres. Land-use varied significantly between scene dates, which are reflected below in Figure 9 and Table 4. LULC (land-use land-cover) change throughout the 29-year study period totaled 6.32 percent, or 0.87 percent annually. This rate of change translates to 105 square kilometers of total change, although the frequency of change varies significantly across the study area (see Figure 10).



Yearly Land-Cover Maps

Figure 9. Yearly land-cover maps for the study area: lowest 14 of 25 sub-basins that comprise the Lower Stanislaus Watershed. New Melones Dam at 120°31' 37°57'.

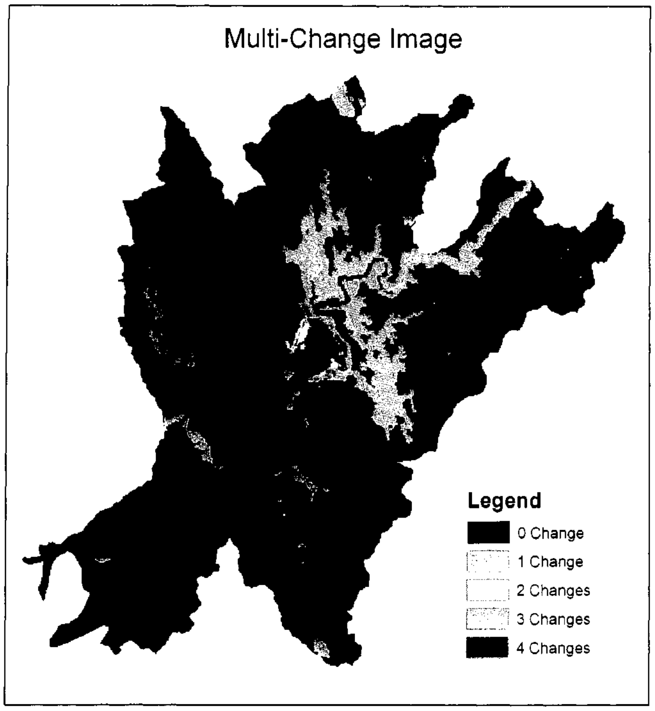


Figure 10. Spatio-temporal LULC change frequency.

	1972	**1980**	**1986**	**1992**	**2001**	**Net change**	
	Area	**Area**	**Area**	**Area**	**Area**	**1972-2001**	
Land-use/land-cover class	**(km^2)**	**(km^2)**	**(km^2)**	**(km^2)**	**(km^2)**	**km^2**	**%**
Water	9.2	20.2	42.4	10.6	42.5	33.3	3.6
Developed	4.1	6.0	6.4	7.1	8.4	4.3	1.1
Mechanically disturbed	0.6	1.7	0.0	31.8	0.0	-0.6	-1.0
Mining	1.5	1.8	1.9	2.1	2.1	0.6	0.4
Naturally barren	1.0	0.0	0.0	0.0	0.0	-1.0	-1.0
Forest	179.6	170.2	154.1	154.1	153.6	-26.0	-0.1
Grass/Shrubland	213.2	208.7	203.9	202.5	201.4	-11.7	-0.1
Agriculture	11.2	11.8	11.8	12.2	12.3	1.0	0.1
Wetland	0.5	0.5	0.4	0.4	0.4	-0.1	-0.1
Total	**420.8**	**420.8**	**420.8**	**420.8**	**420.8**	0.0	0.0

Table 4. LULC class area by date for study area.

1972 to 2001

Common conversions throughout the entire study period are reflected in the following table (see Table 5). Cumulatively, these conversions total 105 square kilometers of land-cover change. Over 90 percent (or 97 km²) of the total change is directly connected to the increase in water upstream of New Melones after dam closure.

1972 to 2001			
Rank	Area (km²)	FROM	TO
1	32.3964	M.Disturbed	Water
2	31.8384	Water	M.Disturbed
3	23.4504	Forest	Water
4	8.3628	Grass/Shrub	Water
5	2.7864	Grass/Shrub	Developed
6	1.4328	Forest	Developed
7	1.2492	M.Disturbed	Grass/Shrub
8	0.9864	Nat. Barren	Water
9	0.9792	Grass/Shrub	Agriculture
10	0.828	Grass/Shrub	M.Disturbed
11	0.5868	Forest	Mining
12	0.5796	Forest	M.Disturbed

Table 5. Common conversions between 1972 and 2001.

The following table illustrates the rate of change for each time interval (see Table 6). However, these values are deceptive because each interval varies in duration. Table 7 normalizes the rate of change by year. The normalized values provide valuable insights, particularly that the third time interval (1986-1992) has the most rapid rate of land-cover change despite the greater overall change in the final time interval (1992-2001).

	% Change
1972 to 1980	3.67%
1980 to 1986	5.70%
1986 to 1992	7.92%
1992 to 2001	7.97%
1972 to 2001	6.32%

Table 6. Rate of change for each time interval.

NORMALIZED to ANNUAL VALUE

	1972 to 1980	1980 to 1986	1986 to 1992	1992 to 2001		1972 to 2001
Annual Change	0.46%	0.95%	1.32%	0.70%		0.87%

Table 7. Normalized rate of change by year.

