Chapter 13. Stormwater Management

Stormwater runoff is generated when rain or snowmelt flows over land or impervious surfaces and does not infiltrate into the ground. Stormwater infrastructure consists of storm drains that collect urban runoff and underground pipes that carry water to a discharge or outlet location, such as a flood control channel (Figure 1). Flood control infrastructure includes creeks, culverts, and channels that drain to the Bay, as well as pump stations where gravity alone cannot drain an area, especially during high tides. Mostly located in low–lying areas near the Bay, pump stations receive water from the conveyance network – that is, the pipes, creeks, and channels – and pump it to an elevation high enough to allow it to then flow by gravity into San Francisco Bay. In the ART project area, stormwater infrastructure is owned and managed by the cities, and flood control infrastructure, through which stormwater ultimately discharges to the Bay, is owned and operated by Alameda County. While precipitation and associated stormwater can cause flooding directly, this assessment addresses only the impacts resulting from the interaction of sea level rise with the stormwater management system – that is, the drains, conveyance network, pump stations, and outfalls that carry stormwater to the Bay. This chapter does not address the potential impacts of climate change on precipitation.

Figure 1. Overview of urban stormwater infrastructure, from curb to Bay. Source: Adapted from www.lastormwater.org/siteorg/general/lastrmdrn.htm

Stormwater is regulated through National Pollution Discharge Elimination System (NPDES) permits under the federal Clean Water Act (CWA), which directs states to adopt and enforce water quality standards, establish maximum allowable pollution levels for water bodies, and monitor and regulate discharges into water bodies. The State Water Resources Control Board, which has overall responsibility for water quality, delegates the administration of NPDES permits to its regional boards. The San Francisco Bay Regional Water Quality Control Board (Regional Board) is therefore in charge of water quality permitting activities for the ART project area. The cities, unincorporated areas, and flood control districts in Alameda County all share one NPDES permit through a consortium of 17 agencies called the Alameda Countywide Clean Water Program (ACCWP).

In the ART project area, stormwater does not receive any significant treatment prior to discharge aside from catch basin sumps that collect coarse-grained sediment, and grates on some outfalls that collect trash and other debris. This means that stormwater can carry a host of pollutants to the Bay, including oil and grease, metals, bacteria, nutrients, and suspended solids (Alameda Local Agency Formation Commission, 2005). To improve the quality of water in the stormwater and flood control system, and to comply with ACCWP's NPDES permit, the cities and counties perform regular maintenance of their infrastructure, including removal of blockages and cleaning inlets and basins, and preventative activities such as street sweeping, public outreach, and inspections for illicit discharge. "Pre-treatment" measures such as vegetated swales, retention ponds, and tree box filters are encouraged and to some extent required as part of the NPDES permit. Such measures also help slow water on its way to the Bay, reducing peak flows through the system.

With the exception of the City of Alameda, where stormwater flows to the Bay in city-owned pipes and channels, the stormwater from cities in the ART project area is routed into a regional flood control system through which it ultimately reaches the Bay. This system is owned and maintained by the Alameda County Flood Control and Water Conservation District (ACFCWCD), which is divided into nine zones, seven of which lie fully or partially in the ART project area (Figure 2 and Table 1). The zones are based on major watershed areas and are treated as separate financial entities for the purposes of maintaining and constructing facilities and for levying assessments. ACFCWCD has capital improvement programs in each zone that budget and plan for major improvements such as building and repairing levees and floodwalls and de-silting channels.

Figure 2. ACFCWCD flood zones, pump stations, and major creeks and channels in the ART project area.

