Ocean and Coastal Management 195 (2020) 105287

Contents lists available at ScienceDirect

Ocean and Coastal Management

journal homepage: http://www.elsevier.com/locate/ocecoaman

Barriers and opportunities for beneficial reuse of sediment to support coastal resilience

Nicola Ulibarri[a,*], Kristen A. Goodrich[b,c], Paroma Wagle[a], Matthew Brand[d], Richard Matthew[a,b], Eric D. Stein[e], Brett F. Sanders[a,d]

[a] Department of Urban Planning & Public Policy, University of California Irvine, 300 Social Ecology I, Irvine, CA, 92697, USA
[b] Irvine Blum Center for Poverty Alleviation, University of California Irvine, 5548 Social & Behavioral Sciences Gateway, Irvine, CA, 92697, USA
[c] Tijuana River National Estuarine Research Reserve, 301 Caspian Way, Imperial Beach, CA, 91932, USA
[d] Department of Civil & Environmental Engineering, University of California Irvine, 5200 Engineering Hall, Irvine, CA, 92697, USA
[e] Southern California Coastal Water Research Project, 3535 Harbor Blvd # 110, Costa Mesa, CA, 92626, USA

ARTICLE INFO

Keywords:
Beneficial reuse of sediment
Coastal management
Sea level rise
California
Tijuana

ABSTRACT

As urbanization and climate change alter sediment fluxes, relative sea level, and coastal erosion around the world, management of sediment as a resource is increasingly important. Sediment is needed to enhance marsh accretion rates, raise the grade elevation of development, and build up beaches and dunes. Beneficial reuse of sediment refers to the repurposing of local sources of sediment for these applications, material typically available from dredging or sediment capture infrastructure, and represents a more sustainable approach compared to the status-quo involving transport to and from distant locations. However, in many locations, beneficial reuse remains a concept or is constrained to small-scale applications. In this paper, we draw on interviews with coastal sediment managers and regulators in Southern California to identify barriers to beneficial reuse and opportunities to overcome them. Interviewees reported numerous regulatory, technical, psychological, financial, and interorganizational barriers in their watersheds and regions. By highlighting these barriers, we aim to identify systemic changes that would make beneficial reuse a realistic and accessible option for Southern California and elsewhere. Most prominently, a more flexible regulatory framework that allows sediment management practices to adapt over time, pilot studies to understand how beneficial reuse works in various settings, and educational programs for regulators and the public could make beneficial reuse a more widespread approach.

1. Introduction

Coastlines around the world are undergoing rapid change, with increasing migration to coastal regions, rapid urbanization, more frequent and intense storms and flooding, and sea level rise (Merkens et al., 2018, 2016; Neumann et al., 2015; Nicholls et al., 2018). Sediment is an important—yet often overlooked—dimension of how resilient coastlines can be to this change (Cappucci et al., 2011; Khalil et al., 2010; Morris, 2012). Humans have significantly altered terrestrial sediment fluxes through changing land use (Syvitski et al., 2005; Trimble, 1997; Warrick et al., 2013) and constructing dams and debris basins that trap sediment and alter streamflow (Kondolf et al., 2014; Syvitski et al., 2005; Willis and Griggs, 2003). In terms of coastline change, these changes have had mixed impacts with some shorelines eroding, some accreting, and some remaining stable (Luijendijk et al., 2018; Syvitski et al., 2005). Within estuarine and coastal embayments, excess sediment tends to degrade water quality and wetland habitat from reduced circulation, block ports and navigation, and increase flood risks due to reduced drainage capacity. On other hand, as the rate of sea level rise increases, there are increasing needs for sediment to nourish wetlands, restore beaches and dune ecosystems, and mitigate against erosion and flooding (Hamm et al., 2002; Hanley et al., 2014; Temmerman et al., 2013).

Given both a supply (e.g., from dredging) and demand for sediment at the same sites, there have been calls for beneficial reuse, or the site-based optimization of coastal sediment by recognizing that it is a valuable resource rather than a waste product (Ewing et al., 2008). Dredging—to address flood control, maintain existing navigation channels, and to construct new terminals, channels, and waterways—produces millions of cubic yards of dredge material each year in Southern

* Corresponding author.
E-mail address: ulibarri@uci.edu (N. Ulibarri).

https://doi.org/10.1016/j.ocecoaman.2020.105287
Received 24 February 2020; Received in revised form 18 May 2020; Accepted 18 June 2020
Available online 30 July 2020

California alone (Krause and McDonnell, 2000). The dredged material is typically shipped to offshore dredged material disposal sites, lost to any potential reuse, yet there is substantial demand for sediment for wetland restoration, beach nourishment, construction, and other goals (Devick, 2019). Beneficial reuse connects the supply and demand, such that sediment can serve a broad public purpose including reductions in the greenhouse gas emissions from the long-distance transport of sediment which promotes greater sustainability. More broadly, beneficial reuse responds to calls for more adaptive management of coastal sediment (Apitz, 2008; Lillycrop et al., 2011).

However, in many locations, beneficial reuse is an aspiration rather than an active practice (Devick, 2019). While collaboration to explore existing beneficial reuse standards and to coordinate source identification, movement, and placement efforts between restoration, flood control, and dredging communities is occurring regionally, many questions about implementing beneficial reuse still remain (Devick, 2019). In this paper, we aim to identify and report barriers to beneficial reuse of sediment and other adaptive approaches to management based on interviews with federal, state and local stakeholders involved in sediment management in Southern California. The overarching objective is to draw attention to the factors prohibiting more sustainable approaches for coastal resilience. We also report on the perceived strengths and weaknesses of existing approaches to sediment management, identify opportunities to overcome barriers to beneficial reuse, and discuss applicability of these approaches elsewhere.

2. Methods

2.1. Case description

Southern California contains a highly urbanized and energetic coastline with regions of both accretion and erosion under both human and natural influences (Flick, 1993; Hapke et al., 2006; Sanders and Grant, 2020; Vitousek et al., 2017). The region's sediment is fed largely by flashy fluvial input, with the majority of riverine sediment movement occurring during occasional storms (Warrick et al., 2015; Warrick and Milliman, 2003) and both increases and decreases in fluxes as a result of stormwater infrastructure (Sanders and Grant, 2020). Many of the region's wide sandy beaches are the result of historical harbor dredging (Flick, 1993), and periodic beach nourishment projects are implemented to maintain beach widths for recreational, economic, and flood mitigation purposes (Flick, 1993; Patsch and Griggs, 2006).