1972 to 1980

This interval reflects nearly 1/3 of the total study period, yet experienced the least amount of change compared to the other three intervals (1980-1986, 1986-1992, and 1992-2001). The rate of change between 1972 and 1980 was 3.7 percent, which is equivalent to 15.4 square kilometers of change. A wide variety of land-cover conversions account for this change. A list of common conversion is reflected in Table 8. Of the top four landscape conversions, three if these reflect a transition from natural land-cover classes (forest, grassland/shrubland, natural barren) to the water class (11 km^2 total). These changes can be directly attributed to the land inundation following the New Melones Dam closure. Other anthropogenic land-cover conversions captured between 1972 and 1980 are conversions to development (1.8 km^2 total), to agriculture (0.5 km^2 total), and to mining (0.3 km^2 total). The only other noteworthy landscape conversions are a series of changes to the transitional mechanically disturbed class, which are temporary changes attributed to dam construction activities.

1972 to 1980			
Rank	Area (km²)	FROM	TO
1	7.7472	Forest	Water
2	2.3112	Grass/Shrub	Water
3	1.0044	Grass/Shrub	Developed
4	0.9864	Nat. Barren	Water
5	0.828	Grass/Shrub	M.Disturbed
6	0.7164	Forest	Developed
7	0.5796	Forest	M.Disturbed
8	0.5184	Grass/Shrub	Agriculture
9	0.3276	Forest	Mining
10	0.1476	Water	Grass/Shrub
11	0.1332	M.Disturbed	Developed
12	0.0828	M.Disturbed	Water

Table 8. Common conversions between 1972 and 1980.

1980 to 1986

The rate of change between 1972 and 1980 was 5.7 percent, which is equivalent to 24 square kilometers of change. Much like other time intervals, a wide variety of land-cover conversions account for the change between 1980 and 1986 (see Table 9). Rapid reservoir infilling accounts for the majority of interval change (16.2 km² total), and is primarily illustrated as a conversion from forest to water (15.7 km² total). Other anthropogenic land-cover conversions occur during this time period, but are minimal relative to the first time interval. All of the instances of the mechanically disturbed class from 1980 have either been inundated by reservoir waters, or have experienced ecologically driven grass succession.

1980 to 1986			
Rank	Area (km²)	FROM	TO
1	15.6708	Forest	Water
2	1.242	M.Disturbed	Grass/Shrub
3	0.4752	M.Disturbed	Water
4	0.3204	Forest	Developed
5	0.1224	Forest	Mining
6	0.1152	Grass/Shrub	Developed
7	0.036	Wetland	Water
8	0.0324	Forest	Grass/Shrub
9	0.0252	Developed	Water
10	0.0216	Grass/Shrub	Mining

Table 9. Common conversions between 1980 and 1986.

1986 to 1992

According to the aforementioned change rate tables, this interval has the largest normalized rate of change. Ninety-six percent of this change is reflected as a conversion from the water class to the transitional mechanical disturbance class (see Table 10). The transition from water to the mechanical disturbance class can be attributed to a drop in reservoir water level. Ancillary data provided by the California Data Exchange Center (CDEC) indicate that the drop in reservoir water is caused by anthropogenic reservoir drawdown, with a minor influence from regional drought (see Figure 11). The influence of reservoir drawdown on the fluctuation in reservoir storage is reaffirmed in Figure 12 reaffirms, which illustrates daily mean streamflow (including releases) below New Melones Dam. The remainder of change between 1986 and 1992 is comprised of transitions to anthropogenic land-use classes, including developed, agriculture, and mining.

1986 to 1992			
Rank	Area (km²)	FROM	TO
1	31.8384	Water	M.Disturbed
2	0.6768	Grass/Shrub	Developed
3	0.4176	Grass/Shrub	Agriculture
4	0.1476	Grass/Shrub	Forest
5	0.1296	Forest	Mining
6	0.0612	Grass/Shrub	Water
7	0.0252	Grass/Shrub	Mining
8	0.0216	Forest	Developed
9	0.018	Forest	Agriculture

Table 10. Common conversions between 1986 and 1992.

