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Re-envisioning Storm Water Infrastructure for Ultra Hazardous Flooding

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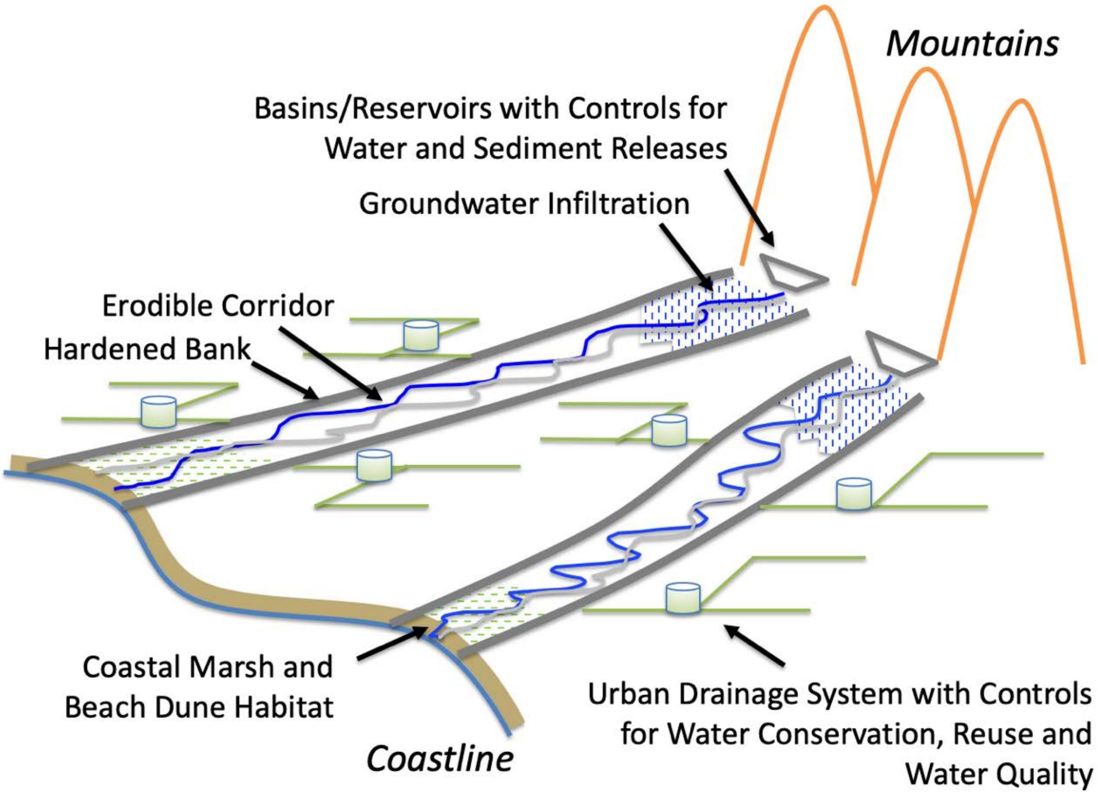
Abstract

Ultra-Hazardous Flooding (UHF) occurs on low relief topography at the foot of mountain catchments and is characterized by rapid-onset, high-velocity flood flows, large fluxes of sediment and debris, and unpredictable flow paths. 20th Century storm water infrastructure seeks to contain UHF, up to a design level, using combinations of basins, reservoirs and flood control channels all optimized for flood conveyance. However, these flood control elements may increase the risk of disasters due to: (1) increasingly frequent and intense wildfires that amplify streamflow and debris fluxes beyond infrastructure design capacity, (2) aging and underfunded infrastructure which is susceptible to clogging and failure during extreme events, and (3) expansive urban development where communities are relatively unaware and underprepared for flooding as a consequence of the "safe development paradox". 20th Century storm water infrastructure for UHF has also left communities with a legacy of social and environmental challenges including poor water quality, degraded habitats, high maintenance costs, unrealized urban amenities, and altered sediment fluxes. Adopting the Los Angeles Metropolitan Region as a type-locality for UHF, we propose a new paradigm for stormwater infrastructure based on the concept of erodible flood corridors. Our vision aims for greater sustainability and resilience to extreme events based on congruency with natural processes, conservation of resources and associated ecosystem services, minimization of flood exposure and vulnerability, and avoidance of legacy risk and energy intensive practices.

Graphical/Visual Abstract and Caption



Graphical Abstract Caption: Ultra hazardous flooding occurs on low relief topography at the foot of mountains, and is characterized by rapid onset, high velocity flooding with loads of sediment and debris and unpredictable flood paths. 20th century stormwater infrastructure has sought to contain flooding and maximize land for development by relying heavily on gray (hardened infrastructure) leaving a legacy of environmental challenges and unrealized urban amenities from riparian corridors. We envision a more sustainable approach involving erodible corridors with engineered systems to control flood peaks and sediment fluxes as well as simulation and forecast systems to support flood risk planning, preparedness and emergency management.

1. INTRODUCTION

Developed areas at the foot of mountains are exposed to Ultra-Hazardous Flooding (UHF) defined here as rapid-onset, high-velocity, erosive, debris-laden flooding with unpredictable flow paths for which elevation on fill cannot be presumed to mitigate damage and public safety risks (NRC 1996). Over the time scale of a single event, UHF flood flows from intense precipitation over mountain catchments may carve new channels, move boulders or large debris, or yield mud flows that pose major damage threats (e.g., Brooks 1982, NRC 1996, Jones 2018). Precipitation on developed areas at the foot of mountains further amplifies flood hazards with stormwater runoff. UHF has also been described as *alluvial fan flooding* for regulatory purposes, but it is not limited to alluvial fans; rather, UHF can occur in numerous geologic settings (e.g., marine terraces) below a topographic break (NRC 1996, Pelletier et al. 2005). Examples of areas exposed to UHF include narrow (~< 50 km) coastal plains found along the west coast of North America and South America, the Mediterranean coast, and elsewhere (IB and WMB, 1907), basin and range landscapes such as those found the Southwestern U.S., and various mountain regions around the world (NRC 1996). With population growth of metropolitan areas of the U.S. (Hobbs and Stoops 2002) and in coastal cities globally (Hinkel et al. 2014), populations exposed to UHF have been increasing.

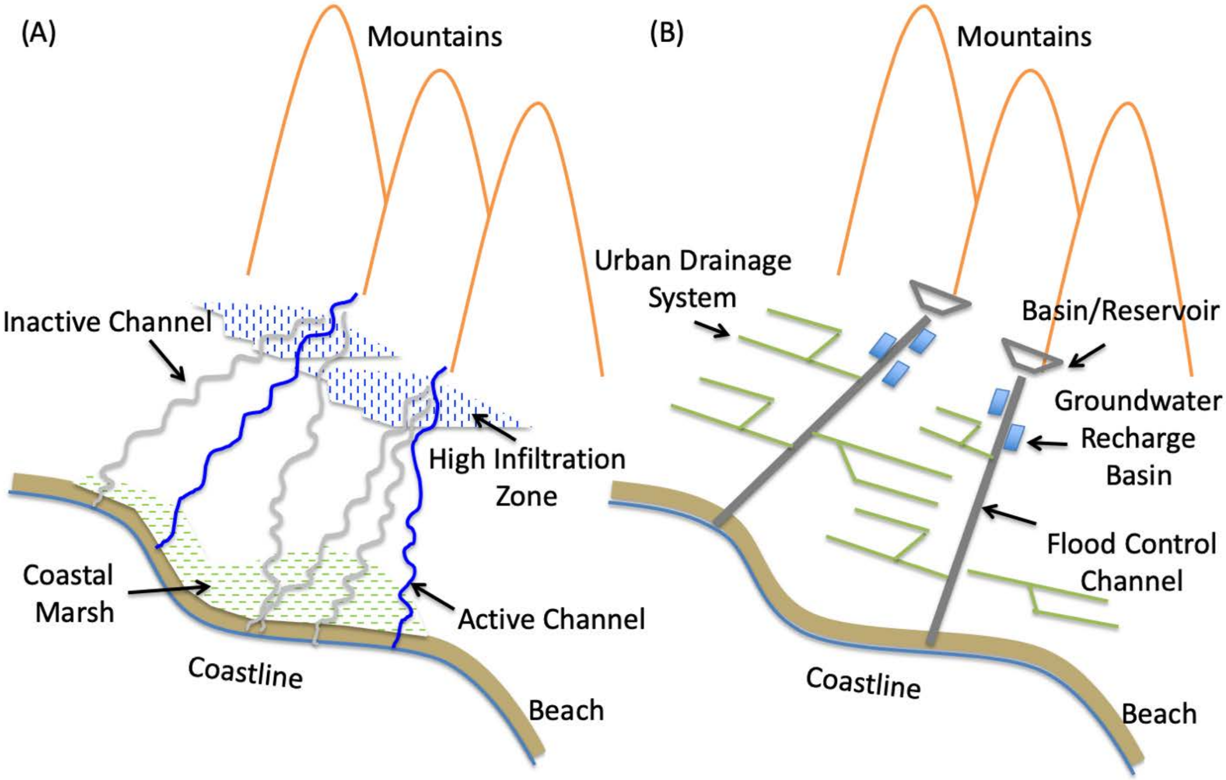


Figure 1. Low relief topography at the foot of mountains (A) is exposed to Ultra Hazardous Flooding (UHF) characterized by rapid-onset, high-velocity flood flows, large fluxes of sediment and debris, and unpredictable flow paths. 20th century stormwater infrastructure (B) maximizes land for development with basins/reservoirs, flood control channels, urban drainage systems and groundwater recharge

basins. This approach comes at the expense of riparian and stream habitats, stream health, water quality, altered sediment fluxes, increased risks of disasters, negative downstream impacts, and high management costs for water treatment, groundwater recharge, and sediment removal/disposal.

