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Sediment yields from small, steep coastal watersheds of California

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ABSTRACT

Study region: Coastal watersheds of southern California, United States.
Study focus: We sought to better understand the rates and variability of suspended-sediment discharge from small coastal watersheds (<100 km^2) of California. Suspended-sediment concentrations and stream discharge were measured with automated samplers near the mouths of four small watersheds (10–56 km^2).
New hydrological insights for the region: The watersheds were found to have suspended-sediment concentrations that extended over five orders of magnitude (1 to over 100,000 mg L^{-1}). Sediment concentrations were weakly correlated with discharge (r^2 = 0.10–0.25), and four types of hysteresis patterns were observed during high flow events (clockwise, counterclockwise, no hysteresis, and complex). Annual sediment yields varied by 400-fold across the four watersheds (e.g., 5–2100 t km^{-2} yr^{-1} during the 2003–2006 water years), and sediment discharge was measurably elevated in one watershed that was partially burned by a late summer wildfire. Dozens of high flow events provided evidence that suspended-sediment yields were generally related to peak stream discharge and event-based precipitation, although these relationships were not consistent across the watersheds. This suggests that watersheds smaller than 100 km^2 can provide large – and therefore important – fluxes of sediment to the coast, but that simple techniques to estimate sediment loads, such as sediment rating curves, hydrologic regressions, and extrapolation using global sediment yield relationships that include watershed area as a primary factor, may provide poor results.

1. Introduction

Small, steep watersheds along land–ocean margins discharge ecologically and geologically relevant masses of sediment, nutrients, carbon and other constituents into the world's oceans (Milliman and Syvitski, 1992; Lyons et al., 2002; Beusen et al., 2005; Milliman and Farnsworth, 2011). Although it has been estimated that over half of the sediment discharged to the sea originates from the cumulative discharge of watersheds smaller than 10,000 km^2 (Milliman and Syvitski, 1992), these computations are hindered by a scarcity of data from the smallest coastal watersheds. For example, the most thorough global database to date by Milliman and Farnsworth (2011) effectively captures ~82% of the ~105 million km^2 of land area

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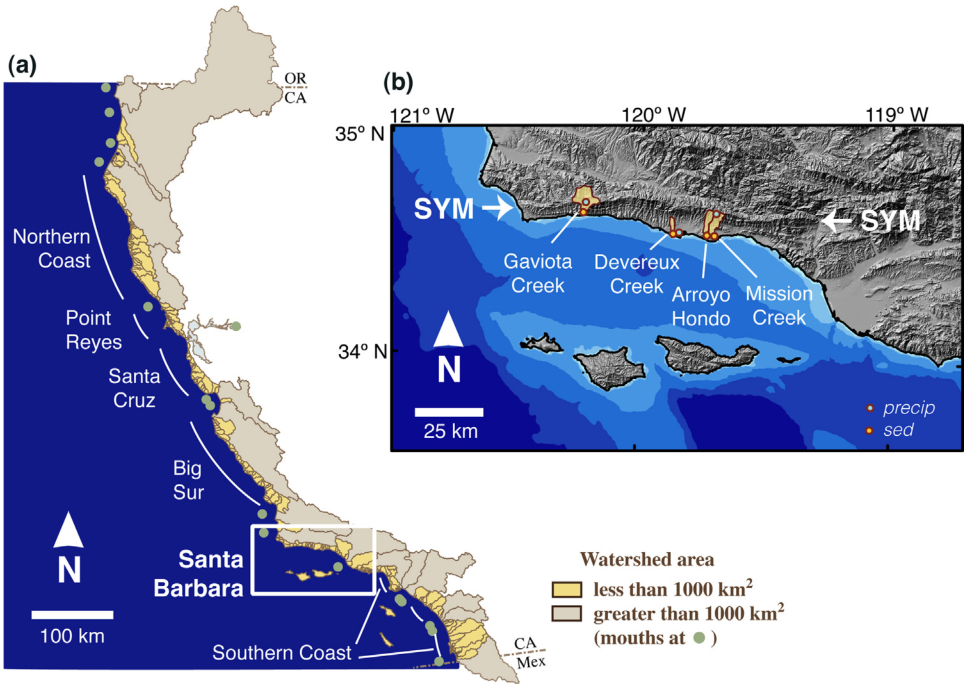

