2.4.1.1 Flood

Codes, Standards, and Regulations

Buildings are designed to meet specific flood design criteria and regulations as part of the NFIP floodplain management ordinance in a community. Per the model building codes, if a building is located within the flood hazard area, then the building shall be designed and constructed according to specific flood requirements. For IRC 2021, a majority of requirements are contained in Section R322. For IBC 2021, the code requirements reference Chapter 5 of ASCE 7-22, ASCE 24-14, and the optional use of IBC 2021 Appendix G: *Flood-Resistant Construction*. Tsunami hazards, which are primarily generated by seismic events in offshore subduction zones, are addressed in the seismic hazard section of this report.

Special Flood Hazard Areas (SFHA) are identified by FEMA as floodplains subject to a 1% or greater chance of flooding in any given year (ASCE 2014, ASCE 2021a). Within Special Flood Hazard Areas (SFHA), there are additional categories of High Risk Flood Hazard Areas and Coastal High Hazard Areas. High Risk Flood Hazard Areas have one or more of the following hazards: alluvial fan flooding, flash floods, mudslides, ice jams, high velocity flows, high velocity wave action, breaking wave heights greater than or equal to 1.5 ft (0.46 m) in Coastal High Hazard Area and Coastal A Zone, or erosion (ASCE 2014). Coastal High Hazard Areas are locations (1) where an area has been designated as subject to high velocity wave action on a community's flood hazard map (V Zones), (2) where the still water depth of the base flood above the eroded ground elevation is greater than or equal to 3.8 ft (1.15 m) (i.e., sufficient to support a wave height equal to or greater than 3 ft (0.9 m) and where conditions are conducive to the formation and propagation of such waves), or (3) where the eroded ground elevation under base flood conditions is 3 ft (0.9 m) or more below the maximum wave runup elevation (ASCE 2014).

Table 2-3: Summary of Hazard Design Criteria and Expected Performance Levels by Building Type

	Flood		Seismic				Wind	
Buildings and Structures	**Hazard Design Criteria**	*Member-based* **Performance Levels**	**Seismic Hazard Design Criteria**	*System-based* **Seismic Performance Levels**	**Tsunami Hazard Design Criteria**	**Tsunami Performance Levels**	**Hazard Design Criteria**	*Member-based* **Performance Levels**
Unoccupied RC I[3] (ASCE 7, ASCE 24)	**ASCE 7** Design Flood[1] **ASCE 24** FDC 1[2]: FHM	**ASCE 7/24** Performance criteria for RC I.	**ASCE 7** Design EQ	**ASCE 7** Performance criteria for RC I	Not Considered	Not Considered	**ASCE 7** Design Wind Reliability-targeted wind using 300-yr MRI.	**ASCE 7** Same as RC II.
Commercial Residential (ASCE 7, ASCE 24) RC II	**ASCE 7** Design Flood **ASCE 24** FDC 2: BFE + 1 ft or DFE	**ASCE 7/24** Resist flotation, collapse, permanent lateral displacement. Elevate lowest floor above flood elev. or protect from floodwater.	**ASCE 7** Design EQ Risk-targeted EQ based on: MCE_R 2,500-yr MRI	**ASCE 7** Life safety for Design EQ. Controlled deformation in selected members. Maintain structural stability. Limited prob. of collapse at MCE_R.	**ASCE 7** Design for MCT Inundation depth if required[5]. *IRC structures are exempt.*	**ASCE 7** Life Safety and Immediate Occupancy.	**ASCE 7** Design Wind Reliability-targeted wind using 700-yr MRI.	**ASCE 7** Life safety for Design Wind. No deformation in structural members.
Critical (ASCE 7, ASCE 24) RC III	**ASCE 7** Design Flood **ASCE 24** FDC 3: BFE + 1 ft BFE + 2 ft for coastal areas; or DFE	**ASCE 7/24** Same as RC II. +Reduce risk of disruption to critical community functions.	**ASCE 7** Design EQ Same as RC II, with RC III importance factor.	**ASCE 7** Same as RC II. +Reduce risk of disruption to critical community functions.	**ASCE 7** Same as RC II, with importance factor.	**ASCE 7** Same as RC II.	**ASCE 7** Design Wind Reliability-targeted wind using 1700-yr MRI.	**ASCE 7** Same as RC II. +Reduce risk of disruption to critical community functions.
Essential (ASCE 7, ASCE 24) RC IV	**ASCE 7** Design Flood **ASCE 24** FDC 4[2]: 100-yr BFE + 2 ft (0.61 m), DFE, or 500-yr DFE (10% in 50 yr)	**ASCE 7/24** Same as RC III. +Immediate occupancy	**ASCE 7** Design EQ Same as RC II, with RC IV importance factor.	**ASCE 7** Same as RC III. +Immediate occupancy	**ASCE 7** Same as RC III.	**ASCE 7** Same as RC II.	**ASCE 7** Design Wind Reliability-targeted wind using 3000-yr MRI.	**ASCE 7** Same as RC III. +Immediate occupancy

