RIVER DISCHARGE PLUMES IN THE SANTA BARBARA CHANNEL

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ABSTRACT

Satellite-derived images of ocean sea surface turbidity and in situ measurements of ocean salinity demonstrate that large areas of the coastal zone in southern California (as much as 8,000 km) can be impacted by discharge from coastal rivers. Such river plumes carry both dissolved and suspended material from California watersheds into the coastal ocean. River plumes can also substantially affect coastal current patterns, particularly in the upper ~5 m of the water column. Typical plumes from the Santa Clara River region, for example, cover a surface area of about 500 km^2 extending up to 50 km into the Santa Barbara Channel under northward regional wind conditions or 70 km southeast into the Santa Monica Basin under southward regional wind conditions. Individual plumes persist for about two to five days. Southward and offshore surface flows during upwelling-favorable wind conditions tend to spread plumes offshore of the river mouth. For example, the plume from the Santa Clara and Ventura rivers in the eastern Santa Barbara Channel frequently reaches the eastern Channel Islands during the strong upwelling events that generally follow major storms. Similarly, in high discharge years, the western Channel Islands are impacted by river discharge plumes that originate north of Point Conception.

INTRODUCTION

River plumes provide a primary mechanism by which material from coastal watersheds and storm runoff is distributed through the coastal zone. The presence of a river plume in a coastal region can also significantly change regional flow patterns, particularly in the upper ~5 m of the water column. Previous studies in the Southern California Bight have not addressed the structure and temporal variability of such features: river plumes occur only during major storms when measurements are difficult to obtain; and they occupy the shallowest portion of the coastal ocean, which is difficult to sample. This paper describes the spatial structure and temporal variability of river plumes that impact the Santa Barbara Channel. A complete discussion of this topic for the entire Southern California Bight is given in Hickey and Kachel (1999).

Significant progress has been made recently in understanding circulation in the Santa Barbara Channel (Hendershott and Winant 1996; Harms and Winant 1998). The large scale circulation patterns described by these studies are a result of wind, wind curl and pressure gradients along the coast. In the upper 5 m of the water column, direct wind forcing (frictional currents) is also important.

River plumes, when they occur, contribute additional complexity to the resulting circulation patterns. When coastal rivers discharge into the coastal ocean, they form a buoyant plume governed by nonlinear dynamics. In the northern hemisphere, and in the absence of ambient currents, such plumes bend toward the right on entering the ocean (e.g., model results in Chao 1988; Kourafalou et al. 1996). The region in which the plume turns is highly nonlinear. Farther downstream, the plume reattaches to the coast to form a (linear) coastal current that hugs the coastline. In the presence of ambient currents, the plume may bend to the left after it leaves the river mouth (e.g., the Columbia River plume in summer); or it may remain adjacent to the coast if the prevailing coastal flow is northward. River plumes are particularly sensitive to changes in local wind conditions, which directly affect flow in the surface Ekman layer (e.g., model results in Chao 1988; Kourafalou et al. 1996). This sensitivity has been demonstrated in the Columbia plume, which moves onshore or offshore as the wind changes direction from northward to southward on scales of two to three days (Hickey et al. 1998). The response time of the Columbia plume to such changes is less than six hours (Hickey et al. 1998). The spatial structure of surface currents during large storms, when plumes occur, is of particular consequence during oil spills and other marine emergencies.

During winter and spring seasons when the principal river discharge events occur, winds with a northward component are generally associated with storms, increased rainfall and northwestward to westward surface flow in the Santa Barbara Channel ("upcoast" flow) adjacent to the coast. Winds with a southward component during those seasons are generally associated with good weather, upwelling of cold water adjacent to the coast, and eastward to southeastward ("downcoast" flow) surface currents near the coast (Hickey 1992; Harms and Winant 1998).

MATERIALS AND METHODS

Time series of daily mean river discharge as well as suspended sediment yield for selected rivers were obtained from the United States Geological Survey (USGS).

Discharge data from 1998 were provided by the United Water Conservation District.

Wind data at a centrally located buoy (National Data Buoy Center Buoy 46025) were obtained from the "Data Zoo" maintained by Scripps Institution of Oceanography (SIO). Buoy location is shown in Figure 1. Comparison with wind data at other sites (Hickey 1992) as well as analysis of wind patterns within the Bight (Winant and Dorman 1997) show that winds from this site are sufficient to provide a general indication of environmental conditions in the nearshore Southern California Bight.

