Coastal flood protection—TR-16 criteria versus site-specific analysis

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ABSTRACT | Coastal resiliency is critical for low-lying wastewater facilities. TR-16, a guide to the important elements to consider in the design of wastewater treatment works, was revised in 2016 to include guidance on coastal resiliency. A case study is presented for a facility in southern Maine already experiencing flood-level issues during high tides with storm surges. In this study, the TR-16 guidance numbers are compared to those from location-specific analysis for projected sea level rise and wave action together with FEMA 100-year base flood elevations for the tidal river on which the facility is situated. The TR-16 criterion using a 100-year flood elevation plus 3 ft (0.9 m) was in good agreement with location-specific analysis for a 50-year design window, the design flood elevation plus small wave runup, and low to moderate sea level rise projections (minor acceleration). For more exposed coastal sites, longer design windows, and higher sea level rise projections, the current TR-16 flood level criteria may not be adequately conservative.

KEYWORDS | Coastal flood design criteria, wastewater treatment facilities

Coastal resiliency, which may be defined as the ability to bounce back after a storm or flood event, is critical for water and wastewater facilities, which are often located in low-lying areas to optimize gravity flow. The normal order of the civilized world, often taken for granted, would rapidly break down without functioning water and wastewater infrastructure. For many coastal communities, water and wastewater infrastructure is a high-priority capital investment for local coastal resiliency.

TR-16 *Guides for the Design of Wastewater Treatment Works* (2016 rev)[1] is a standard for evaluation and design of wastewater treatment facilities, with general guidance for coastal resiliency; however it lacks a timeline and site-specific considerations. Whereas the FEMA flood hazard elevations do not include provisions for sea level rise, TR-16 includes added elevation increase allowances outlined in an Obama-era Executive Order that federally funded projects be designed for flood resistance to 2 to 3 ft (0.6 to 0.9 m) above the FEMA 100-year (1 percent annual chance) flood elevation, based on how critical the structure is to maintaining adequate service.

Real-world application of the TR-16 sea level rise criteria enters a gray area when evaluating different design and service life windows. If the design life is 100 years rather than 50 years, how should the sea level rise allowance be modified? TR-16 does not address this, other than providing lower flood criteria for existing facilities.

Additional open-ended questions develop, such as the amount of freeboard (height above the water level) to be included in the TR-16 allowance. Will waves overtop the flood wall? How should the pumping system be sized to handle flood wall overtopping? And how will that overtopping water volume increase over the years with rising sea levels? It rapidly becomes apparent that the TR-16 allowances are general and not well-defined for either facility risk assessment or design of enhanced flood protection.

The following is a case study of how these questions can be addressed to better define site conditions relative to the TR-16 sea level rise allowances. The treatment facility in this study is on the tidal portion of a river in southern Maine.

The wastewater treatment plant's (WWTP's) proximity to the tidally influenced river puts this facility at significant risk of the effects of sea level rise as well as flooding during extreme weather events. The facility recently experienced hydraulic impacts due to higher-than-normal tide elevations. Hydraulic backups throughout the gravity flow plant process were seen during especially high tides. These concerns have prompted WWTP staff to seek enhanced resiliency to protect the plant and process from rising sea levels. FEMA defines flood hazards using Flood Insurance Rate Map elevation zones; the "AE zones" on those maps are those flood plains where base flood elevations are provided. The current FEMA-mapped AE zone for this WWTP depicts minor impacts for the facility, flooding the plant access street and driveway in two places. Plant design outfall tailwater conditions and plant hydraulics evaluations included multiple tide elevations and sea level rise projections but did not include wave conditions, given the relative depth of submergence at the outfall diffusers.

As the WWTP is considered a service-critical facility, TR-16 guidance of adding 3 ft (0.9 m) to the 100-year flood level—elevation 9 ft (2.74 m)—leads to a TR-16 design flood level of elevation 12 ft (3.65 m) NAVD 88 (North American Vertical Datum of 1988). This design flood level would have a much greater impact on the facility than the FEMA 100-year flood elevation, as it would flood most plant process structures and more deeply submerge the only access street and driveway, though it would spare the main plant buildings.

With a target project service life extension of 50 years (to 2070), a more detailed look at projected future sea level rise and wave action for this site was performed to confirm the TR-16 guidance. The wave action for this site was calculated based on conventional coastal engineering, with two primary longest wind wave fetches (a fetch is the open water length over which wind waves can grow); the longer 3,700 ft (1,128 m) fetch was used. The wave generation wind speed was based on an 83 mph (134 km/h) fastest-mile wind speed, taken from the American Society of Civil Engineers standard *ASCE 7-10* basic wind gust with load factor removed. For wave generation, the calculated equivalent wind to grow fully developed seas was 70 mph (113 km/h) for at least 16 minutes. These wind conditions would develop a 2.6 ft (0.8 m) significant wave height (average of highest one-third of waves) in deeper water. For initial design, an H10 wave (average of the highest 10 percent of waves) was selected with a height of 3.3 ft (1 m). Transforming this wave onto the shoaling shoreline turns it into a breaking wave (dynamic impact load) with about a 2.6 ft (0.8 m) breaker height at the proposed flood wall location.

