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A conceptual model for river water and sediment dispersal in the Santa Barbara Channel, California

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Received 22 December 2003; received in revised form 3 June 2004; accepted 6 July 2004
Available online 25 September 2004

Abstract

The ephemeral Santa Clara River delivers large amounts of freshwater and sediment to the eastern Santa Barbara Channel during brief, episodic discharge events. This discharge into the channel was characterized here with shipboard measurements during floods of 1997 and 1998. Within approximately 1-km of the river mouth, the river discharge quickly stratifies into a freshened, turbid surface plume and a bottom nephloid layer. Observations immediately off the Santa Clara River mouth on a peak day of river discharge revealed that sediment rapidly settled from the freshened surface waters, as suspended sediment in the freshened surface plume contained only ~6% of the sediment mass expected if the sediment mixed conservatively. On the two subsequent days the reduction of sediment mass in the surface plume continued at ~50% per day. These observations suggest that river sediment undergoes rapid initial settling within ~1-km of the river mouth, followed by somewhat slower rates of settling. Although we did not measure sedimentation or bottom boundary layer processes, our mass balance results suggest that almost all of the river sediment either escapes along or deposits upon the inner shelf seabed.
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Keywords: Santa Barbara Channel; Santa Clara River; River plumes; Hyperpycnal; Suspended sediment

1. Introduction

Rivers discharging into coastal margins are an important fresh water source and the dominant source of sediment to the world's oceans (Milliman and Meade, 1983). This river flux is important since it can directly influence coastal circulation, ocean biogeochemistry, coastal sediment budgets,

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0278-4343/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.csr.2004.07.010

and pollution in coastal waters (Wright, 1977; Garvine, 1984; Kourafalou, 1999; Wheatcroft, 2000). For example, floods from the rivers of California have been shown to produce large river plumes (Mertes and Warrick, 2001; Otero and Siegel (in press)), which influence continental shelf currents (Geyer et al., 2000; Pullen and Allen, 2000), coastal phytoplankton blooms (Kudela and Cochlan, 2000), shelf and slope sedimentary deposits (Drake, 1972; Wheatcroft et al., 1997), and are the source of significant amounts of pollution (Bay et al., 1999).

Most river plume observations focus on the positively buoyant, or hypopycnal (Bates, 1953), plumes formed by density differences between freshened river water and saline receiving waters (e.g., Garvine, 1974; Fischer et al., 1979; Muller-Karger et al., 1988; Walker et al., 1996; Warrick and Fong, 2004). As a hypopycnal plume is formed, river sediment often settles to the bottom, where it is transported by bottom boundary layer processes. For example, the Amazon River water is dispersed in a positively buoyant plume (Geyer and Beardsley, 1995; Geyer et al., 1996), while its sediment is dispersed primarily by bottom boundary layer processes on the continental shelf (Kineke et al., 1996).

Recent investigations have focused on small, mountainous rivers with high sediment yields and energetic discharges (Nittrouer, 1999; Kineke et al., 2000; Wheatcroft, 2000), since they are important in global sediment budgets (Milliman and Syvitski, 1992) and may have the ability to produce high density (hyperpycnal) bottom boundary flows of sediment (Mulder and Syvitski, 1995; Warrick and Milliman, 2003). These hyperpycnal plumes are formed by the excess density of suspended sediment particles (specific gravity ~2.6) and driven by gravitational forces. Even if the runoff from these rivers is not negatively buoyant, sediment deposited on the shelf has been observed to mobilize in dense, fluid muds transported offshore by gravity (e.g., Ogston et al., 2000; Traykovski et al., 2000). These fluid muds are increasingly understood to be important across-shelf sediment transport processes (Wright et al., 2002).

In this study we describe observations of horizontal and vertical dispersal of Santa Clara River water and sediment in the Santa Barbara Channel. The Santa Clara River drains the highly erosive western Transverse Range of California and is understood to be the largest sediment source of the Southern California Bight (Schwalbach and Gorsline, 1985). Sufficient field measurements were obtained in our work to calculate mass balances, which were used in turn to produce a conceptual model of dispersal pathways at surface and at depth.

2. Study area

The Santa Barbara Channel incorporates over 6000 km^2 of coastal waters between California and the Northern Channel Islands (Fig. 1). The channel represents the northernmost portion of the Southern California Bight and has an enclosed, anaerobic basin (Dailey et al., 1994; Kennett et al., 1995). A number of watersheds discharge into the Santa Barbara Channel, the largest of which are the Santa Clara and Ventura Rivers (71% and 10% of the total contributing watershed area, respectively; Fig. 1). We focus here on the river plumes produced by the Santa Clara River, because it is the dominant fresh water and sediment source of the Santa Barbara Channel (Schwalbach and Gorsline, 1985; Warrick, 2002). However, the mouth of the Ventura River is only 5 km from the Santa Clara River mouth and the plumes occasionally cannot be distinguished. Therefore, discussion of the Ventura River and its characteristics is included as needed.

River discharge into the channel is driven by episodic winter rainfall, which produces ephemeral, torrential discharges in the region's creeks and rivers. The watersheds draining to the channel also have high sediment production rates (Inman and Jenkins, 1999), which are primarily a function of steep landscape underlain by weak sedimentary rocks (Scott and Williams, 1978). These high rates of sediment production (1500–3600 t km^{-2} yr^{-1}; Warrick, 2002) commonly produce river suspended sediment concentrations greater than 10 g L^{-1} during storm events. The average annual discharge from the Santa Clara River is 160×10^6 m^3 of water and ~ 3.5 Mt of sediment, more

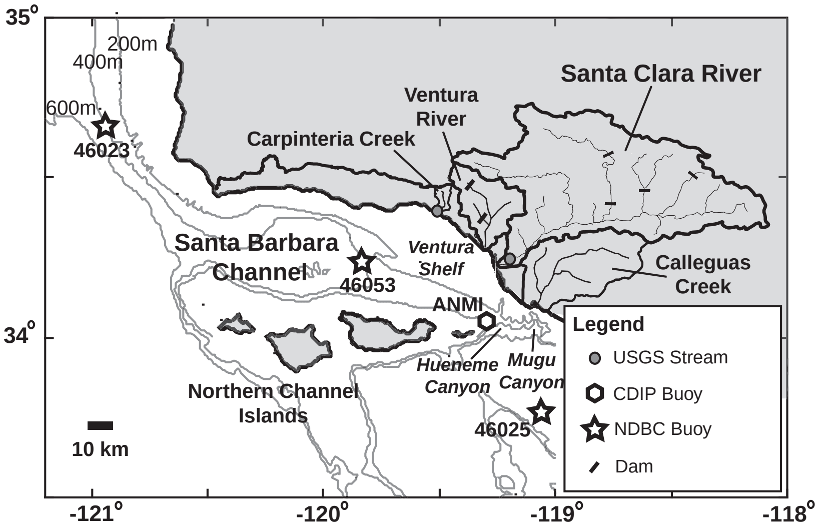

Fig. 1. The Santa Barbara Channel study area including major watershed drainage divides and streams.

than half of which is discharged in the top 1–5 days of flooding per year (Warrick, 2002).