	Flood		Seismic				Wind	
Buildings and Structures	**Hazard Design Criteria**	*Member-based* **Performance Levels**	**Seismic Hazard Design Criteria**	*System-based* **Seismic Performance Levels**	**Tsunami Hazard Design Criteria**	**Tsunami Performance Levels**	**Hazard Design Criteria**	*Member-based* **Performance Levels**

1. Design flood hazard may be defined as a 100-yr flood (1% probability of annual exceedance; 39% probability of occurrence in 50 yr), a 500-yr flood (0.2% probability of annual exceedance; 10% probability of occurrence in 50 yr), or the flood hazard defined on a Flood Hazard Map (FHM).
2. There are four Flood Design Categories (FDC) defined by ASCE 24-14; the greatest elevation of the listed options is used for design.
3. Risk categories (RC) are assigned to buildings to account for consequences and risks to human life (e.g., building occupants or community members affected by failure of structures associated with utilities) in the event of a building or structural failure.
4. Seismic Design Categories (SDC) and Importance Factor (Ie) modify the Design Response Acceleration parameters by Risk Category. Risk Category I, II, or III structures located where the mapped spectral response acceleration parameter at 1-s period, S1, is greater than or equal to 0.75 shall be assigned to Seismic Design Category E. Risk Category IV structures located where the mapped spectral response acceleration parameter at 1-s period, S1, is greater than or equal to 0.75 shall be assigned to Seismic Design Category F. All other structures shall be assigned to a Seismic Design Category based on their Risk Category and the design spectral response acceleration parameters, SDS and SD1.
5. Where required by a state or locally adopted building code statute to include design for tsunami effects, Tsunami Risk Category II buildings with mean height above grade plane greater than the height designated in the statute and having inundation depth greater than 3 ft (0.914 m) at any location within the intended footprint of the structure.

Flood Design Requirements

ASCE 7-22 Chapter 5 provides minimum requirements for flood design loads and requirements "to resist flotation, collapse, and permanent lateral displacement" (ASCE 2021a) of the building structure. These loads are based on the Design Flood Elevation (DFE) which is defined as the elevation of the design flood, including wave height, relative to the datum specified on a community's flood hazard map. Chapter 5 addresses hydrostatic, hydrodynamic, wave, and breaking wave design loads, in addition to stating that erosion and scour effects be included in the calculation of loads.

The provisions in Chapter 5 apply to buildings and other structures located in areas prone to flooding as defined on a flood hazard map. Only breaking wave loads on vertical walls have loads that vary with Risk Category. Specifically, the dynamic pressure coefficient, C_p, for the breaking wave load varies with Risk Category. The probability of exceedance is based on laboratory test data and not the annual probability of exceedance used in calculating the design flood. The distribution of the wave pressures is independent of the water depth. The associated probability of exceedance of the test data and associated building type are summarized in Table 2-4 (ASCE 2021a).

Load combinations in Chapter 2 of ASCE 7-22 address flood hazard loads in combination with dead, live, wind, roof live, rain, and snow loads. The nominal flood load is based on the 100-yr flood (ASCE 2021a). Flood load combinations for coastal and non-coastal areas account for increased uncertainties for flood loads in coastal areas. The recommended flood load factor of 2.0 in V-Zones and Coastal A-Zones is based on a statistical analysis of flood loads associated with hydrostatic pressures, pressures caused by steady overland flow, and hydrodynamic pressures caused by waves.