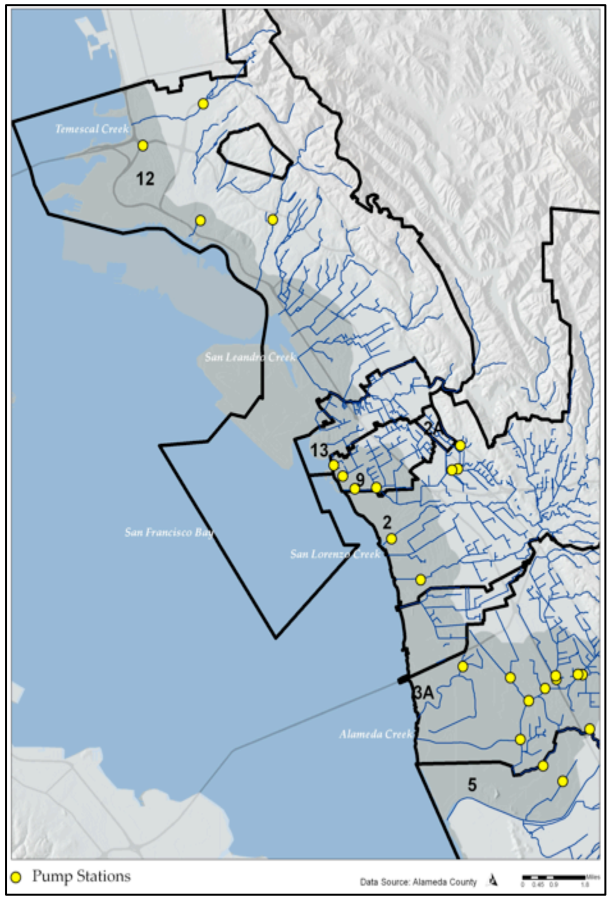

Table 1. Overview of ACFCWCD stormwater drainage systems; flood zones in the ART project area are listed from north to south.

Zone	Communities	Area (acres)	Major Creeks	Pump Stations
12	Emeryville, Oakland, San Leandro	38,000	Temescal, Sausal, Peralta, Lion, Arroyo Viejo, and Elmhurst	5
13	San Leandro	3,200	San Leandro	--
9	San Leandro	2,482		4
2	Hayward, San Leandro, Castro Valley, San Lorenzo, Ashland, Cherryland	40,390	San Lorenzo, Sulphur	--
4	Hayward, Mohrland, Russell City	2,960		--
3A	Hayward, Union City	19,700	Old Alameda, Mt. Eden	10
5	Fremont, Newark, Union City	45,500	Alameda, Old Alameda	3

In the City of Alameda, the stormwater system is divided into four drainage areas on each island (Alameda and Bay Farm), forming a total of eight drainage sub-areas. These sub-areas contain pipes, pumps, culverts, outlets and lagoons, owned and operated by the City, which ultimately discharge into San Francisco Bay. Figure 3 shows the sub-areas and Table 2 summarizes the stormwater infrastructure in each sub-area.

Figure 3. City of Alameda stormwater management sub-areas (Source: Schaaf and Wheeler, 2008).