Satellite images of sea surface temperature, visible imagery, and surface albedo were obtained for selected dates from Ocean Imaging, Inc. Data have a nominal spatial resolution of 1 km. A combination of the first two satellite channels (detecting red and near infrared light, respectively) was used by Ocean Imaging, Inc. to construct a measure of sea surface turbidity using the algorithm of Stumpf and Pennock (1989).

RESULTS

Three major rivers (the Santa Clara and Ventura, the Santa Maria, and the Santa Ynez) have discharge plumes that can affect the Santa Barbara Channel (Figure 1). These discharge plumes are easily identified in satellite-derived images of sea surface turbidity (Hickey and Kachel 1999). The plume from the Santa Clara and Ventura rivers discharges into the channel near its eastern end. Roughly one-third of the plume volume originates from the Ventura River; the remaining two-thirds originates from the Santa Clara River (Hickey and Kachel 1999). The plume from the Santa Maria and Santa Ynez rivers enters the channel from its western end during periods of strong coastal upwelling.

River discharge data demonstrate that major floods from rivers in Southern California occur every few years (30% of the years since 1943) primarily during El Niño conditions (Hickey and Kachel 1999). During flood years, periods of high discharge generally occur for two to ten days on several occasions between January and April. During each storm, river discharge begins abruptly and tapers off over several days (Figure 2). Most rivers flood at roughly the same time. During the strongest El Niños, discharge can remain high for several weeks (Hickey and Kachel 1999). Between flood years, and during summer and fall in all years, southern California rivers are essentially dry.

During flood years, millions of tons of material can be delivered to the Southern California Bight in a very short period of time (one to two days), exceeding the mean annual output of the largest river on the U.S. west coast (the Columbia) (Figure 2 for 1993; see Hickey and Kachel (1999) for additional years. This material is derived from the river drainage basin, including agricultural lands, storm sewers, etc. Pollutants such as pesticides (e.g., DDT), PCB, and oil

