Earthquake-Driven Subsidence and Sea-Level Rise: Compound Flooding Hazards Along the Cascadia Subduction Zone, USA

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Abstract

Climate-driven sea-level rise is increasing the frequency of coastal flooding worldwide, exacerbated locally by factors like land subsidence from groundwater and resource extraction. However, a process rarely considered in future sea-level rise scenarios is sudden (over minutes) land subsidence associated with great (>M8) earthquakes, which can exceed 1 m. Along the Washington, Oregon, and northern California coasts, the next great Cascadia subduction zone earthquake could cause up to 2 m of sudden coastal subsidence, dramatically raising sea level, expanding floodplains, and increasing the flood risk to local communities. Here, we quantify the potential expansion of the 1 % floodplain (i.e., the area with an annual flood risk of 1%) under low (~0.5 m), medium (~1 m), and high (~2 m) earthquake-driven subsidence scenarios at 24 Cascadia estuaries. If a great earthquake occurred today, floodplains could expand by 90 km^2 (low), 160 km^2 (medium), or 300 km^2 (high subsidence), more than doubling the flooding exposure of residents, structures, and roads under the high subsidence scenario. By 2100, when climate-driven sea-level rise will compound the hazard, a great earthquake could expand floodplains by 170 km^2 (low), 240 km^2 (medium), or 370 km^2 (high subsidence), more than tripling the flooding exposure of residents, structures, and roads under the high subsidence scenario compared to the 2023 floodplain. Our findings highlight the need for decision makers and coastal communities along the Cascadia subduction zone to prepare for compound hazards from earthquake-cycle and climate-driven sea-level rise, and provide critical insights for tectonically active coastlines globally.

Significance Statement

In coastal flood hazard analysis, local factors like land subsidence from great earthquakes (>M8) are often overlooked. Along the Cascadia subduction zone (Washington to northern California), the next great earthquake will likely cause 0.5–2 m of sudden subsidence and associated sea-level rise, dramatically expanding coastal floodplains. Earthquake deformation modeling and geospatial analysis show that subsidence from a great earthquake at Cascadia today could double the flood exposure of residents, structures, and roads. By 2100, earthquake subsidence amplified by climate-driven sea-level rise could more than triple the flood exposure of residents, structures, and roads. This study underscores the need to consider combined earthquake and climate impacts in planning for coastal resilience at the Cascadia subduction zone and globally.

Introduction

Climate-driven 21st-century sea-level rise is exposing coastal populations, infrastructure, and ecosystems around the world to more frequent marine inundation [1–4]. At many coastal locations, downward vertical land motion (i.e., land subsidence) sometimes exceeding 5 mm/yr is amplifying local relative sea-level rise (RSLR), defined as the change in sea level at a specific location relative to the land, and increasing flooding frequency [5–10]. However, along much of the coast of Washington, Oregon, and northern California, gradual coastal uplift caused by crustal deformation during the interseismic phase of the current Cascadia subduction zone (CSZ) earthquake cycle locally mitigates the effects of climate-driven sea-level rise [11–14]. Coastal uplift rates of 1-3 mm/yr exceed the current rate of climate-driven sea-level rise at locations such as Astoria, OR, Port Orford, OR, and Crescent City, CA, with tide gauges recording RSL fall. At other locations, such as Yaquina Bay, OR, and Coos Bay, OR, where uplift rates are lower, tide gauges show 0.3-1.2 mm/yr of RSLR, well below the global sea-level rise rate of 4.5 ± 1 mm/yr [14–16]. An exception is Humboldt Bay in Northern California, where complex regional tectonics are causing gradual subsidence, resulting in the highest recorded Pacific-coast RSLR rate of 4.7 mm/yr [17].

The tectonic tempering of climate-driven sea-level rise along the Washington, Oregon, and northern California coasts is projected to be short-lived; by ~2030, rates of climate-driven sea-level rise are expected to outpace gradual uplift. By 2050, central (50th percentile) sea-level projections for a high emissions scenario (SSP3-7.0[18]) show 0.1-0.3 m of RSLR. By 2100, sea levels are projected to rise 0.4-0.9 m. The acceleration of RSLR will require Washington, Oregon, and northern California residents and planners to contend with compromised roadways and bridges, more frequently and/or permanently inundated lifelines and critical infrastructure, increased high-tide flooding and vulnerability to storm-surges, increased coastal erosion and barrier dune breaching, and eroding or inland-migrating coastal marshes [12,19–21].

Yet, gradual climate-driven sea-level rise is not the only inundation threat facing CSZ coastlines. Coastal subsidence from the next great (>M8) CSZ earthquake may produce >1 m of sudden RSLR much sooner than 2100 as evidenced in Cascadia's intertidal wetland stratigraphy[22,23]. Stratigraphic evidence of earthquake-driven subsidence from the most recent great earthquake along the CSZ, which occurred on 26 January 1700 CE, indicates sudden (over minutes) 0.5-2 m RSLR, resulting in submergence of low-lying intertidal wetlands and floodplains that may persist for decades to centuries after an earthquake [23–29]. Radiocarbon dating of plant fragments preserved within pre-earthquake peat or overlying mud suggests >11 great earthquakes along Cascadia's coasts in the last 6-7ka, recurring every ~200-800 years [30].

Earthquake-driven coastal subsidence following recent historical earthquakes has had severe consequences for communities, leading to permanent land loss, infrastructure damage, and forced relocation[31,32]. The 1960 Chile earthquake caused up to 2.5 m of coastal subsidence, permanently submerging coastal pine forests and farms and converting them to intertidal marshes [33], and flooding coastal towns and forcing residents to abandon homes and rebuild inland [34]. In 1964, the Alaska earthquake lowered coastal areas by over 2 m, rendering roads, docks, and waterfront areas uninhabitable, in some cases necessitating relocation of communities to higher ground or raising waterfront facilities and airstrips above high tide[35]. The 2004 Sumatra-Andaman earthquake caused land subsidence of up to a meter that led to chronic tidal flooding in waterfront areas used for aquaculture, resulting in over-salinization [36], and causing coastal erosion and land loss [36]. Similarly, the 2011 Tōhoku earthquake in Japan caused up to 1 m of subsidence, disrupting ports [37], causing shoreline erosion [38], and permanently altering the morphology of river mouths [39].