In a natural state (Fig. 1A), flood flows from mountain canyons spread out and disperse the delivery of water, sediment, energy, and debris. However, this renders virtually all low relief topography vulnerable to flooding at any time given the potential for channels (and flood flows) to avulse and change course over the time scale of a single flood event—a significant barrier to economic development. 20th century storm water infrastructure addresses economic development and safety needs with a minimal spatial footprint that maximizes land for development (Kier 1981). Four common elements are shown in Fig. 1B: (a) basins (or reservoirs) designed to collect coarse sediment and debris from mountain runoff and in some cases attenuate flood peaks, (b) spatially-efficient flood control channels designed to rapidly and safely transport flood water and fine sediment downstream away from development (Brooks 1982), (c) groundwater recharge basins to enhance water supplies, and (d) urban drainage systems that transfer pluvial flood water into drainage channels. Fig. 2 presents some of these features in greater detail based on a small system in Riverside County in Southern California. In this case, the basin's outlet works include a low flow culvert and high flow spillway, and the flood control channel has a smooth concrete surface with a rectangular cross section that supports supercritical flow for rapid movement of flood water downstream (Henderson 1966).

Figure 2. McVicker debris basin in Riverside County, California. Coarse sediment and debris settle in the collection area, while flood water and suspended fines pass through a culvert into a flood control channel. A spillway is used to accommodate high flows. Image source: Google, 2018.

20th Century infrastructure designs can be very effective at preventing life-threatening and costly flood losses during storms smaller than the design capacity. However, this approach leaves communities vulnerable to disasters from events larger than the design capacity—events that are likely to be more common in a warming world (Jones 2018). Indeed, global warming is intensifying cycles of drought, wildfire and rainfall, which collectively increase the potential for mud and debris flows (Westerling et al. 2006, Min et al. 2011, Ren et al. 2011, Dai 2013), as tragically played out in the Montecito and Carpinteria debris flows that followed the Thomas Fire in Southern California (Oakley, et al., 2018). Infrastructure failure also becomes more likely with unmet needs for infrastructure maintenance funding (Vahedifard 2017), and flood risks are compounded by high vulnerability to low probability events—a result of the “levee effect” or “safe development paradox” whereby engineered flood defences create a false sense of safety that leaves communities relatively unaware and underprepared to cope with flood-related disasters (Myers and White 1993, Burby 2006, Montz and Tobin 2008, Di Baldassarre et al. 2015, Cutter et al. 2017, Di Baldassarre et al., 2019, Houston et al. 2019).

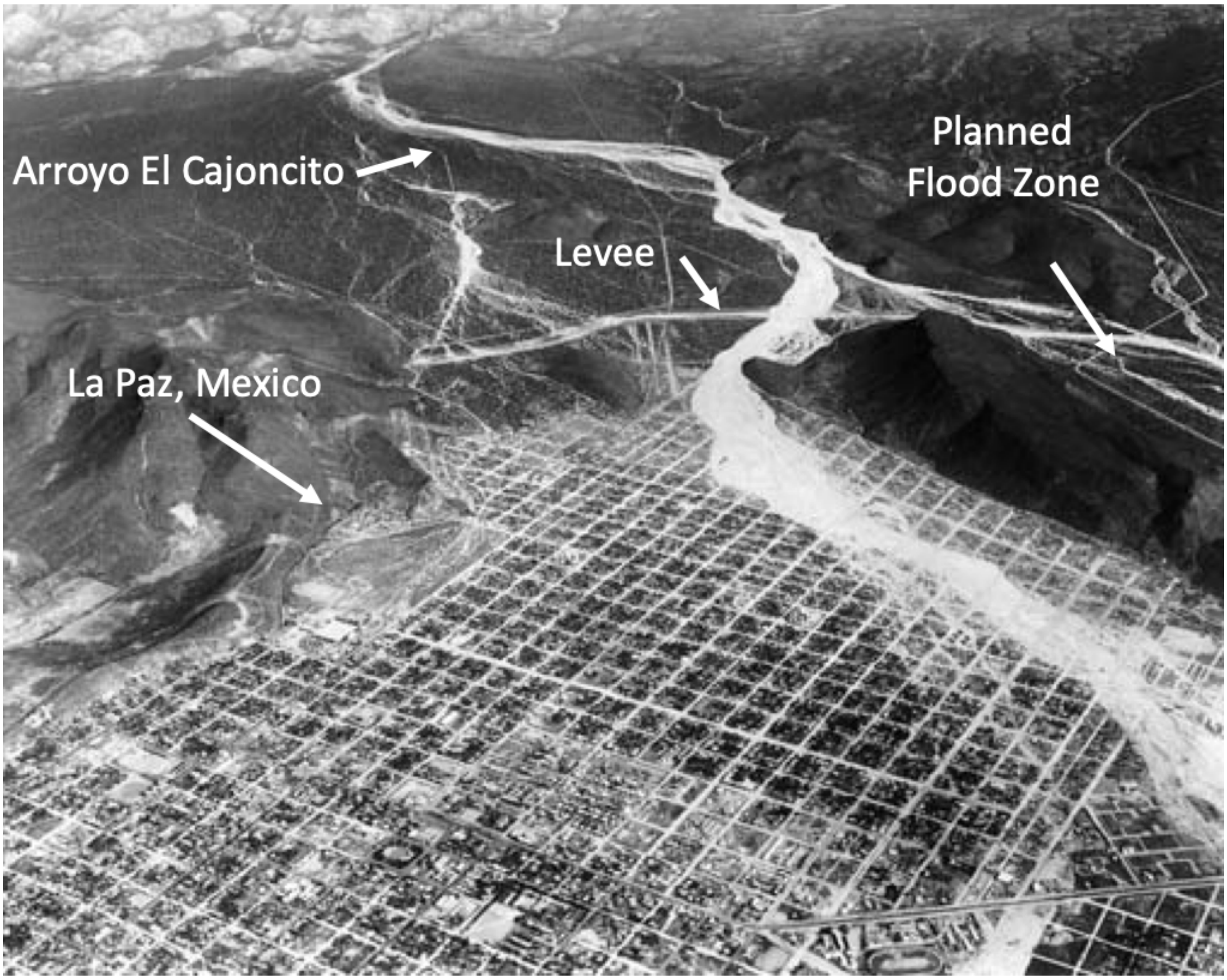


Figure 3. Aerial photo of La Paz, Mexico in October, 1976 after precipitation and runoff from Hurricane Liza caused the Arroyo El Cajoncito to avulse through a protective levee, sending fast moving flood water, mud and debris through an urban development. This event epitomizes ultrahazardous flooding. (Photo by Harry Merrick).

In recent decades, the most prominent flooding disasters in the U.S. have occurred from hurricanes and tropical storms striking low-gradient settings along the Gulf Coast and East Coast (NOAA 2019); such events are expected to increase in the future (Kulp & Strauss 2017, Bilskie et al. 2016, Bilskie et al. 2019). Similarly, when extreme floods occur in high-gradient settings, the damage potential is high. A recent example is the 2013 Colorado Front Range floods which destroyed 1,500 houses, 200 commercial buildings and 30 state highway bridges, damaged nearly 19,000 houses and 800 commercial buildings, 200 miles of roadway, and 20 state highway bridges, and resulted in numerous fatalities (Soden et al. 2017, National Weather Service, n.d.). The damage potential of UHF is especially high as a result of unpredictable flow paths, as was the case when Hurricane Liza struck Baja California in 1976 causing a disaster in La Paz, Mexico. As shown in Fig. 3, intense rainfall over mountain catchments caused the swollen Arroyo El Cajoncito to break through a protective levee and avulse towards the city's center. The ensuing flood water, mud and debris killed hundreds to thousands of people (mud and debris made it impossible to count) and tens of thousands of people were displaced (Associated Press, 1976a,b). This disaster draws attention to the destructive power of UHF, and also illustrates how communities may develop in ways that significantly increase their risk to natural disasters (in this case to UHF) under the pretense that the city's infrastructure (in this case flood control channels) will protect them (Burby 2006, Cutter et al. 2017, Di Baldassarre et al., 2019).