Approximately 85% of the Santa Barbara Basin sediment mass (Schwalbach and Gorsline, 1985) and almost all of the Ventura Shelf sediment (Dahlen et al., 1990) is attributed to discharge from these river sources. Warrick and Milliman (2003) report that the largest flooding events of the Santa Clara River surpass the buoyancy threshold for hyperpyncal plume conditions due to exceptional suspended sediment concentrations. However, following the large 1969 events, the majority of river sediment discharged into the channel settled immediately on the inner (<50-m depth) shelf (Drake et al., 1972), and was then slowly transported into the basin by bottom nephloid layers (Kolpack and Drake, 1985). Large mass movements of terrigenous sediment off the Ventura Shelf and into the Santa Barbara Basin or Hueneme/Mugu submarine canyons (see Fig. 1) appear to be quite rare (>100-year recurrence), although they have corresponded with years of exceptionally high precipitation and river discharge (Gorsline, 1996; Schimmelmann et al., 1998).

Plumes within the channel are subject to currents, which result from a combination of local wind forcing and pressure gradients across the channel (Harms and Winant, 1998; Oey et al., 2001), and are generally equatorward in the spring and poleward from summer through winter. Currents on the broad Ventura Shelf, upon which the Santa Clara River discharges (Fig. 1), are weaker than currents mid-channel and in the western and eastern channel entrances (Dever et al., 1998). During the strong wind conditions of precipitation events, Dever et al. (1998) have noted that shear in the upper 5 m of the water column can be significant.

3. Data and methods

3.1. River discharge

Santa Clara River discharge was evaluated from data obtained at USGS river gauging station 11114000 (Santa Clara River at Montalvo), which incorporates 4185 km^2 (99.2%) of the Santa Clara River drainage area (Fig. 1). This station is the final gauging station on the river (7 km from the river mouth) and has a 52-year record of discharge. The Carpinteria Creek gauge (USGS 11119500; Fig. 1) was also used for periods of limited data availability from the Santa Clara River gauge. Since this gauge incorporates a much smaller drainage area ($34\,km^2$), its peak discharge averages ~35-times less than the Santa Clara River, and these peak discharges typically occur ~4–6 h before the peak discharge in the Santa Clara River (Warrick, 2002).

Suspended sediment monitoring was conducted for 24 years (1969–1993) at the Santa Clara River station by the USGS, which was combined with sampling by Warrick (2002) during 1997–2000 to produce the data shown in Fig. 2. The suspended sediment data were fit with the locally weighted scatter smoothing (LOWESS) function of Cleveland (1979) to produce a rating curve for estimating suspended sediment concentrations in the river (Fig. 2). Residuals about the LOWESS relationship are normally distributed ($\alpha = 0.05$) and inversely related to discharge. Standard errors of the LOWESS relationships for the highest discharge rates ($>100\,m^3\,s^{-1}$) are approximately 0.15 $\log_{10}$ units, equivalent to ~40% error (Warrick, 2002).

Suspended sediment flux from the river was calculated by multiplying discharge data from the USGS gauge (recorded at 15-min intervals) by estimated suspended sediment concentrations from the rating curve (Fig. 2). If the 15-min data were not available (such as in 1998), suspended sediment flux from the Santa Clara River was estimated with the daily average water discharge and the rating curve, multiplied by a correction factor (equal to 1.28), which incorporates the average underestimation of daily sediment loads using the average daily discharge rates (Warrick, 2002). Errors in these sediment loads are approximated to be ±40%.

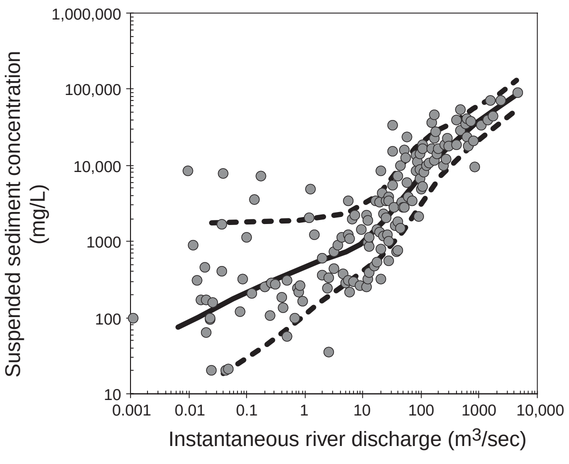

Fig. 2. Suspended sediment-river discharge relationships for the Santa Clara River from the USGS (stream gauge 11114000) and Warrick (2002). Only instantaneous measurements of sediment and discharge were included in this figure. The fitted rating curve along with standard errors (thick and thin lines, respectively) computed by the LOWESS technique of Cleveland (1979).

The buoyancy (g') of the Santa Clara River discharge was assessed with:

$$g' = g\,\frac{\rho_o - \rho_r}{\rho_o}, \tag{1}$$

where g is the gravitational constant, ρ_r is the river discharge density, and ρ_o is the ocean water density. Discharge is hypopycnal when positively buoyant ($g' > 0$) and hyperpycnal when negatively buoyant ($g' < 0$). The river discharge density (ρ_r) will be a function of the concentrations and densities of river water and suspended sediment (Mulder and Syvitski, 1995):

$$\rho_r = \rho_s C_{Vs} + \rho_w C_{Vw}, \tag{2}$$

where ρ_s and ρ_w are the densities of the solid sediment particles ($\sim 2650\,kg\,m^{-3}$) and the river water ($\sim 1000\,kg\,m^{-3}$), and C_{Vs} and C_{Vw} are the volumetric concentrations of sediment and water ($m^3\,m^{-3}$), respectively. Note that C_{Vs} can be calculated from the commonly reported mass concentration of suspended sediment (C_{ss}; $kg\,m^{-3}$, equivalent to $10^3 \times mg\,L^{-1}$ for fresh water) using

$$C_{Vs} = \frac{C_{ss}}{\rho_s}. \tag{3}$$

Thus, for typical Santa Barbara Channel seawater densities of $1025\,kg\,m^{-3}$, the river buoyancy will become zero at approximately $40,000\,mg\,L^{-1}$ of sediment. River discharges with sediment concentrations greater than $40,000\,mg\,L^{-1}$ will theoretically be hyperpycnal.