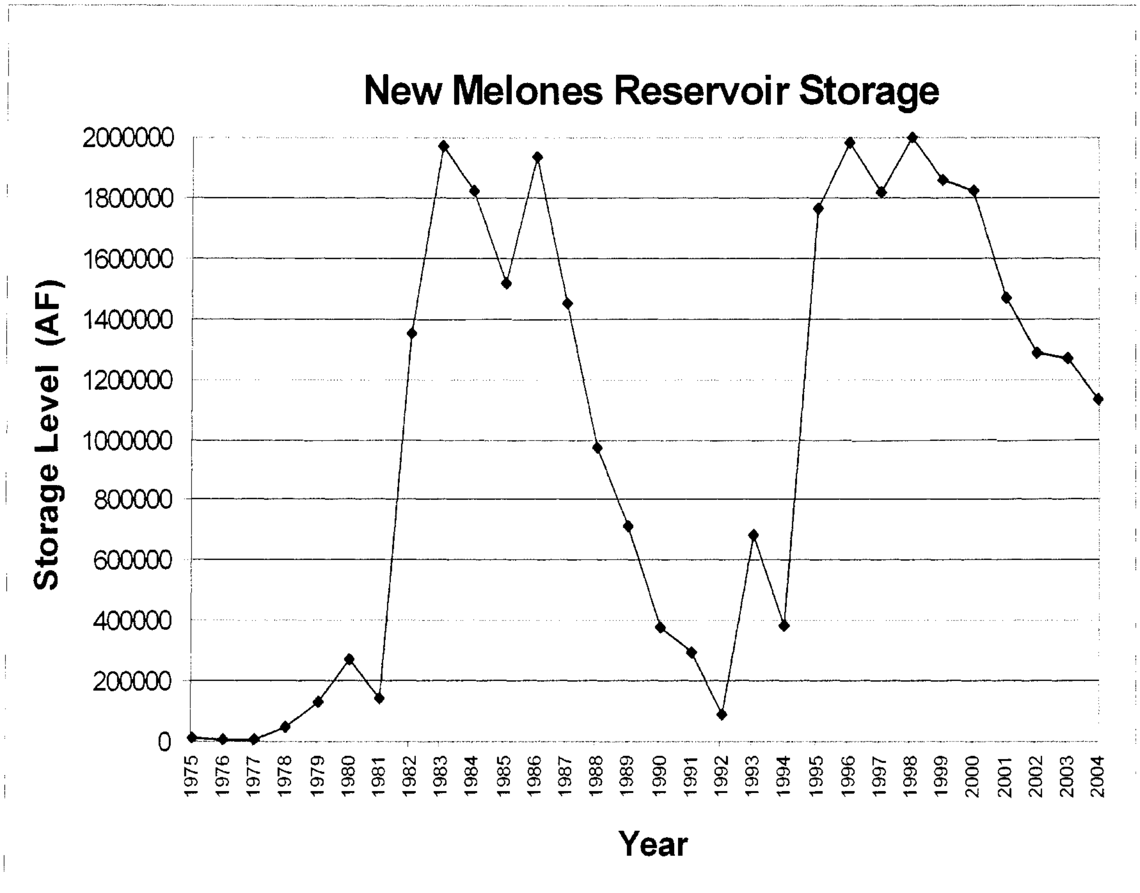


Figure 11. Fluctuating reservoir water level above New Melones Dam (water volume is measured in acre-feet) (California Data Exchange Center [NML]). 1 acre-foot roughly equals 326,000 gallons of water.

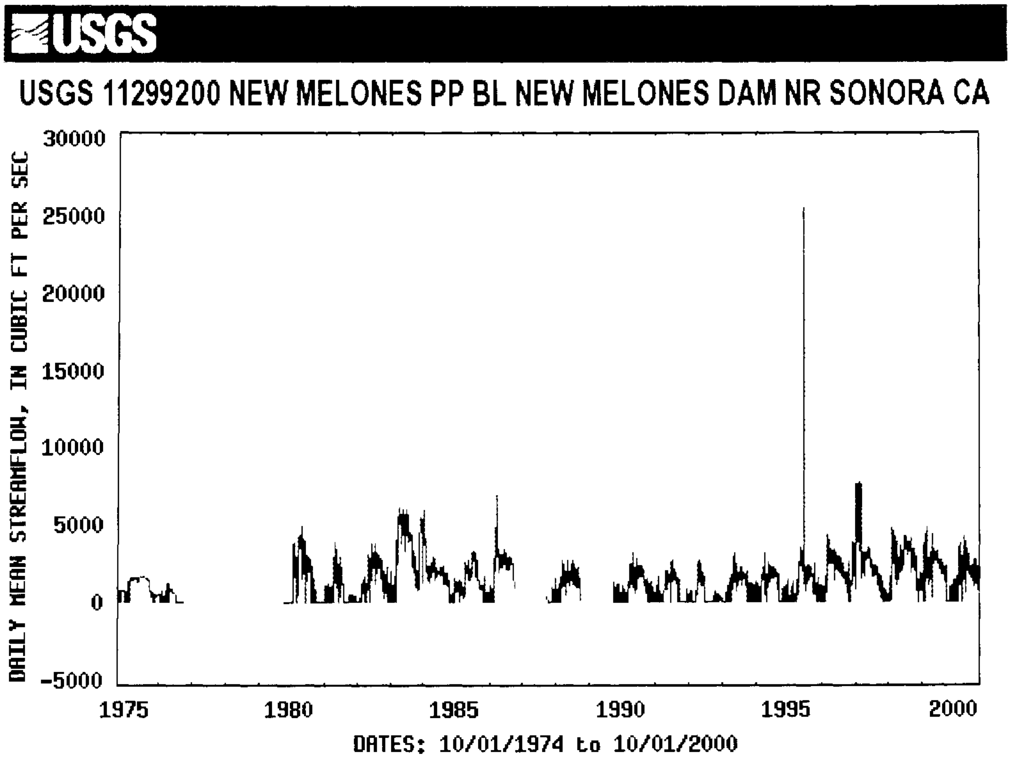


Figure 12. Gage Station Location: Latitude 37°56'47", Longitude 120°31'38" NAD27, Tuolumne County, California, Hydrologic Unit 18040010 (USGS California Water Science Center [11299200]). Note: The spike in streamflow accompanies an El Nino event.

1992 to 2001

As in the period 1986 to 1992, ninety-five percent of this change is reflected as a conversion from a change in reservoir water levels (see Table 11). However, the transitional mechanical disturbance in 1992 converts back to water in 2001. This water-level rise accompanies a spring runoff increase from the Sierra Nevada Mountains following El Nino events. The remainder of change between 1992 and 2001 is comprised of transitions to from natural land-cover classes (grassland/shrubland and forest) to anthropogenic land-use classes, including developed, agriculture, and mining.