At the CSZ, the National Seismic Hazard Model (NSHM) calculates a time-independent 15% probability of a M≥8 rupture sometime in the next 50 years [40]. Such an earthquake could suddenly lower coasts by 0.5-2 m, drastically altering shorelines and causing profound, lasting impacts to coastal populations, infrastructure, and ecosystems. Unlike gradual climate-driven

RSLR, this earthquake-driven RSLR will happen within minutes, leaving no time for adaptation or mitigation. Moreover, climate-driven sea-level rise will make coastal areas even more vulnerable to the effects of future earthquake-driven subsidence as it progresses paired with the increased probability (29%) of a M≥8 earthquake occurring by 2100 [40].

Here, we use earthquake rupture and deformation modeling in combination with geospatial analysis to quantify the projected expansion of coastal floodplains at 24 CSZ estuaries and surrounding communities if earthquake-driven subsidence occurs today (2023), or in 2100, when climate-driven RSLR will amplify flooding. We assess the impacts of expanded floodplains on land-use, residents, structures, and roads, illustrating the importance of considering the compound hazards of earthquake- and climate-driven RSLR in coastal planning on the Pacific coast of the United States and other tectonically active coastlines.

Results

Effects of earthquake-driven subsidence today

Using 2023 as a baseline, we use geospatial analysis to quantify the expansion of the 1% floodplain area following earthquake-driven subsidence and its impact on land-use, residents, structures, and roads at 24 CSZ estuaries and surrounding communities (Fig. 1a; see methods for geospatial dataset information). The 1% (100-year) floodplain includes land that is covered in water during a flood that has a 1% chance of being equaled or exceeded each year. We define the perimeter of the 1% floodplain as the 1% annual exceedance probability water level as measured at a series of National Oceanic and Atmospheric Administration (NOAA) tide gauges along the Washington, Oregon, and northern California coasts (Supplementary methods). Our 1% floodplain perimeters are broadly aligned with the Federal Emergency Management Administration (FEMA) high risk flood zones within which residents and businesses are required to have flood insurance[41]. To depict the floodplains, we overlayed the local 1% annual exceedance probability water-level boundary, which ranges from 1.08 to 1.23 m above mean higher high water (MHHW)(Fig. 1c; Table 1), on 10-m (1/3 arc-second) resolution Digital Elevation Model (DEM) tiles (Supplementary methods). We then adjusted the elevation of the 1% floodplain boundary upwards by the modeled low (50th percentile), medium (10th percentile), and high (maximum recorded) earthquake-driven subsidence projections for each estuary defined in the FakeQuake Catalog, a forward modeling tool for earthquake ruptures used to simulate coseismic subsidence along the CSZ [42,43] (Fig. 1b,c; Table 1). These ruptures range in magnitude from 7.7 to 9.2 and were chosen due to their ability to match the coastal subsidence records correlated to the 1700 CE earthquake. The catalog includes fault slip heterogeneity and variable rupture areas, including both full margin and smaller partial margin ruptures. At the CSZ estuaries analyzed, the modeled low subsidence ranges from 0.23-0.67 m, the medium subsidence ranges from 0.46-1.34 m, and the high subsidence ranges from 0.93-2.67 m. For each subsidence scenario, we use a constant value of subsidence throughout the estuaries and limit our analysis to ~30 km inland from the coast due to the uncertainty in how coseismic subsidence will decay inland [44]. Most sites analyzed lie within 10 km of the coastline, except for those in Washington, which extend out to our 30 km inland analysis limit. We note that we report the change in the floodplain area, rather than the total floodplain area before and after subsidence, since some parts of the current 1% floodplain are already covered by water.

Our analysis shows that if a CSZ earthquake occurred today, earthquake-driven subsidence would increase the area of the 1% floodplain at the 24 estuaries by 90 km^2 (low subsidence), 160 km^2 (median subsidence), or 300 km^2 (high subsidence; Table 2, Figs. 2 and 3). The land-use categories with the largest increase in land area within the 1% floodplain are parks and open space (340 km^2 to 410 km^2) and farm use (100 km^2 to 160 km^2) under the high subsidence scenario. Other notable impacts to land-use under the high subsidence scenario include increased exposure to flooding of residential and rural residential (60 km^2 to 100 km^2) and commercial (100 km^2 to 120 km^2) land.

Along with impacts to land-use, earthquake-driven subsidence will cause significant impacts to coastal residents, structures, and roads (Table 2, Fig. 2 and 3). Within the 2023 1% floodplain at the 24 estuaries, there are 8,120 residents, 13,370 structures, and 700 km of roadway exposed to flooding. Following high-end earthquake-driven subsidence today, an additional 14,350 residents (177% increase), 22,500 structures (168% increase), and 1,250 km of roadway (179% increase) are in the 1% floodplain, more than doubling flood exposure.

We acknowledge that postseismic land-level change occurring in the months to years after the next great CSZ earthquake could either temper or exacerbate cosesimic subsidence. Luo et al. (2022)[45] modeled the coseismic and postseismic deformation of the 1700 CE CSZ earthquake along coast-perpendicular profiles in southern Washington and northern Oregon and found that postseismic deformation from viscoelastic relaxation is negligible after one year, but afterslip—the slip that may occur between the Episodic Tremor and Slip zone and the seismogenic zone—could produce decimeters of uplift along the coast, depending on the downdip width of the afterslip. Also at Cascadia, high resolution dating of post-1700 CE sediments shows the reestablishment of intertidal wetlands following coseismic subsidence takes centuries, suggesting a sustained submergence of the coast [29].

At other subduction zones, geodetic studies following the 2004 Mw 9.2 Sumatra-Andaman earthquake and the 2011 Mw 9.0 Tohoku earthquake show that in some locations, coseismic subsidence has been exacerbated by continued postseismic subsidence [46–48], while other studies show that coastal locations recovered between 10%-50% of their subsidence through postseismic uplift within years [48,49]. In Cascadia, the magnitude and direction of postseismic deformation following a future great earthquake is uncertain. For the purposes of our study, postseismic land-level change may, for example, cause projected subsidence to increase from the “medium” to “high” scenario, or decrease from the “medium” to “low” scenario, depending on postseismic land-level change.