3.2. Wind, waves and currents

Measurements of wind, wave and current conditions in the Santa Barbara Channel region have been made available by the Santa Barbara

Channel–Santa Maria Basin Study (SBC–SMB) of the Center for Coastal Studies at Scripps Institute of Oceanography [data available at: http://www.ccs.ucsd.edu/research/sbcsmb/] and the National Data Buoy Center (NDBC) of the National Weather Service [data available at: http://www.ndbc.noaa.gov/hmd.shtml]. One of the SBC–SMB sites was utilized for this research, ANMI (located in the Anacapa Strait above the 200 m isobath; Fig. 1). ANMI has two vector measuring directional current meters located at 5 and 45 m depth. Longshore and crossshore current vectors were calculated by rotating the ANMI data by $-60°$. The NDBC sites are instrumented to measure wind velocity, wind direction, wave heights, sea-surface temperature and barometric pressure. Two NDBC sites (46023 and 46025; Fig. 1) were used since many periods of non-operation coincided with winter storm seasons and our data collection efforts.

Wave height observations were also obtained for the Ventura Harbor from the California Harbor Patrol. The Ventura Harbor is adjacent to the Santa Clara River mouth, and these unpublished observations represent approximate significant wave heights ($H_{1/3}$) of breaking waves near the mouth (J. Shelton, pers. comm., Ventura County Harbor Patrol).

3.3. Shipboard observations

Two 3-day stormwater cruises of the Santa Clara River plume were conducted for this research. Shipboard observations were made during one event of the 1996–1997 winter and one event of the 1997–1998 winter. The 1997–1998 winter storm season was severe and influenced by ENSO. CTD + BAT (conductivity, temperature, depth, and beam attenuation) profiles were obtained at all stations using a SeaBird Electronics 911*plus* CTD and a Sea-Tech 660-nm beam transmissometer (0.25-m path length). Water depth at each station was determined from the shipboard depth sounder, and the CTD carousel was lowered to within ~1 m of this depth to detail as much of the water column as possible without disturbing the bottom or harming the carousel.

Water samples were taken at 4–6 depths per station, which included surface and bottom samples taken within 1 m of the water surface and at the lowest depth of the cast, respectively. Samples were taken in Niskin bottles on the upward cast and were analyzed for properties including total suspended matter (TSM) >0.4-μm and particulate silica (PSi) >0.4-μm. TSM techniques included filtering 1100 mL water samples in triplicate onto 0.4-μm poretics polycarbonate filters, triple rinsing with distilled water, oven drying, desiccation and weighing. PSi was measured using the techniques of Brzezinski and Nelson (1989) and provide a second measurement of the lithigenic sediment in the river plumes as discussed below. The PSi measurements will include the influence of biological opal, although opal is assumed to be $<5\%$ of PSi, since measured chrolophyll-*a* concentrations in the plume were low ($<1\,\mu g\,L^{-1}$; M. Brzezinski, pers. comm., UCSB). PSi measurements were converted into suspended sediment concentrations by using an average clay molecular weight of $110\,g\,mol^{-1}$ Si (i.e., $1\,\mu mol\,L^{-1}\,Si = 0.11\,mg\,L^{-1}$ sediment). The average clay mineralogy was obtained from measurements by Fleischer (1972) of: 50% montmorillonite, 35% illite and 15% kaolinite.

During 1997, 26 CTD casts were obtained on January 26–28, which corresponded with peak river discharge conditions on January 26 (Table 1). Monitoring during 1998 (February 11–13) followed the peak discharge of February 8 by 3 days. Only seven CTD casts were obtained in 1998 (all on February 11) due to mechanical problems with the shipboard winch. The remaining shipboard dates in 1998 (February 12 and 13) were used to observe surface water chemistry, biology and optics throughout the Santa Barbara Channel (Toole and Siegel, 2001) and are not included in the results presented here. Station locations for the 4 cruise days are shown in Fig. 3.

4. Results

Water and sediment discharge were both greater prior to the 1998 field campaign than during 1997 (Table 1). Peak flow rates in 1997 were $460\,m^3\,s^{-1}$,

Table 1
Characteristics of shipboard observations and Santa Clara River discharge for monitored plume events

	Event 1997	1998
Shipboard sampling dates	Jan. 26–28	Feb. 11–13
Number of CTD casts	26	7
Peak river flow rate ($m^3\,s^{-1}$)	$460\,m^3\,s^{-1}$ (1/26/97)	$\sim 3000\,m^3\,s^{-1}$ [a] (2/8/98)
Event recurrence interval (yrs)	2.2	~ 10
Total water discharge ($\times 10^6\,m^3$)[b]	25 ± 3	130 ± 13
Total sediment discharge (kt)[b,c]	290 ± 120	4700 ± 1900
Average event C_{ss} ($mg\,L^{-1}$)[d]	$12,000 \pm 5000$	$36,000 \pm 15,000$
Peak C_{ss} ($mg\,L^{-1}$)[c]	$\sim 25,000$	$\sim 80,000$
River discharge type[e]	Hypopycnal	Hyperpycnal

[a]Peak discharge rate estimated as 35 times the peak discharge measured at the Carpinteria Creek stream gauge (see text).
[b]For the event periods defined by discharge January 24–27, 1997 and February 6–11, 1998.
[c]Calculated from LOWESS rating curve relationships in Fig. 2.
[d]Calculated as the ratio of total sediment discharge to total water discharge.
[e]Using simple buoyancy relationships of Eqs. (1)–(3), which predict a hyerpycnal threshold of 40 g L^{-1}.