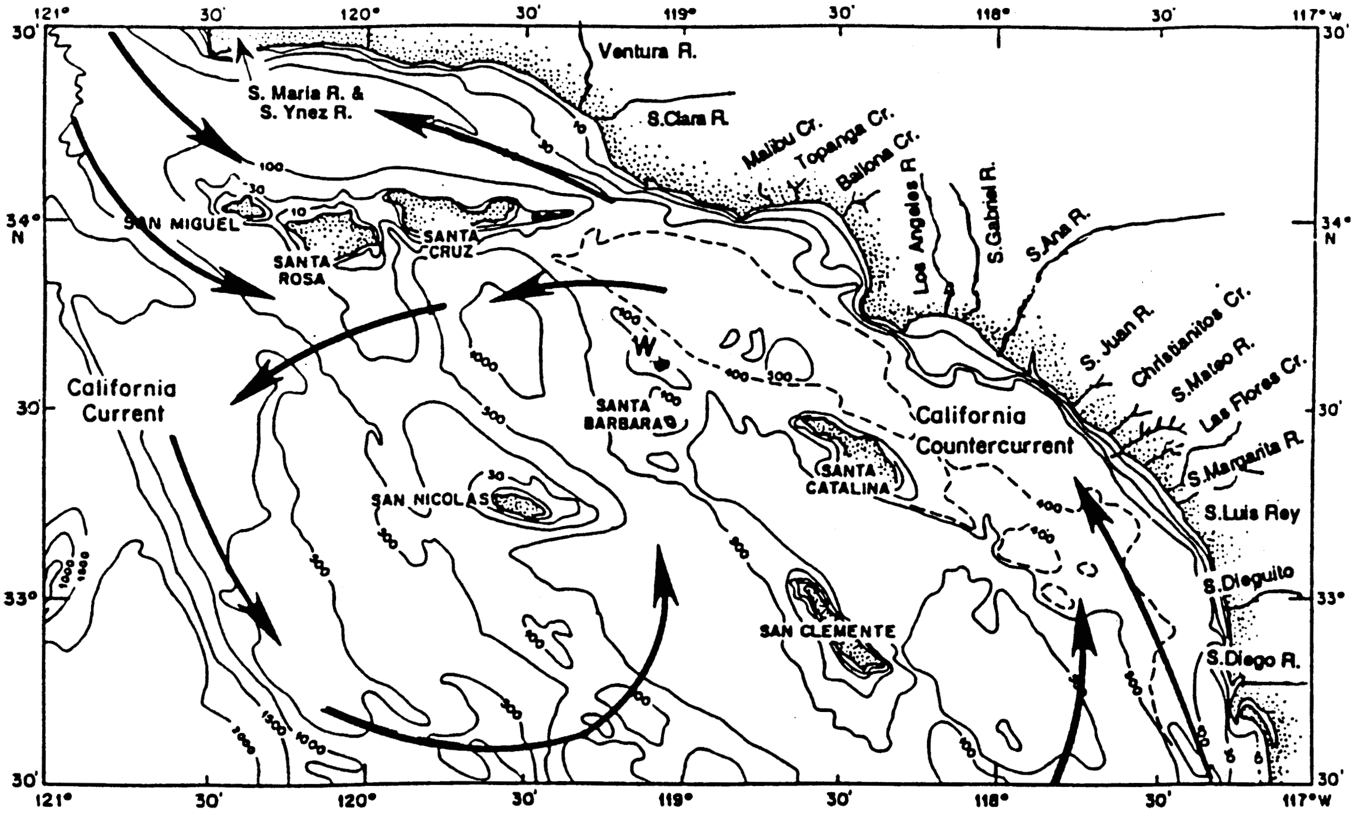
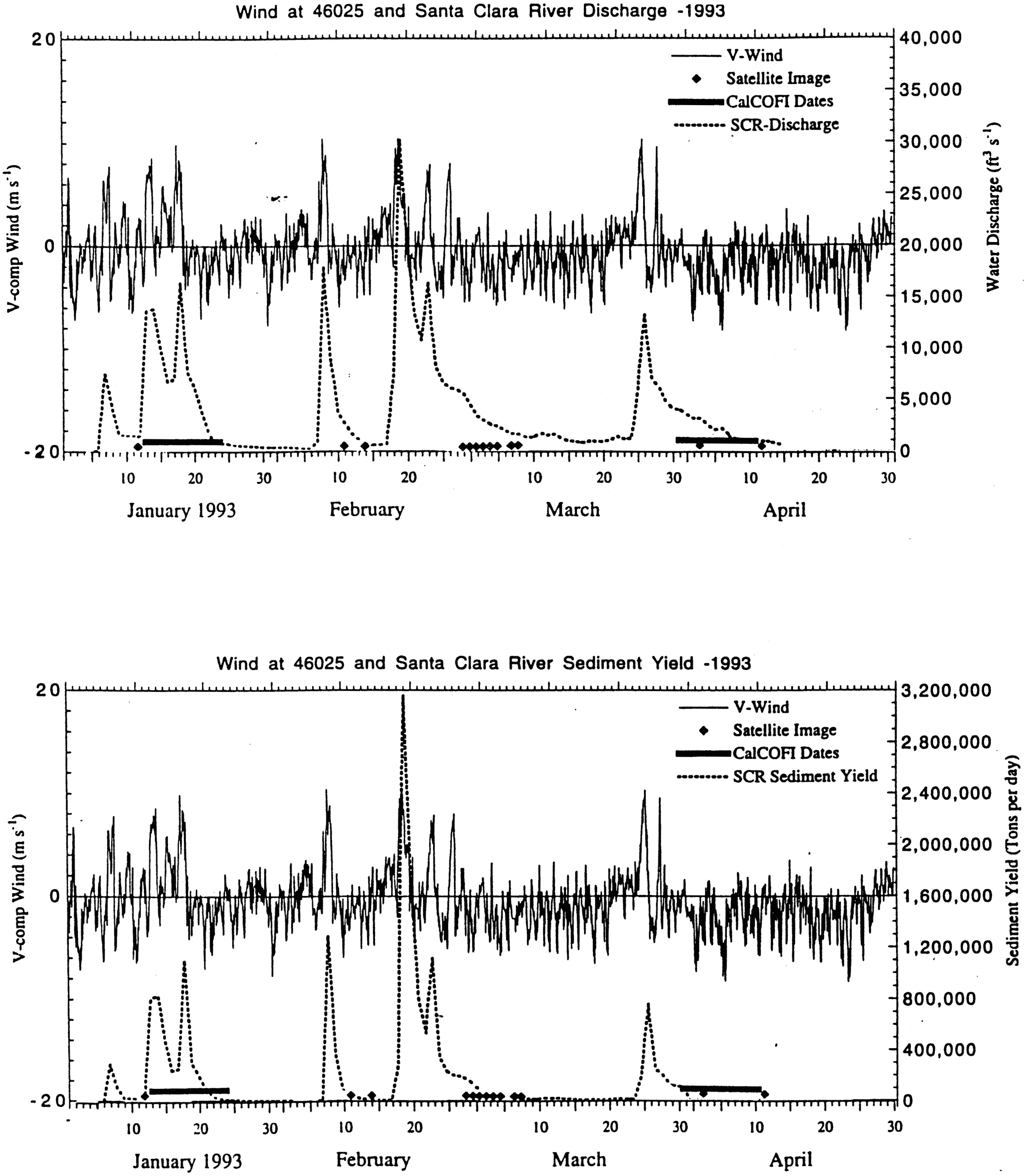