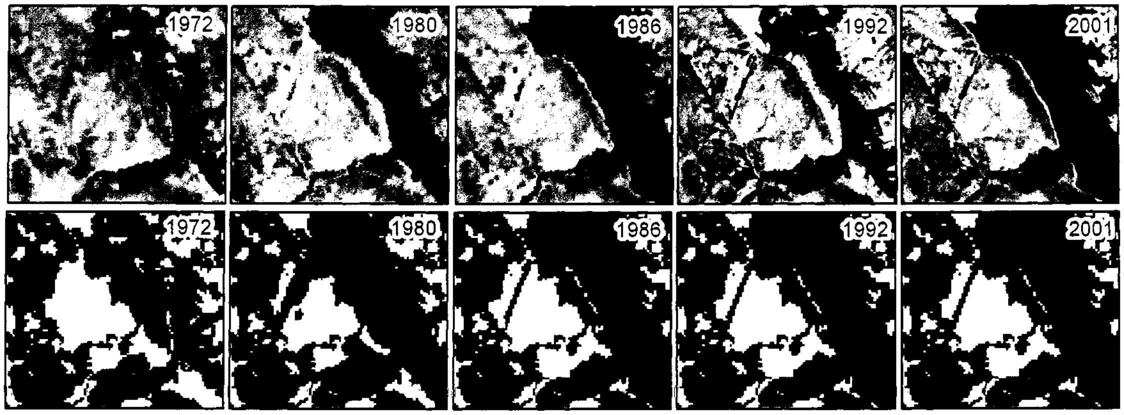
1992 to 2001			
Rank	Area (km^2)	FROM	TO
1	31.8384	M.Disturbed	Water
2	0.99	Grass/Shrub	Developed
3	0.3744	Forest	Developed
4	0.0756	Grass/Shrub	Mining
5	0.0612	Mining	Grass/Shrub
6	0.0504	Forest	Agriculture
7	0.0432	Grass/Shrub	Agriculture
8	0.0324	Forest	Water
9	0.0072	Forest	Mining

Table 11. Common conversions between 1992 and 2001.

Discussion

Mechanical disturbance

The construction phase of the New Melones unit commenced in July 1966. The initial work consisted of building access and haul roads, resident engineer and administration facilities, and a public overlook area. These activities were centralized just downstream of the old dam structure, and are classified as mechanical disturbance in the 1972 land-cover map (see Figure 13). The majority of this work was completed by 1978. The class transition from mechanical disturbance to developed land can be identified on the 1980 thematic map and is reflected in the statistics (see Figure 13). However, much of the mechanical disturbance classified in 1972 does not transition between 1972 and 1980. This is attributable to the constant ground surface irritation caused by machinery work in the area. Additional instances of mechanical disturbance arise in 1980, but these occurrences coincide with documentation regarding secondary construction operations.



Albers Equal Area Projection
Scale 1:150,000

Figure 13. Mechanical disturbance from dam construction and reservoir draw-down.

According the USBR, which took over operation of New Melones Dam in 1979, secondary construction consisted of contracts for a diversion and outlet tunnel, a spillway cut northwest of the dam facility, linking access roads, and the excavation and placing of the dam itself (Simonds 1994). The spillway (5,945 feet long and 200 feet wide) is captured in the developed class in 1980, but the massive disturbance directly surrounding is not entirely attributable to the spillway excavation process. In actuality, material excavated from the area surrounding the spillway was utilized as earthfill in the New Melones Dam embankment. Much of the disturbance in 1980 is no longer present in 1986, and those pixels classified as mechanical disturbance in 1980 have transitioned either to developed land, grassland, or water (due to inundation).

Development

When most people think of anthropogenic change in the context of land-cover, infrastructure development is often the first land-use type considered. Depending on the scale of remotely sensed data and method employed, development can be broken down into classes of varying intensity; however, a single development class is appropriate for the regional-scale interpretation outlined in this project.

These developed pixels were classified through employment of manual interpretation methods, but spectral tone and limitations to the spatial resolution of the Landsat imagery were not sufficient to identify the extent of the developed areas. However, combining interpretation elements such as brightness, texture, and association allowed developed areas to be distinguished from other land-use classes. Ancillary sources such as USGS DOQs with a 1-meter spatial resolution and USGS topographic maps acted as additional aids in the interpretation of developed pixels, particularly because these USGS products can be geospatially referenced (geo-referenced) to the satellite images and land-cover maps. The ancillary data were also helpful in the sense that maps and photographs provide a snapshot of the landscape over time. For example, many of the topographic maps contain a photo revision layer that identifies the location and type of change between dates with a unique color, much like a mylar transparency or digital change layer.

Development is relatively consistent throughout the 29-year study period. Expansion of developed pixels tended to occur along highway corridors or on the fringe of existing towns: Angels Camp, Columbia, and Copperopolis. But perhaps the reason why most development was captured around these areas is due to the concentration of development compared to other areas within the sub-watershed. For instance, individual homes and ranchettes scattered throughout the block are not sufficiently large enough to meet the minimum mapping unit (MMU) by themselves, while clusters of buildings may compose a surface area greater than 60 meters and may be detected by the interpreter.

The expansion of development pixels throughout the study period was not always manifested as building construction. A significant amount of urban growth was related to recreational development. Much of the recreational development within the Lower Stanislaus watershed took the form of off-road jeep trails, which were not large enough to meet the MMU. Yet, other recreation opportunities such as golf courses were large enough to map. The increase in the developed land-cover class between 1992 and 2001 primarily occurs around Angels Camp (see Figure 14). One of the strengths of manual interpretation is that this golf course would not likely be captured as developed if the project relied entirely on automated interpretation methods without any a priori knowledge built into the classifier. If this were the case, a golf course would most likely be classified as agriculture or grassland within this classification scheme. Other non-structural development features captured during the interpretation are three landing strips. Two of these landing strips exist in small communities in the watershed and probably cater to forest fire helicopters and crop-fertilizer airplanes, but a large municipal airport is located just west of Columbia. Columbia Airport's runways are over 120 meters wide, which can accommodate larger aircraft and heavier traffic.