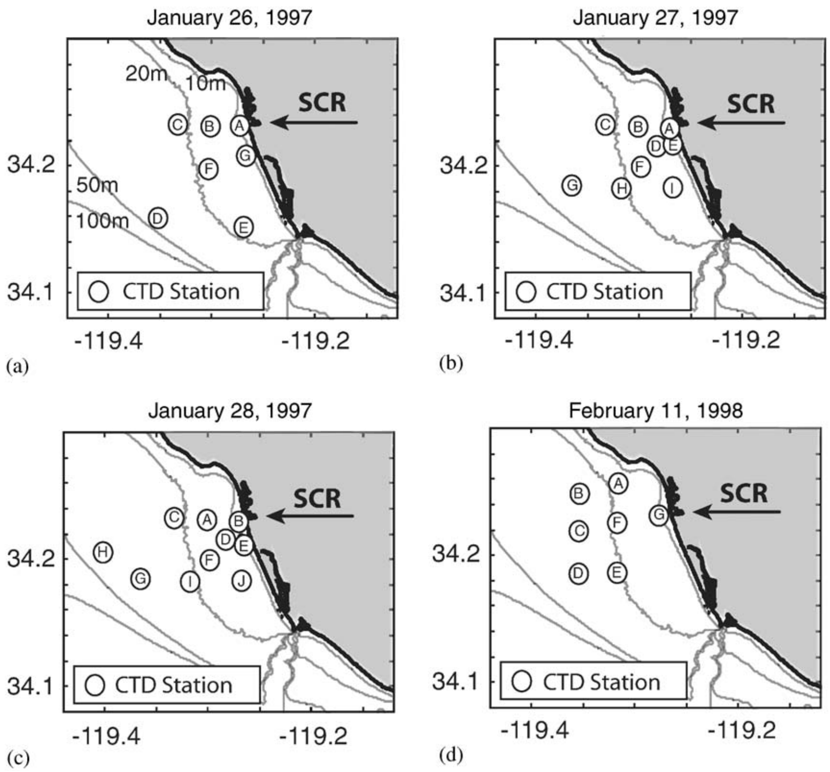

Fig. 3. (a–d) Station locations for river plume oceanographic measurements. The Santa Clara River mouth is identified with arrows, and 10, 20, 50, and 100 m isobaths are shown (gray lines).

while the peak flow rate during 1998 was estimated to be $3000\,m^3\,s^{-1}$ (raw 15-min data are not available for 1998, although the USGS calculated average daily discharge rates). Total water discharge during the events was calculated to be $25 \times 10^6\,m^3$ in 1997 and $130 \times 10^6\,m^3$ in 1998 (with ~10% error associated with the gauging data).

The higher flow rates in 1998 transported greater amounts of sediment at higher concentrations. Total sediment discharge from the Santa Clara River was estimated to be 290-kt during the 1997 event and 4700-kt during the 1998 event (Table 1). The average and peak event sediment concentrations, respectively, were ~10,000 and $\sim 25{,}000\,mg\,L^{-1}$ in 1997 and ~40,000 and $\sim 80{,}000\,mg\,L^{-1}$ in 1998. The relatively higher estimated concentrations for 1998 are supported by measurements of Santa Clara River suspended sediment concentrations of $20{,}600\,mg\,L^{-1}$ (February 3, 1998) and $36{,}500\,mg\,L^{-1}$ (February 23, 1998) during high river discharge (Warrick, 2002). Using the $40{,}000\,mg\,L^{-1}$ hyperpycnal threshold for the Santa Barbara Channel, the suspended sediment concentrations during 1998 may have been adequately high to induce hyperpycnal plumes, while the 1997 event was extremely turbid, but probably not hyperpycnal.

Atmospheric, ocean and river conditions for the 1997 and 1998 cruise dates are summarized in Figs. 4 and 5. In general, winds patterns included poleward wind stress prior and during precipitation and equatorward winds following the storm. Wind speeds during 1998 (up to $20\,m\,s^{-1}$) were approximately twice those measured in 1997 (up to $10\,m\,s^{-1}$; Figs. 4a and 5a). The ANMI current meter observations at 5 m depth reveal that longshore currents were dominantly poleward during the majority of the record during both 1997 and 1998 (Figs. 4b and 5b). This is consistent with the strong average poleward flow during the winter periods as described by Harms and Winant (1998), which can override local wind forcing.

Examples of water column profiles during the plume cruises are shown in Fig. 6 (a complete summary of the profiles is included in Warrick, 2002). A fresh water plume was observed in the upper ~5 m of the water column of each of these profiles, which corresponded with relatively turbid

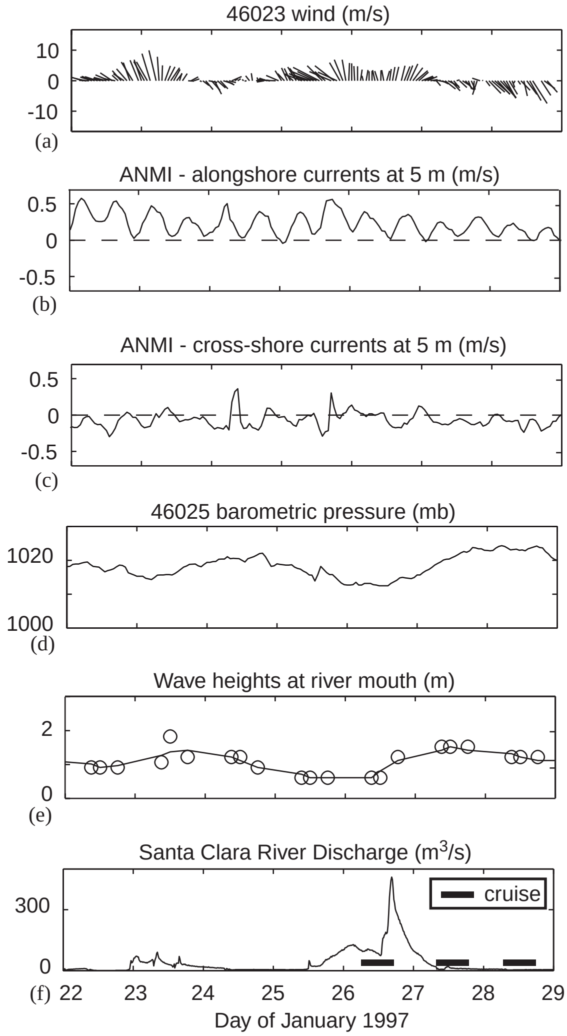

Fig. 4. Atmospheric, oceanic, and hydrologic conditions of the Santa Barbara Channel during the first stormwater plume cruises of January 26–28, 1997: (a) wind vectors for NDBC buoy 46023; (b) and (c) alongshore and cross-shore surface currents at CDIP buoy ANMI, data have been rotated −60°; (d) barometric pressure at NDBC 46025; (e) observed wave heights (circles) and 24-h mean wave heights (line) at the Santa Clara River mouth/Channel Islands Harbor; (f) Santa Clara River discharge with cruise timing highlighted with dark bars.