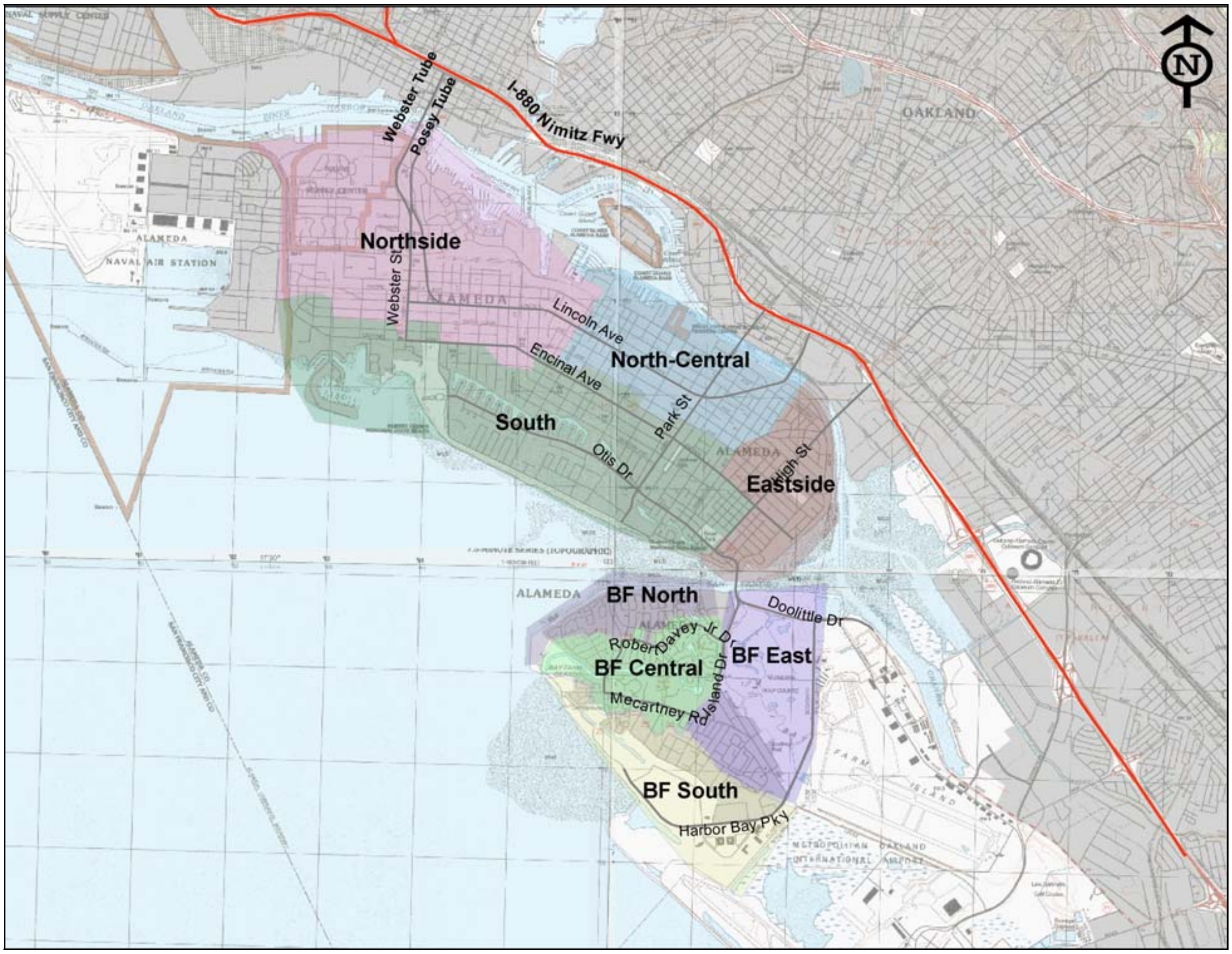

Table 2. Stormwater management infrastructure in City of Alameda sub-areas

Drainage Sub-area	Area (acres)	Miles of Pipes Greater than 12"	Number of Outlets	Pump Stations
Alameda Eastside	448	5	14	1
Alameda North-Central	704	6	11	0
Alameda Northside	1472	25	12	6
Alameda South	1472	11	23	3
Bay Farm East	576	5	2	1
Bay Farm North	243	4	4	1
Bay Farm Central	371	11	33	0
Bay Farm South	544	8	5	1

Exposure

Exposure is the extent to which an asset, in this case, part of the stormwater management system, experiences a specific climate change impact such as storm event flooding, tidal inundation, or elevated groundwater. This report analyzes the exposure of the stormwater system in the ART project area to two sea level rise projections and three Bay water levels. The two sea level rise projections, 16 inches (40 cm) and 55 inches (140 cm), correlate approximately to mid- and end-of-century. These projections were coupled with three Bay water levels: the highest average daily high tide represented by mean higher high water (MHHW), hereafter "high tide" or "daily high tide;" the 100-year extreme water level, also known as the 100-year stillwater elevation (100-year SWEL), hereafter "100-year storm" or "storm event;" and the 100-year extreme water level coupled with wind-driven waves, hereafter "storm event with wind waves" or "wind waves." These water levels were selected because they represent a reasonable range of potential Bay conditions that will affect flooding and inundation along the shoreline. For more information about sea level rise projections and Bay water levels evaluated see Chapters 1 and 2.

The locations and elevations of the pump stations were available in GIS, allowing evaluation of the exposure of each pump station to the daily high tide and storm event flooding. The exposure of the pump stations was determined within a circular 164-foot (50-meter) diameter footprint centered on the point location of the station (see Appendix C). This approach was verified as being representative of the approximate footprint of most assets evaluated in this manner. The average depth of inundation was calculated for the daily high tide and storm event scenarios. Whether the asset was exposed to wind waves only, or was within a disconnected low-lying area[1], was evaluated in a binary, i.e., yes versus no, analysis. Table 3 summarizes the exposure of ACFCWCD pump stations. A similar, GIS-based analysis of pump stations in the City of Alameda was not conducted as part of this assessment. The City has conducted its own stormwater system sea level rise vulnerability assessment, which is discussed in the box in the sensitivity and adaptive capacity section, below.

Beyond the ACFCWCD pump stations, very little GIS data were available for exposure analysis. Critical information, such as the location and elevation of stormwater outfalls into the Bay, was not available and therefore was not analyzed. Likewise, other components such as creeks, channels, and pipes, were not evaluated. The exposure of these features will vary along their extent and will depend on their geometry. The dynamic hydraulic modeling that would be necessary to analyze the interaction of Bay water levels with stormwater in these system components was not performed. However, because of their direct connection with the Bay, these features will be affected by the new daily high tide and storm events. For example, the mouth of Temescal Creek, a flood control channel, is currently subject to tidal action ranging from three to six feet every day (City of Emeryville, 2009). With sea level rise, water depths in Temescal Creek and other creeks and channels will increase, and some outfalls may be underwater. This could result in flooding (overtopping of creeks and channels, and ponding around inlets to pipes), as there may be insufficient storage in these creeks and channels to hold the stormwater until it can be released into the Bay.