Table 2-4: Summary of ASCE 7-22 Table 5.4-1 – Dynamic Pressure Coefficient and Associated Probability of Exceedance by Building Type (Source: ASCE 2021a)

Building Type	Risk Category	C_p	Probability of Exceedance
Residential	II	2.8	1% probability of exceedance of test data
Commercial	I	1.6	50% probability of exceedance of test data
	II	2.8	1% probability of exceedance of test data
Critical	III	3.2	0.2% probability of exceedance of test data
	IV	3.5	0.1% probability of exceedance of test data

Flood load factors in ASCE 7 may not achieve the reliability targets of Table 1.3-1. For structures in the 100-yr coastal flood zone, the load factor of 2.0 was based on a reliability index (beta) value of 2.5 (Mehta et al 1998) rather than 3.0. For structures outside the coastal zone, the load factor of 1.0 reflects the prescriptive minimum 100-yr flood elevation for still water flooding; thus, this flood has a 1% annual chance of being exceeded, which is essentially a beta of 1.3. For Risk Category III and IV structures, no reliability analysis has been performed (ASCE 2021a).

ASCE 24

ASCE 24 (2015) provides minimum requirements for flood resistant design and construction of structures that are subject to building code requirements and that are located, in whole or in part, in a Flood Hazard Areas (FHA). The requirements address flood loads, elevation of structures and utilities, foundations and anchorage, and material usage. For example, ASCE 24 stipulates placing electric power meters at an elevation above the DFE unless the building meets waterproofing requirements. A community may specify more stringent elevation requirements by requiring freeboard (additional elevation) above the BFE.

To provide additional design guidance for design of structures subject to flood hazards, ASCE 24 developed a Flood Design Class (FDC) to expand upon the guidance provided by Risk Categories in ASCE 7-22. FDC and RC are largely the same but criteria for determining the appropriate RC are less prescriptive than those for the FDC, so there may be an interpretation difference between RC and FDC.

FDC is defined in ASCE 24 as “A classification of buildings and other structures for determination of flood loads and conditions, and determination of minimum elevation requirements on the basis of risk associated with unacceptable performance.” (ASCE 2015). The FDC addresses two important components for flood design: location (in or out of the floodplain) and flood depth. The FDC determines minimum elevations for structural member elevations, floodproofing, utilities and equipment, and building access. The 2018 International Building Code requires designers to identify the FDC assigned in accordance with ASCE 24.

Most buildings and structures will be assigned to FDC 2. Buildings and structures for large assemblies typically are assigned FDC 3. FDC 4 includes essential facilities and buildings that provide services for emergency response and recovery. ASCE 24 requires FDC 4 buildings to be elevated or protected to at least the 500-yr flood level. For example, per ASCE 24 Table 4-1, the minimum elevation of the lowest supporting horizontal structural members with an FDC 4 in a Coastal High Hazard Area is the higher of the 1% annual chance of occurrence flood elevation plus 2 ft (0.61 m), the DFE, or the 0.2% annual chance of occurrence flood elevation. Table 2-5 provides a summary of the minimum flood elevation used in design by building type. For residential buildings defined in IRC, specific criteria requirements for flood-resistant construction are in section R322, which generally align with ASCE 24 provisions and FEMA flood design documents. In general, critical/essential buildings have higher flood elevation requirements. It is best practice to locate these facilities outside all special flood hazard areas.

Table 2-5: Summary of ASCE 24 Flood Hazard
Minimum Elevation of Top of Lowest Floor by Building Type (Source: ASCE 2015)

Building Type	Flood Hazard Area (FHA)	
	FHA & High Risk Flood Hazard Area (whichever is higher)	**Coastal High Hazard Area and Coastal A Zones (whichever is higher)**
Residential (Design Criteria: IRC R301.2.4 ref. ASCE 24, ASCE 7 Ch. 5)	**FDC 2:** 100-yr BFE+1 ft (0.3 m) or DFE	**FDC 2:** 100-yr BFE +1 ft (0.3 m) or DFE
Commercial (Design Criteria: IBC Sec. 1612 ref. ASCE 24 and ASCE 7 Ch. 5)	**FDC 1:** DFE FDC 2: 100-yr BFE+1 ft (0.3 m) or DFE	**FDC 1:** DFE **FDC 2:** 100-yr BFE +1 ft (0.3 m) or DFE
Critical/Essential (Design Criteria: IBC Sec. 1612 ref. ASCE 24 and ASCE 7 Ch. 5)	**FDC 3:** 100-yr BFE+1 ft (0.3 m) or DFE **FDC 4:** 100-yr BFE+2 ft (0.61 m), DFE, or 500-yr elevation	**FDC 3:** 100-yr+2 ft (0.61 m) or DFE **FDC 4:** 100-yr BFE +2 ft (0.61 m), DFE, or 500-yr elevation