waters ($\sim 3\,m^{-1}$ BAT; Fig. 6). This freshened surface layer was observed to dilute and thin with distance from the river mouth. At a fixed point during the 1997 cruises, the surface plume diluted and deepened slightly with time. Similarly, surface

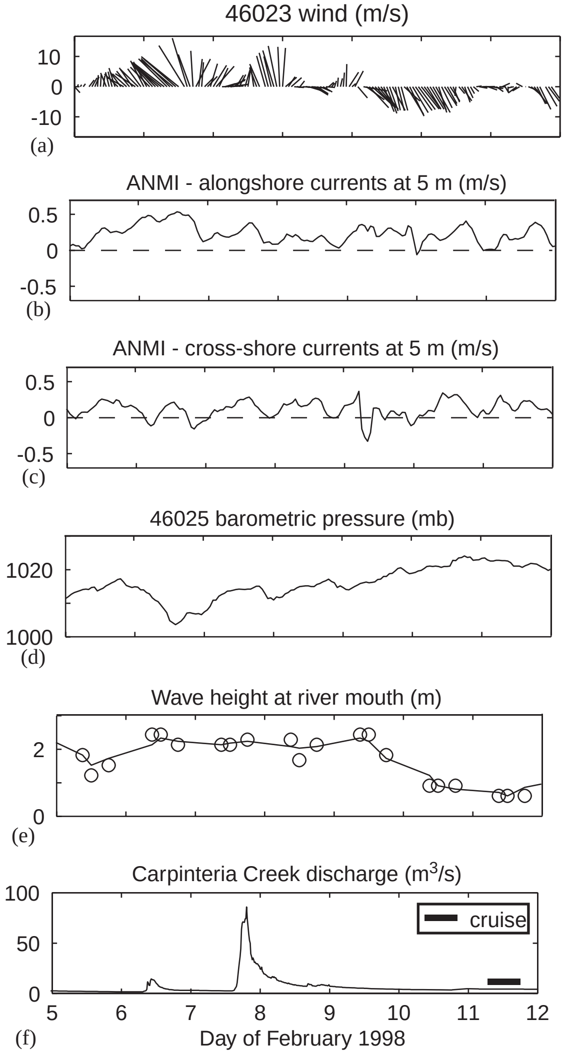

Fig. 5. Atmospheric, oceanic and hydrologic conditions of the Santa Barbara Channel during the second stormwater plume cruise of February 11, 1998: (a) wind vectors for NDBC buoy 46023; (b) and (c) alongshore and cross-shore surface currents at CDIP buoy ANMI, data have been rotated $-60°$; (d) barometric pressure at NDBC 46025; (e) observed wave heights (circles) and 24-h mean wave heights (line) at the Santa Clara River mouth/Channel Islands Harbor; (f) Carpinteria Creek discharge (Santa Clara River discharge $\sim$ 35 times greater and 2–6 h later; see text) with cruise timing highlighted.

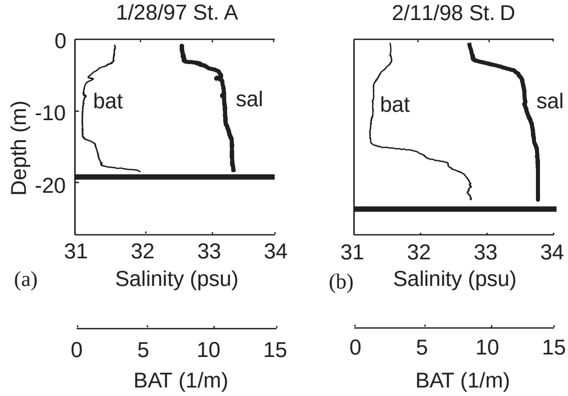

Fig. 6. (a,b) Example profiles of salinity (thick line, 'sal') and beam attenuation (thin line, 'bat') in the Santa Clara River plume. All data shown are unfiltered downward CTD casts. Depth of water column is shown with a dotted horizontal line.

water BAT decreased markedly with time and distance from the river mouth.

It is interesting to note that thick (5–10 m), turbid ($>5\,m^{-1}$ BAT) bottom nephloid layers were present at almost all stations in 1998, while not observed at any of the 1997 stations (Fig. 6). However, since bottom water salinity did not reverse in any of the 1998 profiles, we did not directly observe the entrainment of river freshwater into hyperpycnal plumes (as would be suggested from negative buoyancy). The bottom nephloid layers may represent either the remnants of suspended sediment transported by hyperpycnal plumes or bottom resuspension due to increased wave heights (>2 m) prior to the 1998 cruise (Fig. 5e). Unfortunately without continuous observations of the evolution of the water column (e.g., Traykovski et al., 2000), it is not possible to determine the cause of the thick nephloid layers. However, in the lowest 0.5 m of some of our casts, turbidity was too high to adequately measure ($>20\,m^{-1}$ BAT), which may suggest that highly sediment-laden waters existed immediately above the seabed. The maximum measured TSM of these bottom waters was $33\,mg\,L^{-1}$, which does not suggest fluid mud processes, although our sampling techniques (vertically oriented Niskin bottle) were likely unable to sample such a layer.

The spatial evolution of the surface water plume is shown in Fig. 7. On January 26 the plume is observed primarily near shore, where the water is both fresh and very turbid. On January 27 the fresh water and sediment plumes (Fig. 7) extend

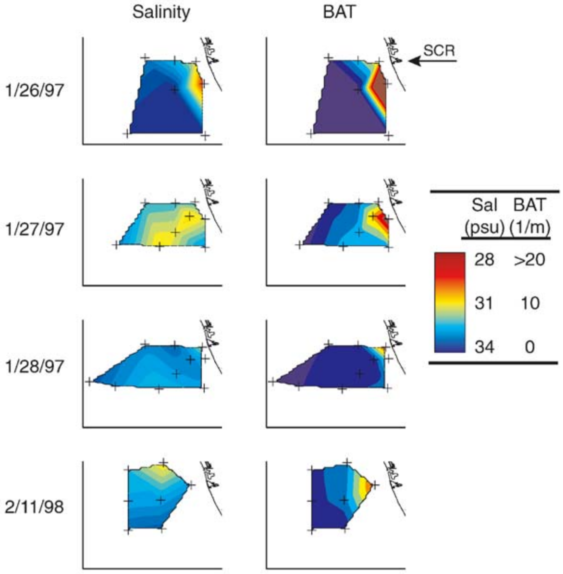

Fig. 7. Surface water measurements of average salinity and beam attenuation coefficient (BAT) of the upper 2 m in the Santa Clara River plume. Station locations shown with '+' symbols. Location of the Santa Clara River mouth is shown with an arrow on the upper right plot.