Figure 2, above, shows the ACFCWCD zones, pump stations, and major flood control creeks and channels in the ART project area. Without vertical elevation data of the stormwater conveyance features or dynamic modeling, this figure serves simply as a first glance at the

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[1] Disconnected low-lying areas are at the same elevation or are lower than an adjacent inundated area. Assets in these areas are not considered exposed because a topographic feature such as a railroad or road embankment should prevent inundation. However, they could be exposed if the protective feature fails. See Chapter 2 for a more detailed explanation.

locations of some stormwater system features within each zone. The next section describes each of the flood zones and details the exposure of the pump stations within each zone (Table 3). However, as stated above, while analysis of pump station exposure is useful in determining the exposure of valuable infrastructure, it does not provide a comprehensive picture of the vulnerability of the stormwater management system, overall, to climate impacts. Further work, such as that conducted by the City of Alameda, and other studies by ACFCWCD underway, should include analysis of the exposure of outfalls and other conveyance features.

ACFCWCD Zones

Figure 4. Pump components of the Ettie Street Pump Station, Oakland.

Zone 12 is 38,000 acres[2] and drains Emeryville, Oakland, and part of San Leandro. It includes a long stretch of shoreline (comprising nearly half of the mainland extent of the ART project area), as well as a large inland area. Stormwater is drained through 12 creeks, more than ten miles of earth and concrete channels, and 49 miles of underground pipes. The major creeks draining into the Bay are San Leandro, Elmhurst, Arroyo Viejo, Lion, Sausal, Temescal, and Peralta. Zone 12 has five pump stations, two of which – Ettie Street (Figure 4) and Lake Merritt – are in the ART project area. With 16 inches of sea level rise, Ettie Street pump station, near the I-80 and I-580 interchange in West Oakland, will be exposed to wind waves during a 100-year storm. At 55 inches of sea level rise, Ettie Street pump station will be exposed to 2 feet of flooding from a 100-year storm event, as well as wind waves. Lake Merritt pump station is not exposed to any of the scenarios.

Zone 13 is 3,200 acres and drains part of San Leandro. The zone consists mostly of lowlands and is bordered by Zone 12 near the base of the hills to the east. San Leandro Creek runs through Zone 13, which is also served by a few miles of earth and concrete channels and 33 miles of underground pipes. Zone 13 does not have any pump stations and relies on gravity drainage to remove stormwater.

Zone 9 is 2,482 acres and drains part of San Leandro. Like Zone 13, it is primarily lowlands and is bordered to the east by Zone 2A (outside of the subregion). It has three miles of natural creeks and approximately three miles of earth and concrete channels. Zone 9 has four pump stations, three along the shoreline and one slightly inland. Pump stations F and H are in disconnected low-lying areas that could be exposed to the daily high tide with 16 inches of sea level rise. All four stations will be exposed to 1 to 2 feet of flooding in a 100-year storm, with additional wind wave impacts. With 55 inches of sea level rise, all four pump stations will be exposed to 2 to 3 feet of inundation by the daily high tide, and 4 to 5 feet in a 100-year storm, with additional wind wave impacts.

Zone 2 is 40,390 acres and serves parts of Hayward and San Leandro, as well as Castro Valley, San Lorenzo, Ashland, and Cherryland. It includes a large upland area in addition to shoreline.

[2] The ACFCWCD website gives an area of 51,200 acres; the figure presented in this report removes the portion of the flood zone in the shapefile provided by Alameda County which is already part of the Bay; that is, a portion of the 51,200 acres is water, not land, and therefore was removed for this analysis.

Zone 2 is drained by over 80 miles of creeks, 17 miles of earth and concrete channels, and 44 miles of underground pipes. Among the 12 creeks in the zone, the major ones that flow to the Bay are San Lorenzo Creek and Sulphur Creek. Two drainage canals, Bockman and Estudillo, also drain directly into the Bay. Zone 2 has two pump stations near the shoreline. With 16 inches of sea level rise, Sulphur Creek pump station will be exposed to wind waves during a 100-year storm. With 55 inches of sea level rise, both pump stations will be exposed to 1 to 2 feet of inundation from the daily high tide and 3 to 4 feet of flooding in a 100-year storm, with additional wind wave impacts.