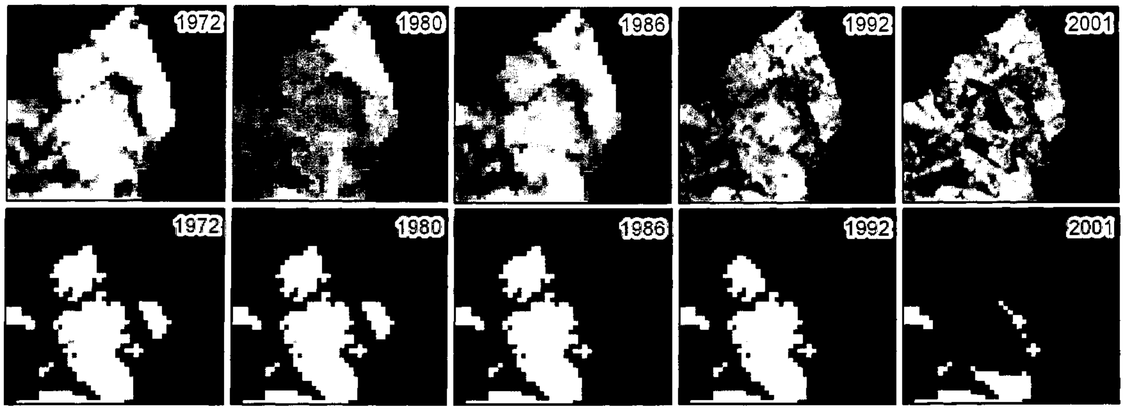
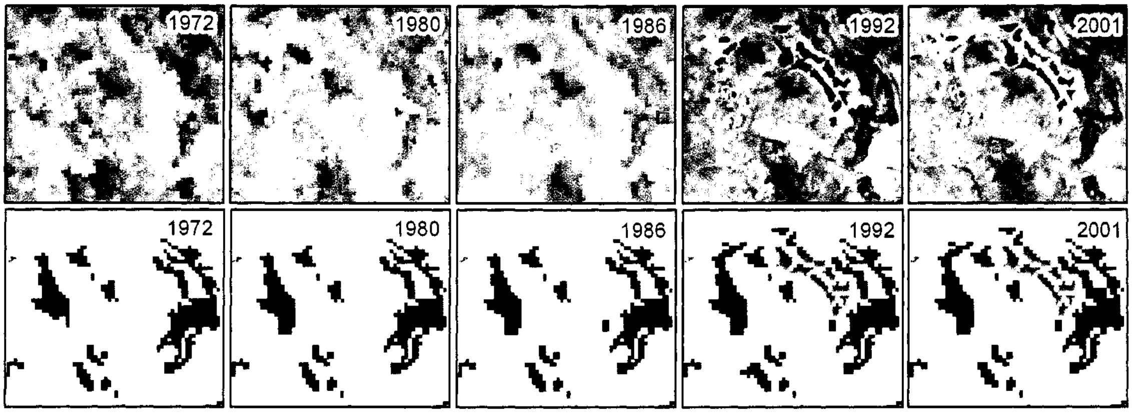


Figure 14. Illustration of growth around Angels Camp.

Although much of the development in this region may be an indirect result of construction of New Melones Dam, some of the development is directly related to the dam projects in the watershed. The dam features being captured during interpretation include the actual dam structures at Tulloch and New Melones, the spillway cut northwest of the New Melones dam structure, and the New Melones powerhouse structure. The two water diversion conduits leading to (Copperopolis and the Lower Tuolomne) do not meet the MMU.

Agriculture

Many of the woodland, shrubland, and grassland communities that thrive within the Lower Stanislaus floodplain have been converted for agricultural uses since 1965 (USFWS 1995). Reduced post-dam flood frequency and good soil development in the floodplain have contributed to this phenomenon. Many of these land-cover conversions are occurring southwest of the study area near the Stanislaus River/San Joaquin River junction, but the land-cover maps and statistics capture a growth of agriculture within the study area following dam closure (see Figure 15). Ancillary data such as aerial photography were a particularly useful aid in the manual interpretation process because the spectral signature of natural grasses and shrubs closely resemble the low-intensity farming and grazing occurring throughout the study area. Aerial photography allowed agricultural structures and crop rows to be identified, thus aiding in the accuracy of the classification.



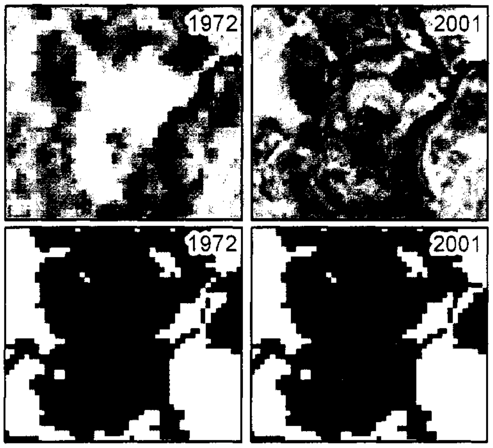
Albers Equal Area Projection
Scale 1:100,000

Figure 15. Agricultural expansion following dam closure.