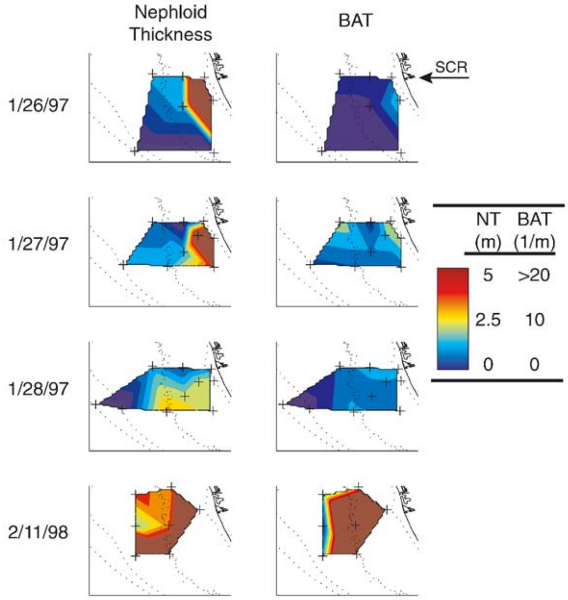

Fig. 8. Bottom water measurements of nephloid layer ($>5\,m^{-1}$ BAT) thickness and average beam attenuation coefficient (BAT) of the bottom 2 m in the Santa Clara River plume. Station locations shown with '+' symbols. Location of the Santa Clara River mouth is shown with an arrow on the upper right plot. The 10, 20, 30, and 40 m isobaths are also shown with dashed lines.

much farther out into the Santa Barbara Channel than on the previous day, although turbidity drops rapidly with distance from the river mouth likely due to particle settling. On January 28, 1997, the surface plume has become much more diffuse and may have advected south of the river mouth region due to the strong northwest winds (Fig. 4a). The turbidity of the surface waters has also dropped significantly from the previous day (Fig. 7).

The surface water observations of salinity on February 11, 1998 (Fig. 7) suggest that the plume has advected to the northwest. Although there may be some influence from the Ventura River plume, the observation is consistent with buoy observations that show that winds had slackened and currents were poleward at ANMI (Fig. 5). The turbidity of the surface waters was elevated throughout the survey region, although was most concentrated immediately off the mouth of the Santa Clara River (Fig. 7).

Summaries of bottom water observations are shown in Fig. 8. During the 1997 event the bottom nephloid layer was generally thinner (<5 m) and less turbid ($<10\,m^{-1}$) than the 1998 observations (>5 m and $>10\,m^{-1}$). The thick bottom plume of 1998 extended beyond the spatial limits of the cruise observations (>15 km from the river mouth and >40 m depth, Fig. 8). This pattern differs from the 1997 bottom conditions, in which all nephloid layers were generally thin and were observed only landward of the 20 m isobath.

5. Discussion

Mass balances of fresh water and sediment were constructed for each event using the CTD casts and water samples. The total fresh water at each station was calculated from reduced salinity measurements of the CTD casts (ambient salinities were 33.4 and 33.8 psu for 1997 and 1998, respectively). These observations were integrated across the total area sampled by linearly

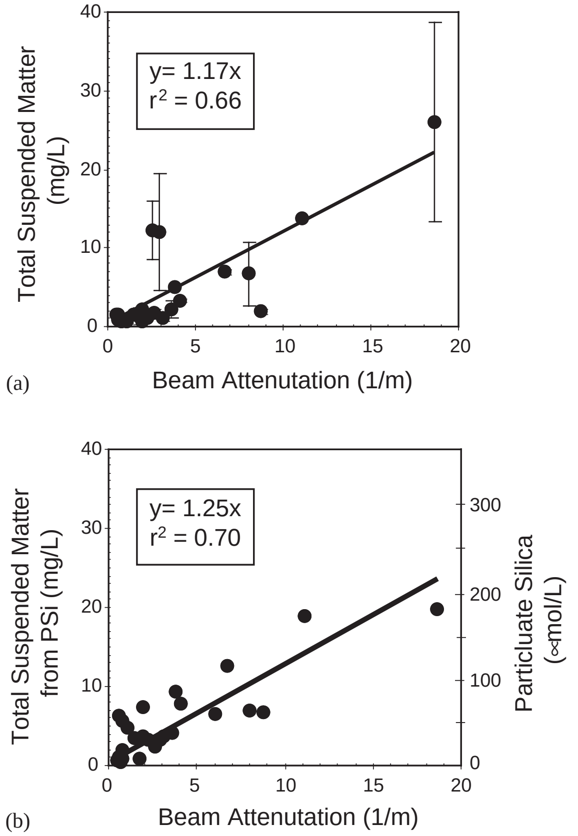

Fig. 9. The relationship between beam attenuation (BAT) and measures of particulate matter from the plume cruises. Samples obtained on sharp BAT interfaces were not included in these figures. (a) Total suspended matter (TSM) from triplicate filtered samples. Error bars equal one standard deviation. (b) TSM from particulate silica (PSi) measurements.

interpolating between the stations. Errors in these calculations are estimated to be ±10%.

Similarly, plume sediment was linearly interpolated between measurements of particulate matter for each cruise station. Unfortunately many TSM samples showed high standard errors (Fig. 9a), the source of which was likely poor filter integrity, since a few of the desiccated filters were observed to have small tears (other potential sources of error include poor sampling and inadequate rinsing). However, the slopes of both TSM and PSi-derived-TSM versus BAT were not significantly different from each other (1.17 ± 0.19 and 1.25 ± 0.12, respectively; Fig. 9), which suggests that these observations are somewhat consistent measurements of suspended matter. Further, these observations are consistent with optical relationships of fine suspended sediment measured by Baker and Lavelle (1984), which suggest slopes of 1.2–1.4 $mg\,m\,L^{-1}$ for clay particles.

Thus, total sediment at each station was estimated by applying the average relationship between suspended sediment and BAT ($TSM = 1.21 \times BAT$; Fig. 9) to the raw downcast BAT data within the range 0–20 m^{-1}. Regions of higher BAT ($>20\,m^{-1}$, approximate upper limit of instrument) were assigned to TSM measurements from samples within the layer. Surface and bottom plumes were distinguished for the sediment mass balance at mid-depth of each profile. Errors in these sediment mass calculations are approximately ±30%. Finally, accumulated errors of multiple measurements were compiled using quadratic sums, which assumes independent, random errors in the measurements.