Figure 1. Location of gauged rivers in the Southern California Bight relative to coastline orientation and bottom topography. A schematic circulation pattern for large scale flow in the Bight near the sea surface is superimposed on the topography (from Hickey 1992).


Wind at 46025 and Santa Clara River Discharge -1993

Wind at 46025 and Santa Clara River Sediment Yield -1993

Figure 2. North–south component of wind and river discharge (upper panel) and wind and sediment yield (lower panel) during periods when satellite data were collected. Time is given in Pacific Standard Time. Dates of satellite images are shown as symbols along the x-axis. In general, southward wind is indicative of upwelling conditions and northward wind is indicative of downwelling conditions.

are transferred from their point of origin or temporary storage to coastal marshes or to the ocean.

The plume from the Santa Clara and Ventura rivers has two dominant orientations: upcoast tending or downcoast tending. Upcoast plumes are generally associated with the occurrence of upcoast winds, hence downwelling and onshore flow that tends to keep plumes confined to the coast (Figure 3, upper panel). Downcoast plumes are generally associated with downcoast winds, hence upwelling and offshore flow that tends to spread plumes off the coast and to the south or southeast (Figure 3, lower panel). For both types of plumes, spatial structure is much less variable than the environmental conditions or recent and ongoing river discharge rate (Hickey and Kachel 1999). This suggests some limitation to growth of turbid plumes. In the images collected (winter to spring 1991, 1993, 1995, 1998), turbid plumes from the Santa Clara and Ventura rivers extended a maximum distance of about 60 km westward into the Santa Barbara Channel or 110 km southeast into the Santa Monica Basin (Hickey and Kachel 1999). Downcoast tending plumes are typically almost twice as long and more than twice as wide as the upcoast plumes, likely a result of enhancement of wind-driven flow as the Ekman layer is compressed by plume stratification. Thus, upwelling conditions are very effective at spreading fine-grained material away from river mouths. For example, the plume from the Santa Clara and Ventura rivers can envelop Anacapa Island during upwelling conditions following major floods.

Each major storm in southern California is generally followed by a strong upwelling event. During these upwelling events, turbid material from flooding rivers north of Point Conception (principally the Santa Maria and the Santa Ynez) enter the Bight from the west where they frequently envelop the western Channel Islands (Figure 3, lower panel). The intrusion of turbid water from north of Point Conception into the Santa Barbara Channel is consistent with silt content in surface sediments (Thornton 1984) as well as light transmission surveys (Drake 1972). Thus, upwelling events following major floods may be more efficient than actual storm conditions at moving finer grained particles away from river mouths along the coast and out to the Channel Islands.

The volume of freshwater discharged into the ocean during a typical five-day flood in the Santa Barbara Channel would occupy a 2 m high column of water over an area of about 10 to 100 km^2. The volume impacted by the discharge can be many times greater than the initial discharge volume. Lower salinity areas at the sea surface as great as 8,000 km^2 have been observed off the southern California coast during periods of highest discharge (Hickey and Kachel 1999). On one occasion, fresher water in the Santa Clara River region occupied an area of about 2,000 km^2. More typical low salinity areas in the Santa Clara region covered a surface area of about 500 km^2. Areas covered by turbid plumes from the Santa Clara River ranged from 100 to 1,500 km^2, although an area of about 3,000 km^2 was covered by the plume during strong upwelling following closest in time to a very high discharge event. Depth strata in which salinity is clearly influenced by river discharge range from the sea surface to 10 or 20 m from the surface (Hickey and Kachel 1999).

DISCUSSION

This paper uses satellite-derived images of sea surface turbidity to provide information on the spatial structure and temporal variability of river plumes in and near the Santa Barbara Channel. Such information is important for providing an accurate picture of surface currents during storms on the California coast as well as for understanding how material in coastal watersheds is distributed to offshore coastal regions.