Beyond increasing disaster risks, 20th Century stormwater infrastructure triggers a set of seemingly intractable environmental and social problems (Walsh et al. 2005, Fletcher et al. 2013, Askarizadeh et al. 2015), or so-called legacy risk (Di Baldassarre et al., 2019). First, downstream delivery of sediment is disrupted. This can lead to downcutting of soft-bottom channels downstream and a deficit of sediment at the coast (Kondolf et al. 2014); in turn, the loss of sediment supply can worsen the impacts of sea level rise on coastal communities (Hanley et al. 2014). Second, infiltration of floodwater into groundwater aquifers is hindered by the: (a) replacement of soft bottom streams with impermeable surfaces (typically made of concrete) on the channel bottom, and (b) inability of flood water to spread out into areas, for example on alluvial fans, with high infiltration capacity. Third, hardened channels undermine nutrient cycling and associated pollutant removal processes that occur naturally in soft bottom channels, leading to poor water quality within the channels and in downstream receiving waters (Walsh et al., 2005; Askarizadeh et al., 2015; Grant et al., 2018). Fourth, hardened channels and impervious surfaces across developed areas limit green spaces and vegetated areas accessible to urban areas impacting local quality of life, including recreation, tourism, amenities, air quality, and education (Kondolf 2011, Everard and Moggridge 2012).

The loss of groundwater recharge is often redressed, as depicted in Fig. 1B, with "groundwater recharge basins". These common features of 20th Century stormwater infrastructure are designed to capture and store mountain runoff and treated wastewater for greater water sustainability (Grant et al. 2012), and sited in areas with high natural permeability. However, without the periodic high-energy flood flows that maintain streambeds in a high permeability state (Stewardson et al., 2016) these groundwater recharge systems quickly clog from the deposition of fine particles (Bouwer, 2002).

Short- and long-term costs are another important consideration, as storm water infrastructure is expensive. In addition to capital costs for construction, property buyers and public agencies who take ownership of flood infrastructure face maintenance costs that over a few decades can exceed original construction costs (Askarizadeh et al., 2015; Keeler et al., 2019). Also problematic is the situation where smaller (typically "green") elements of the flood control system, such as curb cut outs, pass into the hands of private individuals with little knowledge of how to maintain these systems, or even why they are there, post construction. As noted by Ambrose and Winfrey (2015), "transferring maintenance responsibility might be attractive to government agencies; however, distributing responsibility among many parties can be problematic because differing levels of maintenance can occur." For these and other reasons, as noted by Keeler et al. (2019), the long-term durability of stormwater infrastructure is largely determined by "local buy-in and institutional and community capacity". From a system dynamics perspective (Kallis 2010, Gohari et al. 2013, Di Baldassarre et al., 2019), the legacy risks described above reflect the interconnectedness of storm water infrastructure with broader water sustainability challenges, including links and feedbacks among natural, technological and social sub-systems.

The goal of this paper is to reflect on both the dangers of UHF and the legacy risks that have arisen from 20th century infrastructure designs, which have presumed that hardened (grey) designs are the only reliable approach for UHF (NRC 1996), and then consider the possibility of a more sustainable design approach based on a combination of grey and green components, i.e., reliance on natural processes. The paper continues as follows: In Section 2, we use the Los Angeles Metropolitan Region as a "type locality" for UHF, with the goal of highlighting how 20th Century storm water infrastructure can exacerbate both natural disasters and water sustainability challenges. In Section 3, we propose and develop an erodible corridor concept for UHF that combines grey (hardened) and green (natural) elements. Erodible corridors offer space for rivers to move and build complexity through natural processes (Piégay et al. 2005), and are viewed as the most sustainable approach for river restoration (Kondolf 2011), but their applicability to UHF is challenging. With continued urban development around the world and calls for greater urban water sustainability (Grant et al. 2012), especially in arid climates, a re-imagination of storm water infrastructure for UHF is needed. Finally, Section 4 presents concluding remarks.

2. LOS ANGELES AS A TYPE LOCALITY FOR ULTRAHAZARDOUS FLOODING

Figure 4. The LA Metro region is built on a narrow coastal plain between several mountain ranges and the Pacific Ocean. Image source: Google Earth, 2018, with data from SIO, NOAA, U.S. Navy, NGA, GEBCO, USGS, LDEO-Columbia, and NSF.

An exemplar of UHF is the Los Angeles Metropolitan Region (LA Metro) shown in Fig. 4, the second largest metropolitan area in the U.S., and 30th in the world, with a population of over 13 million people. When measured by GDP, it ranks 3rd in the world (Hawksworth et al., 2009). Population and economic assets blanket low relief topography, which is flanked by mountains rising more than 3,000 m to the north and east and the Pacific Ocean to the south and west. Rainfall of 10 inches (250 mm) or more per day has been recorded on several occasions at mountain gages resulting in flash flooding and widespread inundation, and severe rainfall events in the region have been attributed to atmospheric rivers (Fish et al. 2019). The largest documented event, the Great Flood of 1861-1862, impacted the entire west coast of the United States. In the LA Metro region, rainstorms persisted for 28 days (Brewer, 1862) and one gage reported 66 inches (1680 mm) of rain (Jones 2018). At that time, the population of Los Angeles was less than 5,000, land was primarily used for cattle grazing, and small towns were scattered across the coastal plain (Tomasovych and Kidwell 2017, Jones 2018). Jones (2018) writes,

> *[Flood water] extended for four miles around the Santa Ana River in Anaheim, creating an inland sea four feet deep that lasted for a month. When the flood finally receded, the mouth of the river had moved six miles. In Los Angeles, the water was described as extending from mountain to mountain, with no dry land in the fifty miles between the Palos Verdes Peninsula and the San Gabriel Mountains, an area now home to almost ten million people.*

The flood completely destroyed numerous small towns, including Agua Mansa located on the Santa Ana River as shown in Fig. 4, and hundreds of thousands of cattle drowned (Jones 2018). At the time, Agua Mansa was the second largest town in the region after Los Angeles. By 1938, the population of the region had increased to over 1 million, spurred by agricultural and development opportunities made possible by an abundant supply of alpine water from the Owens Valley, east of the Sierra Nevada range, after the construction of the 223 mile (359 km) long Los Angeles Aqueduct. In late February of 1938, the first of two major storms dropped 4 inches (10 cm) of rainfall that saturated hillslopes and caused minor flood damage in the mountains. A subsequent storm on March 1st was much more severe, dropping 10 inches (250 mm) of rainfall on the region and 32 inches (810 mm) in the mountains in just one day. The recorded streamflow in the Santa Ana River stands today as the maximum over the 120 year gage record, as shown in Fig. 5. The resulting $78 million in damages ($1.39 billion in 2018 dollars) included collapsed bridges and broken levees. 5601 homes were outright destroyed, 1500 more were rendered uninhabitable (Romo 1988), and 115 lives were lost (SEMP 2006).