This research uses a comparative case study design (Yin, 2017) to assess the barriers and opportunities to beneficial reuse for watersheds varying across a number of ecological, socioeconomic, and institutional factors. Two locations in Southern California were chosen as sites for the study: (1) Newport Bay Estuary (NBE) and (2) Tijuana River Valley (TRV) (Fig. 1). Both sites share the same climate (warm dry summers and cool wet winters), fall within a coastal valley that is bordered by upland/mesa topography and at the terminus of a mountainous watershed, and contain significant natural wetland resources in the context of a highly developed Southern California (Sanders et al., 2020). However, the sites differ in several ways: First, wetland habitat mainly consists of tidal channels and salt marsh in NBE, while in addition to tidal channels and salt marsh, there is extensive riparian (freshwater) wetland habitat in TRV. Secondly, the coastal valley is highly urbanized in NBE, while the setting is rural in the TRV with land predominately managed as parks and open spaces. Third, the watershed is largely built-out in NBE, while in TRV the watershed is undergoing rapid development. Fourth, the NBE watershed is an order of magnitude smaller in area than TRV's watershed. Fifth, NBE is located in a much wealthier area, with median household incomes three times higher than TRV. And sixth, and most critical with respect to sediment management, NBE has a Total Maximum Daily Load (TMDL) for sediment whereas TRV does not, yet there is a collaborative group of representatives from regulatory agencies, landowners, and other stakeholders that coordinate management. Hence, these two sites in many ways represent end-points for both land uses and management for coastal valleys and embayments of Southern California: one system that is largely built out with a history of regulation under a TMDL, and one system that is rapidly expanding with voluntary collaboration to address sediment management.

2.1.1. Case 1: San Diego Creek/Newport Bay Estuary

The NBE site is at the terminus of the Newport Bay Watershed, which extends to the Santa Ana Mountains to the east and the San Joaquin Hills to the west and southwest (US EPA, 2017). The majority of runoff from the 394 km^2 watershed enters Newport Bay from San Diego Creek, with smaller contributions from the Santa Ana Delhi and Bonita Canyon channels.

The watershed is highly urbanized (nine cities are partly or fully within the watershed) with some agricultural use (US EPA, 2017). Development of this area has occurred mostly in the last 50 years with growth slowing in recent years. The City of Newport Beach is among the most affluent cities in California; in 2015, the median annual household income was $113,071, compared with $64,500 for California as a whole (Sanders et al., 2020).

NBE comprises two geographic areas: (1) the upper region of the bay is a nature preserve characterized by an intertidal marsh that provides habitat for several threatened and endangered species and (2) the lower region (Newport Harbor) falls within the City of Newport Beach and is developed with waterfront homes, marinas for boating and commercial areas; both areas support numerous recreational activities (Sanders et al., 2020). Newport Harbor was developed over the first half of the 20th century on sand dunes and marshlands formed by the interaction of the Santa Ana River with the tides and waves of the Pacific Ocean (Sanders et al., 2020). Sediment has been managed at this site by the Environmental Protection Agency's (EPA) regulatory mechanism of a TMDL since 1999 through investment in infrastructure such as sedimentation basins (Orange County Public Works, 2020). The sediment basins are located underwater at the head of Upper Newport Bay, and thus rely on gravitational settling during storm events. Excessive sedimentation in NBE initially occurred with the construction and erosion of soft-bottom drainage channels (Trimble, 1997), and thus source control in the watershed emphasizes channel armoring.

2.1.2. Case 2: Tijuana River Valley

Geographically, the Tijuana River Watershed is an approximately 4530 km^2 binational area that includes a diverse and complex drainage system ranging from 1800 m pine forest-covered mountains to the tidal saltwater estuary at the mouth of the Tijuana River in the United States, with the Tijuana River originating at the confluence of Arroyo Alamar and Río de las Palmas in Mexico (Tijuana River Valley Recovery Team, 2012). A wide variety of land uses are present in the watershed, from largely undeveloped open space in the upper watershed to highly urbanized,[1] residential, commercial, military, industrial, and agricultural areas in the lower watershed. The Tijuana River Valley was determined to be an area with 'lowest access to opportunity' within the City of San Diego (City of San Diego, 2019), and Imperial Beach is among the least affluent stretches of the Southern California coastline (Sanders et al., 2020). The 2015 median annual household income in Imperial Beach was $46,659 (US Census Bureau, 2020).

Nearly three-quarters of the watershed is located in Mexico, but the Tijuana River drains to the Pacific Ocean through an approximately 8-square mile area called the Tijuana River Valley that is located immediately north of the border and contains one of the largest intact coastal wetland systems in Southern California (Goodrich et al., 2019). Proximity to the rapidly developing and erosive canyon hillsides in Tijuana,

[1] In 2010, the population of the San Diego-Tijuana border region was 4.8 million, making it the largest bi-national metropolitan area shared between the United States and Mexico (Al-Delaimy et al., 2014).

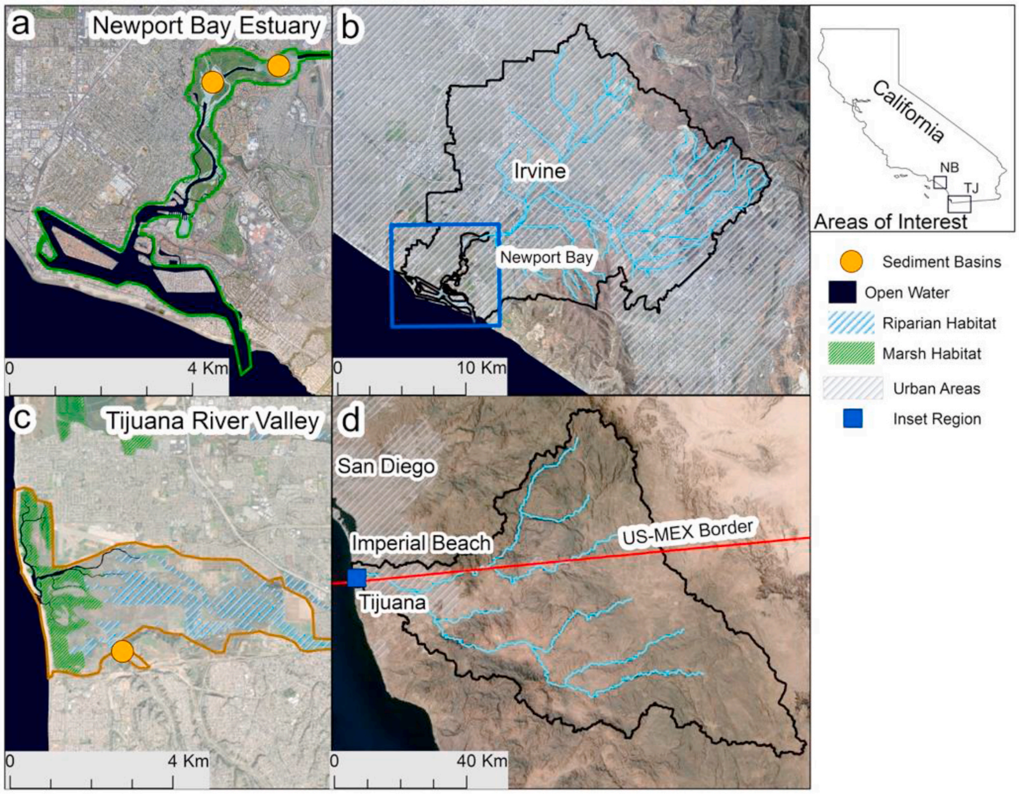

Fig. 1. Map of the case study watersheds. (a) shows NBE, with shading to indicate open water and riparian and marsh habitat and circles to indicate the location of the sediment collection basins. (b) shows the full San Diego Creek watershed. (c) and (d) similarly shows the TRV and the full Tijuana River watershed.

particularly the Los Laureles Canyon (LLC) sub-drainage, presents sedimentation and burial risk to the wetlands downstream during rain events (Goodrich et al., 2020). Sediment basins on Mexican and U.S. sides of the border intercept sediment and debris flows; in a less modified and sediment-disrupted system, some coarse and fine sediment would reach the coastal system through river flow and tidal exchange Nordby, 2019. TRV's sediment basins, unlike NBE, are located within riparian wetland (or arroyo) habitat.