Amplified impacts of earthquake-driven subsidence under climate-driven sea-level rise

The probability of a CSZ earthquake increases with time, and with time, climate-drive sea-level rise will be expanding CSZ floodplains, compounding the impacts of earthquake-driven subsidence when it does occur. To explore this amplification effect, we use a central estimate

(50th percentile) from the Intergovernmental Panel on Climate Change (IPCC) AR6 SSP3-7.0 localized relative sea-level rise projections to depict the climate-driven expansion of the 1% floodplain at the 24 CSZ estuaries for the year 2100 (Fig. 2 and 3)[18,50]. SSP3-7.0 assumes emissions and temperatures rise steadily and CO_2 emissions roughly double from current levels by 2100. Countries become more competitive with one another, shifting toward national security and ensuring their own food supplies. By the end of the century, average temperatures are expected to have risen by 3.6°C (Fig. 1d).

The central estimates of RSLR for 2100 along the Washington, Oregon, and northern California coasts range from 0.4-0.9 m (Table 1). Our geospatial analysis shows that by 2100, climate-driven sea-level rise is projected to increase the land area within the 1% floodplain by 100 km^2. This expansion of the 1% floodplain would produce similar land-use impacts to the low earthquake-driven subsidence scenario described in the previous section (Table 2).

In addition to leaving CSZ shorelines more vulnerable to high-tide flooding and storm impacts [20], the expansion of the 1% floodplain due to climate-driven RSLR will amplify the effects of earthquake-driven subsidence. If a CSZ earthquake occurs in 2100, compared to the 2023 1% floodplain, combined climate-driven RSLR and earthquake-driven subsidence would increase the land area within the 1% floodplain by 170 km^2 (low subsidence), 240 km^2 (median subsidence), or 370 km^2 (high subsidence; Table 2; Fig. 2 and 3). The land-use categories with the largest increase in land area within the 1% floodplain continue to be parks and open space (340 km^2 to 430 km^2), farm use (100 km^2 to 180 km^2), residential and rural residential (60 km^2 to 120 km^2), and commercial (100 km^2 to 130 km^2) under the combined climate-driven SLR and high-subsidence scenario compared to the 2023 1% floodplain.

The combined effects of climate-driven RSLR and earthquake-driven subsidence amplify the impact to coastal residents, structures, and primary roads (Table 2; Figs. 2 and 3). Compared to the 2023 1% floodplain, high-end earthquake-driven subsidence amplified by climate-driven RSLR in 2100 more than triples flood exposure. This most extreme scenario would expose an additional 17,710 residents (218% increase), 29,060 structures (217% increase), and 1,620 km of roadway (231% increase) to flooding.

Discussion

The Cascadia Rising Scenario conducted in 2016 and 2022 outlined the potential impacts of shaking, tsunami inundation, landslides, and liquefaction from a ~M9 CSZ earthquake in Oregon and Washington, projecting >30,000 casualties, 2,000 destroyed bridges, >170,000 damaged or destroyed coastal structures, and heavy damage to >75% of coastal roadways, >60% of coastal fire stations, >75% of coastal schools, and >80% of seaports, for a resulting economic impact of >$81 billion [51–53]. However, the potential impact of earthquake-driven subsidence, which may persist over decades to centuries, and the additional flooding exposure it will cause has not been previously quantified and could significantly increase the timeline to recovery.

Our results demonstrate the significant and lasting impacts that sudden earthquake-driven subsidence would have on low-lying coastal communities along the CSZ and, therefore, the need for considering subsidence in future hazards assessments. We also highlight the role that 21st-century climate-driven RLSR will have in amplifying the impacts of a future earthquake. If a great CSZ earthquake occurred today, between 90 km^2 (low subsidence) and 300 km^2 (high subsidence) of low-lying coastal land area would be lowered into the 1% floodplain by earthquake-driven subsidence. The greatest impacts to people and infrastructure (i.e., structures and roads) are in the more densely populated areas of southern Washington, northern Oregon, and northern California. Farmlands developed for cattle grazing and farming through diking and draining in the early 20th century [54,55] are one of the most heavily impacted land-use categories along the CSZ. More frequent marine inundation of farmlands will result in salination of agricultural soils and higher salt levels in groundwater, resulting in significant economic losses [56,57].

In Oregon, our 2023 high-earthquake-driven subsidence scenario depicts a similar amount of flooding as detailed in the Oregon Sea-Level Rise Inventory for Oregon's estuaries [20] in 2100, which shows that such an expansion of the 1% floodplain would impact 5 airports, 18 critical facilities (e.g., public schools, hospitals, fire stations, police stations, city halls, etc.), 8 wastewater treatment plants, 1 electric substation, and 57 potential contaminant sources (animal feeding operations, gas stations, solid waste facilities, chemical storage, liquid waste storage). And, if the next earthquake occurs in 2100 (after climate-driven RSLR has already begun to impact the coast) and RSLR rates exceed postseismic and/or interseismic uplift rates, low-lying areas along the CSZ may never recover. Today, and more so in 2100, the immediate effect of earthquake-driven subsidence will be a delay in response and recovery to the earthquake due to compromised assets; long-term effects could render many coastal communities uninhabitable [58]. Although we do not quantify damage to seaports, previous reports suggest that earthquake-driven subsidence will also compromise jetties, inlets, and navigation channels, affecting port operations and disaster response [52]. Additionally, liquefaction and lateral spreading could locally amplify subsidence in river valleys, waterfronts, and artificially filled coastal locations where critical assets along the CSZ coastline are often located. [53,59]

Beyond the direct impacts on infrastructure, sudden earthquake-driven subsidence can significantly impact natural systems—particularly coastal estuaries, intertidal wetlands, and protective dunes and beaches. Wetland loss is a primary concern: intertidal wetlands typically migrate inland in response to rising sea levels, but this inland movement can be constrained by topography and human development. This is especially true along the Oregon coast, where Brophy et al. (2018) demonstrated that a sea-level rise of ~2.7 m could lower ~50% of existing Oregon intertidal wetlands to mudflat elevations, a result comparable to that in this study's high-subsidence scenarios in 2100. Thorne et al. (2018)[60], who also considered intertidal wetland accretion rates, found that under ~1.4 m of RSLR, Oregon would lose all of its high and middle intertidal wetland environments. The loss of intertidal wetlands directly impacts ecosystem services such as water filtration, habitat for fisheries and shorebirds, and carbon storage capacity [60]. Intertidal wetlands function as natural carbon sinks, and their erosion or conversion to tidal flats significantly reduces their ability to sequester carbon [61]. The erosion and drowning of coastal wetlands that earthquake-driven subsidence will cause will also diminish their role as natural buffers against storm surges. Intertidal wetlands can dissipate wave energy, keeping storm surges from penetrating inland and preventing sediment erosion and property damage [62,63].