This growth is spatially limited, experiencing a net increase of 1 km² over the 29-year study period, but the consequences are far-reaching. An increase in agricultural land is directly related to increase in agricultural runoff, and this drainage is accountable for nutrient loading responsible for the high algal production in the reservoir and the stream channel. The consequences of algal production will be discussed further in following sections.

Mining

The communities around New Melones Dam (Angels Camp, Columbia, Copperopolis) have a rich mining history, dating back to the California gold rush in the 1850s. Ancillary data sources illustrate the prevalence of many small prospects and mines along and around the Stanislaus River; however most of these are historical and are no longer in operation. Moreover, most of the mining claims are not large enough to not meet the 60-meter MMU. Nevertheless, larger extractive mining operations such as gravel mining, marble quarrying, limestone quarrying, and asbestos mining are captured within this study (see Figure 16). A massive marble mine operation is located just upstream of the study area along the Stanislaus River.



Albers Equal Area Projection
Scale 1:75,000

Figure 16. Asbestos mine along the Stanislaus River.

Mining activities pose a threat to plant and animal life due to the effluent runoff that enters the Stanislaus River. For example, Rogers Creek, which is a tributary to the

Stanislaus River, runs through the asbestos mine and leads directly to the main river channel. The effects of asbestos on animals and humans are well documented. Therefore, transport of asbestos leachate downstream may have consequences beyond the mine site, affecting animal life from the mine to the end user of the water. Gravel dredging may also hinder animal life by eliminating salmonid habitat and spawning gravel. The effect of gravel dredging will be discussed further in a following section of the paper.

Water

The conversion to water is the predominant land-cover change within the spatial and temporal context of this study. Despite fluctuation across the study period, the net increase in the water class was equivalent to 33.3 km^2. This change is entirely affiliated with the construction of New Melones Dam, with the exception of a few agricultural ponds. Change related to dam construction is isolated to the area upstream of New Melones, resulting in the inundation of natural barren limestone cliffs, forest, shrubland, and grassland (see Figure 13). These land-cover classes once comprised pre-dam the riparian corridor, a particularly sensitive ecosystem vital to the fitness of many vertebrates and invertebrates. Loss of this habitat due to dam inundation has potentially far-reaching effects on the entire faunal food chain.

The increase in water associated with the construction of New Melones dam has also led to the inundation of archeological Native American sites and historical mines from the gold rush. The EIS attempted to mitigate the loss of cultural artifacts by relocating certain features (Mark Twain's cabin), but many sites were lost in the fray.

Another possibility is that inundated mines and prospects may leach hazardous materials into the reservoir and the river, although point sources for pollution are difficult to assess given their current condition.

Finally, even though the dam may not directly result in more pollution, resulting growth in the vicinity due to increased water supply has likely led to more water pollution: from increased development, agriculture, and mining.

Natural vegetation

Collectively, the loss of natural vegetation land-cover to anthropogenic land-use has resulted in the most significant change throughout the study period. The sum net loss of the forest (-26 km^2), grassland/shrubland (-11.7 km^2), and wetland (-0.1 km^2) floral communities is 37.8 km^2. The impact of this dramatic loss of natural habitat will be discussed at length in the following section.

Consequences

Fauna

One of the elements included in the 1979 EIS is a biological inventory of floral and faunal species potentially affected by construction and operation of the New Melones Unit (US Army Corps of Engineers 1973). The U.S Fish and Wildlife Service conducted this assessment and concluded that a new dam would not affect endangered species within the watershed, such as the Blunt-nosed Leopard Lizard, Aleutian Canada Goose, Bald Eagle, American Peregrine Falcon, and San Joaquin Kit Fox. However, this conclusion was grounded on the belief that "no land use change is anticipated nor would cropping pattern change" in the watershed after the dam's completion (US Army Corps of Engineers 1973, Appendix 1:3). The expansion of agriculture (1 km^2) and widespread loss of natural vegetation (37.8 km^2) identified in this study disproves the EIS statement. This false assumption is negligible for commensalist species such as the Aleutian Canada Goose because these fowl utilize man-made reservoirs for roosting and agricultural grain as feed; however, certain species rely on native vegetation to thrive. For example, encroachment of anthropogenic land-use classes into critical habitats poses a serious threat to the Blunt-nosed Leopard Lizard because the lizard relies on native vegetation.

Endangered species are not the only species impacted by the New Melones Unit. Many of the species that exist in the Lower Stanislaus basin have generally adapted to humans, but recent land-use changes have threatened many local species. Perhaps the most vulnerable species are those which rely on riparian habitat inundated by the reservoir or those species whose habitat has been converted to agricultural or developed lands. Susceptible species include the water ouzel (dipper), the yellow warbler, and the northern water shrew (US Army Corps of Engineers 1973). These species are particularly dependent on riparian habitat upstream of New Melones Dam, which became inundated once New Melones was completed. This inundation is reflected in the statistical matrix as a net loss of the three natural vegetation classes (forest, grassland/shrubland, and wetland) and illustrated in the land-cover maps as a widening of the river channel.

Although the dams in the Lower Stanislaus Watershed influence the terrestrial fauna, the potential effect of dams on aquatic animals (and invertebrates) is clearly more severe. However, the variables that determine the health of aquatic organisms are quite complex, since the "health of an aquatic system depends on all influences of the channel network and watershed upstream of that point (SNEP 1996, 128)." This makes an assessment of the Lower Stanislaus watershed particularly difficult because the study area is located at the end of the river and influences along the way endanger aquatic creatures. Generally, dams make aquatic organisms vulnerable by altering streams flow regimes or reducing flows altogether. These changes can create fragmented populations, which become susceptible to extirpation due to limited genetic diversity. Additionally, dams may hinder reproductive activity through thermal pollution, block access to spawning grounds, or destroy spawning gravel beds.