In the TRV, there is no TMDL for sediment. Environmental management including sediment and debris challenges are addressed in part by the Tijuana River Valley Recovery Team, a collaborative group including regulatory agencies, landowners, and other stakeholders (Tijuana River Valley Recovery Team, 2012). Additionally, Minute 320, an agreement developed by the International Boundary and Water Commission, guides cross-border collaboration and activities through its conceptual framework (International Boundary and Water Commission, 2015).

2.2. Data and methods

This research uses an inductive, qualitative approach to elicit information on sediment reuse from individuals who are experts on sediment management in Southern California. Our aim is to identify barriers to beneficial reuse—the "cause of an effect" rather than the "effect of a cause" (Smith, 2014)—and a qualitative approach enables the researcher to assemble a causal framework when categories are not known *a priori* (Moon and Blackman, 2014; Yin, 2017).

Twenty-two in-depth, semi-structured interviews were conducted with stakeholders on the current state of sediment management in Southern California, discussing topics such as economics, policies and regulations, extreme events and climate change impacts, and preferred future policy and management interventions. Interviewees were sediment managers, defined as individuals who played a role (e.g., regulatory, programmatic, land management, advocacy) in NBE or TRV, as well as federal and state agency actors who work at the regional or state level. Interviewees represented city and county governments (n = 7), state agencies (n = 6), federal agencies (n = 6), and NGOs (n = 3) (Table 1). The initial list of interviewees included key players in the sediment management system who were either prior contacts to the research team or names obtained upon contacting organizations known to engage in sediment management or regulation. To obtain coverage of organizational perspectives that our initial sample missed, additional interviews were obtained through snowball sampling (Parker et al., 2020; van Rijnsoever, 2017), asking interviewees to recommend additional individuals to speak with. The same interviewer was present at all interviews, with one or two additional interviewers present. Interviews lasted approximately 1 h.

Interview questions were designed to: (1) identify how managers understand the coupled human-natural system they work within; (2) to produce a causal mental map from the vantage point of a sediment manager of how their system — and decision-making related to sediment management in their system — works; and (3) to identify key threats, opportunities, challenges and possible innovations (Goodrich et al., 2019). Importantly, none of the interview questions focused specifically on beneficial reuse; the topic rather emerged when interviewees were asked about their goals for sediment management, current management approaches, and/or their desired innovations. Interviews were recorded and transcribed.

Using a modified grounded theory approach (Corbin and Strauss, 2007), iterative coding was used to identify emergent themes and patterns in the interviews. We began with broad categories based on the interview guide, such as "regulation" to capture any time a respondent discussed existing or proposed regulations or "movement" to capture discussions of sediment transport. These categories were iteratively refined to better match the terminology used by interviewees, and new categories were added when a topic was introduced that didn't fit neatly

Table 1
Interviewees by watershed and organization type.

Organization Type	NBE Focus	TRV Focus	Regional or State Context
City or County	City of Newport Beach, County of Orange (2), Orange County Parks	City of Imperial Beach, City of San Diego	
State Government	CA Department of Fish and Wildlife, Santa Ana Regional Water Quality Control Board	CA State Parks, San Diego Regional Water Quality Control Board	Bay Conservation and Development Commission, CA Coastal Commission, CA Coastal Conservancy
Federal Government		International Boundary and Water Commission, US Fish and Wildlife Service, Tijuana River National Estuarine Research Reserve (TRNERR) [a]	Environmental Protection Agency (2), US Army Corps of Engineers
NGO	Orange County Coastkeeper	Surfrider Foundation, WiLDCOAST	

Note: In reporting interview quotes, we refer solely to organization type (rather than name) to preserve anonymity. [a]TRNERR is a federal-state-NGO partnership.

into an existing category. Subcategories were added to capture detail (e.g., “dredging” added as a subcategory of “management approaches”, and “contaminants” added as a subcategory of “challenges”). For analysis, we focused on categories that were discussed by multiple interviewees. We then assessed which organization types had raised each topic, which watershed they were located in, and how discussion of these categories varied by watershed and by organization type. In the text, we provide quotes that are representative of perspectives raised by multiple organizations.

3. Results

3.1. Perceived strengths and weaknesses of current approaches to sediment management

Current management approaches, as described in Section 2.1, are seen to work in that they keep excess sediment out of the estuaries. Interviewees note that in TRV, for instance, it is far easier to manage excess sediment coming from the canyons that have retention basins than those that don’t (Federal). Likewise, NBE’s TMDL was seen as a pioneering approach to sediment management when it was implemented: “It was the first TMDL for sediment in California … A lot of other agencies look [ed] at [NBE’s] and copied our approach” (State). The TMDL was also the first attempt to address sediment considerations from a watershed approach.

However, there were also many perceived weaknesses of the current approaches in both watersheds, which were described by one interviewee as “inelegant [and] ham-handed” (Federal). First, interviewees noted that the current approach of capture, dredge, and dump is expensive and inefficient. Dredging is “arduous and hard and long and expensive” (City/County), as is trucking sediment off site (Federal, City/County) and maintaining the sediment channels (City/County). Second, the regulatory regime underlying the approach is viewed as complex and at times burdensome. Permits for dredging or construction can take years to get: “If you don’t have an ongoing operation and maintenance program that gets implemented consistently, then you’ve got to jump through all the regulatory and permitting hoops from the very beginning” (City/County). In both watersheds, the permitting process is complicated by endangered species considerations. When sediment is not cleared from the channels or basins at regular intervals, plants take root and create habitat for protected species; as a result, when the sediment managers need to clean the channels or dredge, additional consultations for federal and state endangered species protections are needed: “Since sediments have been there for so long, we have a lot of ESA issues; I mean our basins are full of … all kinds of threatened and endangered species” (Federal, also City/County). This incentivizes the need to dredge in order to ‘prevent’ sensitive habitats from developing, which in turn hinders objectives of wildlife protection programs and regulations. Lastly, multiple interviewees stated that shipping sediment to a landfill was wasteful: “the worst thing is probably put it in a landfill, but … that happens too” (Federal, State).