Earthquake-driven subsidence also puts ocean-exposed sandy coastlines at risk. For example, during the 2015-2016 El Niño year, a modest RSLR of 7-17 cm along the Pacific coast of the United States led to significant coastal erosion, with shoreline retreat 70% greater than during normal winter conditions [64]. Sudden earthquake-driven subsidence can also increase the tidal range within an estuary, exacerbating issues such as high-tide flooding and the impacts of storm surges coinciding with high tides. A study in the Columbia River estuary showed that projected earthquake-driven subsidence could result in up to a 10% increase in the local tidal range [22].

Lastly, sudden earthquake-driven subsidence and climate-driven sea-level rise also need to be considered in tsunami inundation maps. The current tsunami inundation maps for Washington, Oregon, and California take into account the subsidence that will occur during the next CSZ earthquake and how this will increase tsunami inundation [65–67]. However, tsunami hazard maps do not consider climate-driven sea-level rise and the amplification effect it will have on future tsunamis. Dura et al. (2021) showed that under future climate-driven sea-level rise scenarios, tsunamis created by more common, smaller magnitude earthquakes can have the same coastal wave heights as rare, great-earthquake generated tsunamis. This lesser-considered effect of climate-driven RLSR, especially combined with earthquake-driven subsidence and tides, may imply increased flooding risk in future hazards assessments [68,69].

Our findings stress the importance of incorporating the effects of earthquake-driven subsidence into future flood hazards assessments at the CSZ, as well as considering how climate-driven RSLR will amplify the impacts of a future earthquake and tsunami. Preparing for these compound hazards is essential for minimizing long-term damage, ensuring resilient communities, and protecting critical coastal ecosystems from permanent degradation. Given the global prevalence of subduction zones, these insights hold relevance beyond Cascadia, informing hazard assessments and mitigation strategies for tectonically active regions worldwide.

Figure captions:

Figure 1. a) Washington, Oregon, and California coastal estuaries analyzed in this study. The orange polygons depict the 1% floodplain after high earthquake-driven subsidence in 2023 (defined baseline year). b) Modeled earthquake-driven subsidence values (red rectangles) constrained by 1700 CE earthquake geologic subsidence estimates (black dots with uncertainties [23,70] for each estuary. The dark grey continuous line shows one example of the median subsidence from a full margin rupture scenario from the FakeQuake Catalog [43]. c) Cross-section from the Necanicum River estuary showing current MHHW and 1% floodplain elevations and the shift upwards that occurs following both earthquake-driven subsidence and climate-driven RSLR. Location of a-A' in map view is shown in Fig. 3a. d) Climate-driven local sea-level rise projections based on the IPCC AR6 SSP3-7.0 scenario for select sites spanning the

CSZ. Upper and lower bounds of each curve are the 5^{th}-95^{th} percentile range. In this study we use the 50^{th} percentile values. Projections for all sites are available in Table 1.

Figure 2. Floodplain maps and bar graphs depicting the expansion of the 1% floodplain after earthquake-driven subsidence today (2023) and in 2100 when the earthquake-driven subsidence is amplified by climate-driven sea-level rise for a) Grays Harbor; and b) Willapa Bay. Bar graphs to the right of each map set show the amount of land area, residents, structures, roads, and different land-use types in the 1% floodplain following earthquake-driven subsidence today (2023) and in 2100, when the effects of earthquake-driven subsidence are amplified by climate-driven sea-level rise.

Figure 3. Floodplain maps and bar graphs depicting the expansion of the 1% floodplain after earthquake-driven subsidence today (2023) and in 2100 when the earthquake-driven subsidence is amplified by climate-driven sea-level rise for the a) Necanicum River; b) Yaquina Bay; c) Alsea Bay; and d) Humboldt Bay. Bar graphs to the right of each map set show the amount of land area, residents, structures, roads, and different land-use types in the 1% floodplain following earthquake-driven subsidence today (2023) and in 2100, when the effects of earthquake-driven subsidence are amplified by climate-driven sea-level rise.

Materials and Methods

Geospatial Analysis

To assess the impacts of potential earthquake-driven and climate-driven sea-level rise, we created a series of "bathtub" style 1% floodplain contour polygons on 10-m (1/3 arc-second) resolution Digital Elevation Model (DEM) tiles from the United States Geological Survey (USGS) National Map 3DEP Data Collection. The contour polygon elevations were determined from combinations of potential earthquake-driven subsidence and sea-level rise values. Site-specific 1% exceedance water level elevations are from the National Oceanic and Atmospheric Administration's (NOAA) Tides and Currents database for sites at Astoria, OR, Charleston, OR and South Beach, OR. For each site, we apply the closest 1% exceedance water level value to define the perimeter of the 1% floodplain. The starting elevation of the 1% floodplain at each site is reported in Table 1 relative to mean higher high water (MHHW). The 1% floodplain contours presented here closely correspond to the Federal Emergency Management Administration (FEMA) "still water" elevations, and likely represent the lower end of potential impacts, as additional impacts from river flow, snow melt cycles, precipitation and wave action are not included.

To quantify earthquake-driven subsidence and sea-level rise impacts, contour polygons were intersected with a variety of data including state and county-level land use zoning, road, structure footprint, and population data (supplementary material). To remove inconsistencies with land use data coding between states, a unified land use code was created for use in this study. Since a wide variety of subcategories existed within certain land zones like commercial and industrial, these subcategories were combined into a single category for the entire study area, eliminating regional coding discrepancies. We note that our starting 1% floodplain areas include open water and estuary land. Because of this, in the main text we emphasize the change in land area in the 1% floodplain rather than the total area. For our land-use impacts analysis, we removed "shorelands" and "estuary" in order to focus more on on-land impacts. Despite open water sometimes being classified as "parks and open space", we kept it in the dataset because the "parks and open space" category is also often found on land.