Resilience Summary

With regards to resilience of buildings and communities, the design criteria in ASCE 7 (2021a), ASCE 24 (2015) and IBC (2021) provide guidance to reduce flooding damage and loss of functionality. NFIP flood insurance reduces the socio-economic impacts of flooding for buildings currently located in floodplains and sets minimum requirements for development in the floodplain to reduce future physical damage and financial impacts.

However, design flood hazard levels need to be based upon a target reliability, similar to that for other hazards in ASCE 7. Flood hazard design criteria is based on the NFIP program where a 100-yr flood event for buildings located in a designated flood plain or flood prone area are considered for national flood insurance.

2.4.1.2 Seismic

Codes, Standards, and Regulations

IBC (2021) seismic design criteria for new buildings references ASCE 7, in which Chapters 11 to 18 present criteria for the design and construction of buildings and other structures subject to earthquake ground motions. ASCE 41-17 provides a performance-based approach for the evaluation and retrofit of existing buildings for seismic hazards.

The seismic design of residential buildings in IRC (2021) classifies residential buildings by Seismic Design Category (SDC). The SDC for IRC 2021 is based on a short-period spectral response accelerations and Soil Site Class D. Depending on the SDC value, residential buildings may reference requirements per IBC; however, there are SDC-based design requirements in IRC 2021, such as masonry construction requirements. Residential buildings, as defined in IRC, do not use importance factors and are considered to perform at a minimum life safety level.

ASCE 7 Seismic Criteria

Earthquake loads are based upon inelastic energy dissipation in the structure. ASCE 7-22 defines two earthquakes for design:

- Design Earthquake: "The earthquake effects that are two-thirds of the corresponding risk-targeted maximum considered earthquake (MCE_R) effects."
- Risk-Targeted Maximum Considered Earthquake (MCE_R) Ground Motion Response Acceleration: "The most severe earthquake effects considered by this standard determined for the orientation that results in the largest maximum response to horizontal ground motions and with adjustment for targeted risk."

The design and MCE earthquake ground motions are characterized with structural response spectra for ground acceleration scaled to gravity (g) versus the period of shaking in seconds. The design response spectrum is defined by the spectral response acceleration parameters at short periods (less than 1 s) and at 1 s. Soil site class is also considered when determining the design earthquake spectral response acceleration parameters.

Once the design response acceleration parameters are determined and the building's Risk Category and associated Importance Factor are specified, the Seismic Design Category (SDC) of the building is determined. The Importance Factor is used in determining the load design criteria for structural and nonstructural components. The SDC of a building can range from A to F, where SDC A addresses minimum design requirements for structural and nonstructural components, SDC D addresses structures could experience strong shaking, and SDCs E and F address structures located within a few kilometers of major active faults. An example of seismic design criteria for an SDC D building is limits on the use of certain types of lateral resisting systems, such as masonry shear walls, in the building design and special anchorage details for architectural, mechanical, and electrical nonstructural components. Table 2-6 summarizes the Importance Factor, Ie, and Component Importance Factor, Ip, for each building type, where the higher the Risk Category, the higher the importance factor assigned.