Perhaps more importantly, the current approach was not perceived as adaptive to either social or environmental changes. In both watersheds, development patterns are changing, altering sediment loads. Both systems face increasing inundation and growing flood risks with sea level rise (Luke et al., 2018; Sanders et al., 2020; Thorne et al., 2018), and managers did not feel that the current approach would help coastal wetlands keep pace with sea-level rise. In NBE, development has slowed and the watershed has reached close to full urbanization, so less sediment is coming into the drainage basins (City/County). Managers worried that they might “control the sediment input into the bay to a degree where it becomes sediment deficient, [such that] sea level rise will cause habitat loss” (City/County). As an added challenge in NBE, the estuary is surrounded by bluffs, so managers worry that habitat cannot migrate to higher elevations. In Tijuana, development is increasing and was viewed as “uncontrollable” (City/County) because it happens across the border in Mexico. TRV managers thus have to prepare for larger than expected volumes of sediment compared to natural or fully-urbanized watersheds, and there is acknowledgement that changes in land use practices in Tijuana may trigger a different management scenario (Boudreau et al., 2017). They felt that they currently had enough sediment that “we’re going to be fine in terms of salt marsh habitat and sea level rise” (State), but that with more active management they could maintain healthy habitats and recreational spaces as the system shifts.

Finally, managers do not feel that the current regulations and infrastructure are flexible enough to deal with these changes. For instance, regarding the TMDL, an interviewee noted, “What’s frustrating is that it was so prescribed. They didn’t allow it to be flexible, and … what we’re looking for is to allow adaptive management.” (City/County, also State). Another said, “We need flexibility … [T]hose hard prescriptive requirements in the bay and looking at the bay as a static [isn’t flexible]” (City/County).

3.2. Opportunities for beneficial reuse

Given the challenges with the current approach, many of the interviewees discussed the desire to make the sediment system more resilient and sustainable. Approaches discussed include both reusing dredge material to nourish beaches or provide ecological benefits and (in NBE) directly reconnecting the upper watershed (sediment sources) with downstream wetlands and beaches. (“We are beneficially reusing sediment, putting it down drift where it would have gone if … it hadn’t been trapped in harbors” (Federal); We need to ensure “that sediment is present to allow wetlands to keep pace with sea level rise” (Federal, also NGO).) These approaches are seen to both enable adaptation to SLR and changes in development patterns, but also to potentially reduce dredging costs.

In TRV, several projects are completed and underway to explore alternatives to the current practice of disposing of sediment excavated from sediment basins in landfills. One such alterative is nearshore placement; the United States Geological Survey (USGS) conducted a pilot project from 2008 to 2009 at the Tijuana River National Estuarine Research Reserve involving the placement of 45,000 cubic yards of sediment with approximately 40% fine-grained material[2] in the coastal nearshore, and monitoring the processes of fine-sediment transport (Warrick, 2013). Results indicated that the fine-grained sediment was winnowed from the coarse material at the placement site. As a result, coarse material stayed in the nearshore where it could contribute to littoral sediment budgets and the fine material was carried offshore, distributed over long distances, and settled into deeper water where fine sediment makes up the majority of the existing substrate (Farnsworth and Warrick, 2007; Warrick, 2013). The sediment volume was an order of magnitude smaller than the sediment volume associated with an annual river discharge, suggesting that it would take ten such nearshore placement events per year to equal the annual river discharge contribution to the coastal sediment budget. Additionally, no impacts to nearby biological communities were detected (Everest International Consultants, Inc. and Nordby Biological Consulting, 2017). Results from this study were discussed between managers and regulators in focus groups to explore opportunities for future permitting of nearshore placement of dredged sediment, a more beneficial alternative in TRV and elsewhere in the region than disposing of sediment in landfills (Goodrich and Warrick, 2015).

Stakeholders in the TRV region also received funding from the state to plan for the reuse of excavated sediment to restore the Nelson Sloan Quarry, a former sand and gravel quarry in the watershed. This project is in planning phases, and interviewees articulated their aspirations for it: "The hope is that we will be able to take the sediment... out of the sediment basins, …out of other flood control channels in the river valley, and from [the] salt marsh restoration projects and take them to this abandoned quarry and restore that quarry back to natural hillside. That's a cheaper way to manage sediment, because of the proximity. An example … that would not only be economically more viable, but it would have a secondary environmental benefit." (State).

While NBE had not begun any specific projects for beneficial reuse, interviewees also discussed wanting to use thin layer augmentation to restore habitat in the upper bay and nearshore placement to nourish beaches and more cost effectively dispose of dredge material: "We're looking at putting sediment on the habitat to see if the plants can grow up through it, which would allow us to be able to do that in places where we would actually increase the elevation" (Federal). They are currently looking to other areas for guidance. Regarding thin-layer placement, one manager told us of their goal to find a demonstration project elsewhere:

"[In] Upper Newport Bay, it seems like we're a little bit more sediment-starved now. It's been kind of a surprising outcome because for so long, we were so hyper-focused on removing sediment, that now we kind of want it. We're wondering, how are we going to maintain these habitats? We kind of look to Seal Beach Wildlife Refuge [in north Orange County]. They did a lot of the augmentation in their marsh areas because they don't have any sediment inputs. I think the first project failed. I don't know if they're going to attempt it again, because it was pretty expensive. We're sort of kind of looking around to see, okay, well, who's augmenting their habitat [so that we can learn to make it work]." (State).

In NBE, there is also interest in modifying the capture of sediment from upstream portions of the watershed, for instance through less frequent or extensive dredging, to allow more sediment to enter the bay.

Interviewees saw a shift in mindset as being one of the key enablers of this new thinking: "10 years ago we didn't have this conversation about thin layer placement" (Federal). For instance, regulators were perceived as being less rigid regarding the implementation of the TMDL (City/County), which permitted some flexibility around developing pilot projects that meant leaving sediment in Newport Bay.

[2] Coarse and fine grained sediment are a "natural and dynamic element of the California coastal system" (Farnsworth and Warrick, 2007, p. 1).

3.3. Barriers to beneficial reuse

3.3.1. Regulatory barriers

There were numerous perceived barriers to beneficial reuse or other changes that would enable a more sustainable system. First, regulatory inflexibility was seen as a major barrier. In a general sense, the permitting regime was seen as a barrier, as "what any one agency needs to permit [beneficial reuse] and what monitoring they want, and the specific conditions of the permit, that's where things can get jumbled up" (Federal). Interviewees noted that as soon as you add multiple agencies, those permits requirements can conflict with each other and slow down the process (City/County). And existing regulations, like the California Coastal Act, were seen not to match current needs and understandings of natural infrastructure:

"There's an understanding, in general, about how resilient coastlines include things like healthy marshes and different natural infrastructure that can be protective of development behind it, potentially. I think there is a definite openness to innovative approaches. Our challenge, sometimes, is finding how to get those projects, how to get them to a place where it's consistent with the Coastal Act, which hasn't been updated since 1973. That's the challenge." (State).