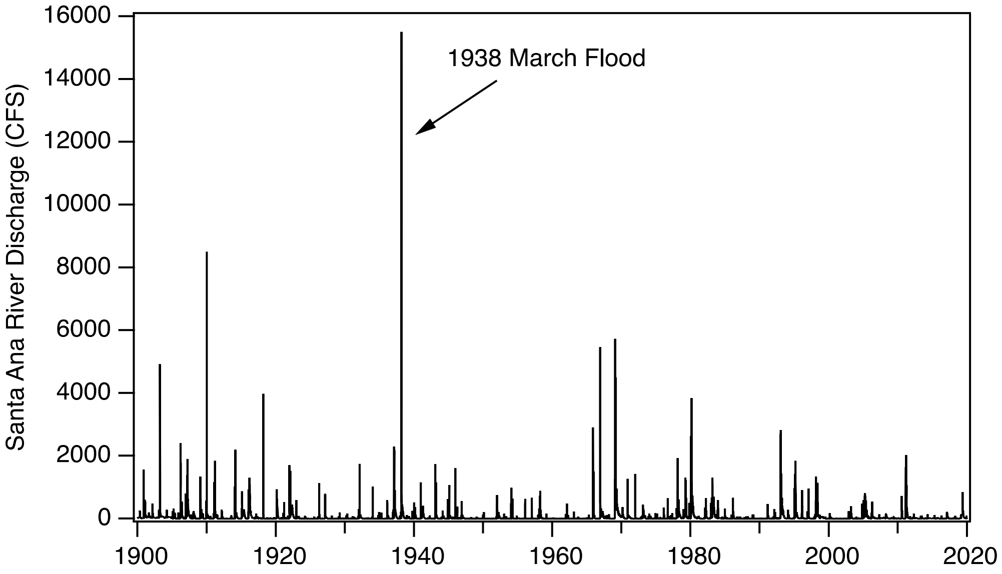


Figure 5. One hundred and twenty years (from January 1, 1900 to January 1, 2020) of daily average discharge upstream on the Santa Ana River (N=43,784), in the foothills of the San Bernardino Mountains (USGS Gage 11051500). Over the entire 120-year period of record, the 1938 March Flood stands out as an exceptional event.

The 1938 floods spurred the passage in the U.S. Congress of the Flood Control Act of 1941, which combined with California flood control policy of 1945, triggered a wave of construction of 20th Century stormwater designs across the State of California (Kier 1981, Kondolf and Lopez-Llompart 2018). Prior to the 1938 event, this design approach shown in Fig. 1B had already been adopted within the Los Angeles River basin and was credited with reducing impacts during the 1938 flood. However, rapid proliferation of these designs across the State stemmed from social factors: the political influence of developers, policy for financing flood control infrastructure, and economic conditions in California after World War II.

As described by Kier (1981), federal funding for planning, design and construction of flood control systems was available to communities on the condition that local sponsors of projects—such as cities, counties or flood control districts—provided the necessary lands, easements and rights of way. This policy meant that local taxpayers would have a stake in flood control projects—and would need to deliberate over the scope and scale of projects and examine the distribution of benefits and that would be realized versus costs. However, the State of California had an enormous budget surplus in 1945 following World War II, which the California legislature decided to put toward eliminating the local match previously required for all flood control projects. This meant total funding for flood control projects—land acquisition, planning, design, construction—was available to communities from state and federal coffers alone. Kier (1981) describes the impact as follows,

> *…there was virtually no way that local officials could say no to a local flood control project. It did not cost them a cent and it made developers and other boosters happy. The planning was done—and still is done—by the federal agencies. The California Legislature authorizes each project for state assistance. The local agency proceeds to buy the necessary lands, relocate railroads and pipelines, raise street and highway bridges, periodically billing the [California Department of Water Resources] for reimbursement. When the project is completed, local government planners and developers attack what was once a riparian system and produce residential, commercial, and industrial properties which, in turn, produce the tax revenues necessary to maintain and operate the flood control project.*

In the decades that followed, low topography across Southern California would be blanketed by development. High levels of impervious surfaces were made possible by stormwater infrastructure requiring a minimal spatial footprint – thus maximizing developable area. From an economic perspective, it can be argued this approach was a major success: as noted earlier, the region ranks 3rd in the world for GDP. And to be fair, the National Research Council Committee on Natural Disasters review of the 1978 and 1980 floods in the LA Metro region, which were both characterized by a 25 year return period and within the design capacity of major stormwater channels, reported that the flood infrastructure prevented an estimated $4B (1980 dollars) in damage (Brooks, 1982). Nevertheless, the risk of a disaster or even catastrophe looms from an event beyond the design capacity of infrastructure that communities are not prepared to manage (Jones 2018). Furthermore, 20th century stormwater infrastructure decimated riparian ecosystems and created a legacy of high management costs without a secure funding mechanism.

Generally, there is broad recognition that funding for the long-term maintenance of storm water infrastructure is a major ongoing challenge (Copeland 2014, Upadhyaya et al. 2014). For example, once a debris basin fills, subsequent floods result in the downstream transport of mud and debris leading to clogged channels, increased flow resistance, and increased risk of out-of-bank flows and infrastructure damage. Government agencies responsible for flood control thus remain active throughout the year maintaining channels, basins and other elements of flood control systems. This maintenance is expensive. Los Angeles County Flood Control District alone operates 14 flood control reservoirs and 162 debris basins and estimates that it will need to manage 51.6 million cubic meters of sediment between 2012 and 2032 (County of Los Angeles, 2013). Trucking costs alone are just shy of $70 million annually (in 2013 dollars, assuming transportation costs ~ $40/cubic meter). The direct costs of keeping these systems functional easily run into the hundreds of millions of dollars annually, not accounting for the unrealized urban amenities (Kondolf et al. 2011, Everard and Moggridge 2012) as well as impacts on coastal infrastructure due to the twin challenge of sea level rise and sediment starvation, as noted earlier (Hinkel et al. 2014, Kondolf et al. 2014).

When maintenance is delayed or postponed, costs can spiral upwards in ways that, from a systems perspective (Gohari et al. 2013, Di Baldassarre et al., 2019), exemplify feedbacks between among natural, technological and social sub-systems. One particular cycle that has played out many times in the LA Metro region goes like this: hard bottom flood control channels collect sediment and debris during storm events, leading to the seeding and growth of vegetation. As the vegetation grows, riparian ecosystems become established and subject to wetland protection and endangered species regulations. The next cycle of channel cleaning (sediment and vegetation removal) triggers violations of federal and/or state laws, costly mitigation measures, and legal costs. For example, the County of Orange was recently required to purchase land and restore an impaired site to mitigate for cleaning a flood control channel—and destroying the habitat that established itself since the last cycle of cleaning. While this cycle can be broken with more frequent channel cleaning, funding shortfalls often undermine common sense solutions. To better position itself to address the management costs of storm water infrastructure, Los Angeles County passed a new property tax in 2018 that charges landowners $0.025 per year per square foot of impermeable area (Agrawal, 2018). The new tax is expected to generate $300 million per year to address storm water quality, fund capital investments into green stormwater infrastructure, and improve water recycling.

Across the LA Metro region, river restoration efforts are also underway. For example, a LA River Master Plan is presently under development with leadership from the County of Los Angeles. Its vision is to achieve “connected open space that includes clean water, native habitat, parks, multi-use trails, art, and cultural resources to improve health, equity, access, mobility, and economic opportunity for the diverse communities of LA County, while providing flood risk management” (County of Los Angeles 2019). Riverside land near downtown Los Angeles has also been acquired and plans for redevelopment of the site are being formulated (City of Los Angeles 2019). While this vision and specific project proposal appear to offer many realizable *social* benefits (although these have been challenged over equity concerns and their potential contribution to so-called Green Gentrification (Nagami, 2019)), the restoration goals are quite modest with respect to overcoming the *hydrologic* shortcomings of stormwater infrastructure discussed herein. Indeed, the need to maintain, and even increase, flood flow capacity of the LA River within a small footprint acts as a major constraint on what can be done with respect to restoring hydrologic and sediment fluxes. Moreover, nowhere in the vision statement is the management of sediment mentioned.

3. ENVISIONING ERODIBLE CORRIDORS FOR ULTRAHAZARDOUS FLOODING

Perhaps the most sustainable strategy for ecological restoration of rivers is an erodible corridor—a space where channel migration and complexity are enabled through natural fluvial processes (Piégay et al. 2005, Kline and Cahoon 2010, Kondolf 2011). The feasibility of erodible corridors is primarily shaped by three factors: (1) stream power; (2) sediment load; and (3) encroachment by development (Kondolf 2011). Large floods in the LA Metro region are characterized by exceptionally high stream power and sediment loads, and thus fall into a category of restoration where hardened infrastructure is presently considered unavoidable (NRC 1996, Kondolf 2011). Moreover, once urban development has encroached on the margins of a narrow concrete channel, widening the channel entails acquisition of parcels adjacent to the channel (on at least one side), which can be both costly (prohibitively so in urban areas with high real estate values) and controversial. Not only is developed land expensive, but channels (and bridges) often need to be widened many-fold to create a soft-bottom riparian corridor within which streams can flood, meander, migrate, erode and deposit. Thus, restoration efforts within the urban core of the LA Metro region have mainly been limited to the delivery of social benefits, such as access to trails and recreational opportunities (Kondolf 2011). This is consistent with the aims of the LA River Master Plan reported above. Nevertheless, as metropolitan areas like LA continue to expand, and as land at the city's fringes are progressively developed, opportunities to implement erodible corridors may present themselves.