Zone 4 is 2,960 acres and serves part of the City of Hayward, as well as the communities of Mohrland and Russell City. It is a small, low-lying zone, bordered to the north by Zone 2, and to the south and east by Zone 3A. Zone 4 has fewer than two miles of creeks, four miles of earth and concrete channels, and nine miles of underground pipes. There are no pump stations, and the creeks and channels in this zone drain to the Bay through a channel that border with Zone 2.

Zone 3A is 19,700 acres and serves a number of communities, including parts of Hayward and Union City. Much of Zone 3A is very low-lying and includes salt ponds as well as some upland portions of Hayward. There are 21 miles of creeks in the Zone, including Old Alameda Creek and Mt. Eden Creek, which flow through salt ponds to the Bay; 25 miles of earth and concrete channels; and 43 miles of underground pipes. It also has ten pump stations within the ART project area, both along the shore and inland. With 16 inches of sea level rise, Besco and Alvarado pump stations will be inundated by 4 and 2 feet, respectively, by the new daily high tide. They will be flooded by 6 and 3 feet in a 100-year storm event and will also be exposed to wind waves. All of the other pump stations in the zone, except for Stratford and Westview, will be exposed to wind waves. Pump stations A-2[3] and Ameron are in disconnected low-lying areas that could be exposed to 100-year storm event flooding; the disconnected low-lying area where A-2 is located could also be exposed to the daily high tide. With 55 inches of sea level rise, Eden Landing, Besco, Ameron, Alvarado, and A-2 pump stations will be exposed to 1 to 6 feet of flooding by the daily high tide. All but Stratford, Westview, and Ruus Road will be exposed to 1 to 9 feet of flooding by a 100-year storm event, and all will be exposed to wind waves.

Zone 5 covers 45,440 acres and serves parts of Fremont, Newark, and Union City. It is mostly low-lying but drains some of the hills of Union City and Fremont. The zone has 37 miles of creeks, including Alameda and Old Alameda, as well as more than 40 miles of earth and concrete channels and 49 miles of underground pipes. It is served by three pump stations, two of which – J2 and J3 – are in the ART project area. Both pump stations are in disconnected low-lying areas that could be exposed to the 100-year storm event with 16 inches of sea level rise. Both will be exposed to wind waves during a 100-year storm. With 55 inches of sea level rise, the pump stations are exposed to 2 to 3 feet of inundation by the daily high tide, and 4 to 6 feet of flooding in a 100-year storm, with additional impacts likely due to wind waves.

[3] A-2 pump station is not identified on ACFCWCD's website, but the GIS data used for this analysis shows this as being within this flood zone.

Table 3. Exposure of ACFCWCD pump stations to the daily high tide and storm event flooding with 16 and 55 inches of sea level rise.

		16" SLR			55" SLR		
		Daily high tide	Storm Event		Daily high tide	Storm Event	
Name	Zone	Average depth (ft)	Average depth (ft)	Exposed to wind waves only	Average depth (ft)	Average depth (ft)	Exposed to wind waves only
Lake Merritt	12						
Ettie St.	12			Yes		2	
Line H	9		2		2	5	
Line F	9		1		2	4	
Belvedere	9		1		2	5	
Line D-1	9		2		3	5	
Roberts Landing	2				1	3	
Sulphur Creek	2				2	4	
Eden Landing	3A		1		2	4	
Besco	3A	4	6		6	9	
Ameron	3A				1	3	
Stratford	3A						Yes
Industrial	3A			Yes		1	
Westview	3A						Yes
Alvarado	3A	2	3		4	6	
Ruus Road	3A			Yes			Yes
Eden Shores	3A			Yes		3	
A-2	3A				1	4	
J-3	5				3	6	
J-2	5				2	4	

Sensitivity and Adaptive Capacity

The sensitivity and adaptive capacity of stormwater infrastructure in the ART project area to three potential climate impacts that could occur due to sea level rise was assessed. The three climate impacts considered are:

- More frequent or longer duration flooding during storm events
- Permanent or frequent inundation by the daily high tide
- Elevated groundwater levels and saltwater intrusion

Sensitivity is the degree to which an asset or entire system (e.g., pump stations, pipes, channels, or entire watershed) would be physically or functionally impaired if exposed to a climate impact. Adaptive capacity is the ability for an asset or system to accommodate or adjust to a climate impact and maintain or quickly resume its primary function.