Sea-level rise Projections

The IPCC AR6 sea-level change projections used in this work are medium-confidence projections for the SSP3-7.0 emissions scenario. The medium-confidence projections use methods and assumptions about the individual processes that contribute to sea-level change that are assessed to have medium confidence or stronger by the IPCC, and therefore do not include contributions that could lead to more extreme sea-level rise, but which have lower confidence levels (such as Marine Ice Cliff Instability). The sea-level rise projections are provided on both a 1x1 degree grid, and at 1030 tide gauge locations from around the world. The sea-level rise projections are provided in decadal time steps starting in 2020 and extending to the year 2150; here, we focus on the 50th percentile of projections for the year 2100 [18,50]—and therefore do not account for the possibility of more extreme, tail-area sea-level rise totals.

For this work, we use the publicly available NASA Sea Level Projection tool to isolate the projected sea-level rise at points that are most relevant for our work. This allows us to select the best sea-level rise value for each location on a case-by-case basis, whether that value comes from the nearest 1x1 degree ocean grid cell in the gridded sea-level rise dataset, or a tide gauge location along the Pacific coast. Because sea-level rise values from the gridded dataset will have interpolations that capture vertical land motion to varying degrees of success, this manual approach to selecting sea-level rise projection values allows us to ensure that we are using the best sea-level projection for each site, based on how well vertical land motion is captured within both the gridded data and the tide gauge data set.

Modeled and Observed Earthquake subsidence estimates

Subsidence estimates are calculated at each site based on about 1,600 kinematic, stochastic slip rupture models [42] of varying magnitudes between 7.7- 9.2. These models come from a larger catalog of 37,500 hypothetical ruptures [43]. Each of these ruptures is unique from one another, with rupture area, amount of slip, and location of dominant slip patches varying between ruptures. These ruptures were initially chosen based on their abilities to match the coastal subsidence records correlated to the 1700 CE event [23,70]. Subsidence estimates for the 1700 CE event are distributed along the entire length of the Cascadia Subduction Zone, likely representing a full-margin rupture. To account for the possibility of shorter, or segmented rupture scenarios each kinematic rupture model must reproduce the observed 1700 CE subsidence for sites located within 50km of the modeled rupture area. This allows for a wider range of subsidence estimates to be modeled.

For each kinematic rupture model, coseismic subsidence is calculated at each site using the analytical solution for angular dislocations for triangular subfaults in an elastic half space [71]. Based on 1,600 model results, three coseismic subsidence values are determined for each site: a small, medium, and high value. We base the high subsidence value on the largest subsidence modeled at each location to function as the "worst case scenario." Stated prior, modeled subsidence values are validated with respect to coastal subsidence estimates previously determined for the 1700 CE event, although not all geologic sites with subsidence estimates are co-located with the 24 sites modeled in this study. As a result, modeled sites closest to the geologic sites with estimated subsidence values more closely resemble the upper bounds of the 1700 CE geologic subsidence estimates. Locations that are farther from sites with observed subsidence estimates are less constrained by the 1700 CE data, and as a result the models produced higher "worst case scenario" subsidence estimates there (e.g., Sixes River, Elk River, Rogue River, Pistol River, Chetco River, Winchuck River, Oregon). Due to modeled subsidence estimates being unrealistically high at these locations, we used the closest, better constrained subsidence estimate (e.g., Coquille River) for these sites (Table 1). At the 24 sites, mean subsidence values are -0.4 m, -0.9 m, and -1.7 m for the low, medium, and high modeled subsidence values, respectively. The modeled subsidence values follow the low (50th percentile), medium (10th percentile), and high (maximum recorded) earthquake-driven subsidence values of the 1,600 ruptures for each site location.

Data availability

All data integral to the stated conclusions are presented within the paper, methods, or Materials and Methods section. All shapefiles generated in this study are available at (https://github.com/DuraGEOSVT/Cascadia).

Digital elevation models are publicly available at the following links: https://www.usgs.gov/the-national-map-data-delivery and https://www.usgs.gov/3d-elevation-program. Geospatial analysis datasets are publicly available at the following links: https://geohub.oregon.gov/datasets/oregon-geo::zoning/about (Oregon Land Use and Land Cover), https://humboldtgov.org/276/GIS-Data-Download (California Land Use and Land Cover), https://geo.wa.gov/datasets/wa-geoservices::washington-state-land-use-2010/about (Washington Land Use and Land Cover), https://www.arcgis.com/home/item.html?id=3bc7bd2ef9e54f66886f4c095a6eb63c (Oregon Roads), https://humboldtgov.org/276/GIS-Data-Download (California Roads), https://www.co.pacific.wa.us/gis/DesktopGIS/WEB/index.html (Pacific County Roads), https://www.graysharbor.us/departments/central_services/GISDataDownload.php (Grays Harbor Roads), https://data.humdata.org/dataset/united-states-high-resolution-population-density-maps-demographic-estimates; https://fema.maps.arcgis.com/home/item.html?id=0ec8512ad21e4bb987d7e848d14e7e24 -overview; https://github.com/microsoft/USBuildingFootprints?tab=readme-ov-file (all sites structures).