For this more detailed flood elevation assessment, the 100-year flood level was also used with an allowance for projected sea level rise over the design life. For this site, the FEMA 100-year flood elevation is 9 ft (2.7 m), rounded to the nearest foot (nearest 0.3 m). The more precise National Oceanic and Atmospheric Administration (NOAA) 100-year flood elevation for 2018 based on tide data is 8.9 feet (2.71 m) for nearby Portland, Maine. The FEMA and NOAA values are very similar and consistent for a site without ocean wave water level setup.

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The allowance for future sea level rise for this study was the *2017 NOAA Tech Report 083*[2] with tabulated values for relative sea level every 10 years, considering land and earth crust vertical movement at selected tide gauge cities. Sea level rise may be a global average change in sea level, as typically provided in governmental sea level rise future projections, or it may be the measured change in sea level at a specific site relative to the local land elevation. Globally, the sea level is rising at an estimated average rate, typically between 0.04 to 0.12 in/year (1 to 3 mm/year), and these estimates vary by method, data, and agency reporting. Where the earth's crust is rebounding (rising) since the last ice age, such as portions of Alaska, Canada, and Scandinavia, a relative drop in sea level has been observed locally. In other areas, such as the mid-Atlantic shoreline in the United States, post-glacial crustal subsidence is occurring, often combined with local soil consolidation subsidence, thus increasing the relative local and regional relative sea level rise. Southern Maine is relatively neutral for post glacial crustal/bedrock vertical movement but may experience local soil subsidence, particularly in areas with soft clay or peat deposits or at historically filled sites. The amount of soil subsidence possible at the site should be evaluated when soil borings are conducted, and a subsidence estimate should be included in relative sea level rise design criteria. The soil subsidence contribution to relative sea level rise would affect structures and buildings on spread footings but may not influence adjacent structures supported on pile foundations driven to bedrock.

The baseline minimum sea level rise design criteria should at least allow for continuation of the existing

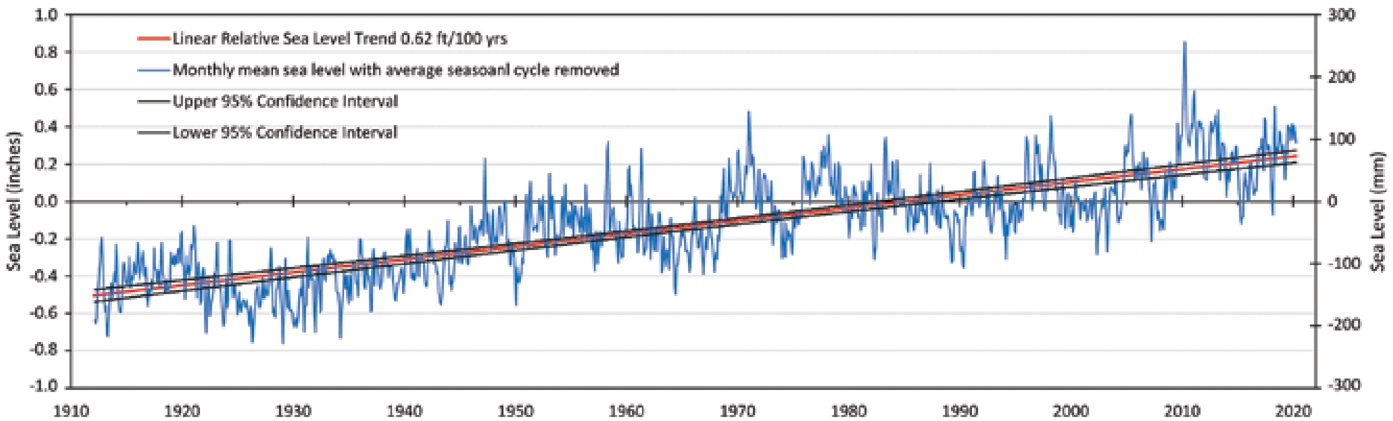

Figure 1. Portland sea level rise trend, NOAA[3]

Table 1. NOAA sea level rise (SLR) projections for Portland

Global SLR Scenario**	Relative SLR by year feet (meters)*			
	2000	2050	2070	2100
Low 0.3 m	0	0.6 (.18)	0.9 (.27)	1.1 (.34)
Inter-low 0.5 m	0	0.8 (.24)	1.2 (.37)	1.5 (.46)
Plausible (RCP 4.5)	**0**	**1.1 (.33)**	**1.6 (.49)**	**2.5 (.76)**
Intermediate 1.0 m	0	1.5 (.46)	2.3 (.7)	3.8 (1.16)
Inter-high 1.5 m	0	2.2 (.67)	3.5 (1)	6.0 (1.83)
High 2.0 m	0	3.0 (.9)	4.9 (1.49)	8.7 (2.65)
Extreme 2.5 m	0	3.4 (1)	5.9 (1.8)	10.8 (3.3)

Source: Sweet et. al. 2017 NOAA tech report Portland ME projections[2]