The stormwater management systems in the ART project area have fairly high sensitivity to all three climate impacts, given their function and direct contact with the Bay. Characteristics of the individual components as well as the overall system contribute to sensitivity. One of the features of the system that makes it sensitive is its reliance on gravity for drainage. As sea levels rise, there will be less of a gradient between the source of the stormwater and its eventual destination, and some of the outfalls will be below sea level during high tide or a storm event. This means that Bay water will enter the stormwater systems and travel up creeks, channels, and pipes. If elevated Bay water levels coincide with a precipitation event, the presence of Bay water in stormwater infrastructure will reduce the system's capacity to store and convey stormwater, which could result in stormwater backing up and causing inland flooding. In addition, saltwater could corrode and otherwise damage infrastructure that is only designed to handle freshwater.

Figure 5. Duckbill check valve discharging water. Photo credit: Tideflex Technologies.

Pipes with the largest excess capacity – that is, the most room to store stormwater when precipitation coincides with high tide – will have greater adaptive capacity. Another way to increase adaptive capacity is to install check valves, such as duckbills (Figure 5), a device that only allows flow in one direction, on the outfalls to the Bay. These valves prevent Bay water from entering the system and taking up pipe capacity needed to convey and store stormwater. Where gravity drainage is insufficient, it may become necessary to install pumps, but these can have high capital improvement and operations and maintenance costs.

Pump stations are sensitive to sea level rise in several ways. They rely on sensitive electric or computerized components that would not be able to function if flooded. Pump stations cannot lift stormwater beyond their design capacity, or above certain elevations. They also require a power supply, which could be disrupted – if access to pump stations is flooded, those without sufficient backup fuel on site could be particularly sensitive. In areas that already require pumping to manage stormwater and control flooding, pumps will have to lift water above the new, elevated Bay water level, which may exceed their capacity. More frequent operation and pumping water to higher elevations will increase energy and maintenance costs and could decrease the operational life of pumps. Retrofitting, adding pumps, or bringing in portable pumps could contribute to adaptive capacity, but as noted above, this would be costly, and backup pumps may not be available. Another feature that contributes to adaptive capacity is a forced main, wherein the discharge pipe is hardened and pumped to maintain positive pressure. This enables the pipe to discharge even when the opening is underwater. The outfall for Ettie Street pump station is permanently underwater, and it is the only pump station in the ART project with a forced main. This may be an option for outfalls that will be permanently or frequently inundated, but it involves costly infrastructure.

Sensitivity and Adaptive Capacity of the City of Alameda Stormwater System

In 2008, the City of Alameda conducted a detailed study to identify sensitivity in their stormwater system (Schaaf and Wheeler, 2008). The most common cause of local flooding is leaf litter in the system, which plugs inlets and outlets and reduces the effectiveness of pump stations, and the obstruction of gutters and culverts by tree roots. Some flooding in extreme events is also caused by limited capacity within the stormwater management system. By modeling tide cycles, precipitation, runoff, and other factors, the City determined where improvements to the storm drain system are necessary to provide a 10-year level of service. This is the ability to meet certain criteria – such as pipe capacity and the level of stormwater in the street – during a 10-year storm event under current climate conditions. Areas currently in need of improvement will be particularly sensitive to sea level rise impacts, as they may already be overwhelmed by extreme events.

The study recommended a number of improvements, primarily focused on increasing the size of certain pipes in problem areas. If implemented, these improvements would contribute to adaptive capacity by providing more storage in pipes so that stormwater could be detained during high tides, when outfalls could be underwater and Bay water would cause backups.

An addendum to this study, conducted in 2009, analyzed the capacity of the system to maintain a 10-year level of service with 18 inches of sea level rise. The study concluded that additional projects would be necessary, including adjusting the recommended size of some of the pipes that were already marked for replacement and the need to expand additional pipes. In addition to recommendations on pipe size, the study evaluated the cost of implementing the initial recommendations, as well as the increased costs of recommended improvements to accommodate sea level rise. Such information is especially useful for weighing the costs and benefits of building extra capacity now or waiting until later to act. In this case, putting in slightly larger pipes than are necessary now may be more expensive in the short term, but is likely to be far less costly than replacing them again when sea level rises.

Stormwater management is also sensitive to rising groundwater. Higher groundwater levels will reduce the capacity for management practices to increase infiltration such as retention and detention, meaning that more precipitation could end up as runoff and have to be conveyed to the Bay in flood control channels and creeks. It could also reduce capacity in channels and creeks connected to the groundwater table. In addition, rising groundwater will increase the risk of liquefaction in a seismic event, which could cause underground pipes to move, bend, or break.