Table 2-6: Summary of ASCE 7-22 Seismic Design Parameters by Building Type (Source: ASCE 2021a)

Building Type	Risk Category	Importance Factor (I_e)	Component Importance Factor (I_p)
Residential	Similar to Commercial buildings if IRC governs		
Commercial	I	1.0	1.0*
	II	1.0	1.0*
Critical	III	1.25	1.0*
	IV	1.5	1.5*

**I_p* magnitude as applicable per ASCE 7 Chapter 13 for nonstructural components.*

ASCE 7 design provisions are based on two levels of performance: (1) acceptable Life Safety risk defined by an “absolute” collapse probability of 1% in 50 yr for a design earthquake event and (2) a “conditional” collapse probability of 10% given MCE_R ground motions (ASCE 2021a). The load combinations in ASCE 7-22 Chapter 2 address earthquake hazard loads as principal loads in combination with dead, live, or snow companion loads. When the load combinations are evaluated with the appropriate factored resistance, the system is deemed to meet the target reliability.

The system reliabilities for earthquake are different from those for other environmental hazards because the design philosophy of the standard is to prevent system collapse in the MCE_R event. The conditional target probability of 10% is based on extensive research documented in FEMA P-695. The absolute probability of 1% in 50 yr and the conditional probability of 10% given MCE_R ground motions were used by the U.S. Geological Survey to develop the probabilistic MCE_R ground motions of ASCE 7-10.

Figure 2-2, illustrates the expected performance level of buildings for each Risk Category for three ground motion levels. For a design earthquake (two-thirds MCE_R), Risk Category II buildings are designed to achieve a life safety performance level. Risk Category III buildings are designed to achieve life safety or immediate occupancy performance levels, and Risk Category IV buildings are design to achieve an immediate occupancy performance level.

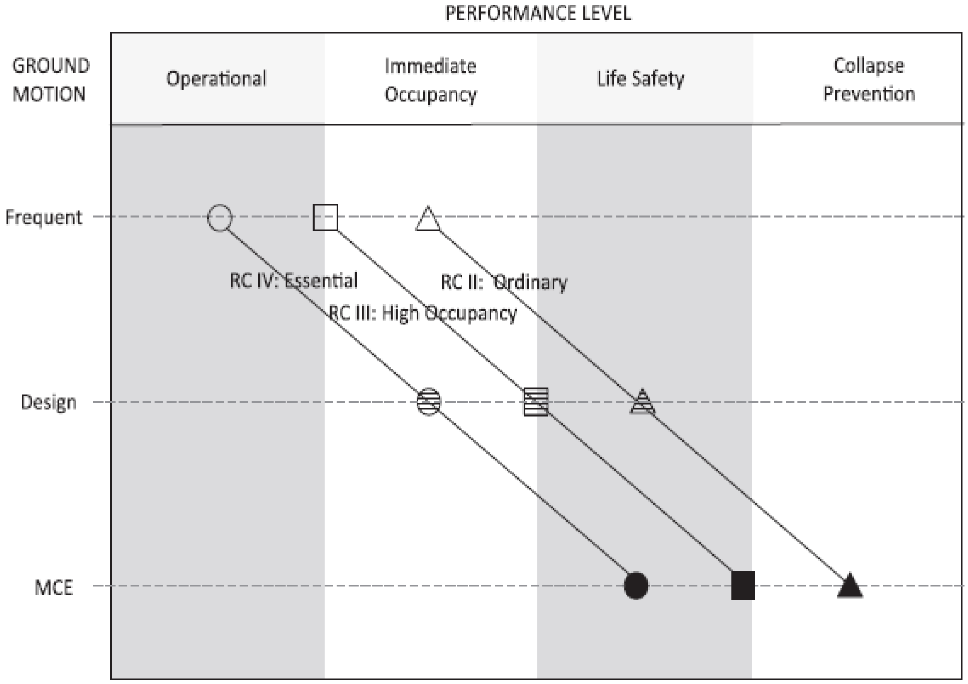


Figure 2-2: ASCE 7-22 Figure C11.5-1 Expected Performance as Related to Risk Category and Level of Ground Motion (Source: ASCE 2021a)

The fundamental purpose of a Risk Category and Importance Factor, and the subsequent requirements that depend on these values, is to "improve the ability of a community to recover from a damaging earthquake by tailoring the seismic protection requirements to the relative importance of a structure" (ASCE 7-22 Section C11.5). This purpose is addressed by requiring improved performance during and functionality following hazard events for essential facilities (RC IV), facilities that may result in a catastrophic loss (RC III or IV), or that house a large number of vulnerable occupants unable to care for themselves (RC II or III). Continuous functionality of a building requires minimal or no damage to the structural frame, building envelope, and nonstructural components, such as mechanical and electrical systems. Functionality of nonstructural components is addressed in Chapter 13 of ASCE 7 (2021a).