The space allocated for erodible flood corridors is typically based on rules-of-thumb, historical patterns of channel migration, and computer simulations of meanders (Piégay et al. 2005, Kondolf 2011). However, these existing approaches are not directly applicable to low relief topography at the foot of mountains in areas, like the LA Metro region, where virtually all developable land has been exposed to channel flows at one time or another. Here, hardened features are needed to constrain the limits of channel migration. This Gordian Knot might be cut with a grey-green hybrid approach that uses hardened (grey) elements for the boundaries of the corridor and soft (green elements) in the interior to promote ecosystem services. Sizing such a corridor will require site specific analyses, but it would likely be at least ten times wider than standard (20th Century) flood control channel designs, to enable meandering and channel complexity, and also to support extreme variability in sediment fluxes and streamflow.

While grey and green urban infrastructure is often framed in the literature as an either this-or-that choice (e.g., Keeler et al., 2019), one benefit of incorporating both elements into erodible corridors is their complementary functionality. Green in-corridor elements can be designed to mimic the natural processes that promote sustainability during non-extreme conditions. Grey elements can be designed to provide a high level of reliability against erosion and flood damage during extreme events, effectively constraining the amount of natural variability (and potential damage) that can occur. Further, the human health, equity, ecological, and economic co-benefits, beyond flood protection, associated with such hybrid systems should engender a broad coalition of support for erodible corridors and increase cost-sharing opportunities (Keeler et al., 2019).

This idea—of incorporating green elements into grey civil infrastructure—is not new. Increasingly, green stormwater infrastructure, such as biofilters and bioswales, is embedded within grey urban drainage systems (Askarizadeh et al., 2015). The green elements enhance local infiltration, reduce runoff, and reduce pollutant loads, while the grey elements (e.g., concrete pipe drainage systems) ensure the conveyance of water towards main stem channels and thereby reduce flood risk (Benedict and McMahan 2002, NRC 2009). Integration of green and grey elements is also gaining interest for coastal protection. "Living shoreline" coastal protection systems combine hardened elements such as sea walls or cobble berms with green elements such as nourished beaches and dunes, artificial reefs, and wetlands and the use of construction materials compatible with ecosystem needs (Gittman et al. 2014, Hanley et al. 2014, Morris et al. 2018). For example, erosion and flooding damage from

Hurricane Sandy was reduced at Bay Head, New Jersey by a buried concrete seawall that helped to dissipate wave energy after the overlying sand was eroded (Smallegan et al. 2016). Note that destruction of green elements is possible, and even likely, during extreme events; indeed, their destruction is part of the planning, design and budgeting process, just as the sand overlying the sea wall at Bay Head, NJ was swept away by Hurricane Sandy.

What might a hybrid green/grey erodible corridor look like? Fig. 6 presents one possible conceptualization that includes: (a) basins/reservoirs for storage and release of water, sediment and debris, (b) an erodible corridor with hardened banks that supports channel complexity, constrains channel migration and provides ample space for groundwater recharge, channel migration and complexity, nutrient processing, natural riparian habitat and coastal wetland and dune habitat, (c) sustainable urban drainage infrastructure with controls for water conservation, reuse and water quality and myriad of co-benefits, including evaporative cooling, opportunities for recreation, education about storm water and flooding, and improved mental health (Engemann et al., 2019). Compared with existing stormwater designs (Fig. 1B), the erodible corridor offers less space for development but greater opportunity for ecosystem services, reduced disaster risks, and reduced legacy risks.

Is this feasible? Dams capable of regulating flows of both water and sediment fluxes are not common, but not for a lack of technology. Kondolf et al. (2014) describe several methods for passing sediment through, or around, reservoirs. These authors also sound the alarm that construction of dams continues worldwide without these important systems. Similarly, soft-bottom channels with hard-banks are not uncommon in UHF settings, but these systems are often challenged by downcutting or aggradation brought on by altered sediment fluxes and stream power (Kondolf 2011). Hence, the success of an erodible corridor for UHF will be linked to the ability to constrain sediment fluxes and stream power through possibly real-time and adaptive engineering controls.

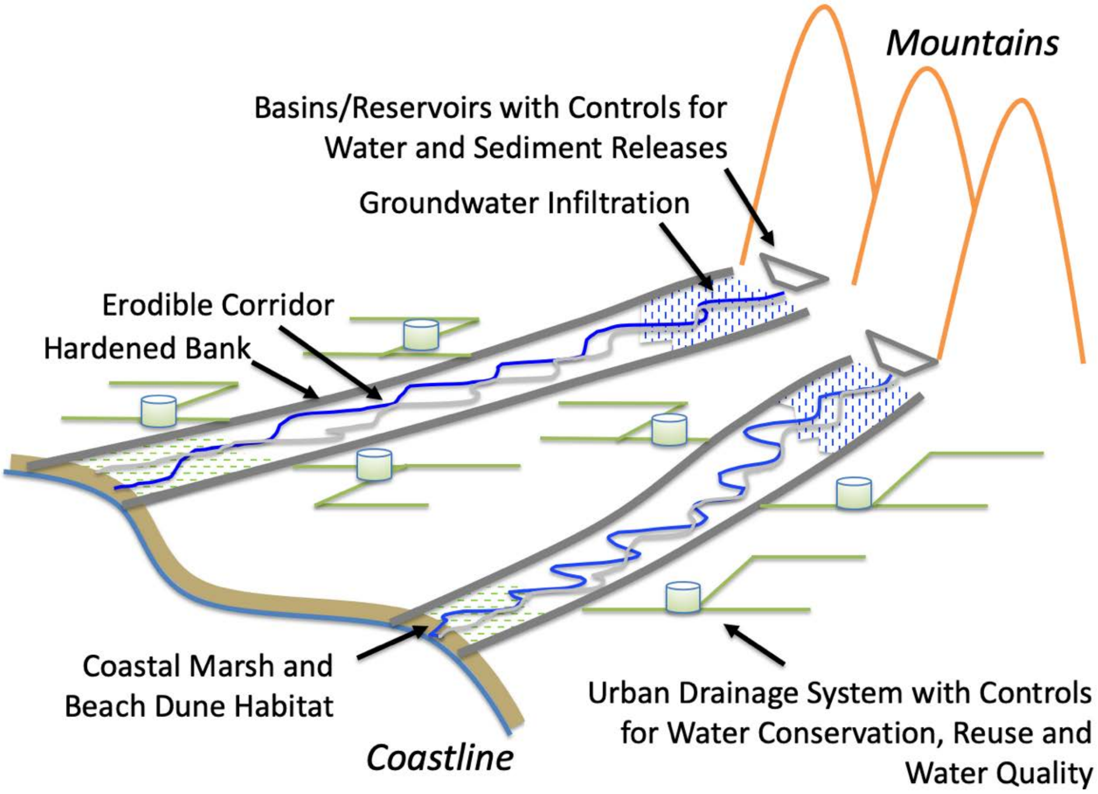


Figure 6. Conceptualization of stormwater infrastructure for UHF including (a) reservoirs at the base of mountains with controls on the storage/release of water, sediment and debris, (b) an erodible corridor with hardened banks and a soft core that provides environmental and social benefits in addition to flood control and (c) urban drainage systems with controls to promote water conservation, reuse and water quality.

Sensing, simulation, and control systems are an emerging (21st Century) feature of storm water infrastructure (Kerkez et al., 2016), and could also play an important role in grey/green erodible corridors. Control on water and sediment fluxes from basins and urban drainage systems (Fig. 6) would give managers the ability to respond to sedimentation trends that lead to unacceptable risks. Since sediment loads scale nonlinearly (as a power law) with stream discharge, the vast majority of transport occurs during the largest events (Warrick and Milliman, 2003). Hence, the key to control is regulating peak flows and sediment supplies. For example, observed trends in channel aggradation could be addressed by trapping more sediment upstream (reducing sediment supplies) and increasing peak flows by coordinated releases from basins/reservoirs and urban drainage systems. Conversely, downcutting could be addressed by increasing sediment supplies from upstream and reducing peak flows during major storm events. Indeed, previous research suggests that strategies for controlling flood peaks and managing flood impacts can be managed in real time (Sanders and Katopodes 1999, Sanders et al. 2006).

Sensing and control systems would also contribute to our vision of the erodible corridor. For example, groundwater infiltration can be enhanced by capturing more flood water during small events and timing the release for capture within infiltration areas (Fig. 6), while recognizing that downstream delivery of mountain runoff from most events is important for the overall health of the stream corridor; e.g., sediment mobility, water quality, vegetation, and wetlands. Such designs will not be free from maintenance costs. But by harnessing natural processes for the downstream delivery of sediment and debris, they should radically reduce the excavation and trucking requirements that currently dominate maintenance budgets, and may very well save money in the long run. Water quality improvement is another area where sensing and control systems might augment the functionality of hybrid green/grey erodible corridors. For example, Mullapudi et al. (2017) argue that real-time control of water movement through soft-bottom elements of flood control systems can be manipulated so as to maximize the removal of bioreactive nitrogen (e.g., nitrate) by biologically mediated denitrification.