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Author contributions

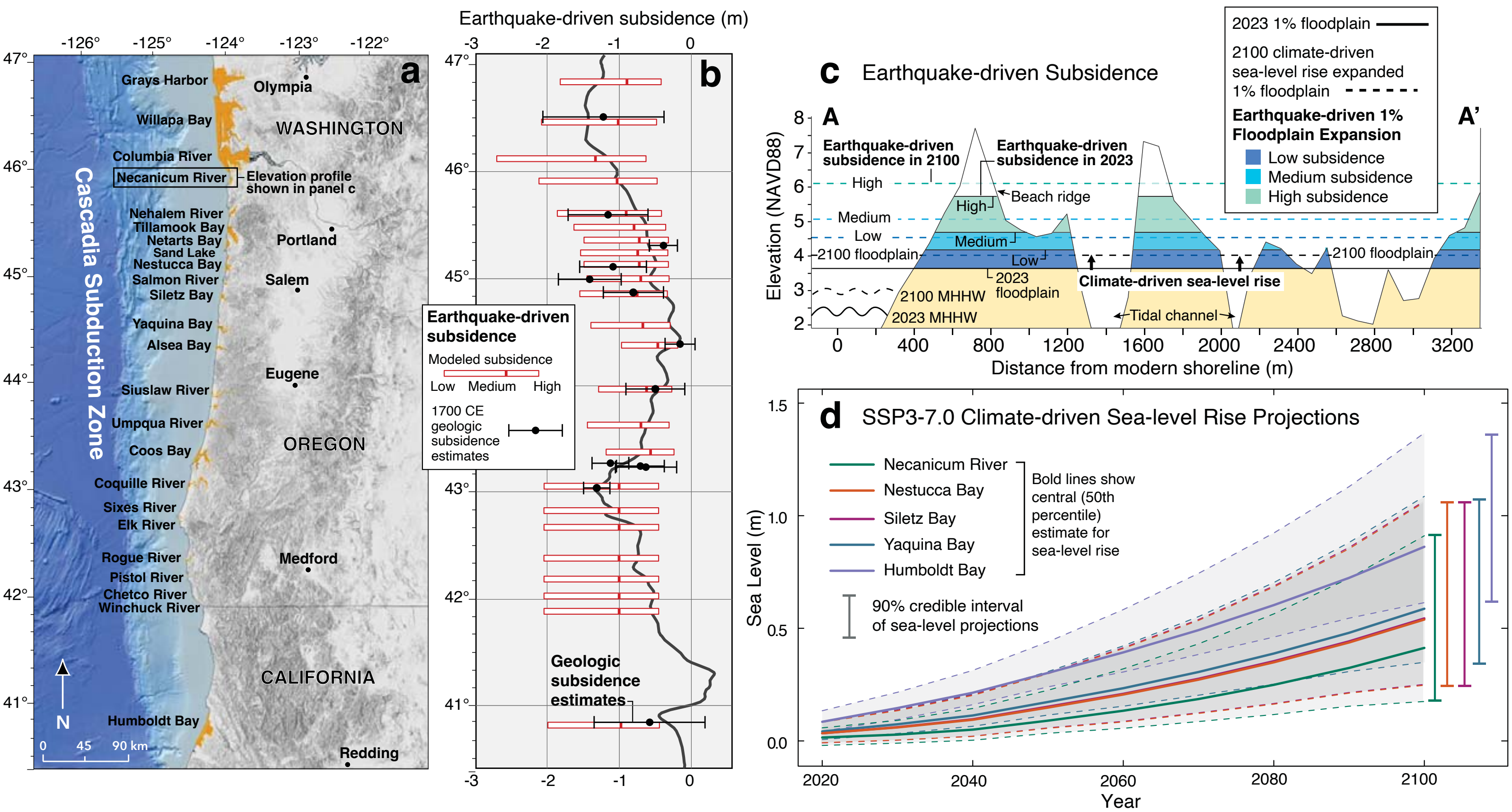
T.D. designed the study with the input of all coauthors. T.D. and W.C. collected and synthesized data and performed geospatial analyses. T.D., W.C., and A.J.G. prepared the figures and tables. D.S. and D.M. ran and analyzed the earthquake simulations. A.J.G. provided the local probabilistic sea-level rise projections based on analysis of IPCC datasets. L.S., R.C.W., R.W.B, and A.R.N. contributed to the earthquake probability estimates. T.D., W.C., D.S., A.J.G., A.H., D.M., S.E.E., L.S., R.C.W., A.R.N., H.M.K., J.A., D.B., J.D., R.W.B., R.W., S.L., M.W., and B.P.H. wrote the paper.

Competing interests

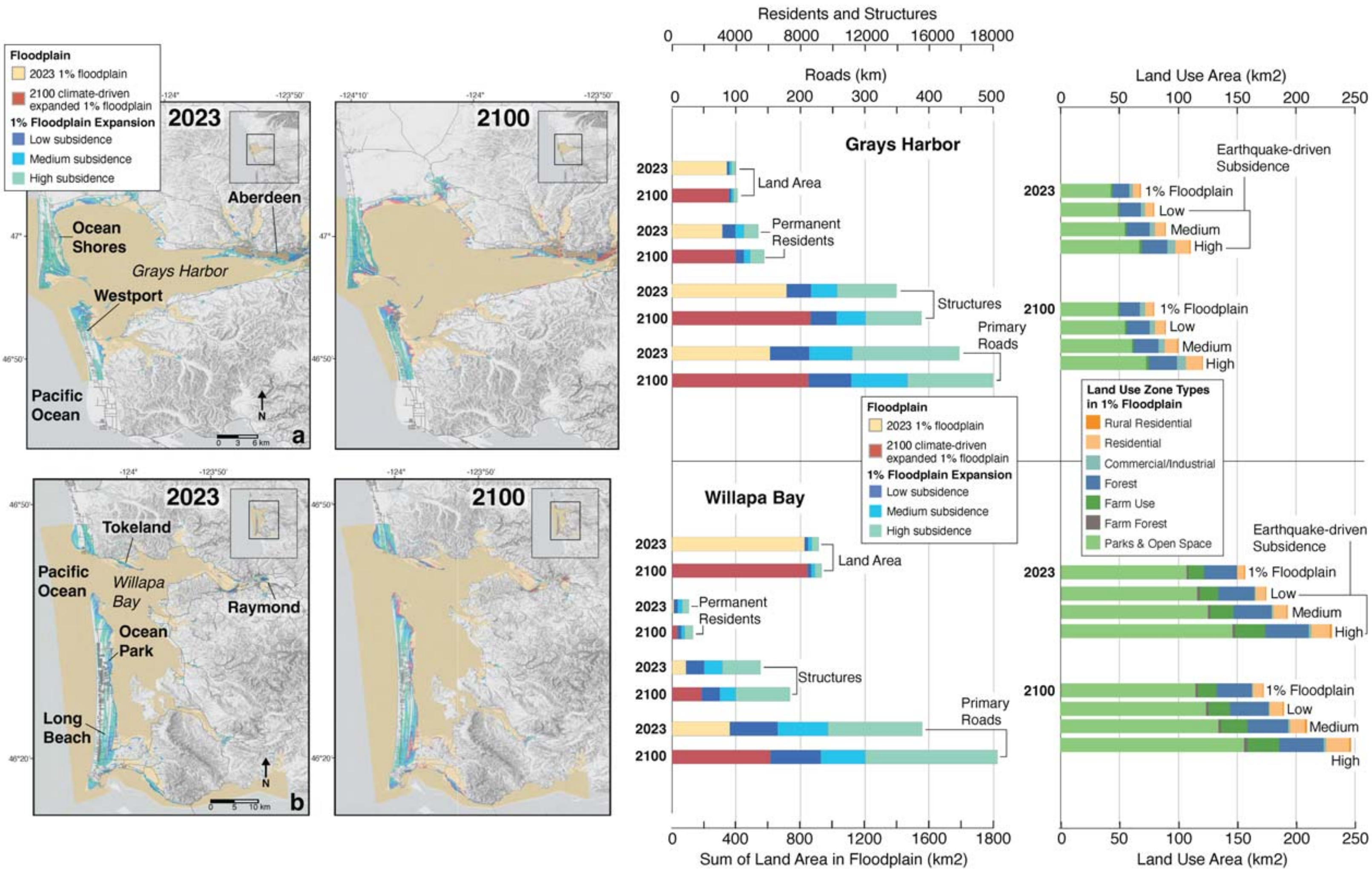
The authors declare no competing interests.