* Based on zero vertical land movement

** Global SLR projections with Representative Concentration Pathways (RCP) models:
1.9 ft (0.58 m) median for RCP 2.6 by 2100
2.3 ft (0.7 m) median for RCP 4.5 by 2100
2.95 ft (0.9 m) median for RCP 8.5 by 2100

sea level rise trend, which is typically the lower projection curve in most guidelines. For Portland, the NOAA developed trend is 0.6 ft per 100 years (1.83 mm/year).[3]

The latest *U.S. National Climate Assessment* references sea level rise projections in *Sweet et.al. 2017, NOAA Technical Report 083*.[2] This report presents the latest sea level rise projections (using computer models), but the presentation is complicated with multiple greenhouse gas emissions "Representative Concentration Pathways" (RCPs) and assigns exceedance probabilities that are extremely low for the higher sea level rise projection curves. In selecting an RCP for design, RCP 8.5 was dismissed as unrealistic based on *Ritchie & Dowlatabadi, (2017)*[4], and a more plausible interpolated RCP of 4.5 was used instead with a projected sea level rise of 1.6 ft (0.49 m) by 2070. In the comparison of sea level rise data, both tide gauge and satellite altimetry are running below all the NOAA sea level rise acceleration curves, which start in 2000. The sea level rise observations closely follow the low-limit linear projection scenario of 1 ft (0.3 m) rise per century.

As noted by *NOAA Tech Report 083*, these projections for sea level rise do not include an acceleration in polar ice cap melt. The change in trend for ice cap melt may not have been included in the NOAA projections, because the data records for polar ice cap melting or snow mass accumulation cover too short a time to define a trend or support sea level acceleration projections. Some recent papers indicate ice cap melt deceleration, ice cap snow mass gains, and new findings that the ice cliffs are stable.[5,6] Within NASA, opposing journal papers exist, some claiming ice mass loss and others indicating increasing snow mass gains.[7] Two of the last three winters in Greenland have shown above average snow mass gain,[8] but many decades are needed to show a trend of melt or snow mass gain.

Based on the available information and analysis, a new floodwall was recommended for the facility to manage a minimum sea level rise of 0.6 ft (0.18 m) based on the long-term trend measured in Portland. Increasing this sea level rise allowance to 1.6 ft (0.49 m) may be cost-effective to account for the projected accelerating future sea level rise by 2070, even if this expectation is less likely to occur.

The floodwall design must include freeboard above the still water level to account for wave action at the floodwall, with calculations based on allowable wave overtopping and ability to pump away this water. The floodwall height above the 100-year flood level, allowing for accelerating sea level rise and wave overtopping freeboard, is expected to exceed the 100-year flood plus 3 ft (0.9 m) TR-16 criteria for both breaking and non-breaking waves. Since wave heights vary within a statistical range and periodic wave overtopping is likely, a pump station should be considered for rain and floodwater within the floodwall. While wave heights are not included in the hydraulic analysis of the plant and outfall due to water depths at the diffusers, the design does include sea level conditions for analysis of outfall tailwater effects.

Table 2 shows an elevation combination matrix example. The summation to minimum floodwall elevation in Table 2 shows good agreement with the TR-16 guidance for this coastal site having limited wave exposure, minimal vertical land movement, and the RCP 4.5 carbon emissions scenario for a 50-year design window. However, these elevations do not include a freeboard allowance, and additional freeboard allowance is recommended as wave height distribution varies in any given wave field. The freeboard allowance should also be related to the capacity to pump out rain, seepage, and overtopping water from inside the flood barrier. Not clear from TR-16 is if the 100-year flood plus 3 ft (0.9 m) criterion includes a freeboard allowance or how that calculated freeboard could decrease over years of relative sea level rise.

Although TR-16 guidance is a good starting point, every coastal infrastructure project must be evaluated to ensure that resilience designs account for all the site-specific geotechnical and atmospheric variables that apply. Within the relatively sheltered site-specific limitations of the presented case, and for a 50-year design window, the TR-16 guidance fits well when combined with a more detailed flooding analysis. Further evaluation is expected to be needed, however, to ensure effective resilience design for sites with more ocean wave exposure, with relative land/crustal subsidence, or, assuming sea level rise continues, for longer design life windows.

Table 2. Floodwall height matrix with comparison to TR-16 criterion

	Projected Height feet (meters)	
	FEMA	GHG RCP 4.5
FEMA Flood Level Elevation*	9 (2.74)	9 (2.74)
Sea Level Rise Allowance	+ 0.6 (.18)**	+ 1.6 (.49)
Estimate H_{10} Breaking Wave**	+ 2.0 (.6)	+ 2.0 (.6)
(Sum) Minimum Wall Elevation†	**11.6 (3.5)**	**12.6 (3.8)**
*TR-16 100-yr+3 ft**	*12 (3.6)*	*12 (3.6)*

GHG = Greenhouse Gas. RCP = Representative Concentration Pathways
* North American vertical datum of 1988
** Based on +3 mm/year global average rate of sea level rise (various gauges) since 1992
† Breaking wave freeboard allowance

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