Likewise, while USACE does some sand sorting to make dredged material more easily reusable, they can't keep the sediment for too long because that triggers regulations that "restrict … selling federal property for beneficial reuse" (Federal).

These regulatory challenges have definitely limited change in both watersheds. The current innovations in TRV, like Nelson Sloan Quarry, were perceived to be "held up" in bureaucratic processes (City/County, State), despite stakeholders having funding to implement them. For instance, after receiving a grant from the state, the City of Imperial Beach was told they could not maintain the Quarry on their own, but would need jurisdictional agreements from the State Park and San Diego County. Likewise, stakeholders in NBE felt constrained by the TMDL. As one interviewee said, "We've done our job, we've met our objectives [of reducing sediment loads]. We want out … [but] Once you're in the TMDL hotel, you're never checking out." (City/County).

3.3.2. Technical barriers

Second, reusing sediment faced several technical challenges. Contaminated sediments were a concern in both watersheds, with selenium (in NBE), trash, and sewage all mentioned. In both watersheds, stakeholders also raised the need to match the grain size of available sediment to its use. For instance, in a project in Imperial Beach, TRV stakeholders discovered the importance of grain size: "It ended up being that the sand was really coarse. Well, the science at the time said use coarse sand [because] it sticks around longer … One of the consequences of having coarse sand is then you had more water flowing in through it and we had some inundation problems with, somehow, water washing up on the back beach soaking into the sand. Instead of draining back out towards the ocean, [it] drained back out towards the estuary." (City/County). Another interviewee noted that conversations can stall because people get "hung up on grain size" (Federal). And lastly, interviewees noted that there are still many uncertainties about how to do placement effectively (NGO). The uncertainties are compounded by the fact that much of what managers do know comes from a few pilot projects in the region and elsewhere: "I think you have to think very hard about what you're intending to scale up … You just can't get around the site-specific nature of all of our estuaries and bays. That is just how it is. If you try too hard to take an approach and fit it exactly into a different—you just increase the chance of failure." (State).

Interviewees also felt that the scalability challenge interacted with regulatory inflexibility, as pilot projects didn't serve as a strong enough basis to update regulations: "I think changing policies on any one pilot is hard. If there were several pilots, say, along the coast … and we found consistent results and this and this is—then that starts being like, "Okay, we have a basis for making decisions." (Federal, also State).

A final technical challenge related to the timing of placements. Sediment placement had to coincide with optimal hydrological conditions: “We would do a placement activity potentially when the river’s flowing, and it would be just a blip in the radar compared to what’s coming down through the system naturally” (Federal). Given Southern California’s infrequent but large rainstorms, this could be challenging. And specifically for beneficial reuse, the sediment had to be available at the same time as its designated use: “It’s really hard to logistically match up a restoration project with a dredging project. It’s just the timing and the access. They’ve got to be dredging exactly when you need the sediment because they don’t want to stockpile it, and [it] can’t sit on the boat.” (Federal).

Interestingly, some of the technical uncertainties raised may be more perceived than real. Regarding grain size, the “80/20 rule”, which prohibits the use of material containing more than 20% fines for beach nourishment purposes, was cited by multiple interviewees. However, interviewees disagreed whether this was a hard-and-fast regulation (Federal) or simply a “rule of thumb” that could be treated more as a guideline (State). During a focus group held in 2014, where the implications of the 80/20 rule were discussed by sediment and coastal managers, it was clarified that regulatory agencies rely more on site information (i.e., appropriate grain size) when making decisions, rather than considering this as an exclusionary rule of thumb (Goodrich and Warrick, 2015; see also California Coastal Sediment Management Workgroup, 2005).

Similarly, regarding contamination, interviewees in TRV disagreed whether they had clean sediment if all of the trash and debris was removed. For instance, one interviewee said, “mostly in the sediment in the valley itself, the sediment has been pretty clean. There have been some residual pesticides. It’s actually really high-quality beach sand.” (State). From another perspective, “We have no idea what’s in the sediment. There’s a very strong suspicion that there’s something well beyond just sewage. We’re talking about suspected chemicals in heavy metals.” (NGO).

3.3.3. Psychological barriers

Third, interviewees recognized that there were psychological barriers that would have to be overcome in order to implement beneficial reuse. For instance, in NBE, beach visitors have complained that placed sediment is polluted because it looks different than the white beaches they’re used to (City/County). And in TRV, there is a perception that reconnecting the system would introduce trash from the Mexican side of the border (State). More broadly, long held assumptions about ‘effective’ management would have to change in both watersheds. For instance, among environmentalists, many are uncomfortable with managed restoration, thinking that work with machines can’t be “natural”: “We’ve received so many calls from people like, ‘There’s a bulldozer in the estuary. Oh my God. What are you guys going to do? Are you going to go chain yourselves to it?’ We’re like, ‘No. We actually want it in there.’” (NGO). Similarly, environmental groups felt that many engineers and regulators are more supportive of hard structures because they provide more certain performance (State). Interviewees described the need to change these assumptions as affecting many different individuals, from educating visitors to the beach to needing to convince the “chain of management” that a new approach is better (Federal).

3.3.4. Financial barriers

The fourth set of barriers were financial. Stakeholders in both watersheds raised concerns about the monetary costs associated with getting the sediment, transporting the sediment, and changing the regulations (e.g., the TMDL) to allow reuse. Nourishment would still require the dredging of sediment, but with potentially increased transportation costs: “we can barely get enough money to just take that material, dredge it, and put it right down coast” as opposed to move it the longer distances potentially needed for beneficial reuse projects (Federal, also City/County). For projects under US Army Corps of Engineers (USACE) authority,[3] this is a major barrier, as they are required to choose the least-cost option, even if that option does not provide as many benefits; most dredging projects require USACE authorization. Other financial concerns revolved around the costs of restoration (State), reconnecting the upper watershed to the lower estuary to enable sediment to move through (State), and even paying to update the TMDL technical report (City/County).

3.3.5. Inter-organizational barriers

The final challenge relates to collaboration and coordination between organizations. Because there are many players and jurisdictions engaged in sediment management, individuals have to work across organizational boundaries, but it’s hard to initiate and maintain collaboration. Working between agencies is difficult because each organization has different goals: “Having multiple agencies make it even more difficult because here we’ve got to deal with the federal government. We’ve got to deal with the Coastal Commission and all the state regulatory agencies and they don’t always agree among themselves.” (City/County). In instances where there is coordination, a lack of leadership still hinders progress: “We go to meetings, but we don’t have any follow-up actions because there’s no one championing this” (City/County). And in other cases, collaborations that were once perceived as successful are now “shutting down.” For instance, regarding the cross-border collaboration created by Minute 320, one interviewee said, “Now because it’s turned into a legal issue, certain people are not coming to the table anymore, because that’s the advice that their counsel [gives]” (State).