Supplementary information

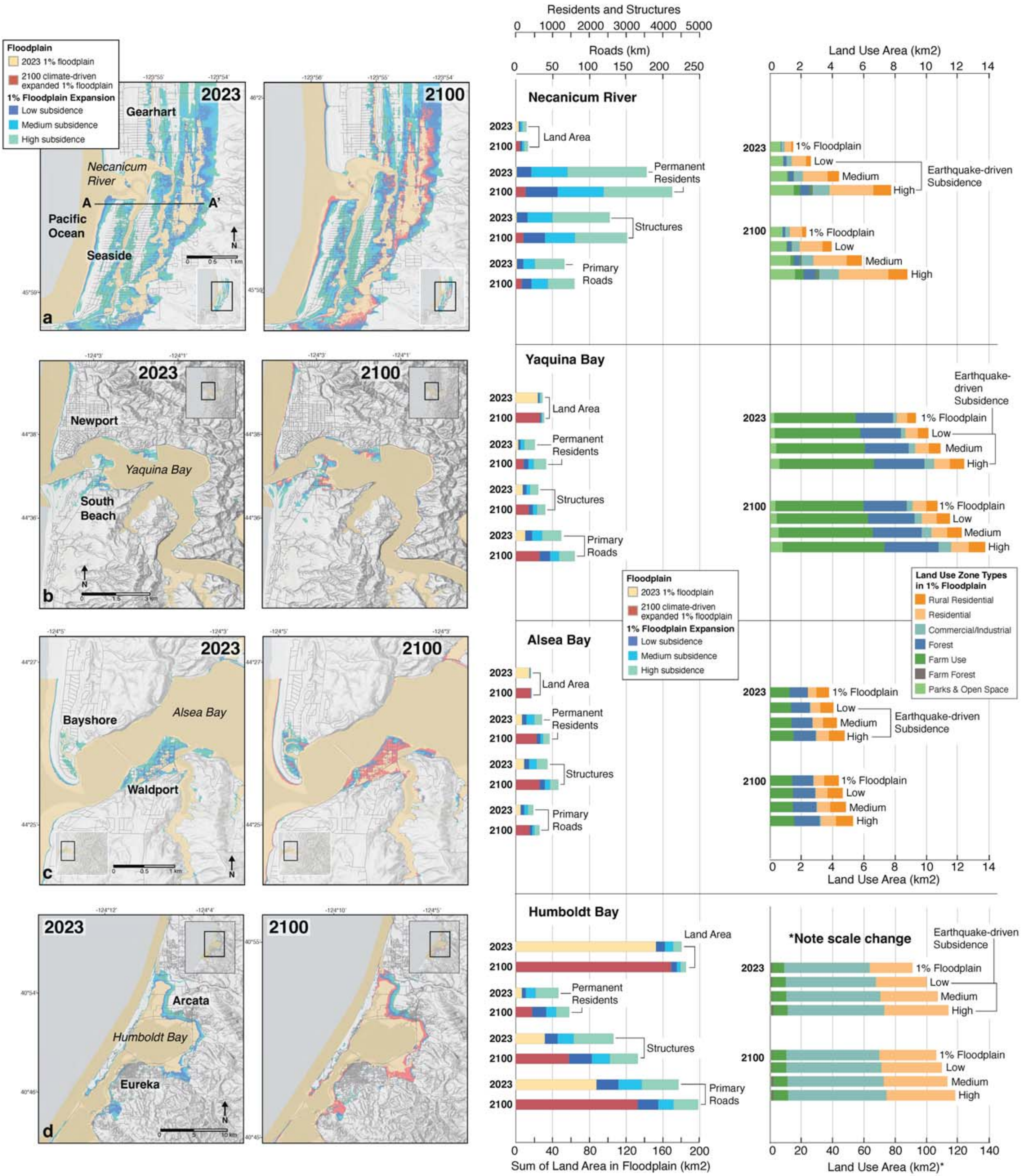
Links to PDFs and spreadsheet will go here.