The sensitivity of the overall system – from the top of the watershed to discharge locations – is affected by a number of factors. The age of the stormwater infrastructure and the limited funds for repair, upgrade, and ongoing maintenance makes stormwater management very sensitive. In most parts of the ART project area, property assessments and other fees are insufficient to cover expenses for maintenance or expansion of the stormwater system, and general fund revenues must be used. Additionally, stormwater assessments are considered property-related fees under Proposition 218, so a two-thirds vote would be necessary to increase them, which limits adaptive capacity.

Regular maintenance of stormwater infrastructure, such as keeping storm drains clear of debris and trash, contributes to adaptive capacity. Such maintenance is required in NPDES permits, and the ACCWP reports regularly to the Regional Board on compliance. As mentioned above, the ACFCWCD has a capital improvement program in each zone that prioritizes and funds infrastructure repair and construction. In addition, ACFCWCD works with other entities to restore creeks in the system to a more natural condition, which can improve flood control as well as providing habitat and recreational values. The City of Alameda also has a small fund for maintenance and capital improvement, raised through the local urban runoff property tax and grants; however, this is insufficient for implementing all of the necessary improvements identified by the City in the study discussed above.

Inland flooding problems caused or exacerbated by sea level rise could perhaps be mitigated by improving stormwater management throughout each watershed, not just through flood control infrastructure. A large portion of each watershed in the ART project area is developed, and the impervious surfaces common to developed areas mean that stormwater does not infiltrate and instead makes its way to the Bay through the stormwater and flood control infrastructure. The Mediterranean climate of the area also means that, while annual precipitation is relatively low, most rainfall usually occurs within a short period of time, saturating the ground and sometimes filling the stormwater system to capacity (referred to as “surcharging”).

Efforts to reduce runoff by increasing infiltration throughout the watershed contribute to adaptive capacity. One way to achieve this is through the use of low impact development (LID) principles. One principle of LID is to capture and store water in ponds or bioswales high in the watershed, resulting in reduced and/or delayed peak discharge into downstream infrastructure. Another approach is to reduce impervious surfaces through the use of semi-pervious or pervious surfacing materials for parking areas or sidewalks, allowing more water to infiltrate rather than flowing into stormwater infrastructure. Another element of LID is to capture rainfall for later use in rain barrels or rain gardens.

While LID can be implemented on a case-by-case basis, integrating it into a stormwater management system takes time, planning, and money, and requires the participation of the entire watershed. As explained above, ACFCWCD is responsible for the flood control infrastructure, while the cities are responsible for the initial capture of stormwater. The generation of stormwater is highly dependent on the amount of pervious surface where precipitation falls. Development and land use are determined by a number of entities, and there is currently little coordination between ACFCWCD and the cities and others who determine land use throughout the watershed.

Some investment in LID is already taking place. As part of their NPDES Permit, for example, the cities and counties in the ART project area require new and redevelopment projects to incorporate stormwater treatment measures or Best Management Practices (BMPs) to minimize pollutants in the stormwater management system. However, this only applies to new development, redevelopment, and certain changes to the land surface in already developed sites. These areas account for a relatively small percentage of runoff in the area. Unless retrofitting ground covers and other stormwater management practices in existing developed areas becomes widespread, the majority of precipitation will still become runoff and enter the stormwater and flood control system rather than being retained or infiltrated. Over time, however, both permit-mandated LID and special projects can contribute to the retention, detention, and infiltration of stormwater in the ART project area, increasing the adaptive capacity of the stormwater management system as a whole.

Consequences

The potential consequences of the climate impacts on stormwater management are considered for the ART project area. Consequences are the magnitude of the economic, social, environmental, and governance effects if an impact occurs. Factors that inform the magnitude of the potential consequences include the severity of the impact on operations and maintenance or capital improvement costs, the size and demographics of the population affected, and the types of natural resources affected.

Economy
If the stormwater system is impaired by sea level rise, either through storm events, tidal inundation, or rising groundwater, there will be direct and indirect economic consequences. One direct consequence is the cost of water removal, cleanup, and repairs to structures and landscapes damaged by flooding. Major flooding could also damage stormwater infrastructure itself, such as pumps, channels, inlets, and outfalls, which would then need to be repaired. In the City of Alameda, for example, while flooding has historically not caused significant structural damage, it has required City staff resources to prepare for, handle, and recover from flood events (Schaaf and Wheeler, 2008). Saltwater intrusion could also cause economic consequences by damaging equipment through corrosion. An indirect economic consequence is the business or productivity that could be lost due to commercial buildings being inaccessible if they or the roads required to reach them are flooded. For example, most of Emeryville's main shopping areas are near the shoreline. If they are forced to close because of flooding, or if workers or customers can't reach them due to road closures, they would lose business, which could result in economic losses for the city and the region.