ASCE 7 Tsunami Criteria

Tsunami hazards, which are primarily generated by offshore subduction seismic events, are addressed in ASCE 7 (2021a) chapter 6. Tsunami design requirements for critical facilities are closely tied to seismic design requirements in ASCE 7-22. The tsunami hazard level for design purposes is the maximum considered tsunami (MCT), which is the tsunami caused after an MCE_R seismic event.

ASCE 7 provisions require critical and essential buildings (RC IV) located within the Tsunami Design Zone, RC III buildings with inundation depths greater than 3 ft (0.9 m), and RC II buildings when designated by local officials, to be located above the tsunami inundation elevation or designed for inundation loads and debris impact. Tsunami vertical evacuation refuge structures are included in Tsunami Risk Category (TRC) IV. To support facility functionality, all designated nonstructural components and systems for operations in designated facilities are required to be above inundation level or protected from inundation effects.

A number of Essential Facilities do not need to be included in TRC IV because they should be evacuated before the tsunami arrival, such as fire stations and ambulance facilities. These facilities may be located within the Tsunami Design Zone to serve the public interest on a timely basis but designing the structures for tsunami loads and effects could be costly with minimal benefit to the resilience of the community. RC I and II buildings may be damaged or fail when exposed to design level tsunami inundation. In order to reduce tsunami damage and losses, community resilience goals may include restrictions on new RC II buildings in Tsunami Design Zones.

ASCE 41

ASCE 41 (2017) provides a performance-based approach for existing buildings subject to seismic hazards. Table 2-7 lists the seismic hazard levels used in ASCE 41-17, which are based on the Basic Safety Earthquake (BSE) for existing (E) and new (N) buildings. Before the use of MCE_R in the seismic hazard level definition, a 10% probability of exceedance in 50 yr (MRI = 475 yr) was used for BSE-1N and a 2% probability of exceedance in 50 yr (MRI = 2475 yr) was used for BSE-2N to determine the seismic hazard level for new buildings.

Table 2-7: Summary of Basic Safety Earthquake Seismic Hazard Level Definitions (Source: ASCE 2017)

Seismic Hazard Level Definitions	
BSE-1E	20% probability of exceedance in 50 yr (MRI = 225 yr)
BSE-2E	5% probability of exceedance in 50 yr (MRI = 975 yr.)
BSE-1N	2/3 of BSE-2N
BSE-2N	MCE_R per ASCE 7 at site

The Performance Objective for evaluation and retrofit design is defined in ASCE 41 as "one or more pairings of a selected Seismic Hazard Level with both an acceptable or desired Structural Performance Level and an acceptable or desired Nonstructural Performance Level." The basic performance objective is based on Risk Category and Seismic Hazard Level as shown in Table 2-8 unless otherwise mandated by the AHJ.

For a selected performance objective, there is a Structural Performance Level with associated acceptance criteria for the strength and deformations of structural components. There is also a Nonstructural Performance Level with associated acceptance criteria for components that are part of life safety systems, anchorage of lighting fixtures, mechanical equipment, and furnishings. ASCE 41 defines nonstructural components as "an architectural, mechanical, or electrical component of a building that is permanently installed in, or is an integral part of, a building system."

Resilience Summary

Seismic design criteria address functionality for new and existing buildings, with a focus on essential facilities and the performance of the entire buildings, including nonstructural components. Currently, the seismic provisions in ASCE 7-22 (and ASCE 41-17) are 'deemed to comply' with performance levels defined by Risk Category. The inclusion of structural and nonstructural component performance criteria is a necessary step for supporting community resilience goals. However, under current design criteria, the building's response following a seismic event may include structural elements that have yielded, buckled, and otherwise behaved inelastically.