Thermal pollution is the primary concern in the Lower Stanislaus Watershed mainly because of the dynamics of the New and Old Melones Dams. According to the USBR, cold water does not circulate through the outlet of the new dam because it becomes trapped behind the old dam. This problem is exacerbated when the layer of cold water above the old dam drains below 350,000 acre-feet. Once this occurs, the temperature of water released can rise above 57 degrees Fahrenheit, which can cause fish hatchlings to die (Simonds 1994). The USBR has attempted to resolve thermal pollution issue by maintaining a minimum water level above 350,000 acre-feet, but this level is difficult to sustain when inflows are low or if hydroelectric power revenues are sacrificed. Although the land-cover maps and ancillary information in this study do an adequate job of estimating reservoir water level and the general quality of reservoir water releases, the absence of temperature data for the reservoir limits the validity of ecological inferences regarding thermal pollution.

A secondary factor that affects fish reproductive behavior is the physical impedance to spawning pools. Each dam in the study area is an obvious barrier, but irrigation pumping also results in temporary earth dams within the river channel that prevent king salmon and steelhead trout from accessing upstream pools. Moreover, low flows exasperated by the new dam provide a physical restriction to and from spawning pools.

The third influence on the aquatic organisms within the study area is the obstruction of natural recruitment of gravel below New Melones, Tulloch and Goodwin dams. Prior to dam expansion, the amount of available gravel for king salmon was steadily declining within the Lower Stanislaus Watershed, either due to gravel mining or due to flow obstruction related impacts caused by the dams along the Stanislaus River (Kondolf et al. 2001). This is particularly true for the area below Goodwin Dam, which is just outside of the study area. A reconnaissance level assessment within this region led Kondolf and others (2001) to estimate watershed gravel extraction between 1939 and 1999 at 1,031,800 cubic-yards from the active channel, and 5,292,500 cubic-yards in the floodplain below Goodwin Dam. Additionally, dam induced flow obstruction directly reduces gravel dispersal downstream, while indirectly reducing gravel recruitment from vegetation encroachment due to low flows. Gravel bed degradation is likely occurring at a greater rate post-construction, due to the proportions of the New Melones Unit and because an expansion in developed lands is directly correlated to an increase in gravel mining. The loss of spawning gravels will likely have a widespread impact on king salmon populations, both spatially and temporally. Recent ecological restoration research predicts that gravel losses over the past 50 years will take 300 to 400 years to restore if mining were to cease today and the natural annual sediment supply was restored (Kondolf et al. 2001). Despite the pervading evidence in the literature regarding flow obstruction along the Stanislaus River, the scale of this interpretation fails to capture much evidence of earth dams along the Stanislaus River and mining expansion within the floodplain.

Dams also have an indirect impact on flora and fauna, which can be attributed to the human population growth made possible through increased access to municipal and irrigation water. Growing human influence in the Lower Stanislaus Watershed has adversely impacted native flora and fauna by compounding water pollution. For example, development and agricultural expansion, which cumulatively account for 5.3 km^2 of net change in the statistics, result in an increase in sewage and agricultural drainage. This effluent directly hinders fish oxygen absorption by creating a dissolved oxygen deficiency. Moreover, the oxygen deficiency is indirectly compounded by an increase in algae growth, initiated by the fertilizer-rich agricultural runoff. According to the EIS, this increase in water pollution affects fish either by impairing migration endurance or by directly killing fish via suffocation (US Army Corps of Engineers 1973). Therefore, the presence of dams along the lower reach of the Stanislaus River directly and indirectly jeopardizes the stamina of fish species. Additionally, the impact on these species from disrupted hydrological regimes has likely influenced animals higher on the food chain that depend on aquatic species to survive.

Humans

Although anthropogenic landscape change may appear to be restricted to native flora and fauna species, many of the aforementioned environmental consequences induced by human pollution and resource consumption have regional economic implications. Before the dam expansion project, Stanislaus River waters provided an optimal irrigation supply, not only due to the sheer abundance of water utilized for irrigation, but also because of its low saline conductivity (US Army Corps of Engineers 1973). This "pure" water source benefited agriculture in the San Joaquin Valley by diluting the saline waters of the San Joaquin River, which farmers heavily rely on as an irrigation source. Low flows, which are noted in the literature and evident in USGS streamflow data (see Figure 12), have prevented this diluting effect, consequently leaving farmers in San Joaquin Valley with saline irrigation water, which leads to long-term soil infertility. Therefore, despite a net increase in agricultural acreage in the study area, the sustainability of the regional agriculture has been compromised.