For each cruise date a significant amount (7–37%) of the discharged Santa Clara River fresh water was observed within the cruise surveys (Table 2). During January 26, 1997 only ~11% of the total event runoff water could be accounted for within the area surveyed. However, on the two subsequent days much more of the fresh water was observed (~37% and ~28%). This is consistent with river discharge peaking during the end of the first cruise day (Fig. 4f). By January 28, the fresh water plume is more dispersed than January 27 as shown by less fresh water (7.0 versus $9.3 \times 10^6\,m^3$) measured within a larger region (46 km^2 versus 39 km^2; Table 2). During the 1998 cruise only ~7% of the discharged fresh water was observed within the survey stations, which suggests that much of the plume water had advected away from the river mouth region.

Although a significant amount of the river fresh water was observed during the cruises, very little of the total discharged sediment (0.08–1.2%) could be accounted for within the surveys (Table 2). During 1997 the total sediment observed increased from 3.0 kt (~1% of discharge) on January 26 to 3.4 kt (~1.2%) on January 27, which is consistent with the development of the plume as discussed

Table 2
Summary of Santa Clara River discharge and ocean cruise observations of fresh water and sediment

	Jan. 26, 1997	Jan. 27, 1997	Jan. 28, 1997	Feb. 11, 1998
Santa Clara River discharge				
Water ($10^6 \times m^3$)	25 ± 3	25 ± 3	25 ± 3	130 ± 13
Sediment (kt)	290 ± 120	290 ± 120	290 ± 120	4700 ± 1900
Ocean observations				
Area surveyed (km^2)	61	39	46	25
Fresh water ($10^6 \times m^3$)	2.8 ± 0.3	9.3 ± 0.9	7.0 ± 0.7	8.5 ± 0.8
Percent of river discharge (%)	$11 \pm 2\%$	$37 \pm 5\%$	$28 \pm 4\%$	$7 \pm 1\%$
Plume sediment (kt)				
Surface	2.0 ± 0.6	2.3 ± 0.7	1.1 ± 0.3	1.8 ± 0.5
Bottom	1.0 ± 0.3	1.1 ± 0.3	1.3 ± 0.4	2.1 ± 0.6
Total	3.0 ± 0.9	3.4 ± 1.0	2.4 ± 0.7	3.9 ± 1.2
Percent of river discharge (%)	$1.0 \pm 0.3\%$	$1.2 \pm 0.4\%$	$0.8 \pm 0.3\%$	$0.08 \pm 0.03\%$
R_{sed}[a]	$6 \pm 3\%$	$2.1 \pm 1.1\%$	$1.4 \pm 0.7\%$	$0.6 \pm 0.3\%$

[a]Ratio of sediment concentrations (computed by Eq. (3)).

previously. By January 28 total observed sediment dropped to 2.4 kt (~0.8%), although a larger ocean area was surveyed. This sediment was partitioned somewhat more in the surface plume on January 26 and 27 and somewhat evenly into surface and bottom plumes on January 28 (Table 2). On February 11,1998, 3.9 kt of sediment was observed in the plume of the Santa Clara River (Table 2), although this mass of sediment accounted for only ~0.08% of the total river sediment output. During the 1998 cruise, approximately half the measured sediment mass resided in the surface plume, whereas the remaining half existed in the thick bottom nephloid layers.

The amount of sediment discharged by the river and *not* observed directly in the plumes was substantial during each cruise date. A measurement of this lost sediment is the ratio of sediment concentrations (R_{sed}), which is defined by

$$R_{sed} = \frac{Sed_{obs}/FW_{obs}}{Sed_{dis}/FW_{dis}}, \tag{4}$$

where Sed_{obs} and FW_{obs} are the masses of sediment and fresh water observed in the surface plume, and Sed_{dis} and FW_{dis} are the masses of river sediment and fresh water discharged. If sediment mixes conservatively with river plume waters (i.e., there is no settling), the surface water R_{sed} will be equal to unity. Values lower than this reveal the portion of discharged river sediment remaining in the plume. Calculations of R_{sed} (Table 2) suggest that the total observed sediment in the freshened plume was much less (0.6–6%) than would have been expected if sediment was a conservative tracer of river water. During the peak discharge date of January 26, river sediment observed in the surface plume was only ~6% that expected from conservative mixing (this value would be only 9% if the sediment from the entire water column is considered). Thus, a vast majority of sediment had settled from the surface plume *rapidly* and *inshore* of the cruise limits (i.e., <1 km from the river mouth). On subsequent days R_{sed} decreased to 2.1% and 1.4% for the surface plume, which is equivalent to removal of 67% and 33% of the sediment mass per day, respectively. This suggests continued sediment settling from the river plume. During the 1998 cruise date, R_{sed} in the surface plume was ~ 0.6%. This very low value is not unusual, since these observations were obtained on the third day following the storm event. Comparing with the 1997 observations, the 1998 value is approximately half the second day R_{sed} value of 1.4% measured on January 28, 1997, which may suggest that suspended sediment continues to settle at relatively constant rates (~50% per day) following dispersal.

6. Summary

The energetic Santa Clara River plume delivers large amounts of freshwater and sediment to the eastern Santa Barbara Channel during brief, episodic discharge events. The pathways and fate of these materials can be understood from the results of the oceanographic observations described here coupled with results of other researchers' work. A conceptual model of Santa Clara River plume pathways based on these results is shown in Fig. 10.