Table 2-8: ASCE 41-17 Table 2-1 Basic Performance Objective for Existing Buildings and Table 2-3 Basic Performance Objective Equivalent to New Building Standards (Source: ASCE 2017)

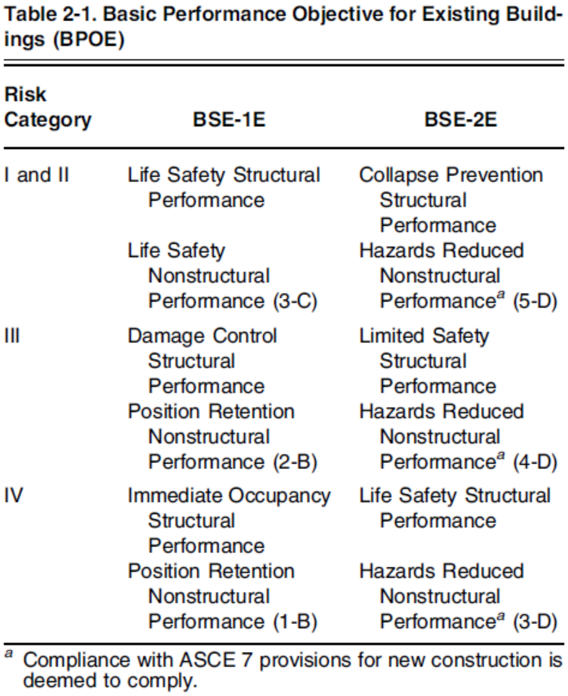


Table 2-1. Basic Performance Objective for Existing Buildings (BPOE)

Risk Category	BSE-1E	BSE-2E
I and II	Life Safety Structural Performance Life Safety Nonstructural Performance (3-C)	Collapse Prevention Structural Performance Hazards Reduced Nonstructural Performance[a] (5-D)
III	Damage Control Structural Performance Position Retention Nonstructural Performance (2-B)	Limited Safety Structural Performance Hazards Reduced Nonstructural Performance[a] (4-D)
IV	Immediate Occupancy Structural Performance Position Retention Nonstructural Performance (1-B)	Life Safety Structural Performance Hazards Reduced Nonstructural Performance[a] (3-D)

[a] Compliance with ASCE 7 provisions for new construction is deemed to comply.

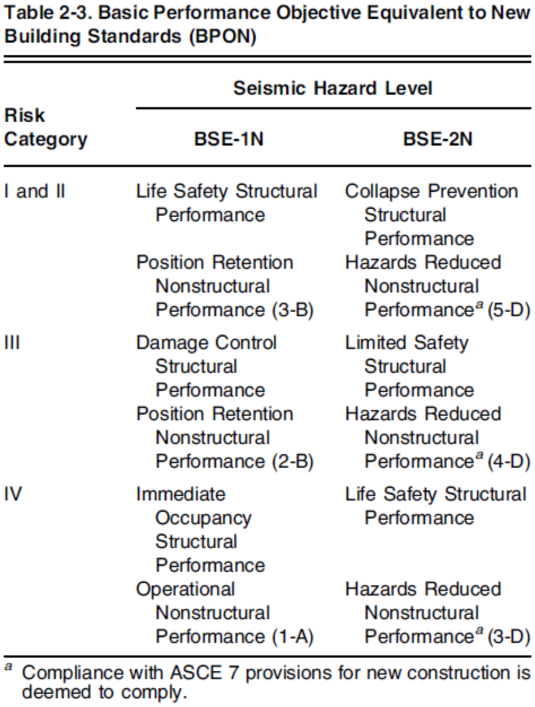


Table 2-3. Basic Performance Objective Equivalent to New Building Standards (BPON)

Risk Category	Seismic Hazard Level	
	BSE-1N	BSE-2N
I and II	Life Safety Structural Performance Position Retention Nonstructural Performance (3-B)	Collapse Prevention Structural Performance Hazards Reduced Nonstructural Performance[a] (5-D)
III	Damage Control Structural Performance Position Retention Nonstructural Performance (2-B)	Limited Safety Structural Performance Hazards Reduced Nonstructural Performance[a] (4-D)
IV	Immediate Occupancy Structural Performance Operational Nonstructural Performance (1-A)	Life Safety Structural Performance Hazards Reduced Nonstructural Performance[a] (3-D)

[a] Compliance with ASCE 7 provisions for new construction is deemed to comply.