Advanced flood simulation tools are needed to implement these real-time (cyberinfrastructure enabled) controls, and to manage and communicate risks within the erodible corridor (Pelletier et al. 2005, Luke et al. 2018, Sanders and Schubert 2019, Sanders et al. 2019). Applications include forecasts for when grade level roadways may become impassable and in-corridor recreational facilities should be closed. They can also be used to assess the risks and benefits of utilizing erodible corridor for seasonal land uses, such as urban agriculture. These systems will also help manage risks of flooding outside the erodible corridor, including pluvial flooding from intense rainfall and excess mountain runoff not contained by the erodible corridor, or from the failure of grey infrastructure. This perspective reflects a shift in design philosophy for civil infrastructure from “fail-safe,” which promotes the false narrative, underlying the safe-development paradox mentioned earlier, that a hardened system can never fail, to “safe to fail,” which builds-in a level of preparedness and planning for extreme events (Ahern 2011, Kim et al. 2017). Recent research from the LA Metro region points to the ability of advanced modeling systems to simulate urban flooding in real-time with street-level precision (Sanders and Schubert 2019), and meet a wide range of end-user needs including planning, preparedness and emergency action plans (Luke et al. 2018, Sanders et al. 2019). The key to success is an iterative process of community engagement, so the decision-points supported by the modelling system align with decision-making needs among diverse end-users (DeLorme et al. 2016, DeLorme et al. 2018, Sanders et al. 2019). A premium will also need to be placed on improving model skill for predictions of flooding, sediment mobility, and morphologic change within erodible flood corridors.

4. CONCLUDING REMARKS

The destructive power of UHF is formidable and unpredictable, as tragically evidenced by the impact of Hurricane Liza on La Paz, Mexico in 1976 (Fig. 3), as well as many other events. Across the LA Metro region, where over 13 million people live on a narrow coastal plain exposed to UHF, economic growth following extreme events, such as the 1978 and 1980 floods, underscore the effectiveness of 20th century stormwater infrastructure. On the other hand, the recent Montecito debris flow serves as a vivid reminder that events outside of the design capacity are highly destructive (Oakley, et al., 2018), and it is important to anticipate the scale and scope of destruction, and the national and international ripple effects, that would result if a flood comparable to the Great Flood of 1862, or even the March flood of 1938 (Fig. 5), occurred in the LA Metro region today (Jones 2018). Also important is recognition that 20th century storm water infrastructure resulted in a host of social, equity, and environmental problems that impair sustainability, including negative impacts to water supplies and ecosystems, unrealized ecosystem services for urban communities, and disrupted sediment supplies that hamper responses to sea level rise. How this path of development transpired, in particular the role of governance and financing, points to system complexity (Kier 1981, Di Baldassarre et al. 2019).

20th Century flood control infrastructure aims to maximize the land available for development (Kier 1981), making restoration of flood control channels into riparian corridors prohibitively expensive, except perhaps for modest measures that address social needs, such as access trails and educational programs (Kondolf 2011). Gobally, as the fringes of urban cores move out to the base of mountains, or as new cities are planned, there will be opportunities for more sustainable design approaches to address UHF. We argue that hybrid erodible corridors are a intriguing alternative to conventional designs that deliver the complementary benefits of green and grey elements, and can be outfitted with advanced sensing, simulation and control systems to manage flood risks and regulate flood peaks, sediment fluxes, and water quality. More research is needed to examine the feasibility of this approach and to develop design guidelines.

The land required to support erodible corridors, as depicted in Fig. 6, would be significant and the costs would motivate influential economic arguments for more space-efficient infrastructure designs, as shown in Fig. 1B, especially based on the potential for property tax revenue, business activity and political pressures, as we have observed in the past (Kier 1981, Burby 2006, Cutter et al. 2017). However, cost-benefit analyses should take into consideration all ecosystem services provided by the hybrid erodible corridor, in comparison to that delivered by 20th Century channelized designs (Benedict and McMahon 2002, Morris et al. 2018; Keeler et al., 2019), as well as the legacy risks and disaster risks associated with catastrophic failure (Burby 2006, Davis 2007, Cutter et al. 2017, Di Baldassarre et al., 2019), and the equitable distribution of costs and benefits across stakeholders .

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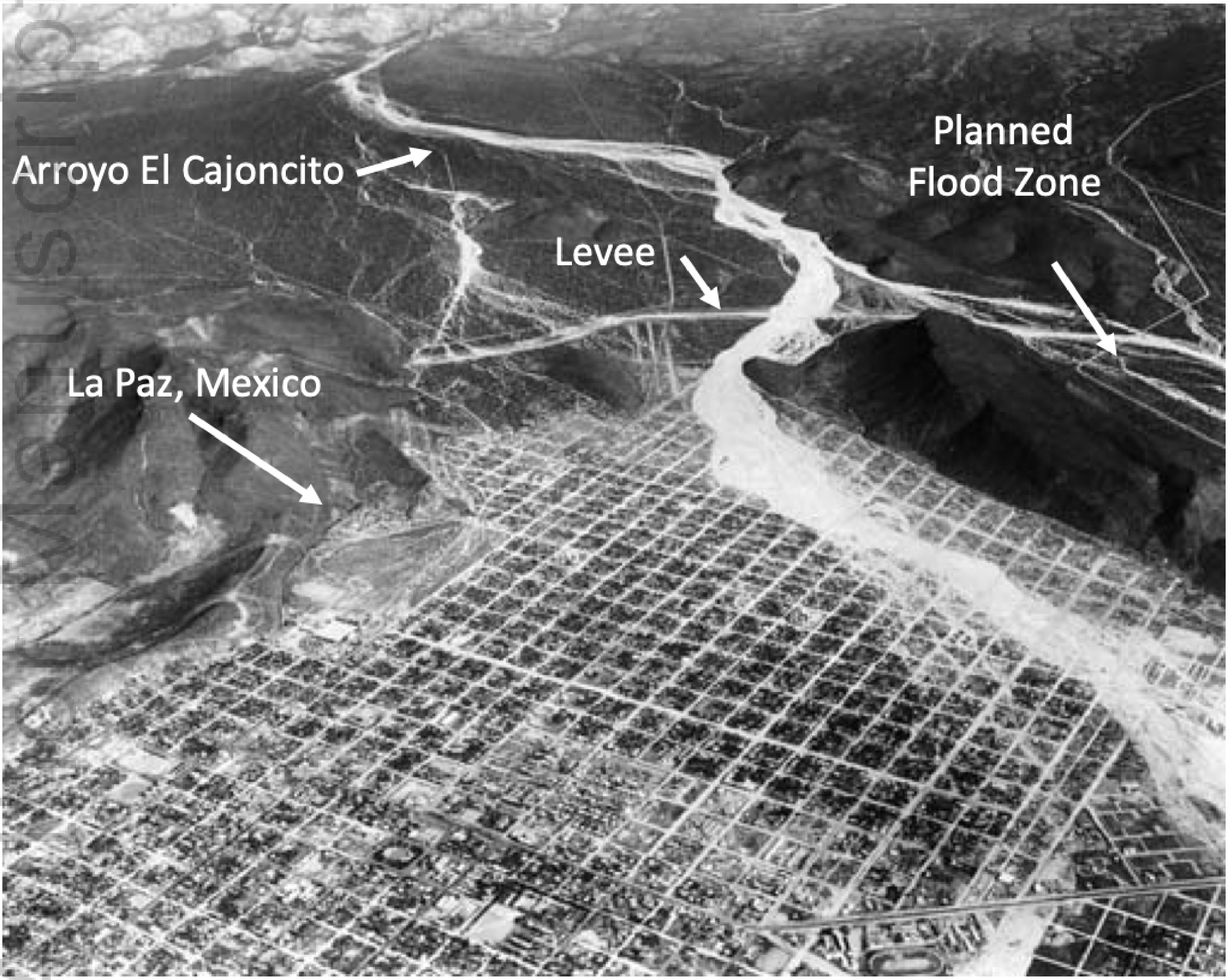