Society
The social consequences of an impaired stormwater system are similar to the economic ones – people's lives will be disrupted if their homes or places of employment are damaged or closed, or if they are isolated due to road closures. Flooding could impede emergency response, important not only for immediate problems that could be caused by flooding, but also for medical or other emergencies that require urgent attention. If floodwaters are not removed quickly, they could become breeding grounds for mosquitoes and other disease vectors. There are also equity concerns, as low-lying areas in the ART project area that currently need to be pumped to maintain positive drainage tend to have lower-income residents. These residents may be particularly vulnerable, especially where there are language barriers or poorly maintained infrastructure that could exacerbate the problem.

Environment
Environmental concerns related to stormwater include the redistribution of contaminants that water picks up from the land surface. An impaired stormwater system would distribute contaminated runoff differently – rather than flowing directly to the Bay, pollutants could be deposited wherever the floodwaters flow. In addition, floods could destroy sensitive habitats or areas under restoration, or redistribute pollutants from contaminated lands or hazardous materials sites into natural areas.

Governance
A key governance issue related to stormwater is the need to manage it across the entire watershed, while jurisdiction over each watershed is divided across cities and counties. As noted above, with the exception of the city of Alameda, all of the cities in the ART project area ultimately channel their stormwater into Alameda County's floodwater infrastructure. While ACFCWCD zones are roughly based on watersheds, each watershed (and zone) is made up of portions of several cities and unincorporated communities, which manage the initial stormwater capture and have a role in determining land use, which in turn affects the degree of

development and pervious surface in the watershed. The number of jurisdictions involved, and the need for coordination between the upper watersheds and the point of discharge, can make it difficult to prioritize and implement management strategies such as LID. If one adaptation strategy is to reduce peak flows entering this system, Alameda County will need to coordinate with each of the cities to improve stormwater management at all levels of the watershed.

Key Findings

Stormwater infrastructure consists of storm drains that collect urban runoff and underground pipes that convey flows to a discharge outlet. Stormwater outlets are often located with flood control infrastructure along the Bay shoreline. Flood control infrastructure includes creeks, culverts, and channels that drain to the Bay. In some cases there are also associated pump stations where drainage cannot be achieved by gravity alone. The capacity to discharge stormwater is sensitive to sea level rise and will depend on the elevation and location of the outlet and the storage and flow capacity of the underground pipe system. If elevated Bay water levels coincide with a precipitation event, the presence of Bay water in stormwater infrastructure will reduce storage in the system, which could result in stormwater backing up and causing inland flooding.

A total of 20 pump stations in the ART project area, excluding the City of Alameda (which has conducted its own analysis and identified parts of the system that should be upgraded to accommodate sea level rise), were evaluated. With 16 inches of sea level rise, very few pump stations are exposed to the daily high tide, but nearly all are exposed to storm event flooding or wind waves. About two thirds of the pump stations are exposed to the daily high tide with 55 inches of sea level rise, and all but one are exposed to wind waves. Pump stations are sensitive to sea level rise because they require power and may have electronic or computerized components that cannot get wet. Many also have limited adaptive capacity due to their age or ongoing need for maintenance, and funds are limited due in part to legislation that prohibits increasing property assessments to fund system improvements. Pump stations with access to a backup power supply and sufficient fuel will have higher adaptive capacity.

The lack of key data (e.g., elevation of inlets and outfalls) and modeling capacity (e.g., dynamic modeling showing the interaction of stormwater conveyance and Bay water levels) makes it difficult to fully understand the vulnerability of the stormwater system to sea level rise. Further work to identify the elevation of key features of the stormwater system, as well as modeling of Bay water and stormwater interaction within pipes, channels, and creeks, is necessary to better analyze the exposure and overall vulnerability and risk of the stormwater system.

Improvements to the stormwater system as a whole will require interagency collaboration and coordination between those responsible for the source of stormwater – the upper watersheds (managed by cities, property owners, state regulations, etc.) – and those who manage stormwater at the shoreline (e.g., ACFCWCD). Currently, there is not a framework in place to make comprehensive, watershed-based decisions to improve the adaptive capacity of stormwater and flood control infrastructure.

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