a
b
Earthquake-driven subsidence (m)
Cascadia Subduction Zone
WASHINGTON
OREGON
CALIFORNIA
Grays Harbor
Willapa Bay
Columbia River
Necanicum River
Elevation profile shown in panel c
Nehalem River
Tillamook Bay
Netarts Bay
Sand Lake
Nestucca Bay
Salmon River
Siletz Bay
Yaquina Bay
Alsea Bay
Siuslaw River
Umpqua River
Coos Bay
Coquille River
Sixes River
Elk River
Rogue River
Pistol River
Chetco River
Winchuck River
Humboldt Bay
Olympia
Portland
Salem
Eugene
Medford
Redding
N
0 45 90 km
Earthquake-driven subsidence
Modeled subsidence
Low Medium High
1700 CE geologic subsidence estimates
Geologic subsidence estimates
c Earthquake-driven Subsidence
A
A'
Elevation (NAVD88)
Distance from modern shoreline (m)
Earthquake-driven subsidence in 2100
Earthquake-driven subsidence in 2023
Beach ridge
High
Medium
Low
2100 floodplain
2023 floodplain
2100 MHHW
2023 MHHW
Climate-driven sea-level rise
Tidal channel
2023 1% floodplain
2100 climate-driven sea-level rise expanded 1% floodplain
Earthquake-driven 1% Floodplain Expansion
Low subsidence
Medium subsidence
High subsidence
d SSP3-7.0 Climate-driven Sea-level Rise Projections
Sea Level (m)
Year
Necanicum River
Nestucca Bay
Siletz Bay
Yaquina Bay
Humboldt Bay
Bold lines show central (50th percentile) estimate for sea-level rise
90% credible interval of sea-level projections



Floodplain
2023 1% floodplain
2100 climate-driven expanded 1% floodplain
1% Floodplain Expansion
Low subsidence
Medium subsidence
High subsidence
2023
2100
Aberdeen
Ocean Shores
Grays Harbor
Westport
Pacific Ocean
a
Tokeland
Pacific Ocean
Willapa Bay
Raymond
Ocean Park
Long Beach
b
Residents and Structures
Roads (km)
Grays Harbor
Land Area
Permanent Residents
Structures
Primary Roads
Willapa Bay
Sum of Land Area in Floodplain (km2)
Land Use Area (km2)
Earthquake-driven Subsidence
1% Floodplain
Low
Medium
High
Land Use Zone Types in 1% Floodplain
Rural Residential
Residential
Commercial/Industrial
Forest
Farm Use
Farm Forest
Parks & Open Space



Residents and Structures
0 1000 2000 3000 4000 5000
Roads (km)
0 50 100 150 200 250
Land Use Area (km2)
0 2 4 6 8 10 12 14
Floodplain
2023 1% floodplain
2100 climate-driven expanded 1% floodplain
1% Floodplain Expansion
Low subsidence
Medium subsidence
High subsidence
2023
2100
Gearhart
Necanicum River
A
A'
Pacific Ocean
Seaside
N
a
Necanicum River
Land Area
Permanent Residents
Structures
Primary Roads
1% Floodplain
Low
Medium
High
Earthquake-driven Subsidence
Newport
Yaquina Bay
South Beach
b
Yaquina Bay
Land Use Zone Types in 1% Floodplain
Rural Residential
Residential
Commercial/Industrial
Forest
Farm Use
Farm Forest
Parks & Open Space
Bayshore
Alsea Bay
Waldport
c
Alsea Bay
Arcata
Humboldt Bay
Eureka
d
Humboldt Bay
*Note scale change
0 40 80 120 160 200
Sum of Land Area in Floodplain (km2)
0 20 40 60 80 100 120 140
Land Use Area (km2)*

Table 1. *Low (50th percentile), medium (10th percentile), and high (maximum recorded) earthquake-driven subsidence values modeled with the FakeQuakes module (Small and Melgar, 2021). ** Mean higher high water (MHHW). ***50th percentile value of the IPCC AR6 SSP3-7.0 local sea-level projections for each estuary in this study.

	Earthquake-driven Subsidence*				
Site	**Low (m)**	**Medium (m)**	**High (m)**	**Starting elevation of 1% floodplain, relative to MHHW** in meters**	**Climate-driven sea-level rise in 2100 in meters*** **
Grays Harbor	0.45	0.90	1.80	1.20	0.44
Willapa Bay	0.51	1.02	2.05	1.20	0.44
Columbia	0.67	1.34	2.67	1.20	0.41
Necanicum River	0.52	1.04	2.08	1.20	0.41
Nehalem Bay	0.46	0.91	1.83	1.21	0.54
Tillamook Bay	0.40	0.80	1.59	1.21	0.54
Netarts Bay	0.36	0.73	1.45	1.22	0.54
Sand Lake	0.37	0.75	1.50	1.22	0.54
Nestucca River	0.36	0.73	1.45	1.22	0.54
Salmon River	0.35	0.70	1.41	1.22	0.54
Siletz Bay	0.38	0.75	1.51	1.23	0.54
Yaquina Bay	0.34	0.67	1.35	1.23	0.59
Alsea Bay	0.23	0.46	0.93	1.22	0.59
Siuslaw River	0.31	0.62	1.25	1.19	0.54
Umpqua River	0.35	0.70	1.41	1.16	0.56
Coos Bay	0.28	0.57	1.14	1.14	0.52
Coquille River	0.50	1.01	2.01	1.13	0.52
Sixes River	0.50	1.01	2.01	1.12	0.51
Elk River	0.50	1.01	2.01	1.12	0.51
Rogue River	0.50	1.01	2.01	1.10	0.51
Pistol River	0.50	1.01	2.01	1.09	0.51
Chetco River	0.50	1.01	2.01	1.08	0.39
Winchuck River	0.50	1.01	2.01	1.08	0.39
Humboldt/Eureka	0.49	0.98	1.96	1.09	0.86

Table 2. The change in the land area, residents, structures, and roads in the 1% floodplain today (2023) and in 2100, and the impact of low, medium, and high earthquake-driven subsidence at each time period. Total change calculations are made relative to the starting 2023 value in each category. All values are rounded to the nearest 10.

	Change in 1% floodplain area (km^2)	Permanent residents in 1% floodplain	Total change	% change	Structures in 1% floodplain	Total change	% change	Kilometers of primary roadway in 1% floodplain	Total change	% change
2023 1% Floodplain		8120			13370			700		
Low subsidence	90	11100	2980	37	18180	4810	36	990	290	41
Medium subsidence	160	14740	6620	82	23830	10460	78	1300	600	86
High subsidence	300	22470	14350	177	35870	22500	168	1950	1250	179
2100 1% Floodplain	100	11530	3410	42	18970	5600	42	1040	340	49
Low subsidence	170	15000	6880	85	24550	11180	84	1350	650	93
Medium subsidence	240	19060	10940	135	30350	16980	127	1670	970	139
High subsidence	370	25830	17710	218	42430	29060	217	2320	1620	231

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