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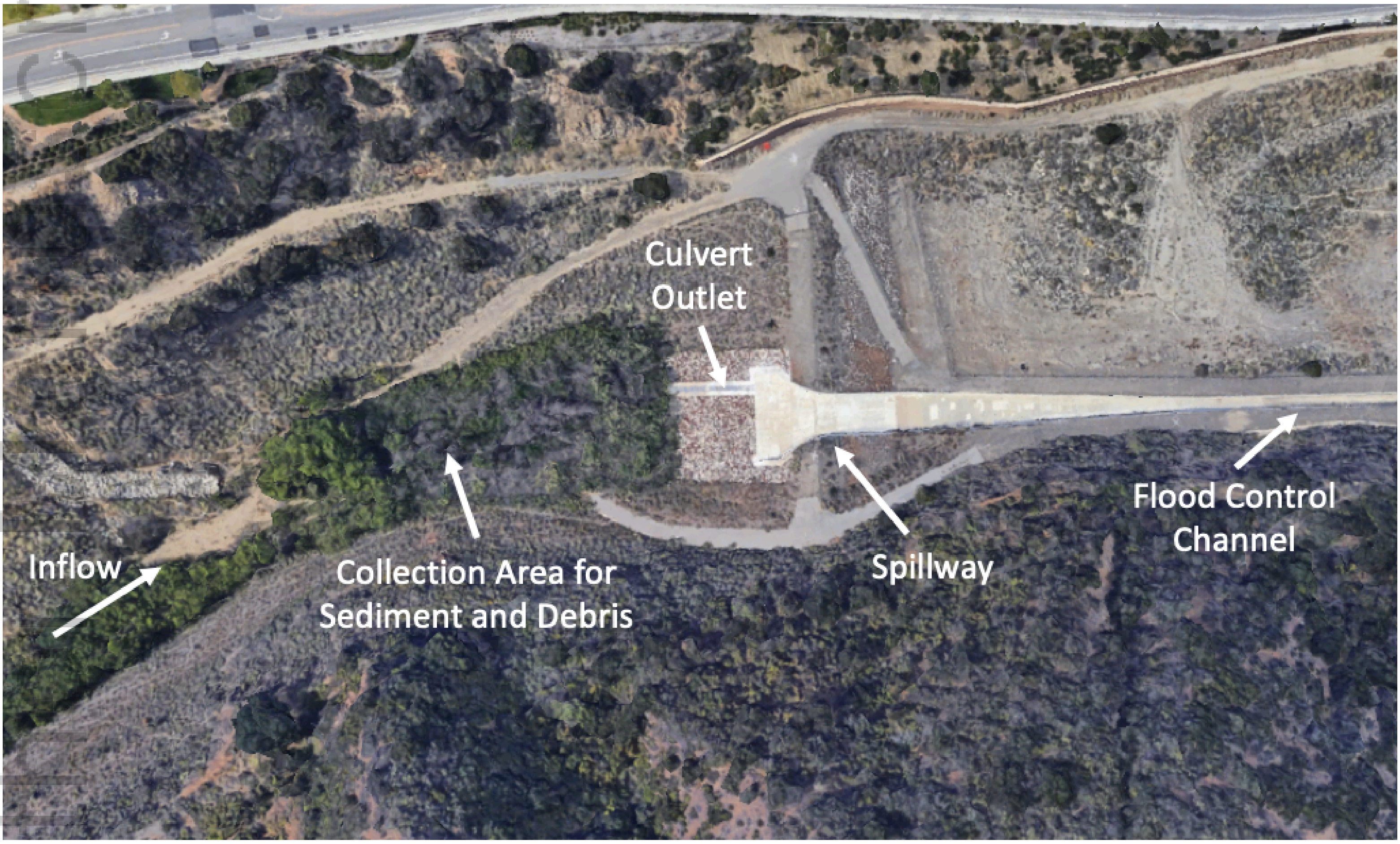

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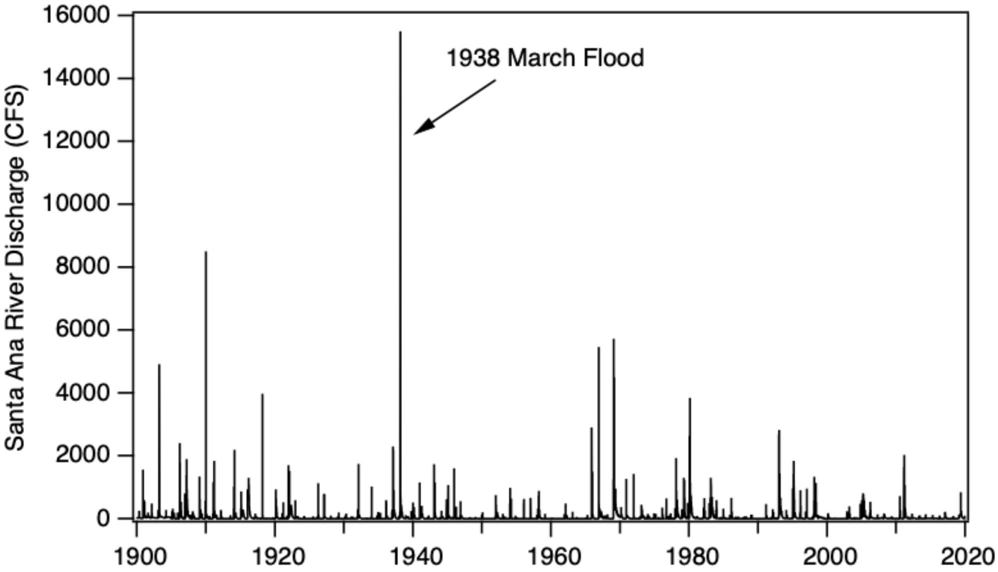

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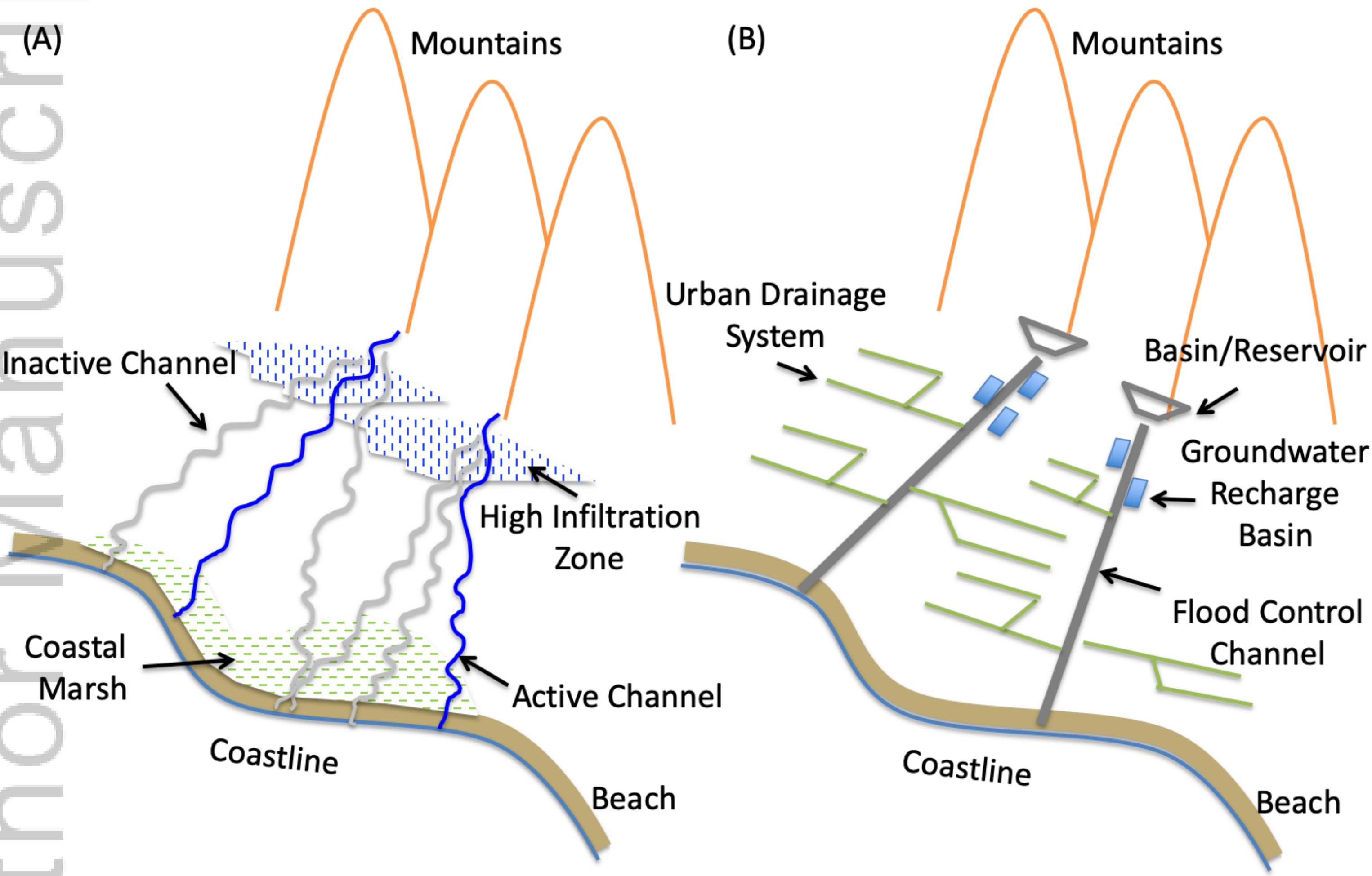