4. Discussion

In both NBE and TRV, interviewees articulated clear goals for what they envision as sustainable coastal sediment management to entail, particularly relating to beneficial reuse of sediment. Indeed, they were enthusiastic for the possibilities that beneficial reuse raises for their watersheds. And in both cases, though more prominently in TRV, stakeholders are actively making changes via pilot projects and infrastructure development to become more sustainable. However, we found that managers face substantial constraints to changing the system, including regulatory inflexibility, technical difficulties, psychological barriers, financial constraints, and inter-organizational collaboration and coordination challenges. These barriers pose a problem for long term resilience, given that both watersheds have already-degraded ecosystems and face future changes from sea-level rise and altered urbanization patterns.

Table 2 summarizes the perceived barriers to beneficial reuse of sediment, along with which types of organizations mentioned them. All of the barriers were mentioned by interviewees in both watersheds, although the exact characteristics varied. Table 2 also shows that all of the barriers were cross-cutting by organization type, with all mentioned

Table 2
Organization types mentioning perceived barriers to beneficial reuse of sediment.

Barrier	City	County	State	Federal	NGO
Regulatory	X	X	X	X	
Technical		X		X	X
Psychological		X	X	X	X
Financial	X	X	X	X	
Inter-organizational	X		X		

[3] USACE is the primary federal regulator of sediment under §404 of the Clean Water Act (Ulibarri and Tao, 2019).

by multiple organization types and all but inter-organizational collaboration mentioned by all organization types. This suggests that these are widespread challenges that are not unique to a single agency or organization.

At the same time, this study suggests several promising dimensions of sediment management. First, while this study was framed as a comparative case study given the strong differences in context, both watersheds actually faced very similar opportunities and barriers. Despite the watersheds' drastically different sizes, financial setting, trends in development (TRV's rapid urbanization versus NBE's slowing development), and overall level of infrastructure development, interviewees in both watersheds articulated the same desire to see increased beneficial reuse and the same set of challenges. The only exceptionally distinct difference was the binational setting in TRV, which made for a much more complicated governance setting. However, the same challenges of working across organizational and jurisdictional settings was articulated by NBE interviewees. This suggests that perhaps the categories of barriers to beneficial reuse that we identified are fairly universal across different physical and socioeconomic settings.

Additionally, many of the interviewees pointed to other locations, for example elsewhere in California and on the East Coast, for possible options for sediment management. This shows a willingness to change and innovate, which is quite different than other sectors (like water) where managers tend to be conservative and resistant to innovation (Lach et al., 2005). This also suggests that any barriers to innovation are not due to a lack of awareness or knowledge about potential options.

5. Recommendations

As beneficial reuse of sediment has the potential to bolster coastlines against sea level rise, finding ways to implement it more effectively and efficiently is critical. In this study, we found that despite a common desire to incorporate beneficial reuse more prominently as a management approach in both case study watersheds, regulatory inflexibility, technical difficulties, psychological barriers, financial constraints, and inter-organizational collaboration and coordination challenges limited the ability of stakeholders to do so.

While we have focused on identifying barriers, each barrier also highlights opportunities that would help make beneficial reuse an achievable approach for Southern California, and likely for other regions.

Regulatory.

- Create streamlined permitting approaches for beneficial reuse projects meeting certain predefined criteria.
- Consider benefits of sediment to the coast during when issuing or updating a sediment TMDL.
- Clarify expectations around the 80/20 rule—that it is a rule, not a regulation—for project proponents with projects that involve fine grained sediment.

Technical.

- Support additional studies, modeling, and pilot projects to advance the practice of beneficial reuse. In particular, consider projects that advance knowledge about scaling up or translating results between locations. This includes the optimal frequency (or triggers) for implementing reuse.

Psychological.

- Educate the public about the benefits and hazards of sediment placement, especially for beaches or recreational areas.
- Engage in pilot projects to reassure skeptical managers, regulators, and publics about its effectiveness.

Financial.

- Relax the requirement for governments to use the lowest-cost option when an alternative meets diverse social or environmental needs.
- Provide funding for both pilot and large-scale projects (especially those that provide insight that can apply to other regions or coastlines).
- Allow for credit trading with potential users of sediment to reduce dredging cost.
- Allow the benefit of sediment delivery to coastal environments to be considered in benefit-cost analysis.

Inter-organizational:

- Provide facilitation and incentives for inter-organizational coordination and innovation.
- Support organizations to act as leaders in regional sediment management via funding.
- Support existing interagency sediment management workgroups to better coordinate activities.
- Explore opportunities to "match" entities with excess sediment from projects to entities that need sediment for restoration projects.

Many of these recommendations are most relevant for federal and state agencies that hold regulatory authority and have the most resources to support new studies and coordination approaches. However, addressing technical, psychological, and inter-organizational barriers can be more effective if all organization types (cities, counties, and NGOs) are engaged, since these organizations have strong local knowledge and connections with the affected public.

Although these recommendations are specific to Southern California, we anticipate that similar recommendations would apply elsewhere. The two watersheds have very different socio-environmental contexts, but the barriers we identified were cross cutting: they were raised by a diversity of organization types and by interviewees in both watersheds, suggesting more widespread applicability. For instance, while NBE's TMDL was developed specifically for that watershed's sediment and land use context, it is likely that other locations have rigid regulations that may constrain future innovation. Thus, providing financial incentives, making regulations more flexible, conducting pilot studies and building models to grow knowledge about beneficial reuse in a particular context (or under various scenarios), educating the public and decision-makers, and providing support for inter-organizational coordination will likely pave the way for more implementation of beneficial reuse around the world.

Declaration of competing interest

The authors declare no conflict of interest.

Acknowledgements

The authors thank the interviewees and other SedRISE project Management Translation Advisory Group (MTAG) members for sharing their valuable time and expertise. This work is made possible by a grant from the National Oceanic and Atmospheric Administration Ecological Effects of Sea Level Rise Program (#NA16NOS4780206).

References

Al-Delaimy, W.K., Larsen, C.W., Pezzoli, K., 2014. Differences in health symptoms among residents living near illegal dump sites in Los Laureles canyon, Tijuana, Mexico: a cross sectional Survey. Int. J. Environ. Res. Publ. Health 11, 9532–9552. https://doi.org/10.3390/ijerph110909532.

Apitz, S.E., 2008. Adaptive management principles and sediment management. J. Soils Sediments 8, 359–362. https://doi.org/10.1007/s11368-008-0040-2.