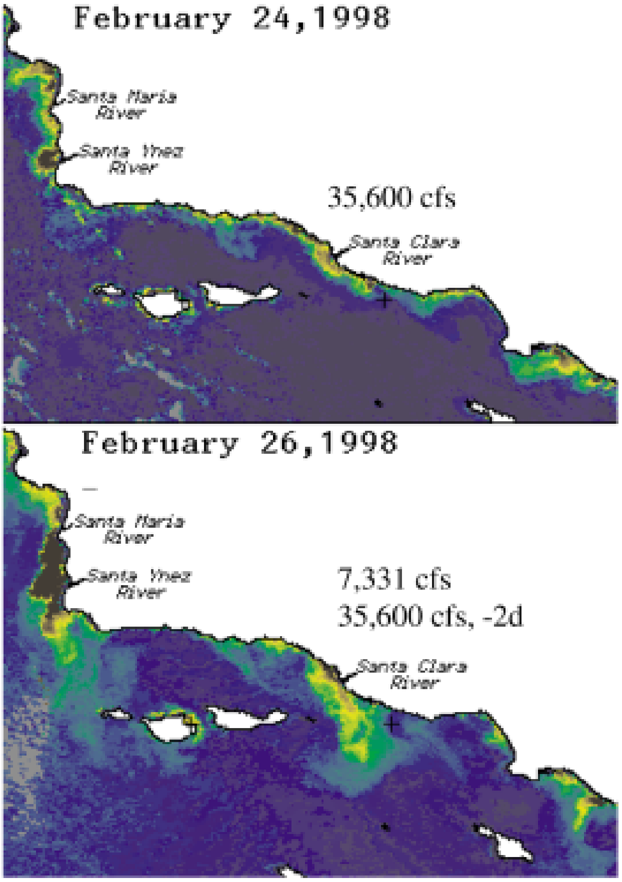


Figure 3. Satellite images of sea surface turbidity for the Southern California Bight for downwelling conditions (February 24, 1998; upper panel) and upwelling conditions (February 26, 1998; lower panel). Discharge from the Santa Clara River on the image dates and the value and date of any recent discharge maximum (subtract the number of days given from the image date) are listed. Turbidity scales are relative only.

Results demonstrate that river plumes can readily distribute this material throughout a large portion of the coastal zone. During a particular flood, large particles may be deposited in the vicinity of the river mouth. Finer particles can be carried tens and hundreds of kilometers from the river mouth. Some of the fine material may form aggregates and settle more rapidly. While the particles are in the upper water column interactions with the biota can occur: particles may be consumed by marine animals and utilized by plants. These in turn are ingested so that any pollutants move up the food chain to birds and mammals. Marine birds, in particular, are often found at density fronts near the edges of river plumes because water convergence at the front increases food density.

Because sediment falls from the water column, the depth and area influenced by river turbidity may differ from that of water properties. Area influenced at the sea surface is likely smaller for turbidity than for salinity. However, turbidity could affect a larger area in the water column than salinity at deeper depths and the area influenced might be expected to increase with depth. Areas covered by turbid plumes shown in the majority of available satellite images may underestimate areas that would be covered at peak flood. On the other hand, fallout of particulates from the plume, as well as processes such as flocculation, which accelerate fallout rates (Baker and Hickey 1986), appears to limit the size of turbid plumes.

The greatest impact on the Channel Islands likely occurs during coastal upwelling, which spreads river discharge plumes from the eastern channel offshore toward Anacapa Island, and spreads discharge plumes from north of Point Conception into the western channel entrance where they encounter the western Channel Islands. Upwelling conditions cause plumes to thin and spread out so that the total surface area is many times that observed during the actual storms responsible for the rainfall that caused the river plumes.

Impacts on flow fields cannot be ascertained from satellite imagery. However, results from other studies (e.g., Hickey et al. 1998) and model results (e.g., Kourafolou et al. 1996) suggest that effects in the upper 10 m of the water column are significant. Current speeds of 10 to 20 cm s^{-1} above ambient flow would not be unreasonable. Moreover, current direction in the vicinity of the plume would likely be altered: for example, currents in the upper 5 to 10 m of the water column a few kilometers from a river mouth would tend to parallel density contours and be concentrated along density fronts. Hence, particularly during strong upwelling, current patterns in the upper water column might differ significantly from those observed in the absence of river plumes.

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