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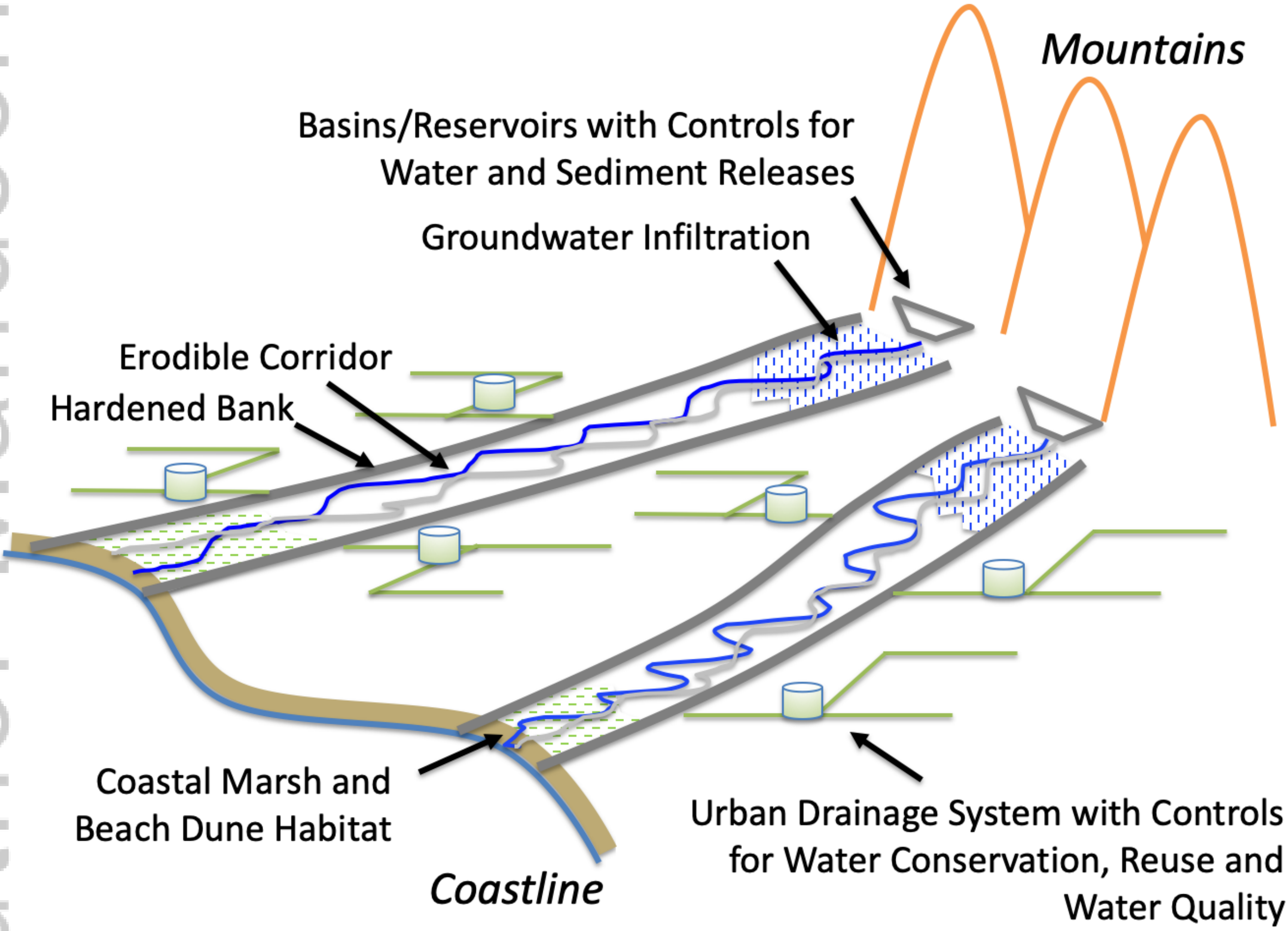

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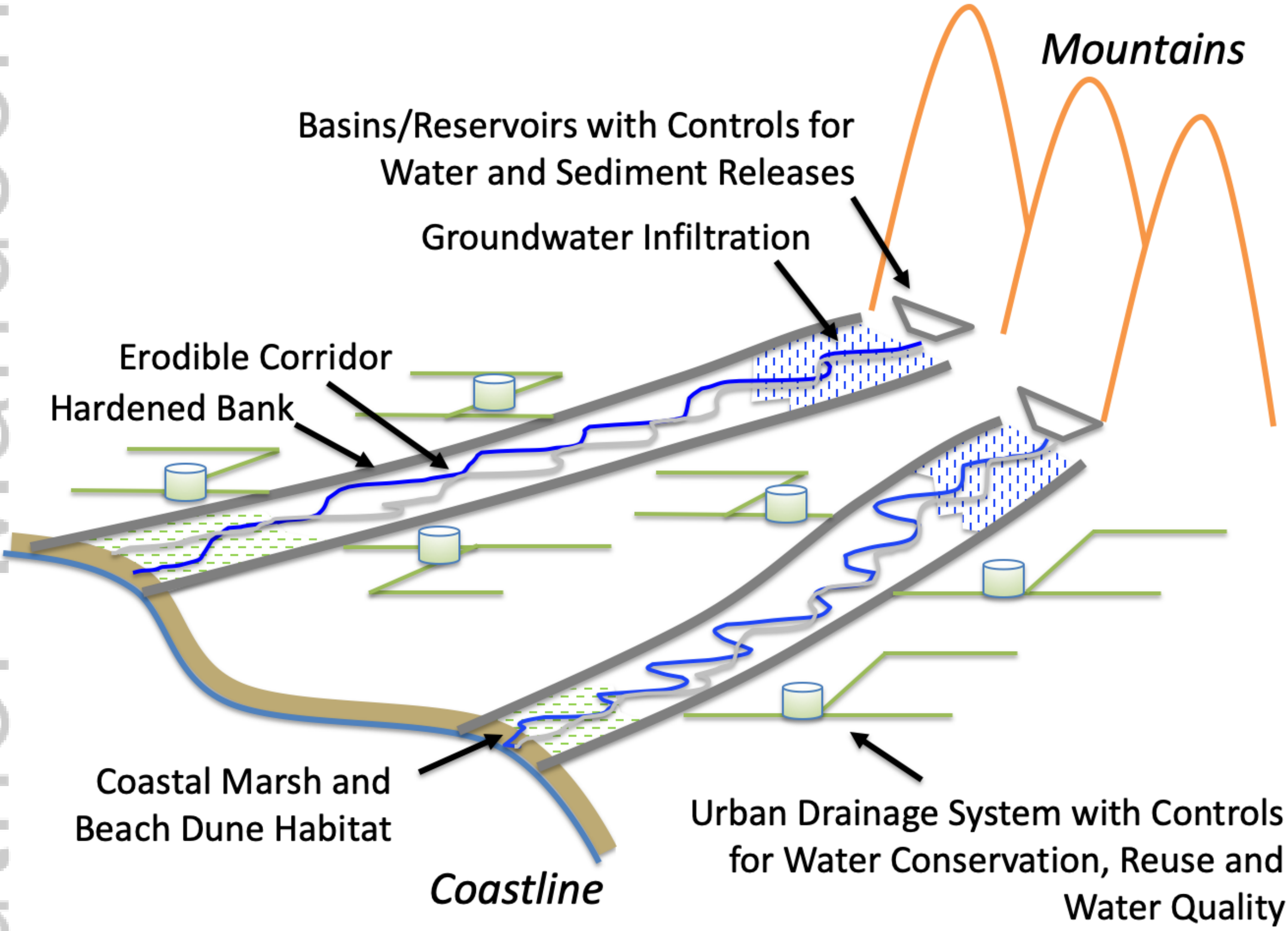

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