Boudreau, D., Crooks, J.A., Goodrich, K., Lorda, J., 2017. Preparing for Climate Change in the Tijuana River Valley. Tijuana River National Estuarine Research Reserve, Imperial Beach, CA.
California Coastal Sediment Management Workgroup, 2005. Results from CSMW Task 5: 80/20 Coarse-To-Fines Rule of Thumb. California State Parks.
Cappucci, S., Scarcella, D., Rossi, L., Taramelli, A., 2011. Integrated coastal zone management at Marina di Carrara Harbor: sediment management and policy making. Ocean Coast Manag. 54, 277–289. https://doi.org/10.1016/j.ocecoaman.2010.12.006.
City of San Diego, 2019. San Diego's Climate Equity Index Report (San Diego).
Corbin, J., Strauss, A., 2007. Basics of Qualitative Research: Techniques and Procedures for Developing Grounded Theory, third ed. Sage Publications, Inc, Los Angeles.
Devick, C., 2019. Larger Trends in Beneficial Reuse of Dredged Sediment: what This Means for the Great Lakes. SmithGroup. URL. https://www.smithgroup.com/perspectives/2019/larger-trends-in-beneficial-reuse-of-dredged-sediment-what-this-means-for-the. accessed 2.21.20.
Everest International Consultants, Inc, Norby Biological Consulting, 2017. Tijuana River Estuary Fate & Transport Study: Summary Report for Coastal Managers.
Ewing, L., Synolakis, C., Kalligeris, N., Foteinis, S., Evangelos, V., 2008. The role of regional sediment management in coastal zone management. In: Coastal Engineering 2008. https://doi.org/10.1142/9789814277426_0337.
Farnsworth, K.L., Warrick, J.A., 2007. Sources, dispersal, and fate of fine sediment supplied to coastal California (Scientific Investigations Report No. 2007–5254). US Geological Survey. https://pubs.usgs.gov/sir/2007/5254/sir2007-5254.pdf.
Flick, R., 1993. The myth and reality of southern California beaches. Shore Beach 61, 3–13.
Goodrich, K.A., Basolo, V., Feldman, D.L., Matthew, R.A., Schubert, J.E., Luke, A., Eguiarte, A., Boudreau, D., Serrano, K., Reyes, A.S., Contreras, S., Houston, D., Cheung, W., AghaKouchak, A., Sanders, B.F., 2020. Addressing pluvial flash flooding through community-based collaborative research in Tijuana, Mexico. Water 12, 1257. https://doi.org/10.3390/w12051257.
Goodrich, K.A., Ulibarri, N., Matthew, R., Wagle, P., Brand, M., Stein, E., Sanders, B., 2019. Co-development of coastal sediment management approaches in social ecological systems in southern California. In: Coastal Sediments 2019. WORLD SCIENTIFIC, pp. 1821–1825. https://doi.org/10.1142/9789811204487_0157.
Goodrich, K.A., Warrick, J.A., 2015. Fines: rethinking our relationship. In: Coastal Sediments 2015. WORLD SCIENTIFIC. https://doi.org/10.1142/9789814689977_0148.
Hamm, L., Capobianco, M., Dette, H.H., Lechuga, A., Spanhoff, R., Stive, M.J.F., 2002. A summary of European experience with shore nourishment. Coastal Engineering, Shore Nourishment in Europe 47, 237–264. https://doi.org/10.1016/S0378-3839(02)00127-8.
Hanley, M.E., Hoggart, S.P.G., Simmonds, D.J., Bichot, A., Colangelo, M.A., Bozzeda, F., Heurtefeux, H., Ondiviela, B., Ostrowski, R., Recio, M., Trude, R., Zawadzka-Kahlau, E., Thompson, R.C., 2014. Shifting sands? Coastal protection by sand banks, beaches and dunes. Coastal Engineering, Coasts@Risks: THESEUS, a new wave in coastal protection 87, 136–146. https://doi.org/10.1016/j.coastaleng.2013.10.020.
Hapke, C.J., Reid, D., Richmond, B.M., Ruggiero, P., List, J., 2006. National assessment of shoreline change Part 3: historical shoreline change and associated coastal land loss along sandy shorelines of the California Coast (No. Open-File Report 2006-1219). US Geological Survey. https://pubs.usgs.gov/of/2006/1219/of2006-1219.pdf.
International Boundary, Water Commission, 2015. Minute 320: General Framework for Binational Cooperation on Transboundary Issues in the Tijuana River Basin. International Boundary and Water Commission, Tijuana.
Khalil, S.M., Finkl, C.W., Roberts, H.H., Raynie, R.C., 2010. New approaches to sediment management on the inner continental shelf offshore coastal Louisiana. J. Coast Res. 591–604. https://doi.org/10.2112/10A-00004.1.
Kondolf, G.M., Gao, Y., Annandale, G.W., Morris, G.L., Jiang, E., Zhang, J., Cao, Y., Carling, P., Fu, K., Guo, Q., Hotchkiss, R., Peteuil, C., Sumi, T., Wang, H.-W., Wang, Z., Wei, Z., Wu, B., Wu, C., Yang, C.T., 2014. Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents. Earth's Future 2, 256–280. https://doi.org/10.1002/2013EF000184.
Krause, P.R., McDonnell, K.A., 2000. The Beneficial Reuse of Dredged Material for Upland Disposal. Harding Lawson Associates, Novato, CA.
Lach, D.H., Ingram, H., Rayner, S., 2005. Maintaining the status quo: how institutional norms and practices create conservative water organizations. Tex. Law Rev. 83, 2027–2053.
Lillycrop, L.S., McCormick, J.W., Parson, L.E., Chasten, M.A., 2011. Adaptive management through regional sediment management. In: Proceedings of the Western Dredging Association (WEDA XXXI) Technical Conference and Texas A&M University (TAMU 42) Dredging Seminar. Nashville, Tennessee, pp. 178–187.
Luijendijk, A., Hagenaars, G., Ranasinghe, R., Baart, F., Donchyts, G., Aarninkhof, S., 2018. The state of the world's beaches. Sci. Rep. 8, 1–11. https://doi.org/10.1038/s41598-018-24630-6.
Luke, A., Sanders, B.F., Goodrich, K.A., Feldman, D.L., Boudreau, D., Eguiarte, A., Serrano, K., Reyes, A., Schubert, J.E., AghaKouchak, A., Basolo, V., Matthew, R.A., 2018. Going beyond the flood insurance rate map: insights from flood hazard map co-production. Nat. Hazards Earth Syst. Sci. 18, 1097–1120. https://doi.org/10.5194/nhess-18-1097-2018.
Merkens, J.-L., Lincke, D., Hinkel, J., Brown, S., Vafeidis, A.T., 2018. Regionalisation of population growth projections in coastal exposure analysis. Climatic Change 151, 413–426. https://doi.org/10.1007/s10584-018-2334-8.
Merkens, J.-L., Reimann, L., Hinkel, J., Vafeidis, A.T., 2016. Gridded population projections for the coastal zone under the Shared Socioeconomic Pathways. Global Planet. Change 145, 57–66. https://doi.org/10.1016/j.gloplacha.2016.08.009.