Fig. 1. Coastal watersheds of California and the Santa Barbara study area. (a) Watersheds of the California coast, highlighting the smallest of these watersheds (i.e., those with drainage areas less than 1000 km^2) in yellow. Coastal regions receiving drainage primarily from these smaller watersheds are named and labeled. (b) The Santa Barbara Channel coastal region including four watersheds draining the Santa Ynez Mountains (SYM) that were monitored for this study. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

draining to the world's oceans. Although this database includes hundreds of watersheds smaller than 10,000 km^2, there are over ten thousand coastal watersheds ranging between 10 and 10,000 km^2 – and representing roughly 18% of the Earth's land surface – for which no discharge data exist (Milliman and Farnsworth, 2011).

Thus, global biogeochemical inventories lack information from the smallest watersheds of the world, which likely have high yields of sediment, nutrients and carbon (Vörösmarty et al., 2000; Gomez et al., 2003; Ludwig et al., 2009; Milliman and Farnsworth, 2011). It is, therefore, important to better quantify material fluxes from small coastal watersheds to better constrain regional and global assessments of biogeochemical cycles including sediment budgets.

At regional scales, such as the coast of California in North America (Fig. 1a), small watersheds are the only drainage type for long coastal stretches. For example, the 'Northern Coast' and the 'Big Sur' coastal regions of California are both over 150 km long yet have no watersheds greater than 1000 km^2 draining into them (Fig. 1a). Although there is a scarcity of discharge information for these smaller watersheds (cf. Farnsworth and Warrick, 2007), there is substantial need for these data largely owing to the high marine biodiversity and productivity along these steep, rugged coastal sections (Duggins et al., 1989; Croll et al., 2005) and the potential for fluvial inputs to these marine systems to influence habitats, water quality and ecosystem functions (Warrick et al., 2005; Page et al., 2008; Foley and Koch, 2010; Goodridge and Melack, 2012).

Substantial improvements have occurred in the hydrologic monitoring techniques and understanding of small mountainous watersheds, although much of this understanding has arisen from the study of headwater tributaries within larger watersheds (de Vente et al., 2011; Hinderer et al., 2013). These headwater studies suggest that there are fundamental differences in the frequency and magnitude of sediment discharge in the smaller, low-order drainage basins compared to the larger, high-order drainage basins (Walling, 1974; Graft, 1988). For example, sediment discharge from small watersheds is commonly ephemeral, and the majority of the long-term sediment discharge occurs during and immediately following infrequent heavy precipitation when suspended-sediment concentrations can rise to grams or hundreds of grams per liter (Tropeano, 1991; Coppus and Imeson, 2002; Milliman and Kao, 2005; Galewsky et al., 2006; Mano et al., 2009; Grodek et al., 2012; Conaway et al., 2013). Additionally, several factors can exacerbate erosion within and sediment yields from these small watersheds, including: ground shaking from seismic activity (Dadson et al., 2004; Hovius et al., 2011); vegetation clearing and sediment release after wildfire (Shakesby and Doerr, 2006; Malmon et al., 2007; Lamb et al., 2011; Warrick et al., 2012), glacial processes (Hinderer et al., 2013); shifts in climate (Galewsky et al., 2006); geomorphic change of the watershed landscape (Nearing et al., 2007; Nadal-Romero and Regüés, 2010); human-derived disturbances from land use and channel alterations (Trimble, 1981, 1997; Owens et al., 2010; de Vente et al., 2011); and combinations of these effects (Madej and Ozaki, 1996; Pinter and Vestal, 2005; Warrick and Rubin, 2007; García-Ruiz et al., 2013).

The coastal watersheds of the Santa Barbara Channel region (Fig. 1) provide an excellent setting to sample and characterize sediment discharge from small watersheds, owing to the long, straight Santa Ynez Mountain range that results in a series