Discharge from the Santa Clara River is very heavily laden with sediment, which may produce dense, hyperpycnal discharges ($>40\,\mathrm{g\,L^{-1}}$ suspended sediment). Although direct ocean observations of hyperpycnal conditions were not obtained in this research, other results (Wright et al., 1990; Chow, 1998) suggest that hyperpycnal plumes may not travel far out onto continental shelves due to additional friction on the upper plume boundary and rapid sedimentation rates. Regardless if the river discharge exceeded the hyperpycnal density

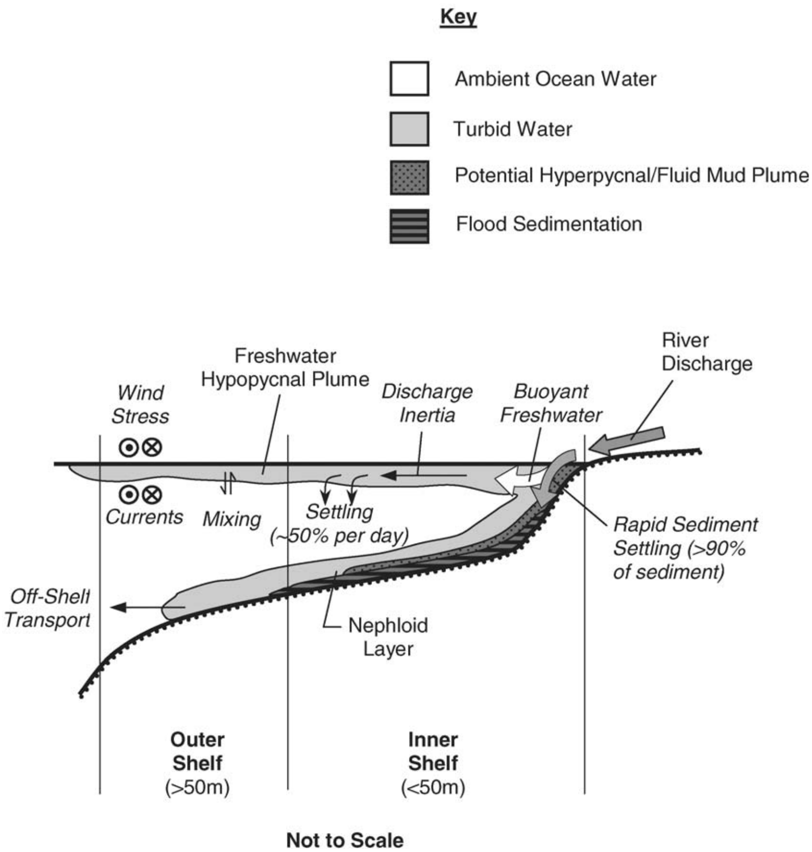

Fig. 10. Conceptual model of Santa Clara River discharge into the Santa Barbara Channel emphasizing the major river water and sediment pathways. Zones of rapid sediment settling, momentum dominated discharge, and potential hyperpycnal plumes are suggested. Significant vertical exaggeration is used to illustrate vertical variation in properties.

threshold during our observations, exceptional amounts of river suspended sediment was removed from the surface hypopycnal plumes. This rapid settling of suspended sediment removed over 90% of river sediment almost *immediately* upon discharge and within ~ 1 km of the river mouth. Thus, sediment is non-conservative in the mixing of river and ocean waters and most of the removal of sediment occurs directly offshore of the river mouth (Fig. 10). The removal of sediment may be due to buoyancy phenomena of the high river sediment concentrations (e.g., Parsons et al., 2001) or to high rates of flocculation (e.g., Hill et al., 2000), neither of which can be evaluated with our data. Sediment remaining in the surface hypopycnal plume gradually settles (in part, presumably, due to flocculation) at a rate that reduces the sediment mass by ~50% per day (Table 2, Fig. 10).

The freshwater hypopycnal plume is advected in jet-like structures within ~ 10 km of the river mouth due to the high discharge inertia (Warrick et al., 2004; Fig. 10). Offshore of this inertia-dominated zone, Warrick et al. (2004) suggest that surface plume transportation is largely a function of local wind stress and ocean currents, which is supported with the observations presented here (Fig. 7). Once offshore, the hypopycnal plume slowly mixes with the ambient seawater, which decreases plume salinity and deepens the salinity anomalies.

Immediately off the river mouth, the majority of the discharged sediment appears to be transported within ~ 1 m of the bed, below the extent of our observations (Fig. 10). Occasionally the lowest 0.5 m of our BAT casts had turbidities too high to adequately measure ($>20\,m^{-1}$), which may suggest that highly sediment-laden waters existed immediately above the seabed. However, the total mass of sediment within the depths of our observations only accounted for less than 2% of the total discharged sediment mass (Table 2), which suggests that the majority of river sediment is not transported within these regions of the water column.

Our observations are consistent with Drake's (1972) observations that much of the Santa Clara River sediment from the large 1969 events settled very close to shore (within 20 km of the river mouth). Although we did not measure sedimentation or bottom boundary layer processes, our mass balance results suggest that almost all of the river sediment either escapes along or deposits upon the inner shelf seabed. This may produce a situation in which fluid mud transport is likely (e.g., Ogston et al., 2000; Traykovski et al., 2000; Wright et al., 2002). However, if and when dense hyperpycnal plumes and/or fluid muds occur, they appear to rarely extend past the continental shelf (>200 m isobath) into the Santa Barbara Basin or the Hueneme/Mugu Canyons since sediment records reveal only a limited number of these events (Gorsline, 1996; Schimmelmann et al., 1998). On the contrary, the majority of terrestrial sediment entering the Santa Barbara and other surrounding basins (see Schwalbach and Gorsline, 1985) is transported rather slowly and continually by nephloid layers as reported by Drake et al. (1972), Kolpack and Drake (1985), and Thunell et al. (1995). Thus, although the bottom nephloid laters observed here contained little of the total discharged river sediment mass, transport within these layers into the surrounding basins appears to be the dominant off-shelf sediment transport mechanism over annual time scales (Fig. 10).

7. Conclusion

Shipboard observations of the Santa Clara River plume are presented and summarized into water and sediment mass balances and a conceptual model of plume dispersal. During large runoff events, suspended sediment in the freshened surface plume was reduced to only ~6% of the total sediment discharged, which suggests very rapid initial settling within ~1-km of the river mouth. The sediment mass in the surface plume was then reduced by ~50% per day during the following 2 days, which suggests continued settling at rates lower than during plume initiation. These findings suggest that most of the discharged river sediment settles quickly on the continental shelf, and then is transported into the surrounding basins by nephloid layers.

Acknowledgements

This manuscript was significantly improved by two anonymous reviewers. Funding provided by the NASA Earth System Science Fellowship program, NOAA and NASA support of the UCSB Plumes and Blooms research group, and NSF Long Term Ecological Research (LTER) funding for the Santa Barbara Channel LTER. We are also grateful for the assistance and support of the NOAA Channel Islands National Marine Sanctuary for cooperation and use of the R/V Ballena. Further assistance was provided by John Milliman, Ceretha MacKenzie, Jeanne-Marie Hermann, Mark Otero, Jens Sorensen, Michael Neumann, Dede Toole, Karen Patterson, Scott Valentine, and Olga Polykov.

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