Moon, K., Blackman, D., 2014. A guide to understanding social science research for natural scientists. Conserv. Biol. 28, 1167–1177. https://doi.org/10.1111/cobi.12326.
Morris, R.K.A., 2012. Managed realignment: a sediment management perspective. Ocean Coast Manag. 65, 59–66. https://doi.org/10.1016/j.ocecoaman.2012.04.019.
Neumann, B., Vafeidis, A.T., Zimmermann, J., Nicholls, R.J., 2015. Future coastal population growth and exposure to Sea-level rise and coastal flooding - a global assessment. PloS One 10, e0118571. https://doi.org/10.1371/journal.pone.0118571.
Nicholls, R.J., Brown, S., Goodwin, P., Wahl, T., Lowe, J., Solan, M., Godbold, J.A., Haigh, I.D., Lincke, D., Hinkel, J., Wolff, C., Merkens, J.-L., 2018. Stabilization of global temperature at 1.5°C and 2.0°C: implications for coastal areas. Phil. Trans. Math. Phys. Eng. Sci. 376, 20160448. https://doi.org/10.1098/rsta.2016.0448.
Nordby, C, 2019. 40 years of restoration at Tijuana Estuary, California: Lessons Learned. California Coastal Conservancy.
Orange County Public Works, 2020. Sediment TMDL annual report 2017-18 [WWW document]. Newport bay sediment TMDL. URL. http://www.ocwatersheds.com/programs/waterways/tmdl/npbsedimenttmdl. accessed 2.21.20.
Parker, C., Scott, S., Geddes, A., 2020. Snowball sampling. In: Atkinson, P., Delamont, S., Cernat, A., Sakshaug, J.W., Williams, R.A. (Eds.), SAGE Research Methods Foundations. SAGE Publications Ltd, London. https://doi.org/10.4135/9781526421036831710.
Patsch, K., Griggs, G., 2006. Littoral Cells, Sand Budgets, and Beaches: Understanding California's Shoreline. Institute of Marine Sciences, University of California, Santa Cruz, Santa Cruz: CA.
Sanders, B.F., Grant, S.B., 2020. Re-envisioning stormwater infrastructure for ultrahazardous flooding. WIREs Water 7, e1414. https://doi.org/10.1002/wat2.1414.
Sanders, B.F., Schubert, J.E., Goodrich, K.A., Houston, D., Feldman, D.L., Basolo, V., Luke, A., Boudreau, D., Karlin, B., Cheung, W., Contreras, S., Reyes, A., Eguiarte, A., Serrano, K., Allaire, M., Moftakhari, H., AghaKouchak, A., Matthew, R.A., 2020. Collaborative modeling with fine-resolution data enhances flood awareness, minimizes differences in flood perception, and produces actionable flood maps. Earth's Future 8. https://doi.org/10.1029/2019EF001391 e2019EF001391.
Smith, H.L., 2014. Effects of causes and causes of effects: some remarks from the sociological side. Socio. Methods Res. 43, 406–415. https://doi.org/10.1177/0049124114521149.
Syvitski, J.P.M., Vörösmarty, C.J., Kettner, A.J., Green, P., 2005. Impact of humans on the flux of terrestrial sediment to the global coastal ocean. Science 308, 376–380. https://doi.org/10.1126/science.1109454.
Temmerman, S., Meire, P., Bouma, T.J., Herman, P.M.J., Ysebaert, T., Vriend, H.J.D., 2013. Ecosystem-based coastal defence in the face of global change. Nature 504, 79–83. https://doi.org/10.1038/nature12859.
Thorne, K., MacDonald, G., Guntenspergen, G., Ambrose, R., Buffington, K., Dugger, B., Freeman, C., Janousek, C., Brown, L., Rosencranz, J., Holmquist, J., Smol, J., Hargan, K., Takekawa, J., 2018. U.S. Pacific coastal wetland resilience and vulnerability to sea-level rise. Science Advances 4. https://doi.org/10.1126/sciadv.aao3270 eaao3270.
Tijuana River Valley Recovery Team, 2012. Recovery Strategy: Living with the Water. Tijuana River Valley Recovery Team, San Diego.
Trimble, S.W., 1997. Contribution of stream channel erosion to sediment yield from an urbanizing watershed. Science 278, 1442–1444. https://doi.org/10.1126/science.278.5342.1442.
Ulibarri, N., Tao, J., 2019. Evaluating environmental permitting process duration: the case of clean water act Section 404 permits. J. Environ. Plann. Manag. 1–21. https://doi.org/10.1080/09640568.2018.1534730, 0.
US Census Bureau, 2020. Table S1901: income in the past 12 Months (ACS 5-year Estimates) [WWW document]. Data.gov. URL. https://data.census.gov/cedsci/table?q=Median%20Income%205%20year%20estimates&tid=ACSST5Y2018.S1901&t=Counts,%20Estimates,%20and%20Projections%3AIncome%20%28Households,%20Families,%20Individuals%29. accessed 2.21.20.
US EPA, R. 9, 2017. Newport bay watershed [WWW document]. URL. https://19january2017snapshot.epa.gov/www3/region9/water/watershed/measurew/newport-bay/index.html. accessed 2.21.20.
van Rijnsoever, F.J., 2017. (I Can't Get No) Saturation: a simulation and guidelines for sample sizes in qualitative research. PloS One 12. https://doi.org/10.1371/journal.pone.0181689.
Vitousek, S., Barnard, P.L., Limber, P., Erikson, L., Cole, B., 2017. A model integrating longshore and cross-shore processes for predicting long-term shoreline response to climate change. J. Geophys. Res.: Earth Surface 122, 782–806. https://doi.org/10.1002/2016JF004065.
Warrick, J., 2013. Dispersal of fine sediment in nearshore coastal waters. J. Coast Res. 29, 579–596. https://doi.org/10.2307/23486341.
Warrick, J.A., Madej, M.A., Goñi, M.A., Wheatcroft, R.A., 2013. Trends in the suspended-sediment yields of coastal rivers of northern California, 1955–2010. J. Hydrol. 489, 108–123. https://doi.org/10.1016/j.jhydrol.2013.02.041.
Warrick, J.A., Melack, J.M., Goodridge, B.M., 2015. Sediment yields from small, steep coastal watersheds of California. J. Hydrol.: Reg. Stud. 4, 516–534. https://doi.org/10.1016/j.ejrh.2015.08.004.

Warrick, J.A., Milliman, J.D., 2003. Hyperpycnal sediment discharge from semiarid southern California rivers: implications for coastal sediment budgets. Geology 31, 781–784. https://doi.org/10.1130/G19671.1.

Willis, C.M., Griggs, G.B., 2003. Reductions in fluvial sediment discharge by coastal dams in California and implications for beach sustainability. J. Geol. 111, 167–182. https://doi.org/10.1086/345922.

Yin, R.K., 2017. Case Study Research and Applications: Design and Methods, sixth ed. SAGE Publications, Inc, Los Angeles.