Another economic implication is the impact of New Melones Dam on recreational activities. Although the construction of New Melones and other dams in the study area have expanded the water sport market (the EIS anticipated New Melones recreation benefits to average $910,000 per year, but most of this benefit is expected in the water-sport market), the negative impacts on terrestrial and aquatic wildlife associated with these dams (discussed earlier) have devastated the hunting, river fishing, and kayaking industries (US Army Corps of Engineers 1973). The EIS projected the New Melones Project to cause a net decrease in wildlife habitat due to human expansion. The results confirm this projection, with the loss of 37.8 km^2 of natural land-cover in a 29-year span. The hunting industry and the game rely on this habitat to thrive. Therefore, the decrease in habitat has resulted in a reduction in hunting as a local recreational activity. The Lower Stanislaus basin has experienced a net increase in fishing since dam expansion, particularly due to the growth of fishing in the reservoir, but this evidence is deceptive since it does not reflect the drop in fishing along the Stanislaus River. Fish stocking in the river has been increased to offset fish kills, but the effects of fish stocking on the genetic integrity of native fish is difficult to assess. Another distressed river-driven recreation activity is kayaking. The narrow river channel that existed prior to dam expansion created optimal rapid conditions for kayakers, but the widening of the river channel illustrated in the land-cover maps has ruined these conditions. Dam construction along the Stanislaus River has caused the loss of world-famous rapid sites, thus halting a once thriving portion of the regional recreational economy.

Although the economic losses attributable to the New Melones can be quantified easily in terms of lost revenue, the invaluable cultural resources lost as a result of dam expansion cannot be easily measured. According to DOI's Consulting Archeologist, over 500 archeological and historic sites (reflecting over 3,000 years of California history) are present in the Lower Stanislaus basin (US Army Corps of Engineers 1973). The prehistoric sites chronicling Miwok and Yokut inhabitation include middens, caves, mortars, and petroglyphs. In all, 230 of these sites have been identified in and around the pre-expansion lake area (US Army Corps of Engineers 1973). This concentration of Native American activities can be explained by the fact that these two tribes primarily inhabited areas near the Stanislaus River and its tributaries. The remaining sites identified in the EIS include historical resources spanning from the Gold Rush of 1848 to the present. These locations encompass mining structures (shaft, pits, prospects), homesteads, mills, bridges, and ferry crossings. Construction of New Melones resulted in the inundation of many of these prehistoric and historic sites, while preserving profitable landmarks such as Mark Twain's Cabin and Tuttletown. Qualitative analysis of land-cover maps with cultural resource maps confirm the loss of sites identified in the EIS. Therefore, with the exception of direct revenue from cultural site tourism, the societal cost from loss of cultural resources to the New Melones Project cannot be quantified, and has generally been disregarded in the cost analysis.

Conclusion

On a whole, California's dams and diversions provide a significant economic benefit, particularly by supplying hydroelectricity, irrigation water, flood control, recreation, navigation, and emergency water storage. For example, average annual benefits for New Melones Dam are estimated at $13.5 million (US Army Corps of Engineers 1972). The majority of this economic benefit comes from power generation, irrigation, and flood control. However, the development of streams jeopardizes ecological integrity and long-term socioeconomic sustainability by inundating natural habitats and cultural resources, changing flows patterns, hindering the natural flushing of harmful materials from streams, and contributing to thermal river pollution. In the past 35 years, government regulation has mandated that water projects account for these environmental impacts. New Melones Dam was one of the first dams in California to require an environmental impact statement. Despite optimistic projections concerning the environmental cost of dam construction, this study suggests that New Melones Dam is no exception in regard to environmental degradation.

This study, which incorporated the lowest 14 of 25 sub-basins composing the Lower Stanislaus Watershed, comprised a total of 420.8 square kilometers. LULC change throughout the 29-year study period totaled 6.32 percent, or 0.87 percent annually. Cumulatively, these conversions total 105 square kilometers of land-cover change, which is equivalent to 3.6 square kilometers of change per year. Over 90 percent (or 97 km^2) of the total change is directly connected to the increase in water upstream of New Melones after dam closure, which in turn led to the inundation of critical grassland, chaparral, woodland, and upstream aquatic habitats. Additionally, cultural resources from Native American settlement and 19th century mining were also inundated by waters collecting behind New Melones Dam. Downstream land-cover change was not as significant in this study, although the consequences of dam closure are far reaching. Low flows and altered water temperatures below New Melones Dam pose a significant threat to aquatic organisms (fish and invertebrates) along the Lower Stanislaus River. Furthermore, the reduction in flushing flows initiated by the construction of New Melones Dam has impacted farmers in the San Joaquin who previously relied on Stanislaus River flows to dilute saline waters in the San Joaquin River.

One of the many benefits of selecting New Melones Dam as a case study is that the watershed is relatively pristine compared to most of the watersheds in California. However, the existence of the old Melones Dam within the watershed illustrates one of the potential flaws of this study. According the Kattelmann (1996, 891), "we lack any information about the condition of channels before placer mining and dam construction." In this particular instance, no aerial photography exists before 1926 that would provide insight into the so-called natural channel of the Lower Stanislaus River before the first Melones Dam was constructed. Historical ground photography may exist for this region, and could be compared with contemporary photographs to get insights into predevelopment land-cover, but repeat photography studies are limited to select photographic waypoints and are not inherently wall-to-wall (Turner et al. 1980). Since historical resources are scant, the amount of land-cover change identified in this study may be underestimated.

The resolution of the satellite interpretation may also account for an underestimate of land-cover change in the Lower Stanislaus River over the 29-year study period. According to the SNEP Science Team, portions of the Lower Stanislaus River have experienced vegetation encroachment into river channels; however, the transition from water to vegetation was not captured around each reservoir during this interpretation (Kattelmann 1996). The analysis is limited by the spatial and spectral resolution of the Landsat satellite and ancillary data sources, which prevent small vegetation communities and changes in these communities (below the MMU) from being mapped. Furthermore, the Landsat resolution may have also been too crude to identify channel incision noted in the literature, although issues related to channel incision may be resolved to some extent by flood mimicry mitigation efforts (Kattelmann 1996).

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