2.4.1.3 Wind

Codes, Standards, and Regulations

Wind loads and associated design criteria for buildings in IBC (2021) and IRC (2021) reference ASCE 7 Chapters 26 through 30. Table 2-9 summarizes the wind speed criteria used to determine wind loads for each building type. Building performance levels for wind design are addressed through assignment of Risk Categories. Individual buildings are designed to withstand a specified level of wind hazard that meet the target reliabilities established for each RC in ASCE 7 Chapter 1 (ASCE 2021a).

IBC

IBC identifies deflection limits as part of the serviceability requirements in building design primarily for occupant comfort, to limit cosmetic damage to finishes, and to ensure operation of sensitive equipment. Table 1604.3, Deflection Limits, indicates wind deflection limits for various building members (e.g., roof, floor, walls) using a wind MRI of 10 yr (IBC 2021).

IBC includes other specific provisions, such as not permitting aggregate roof material in hurricane-prone regions, as defined in Section 1504.8. Additionally, windborne debris within the hurricane-prone regions are addressed in provisions for glazing based on the elevation of the building location and glazing openings above ground.

Table 2-9: Summary of ASCE 7-22 Basic Wind Speed Criteria by Building Type (Source: ASCE 2021a)

Building Type	Basic Wind Speed Probability of Exceedance
Residential (Design Criteria: IRC 2021 R301.2.1)	7% probability of exceedance in 50 yr (MRI = 700 yr)
Commercial (Design Criteria: IBC 2021 Sec. 1609 ref. ASCE 7-22 Ch. 26–31)	RC I: 15% probability of exceedance in 50 yr (MRI = 300 yr) RC II: 7% probability of exceedance in 50 yr (MRI = 700 yr)
Critical (Design Criteria: IBC 2021 Sec. 1609 ref. ASCE 7-22 Ch. 26–31)	RC III: 3% probability of exceedance in 50 yr (MRI = 1700 yr) RC IV: 1.6% probability of exceedance in 50 yr (MRI = 3000 yr)

In addition to building design requirements for strength, stability and serviceability, some mitigation measures have been incorporated into design requirements in IRC, IBC, ASCE 24, and ASCE 41. At a national scale, the National Institute of Building Science (NIBS) *Natural Hazard Mitigation Saves* report illustrates that mitigation efforts such as retrofitting existing buildings and designing to the latest model code can have at least a 4:1 Benefit-to-Cost Ratio (NIBS 2019).

IRC

In IRC (2021), wind speed maps for residential construction are based on ASCE 7 Risk Category II wind maps. In regions where wind speeds exceed 130 mph (3-s gust wind speed), residential buildings use one or more of the methods provided by the AWC *Wood Frame Construction Manual* (AWC 2018b), *ICC Standard for Residential Construction in High-Wind Regions* (ICC 600), ASCE 7 (2021a), *AISI Standard for Cold-Formed Steel Framing* (AISI S230), or IBC (2021). IRC includes glazing provisions for windborne debris regions similar to those in IBC (2021).

ASCE 7 Wind Criteria

Hurricanes, tornados, derechos, and other wind events can impact large geographical areas and cause widespread building damage in communities. Building wind performance can be improved with enhanced performance objectives to reduce the likelihood of economic and community impacts. Examples of buildings that may have community impacts include data centers, research laboratories, manufacturing facilities, and municipal facilities that support recovery of community functions. FEMA 577 (FEMA 2007b) provide enhancement techniques for facilities such as hospitals.

Buildings depend on local services for utilities, transportation, and communication. Minor to severe service interruption may occur, depending on the wind intensity and design basis of the infrastructure system. Enhanced performance objectives for building mechanical or utility infrastructure can increase building and community resilience during the short-term recovery phase (ASCE 2019). This is an important consideration for critical and essential buildings as the loss of power, water, or sewer can cause closure or evacuation of facilities. See FEMA P-1019 (2014b) for guidance on emergency power systems for critical facilities. FEMA 543 (2007a) includes recommendations to enhance water and sewer systems from flooding and high winds. Additional resilience references can be found in the FEMA Building Science Series: https://www.fema.gov/building-science-publications-flood-wind.

Wind loads in ASCE 7-22 for the structural framing, also referred to as the main wind force resisting systems (MWFRS), and components and cladding (C&C) are calculated using geographical and building shape factors such as exposure, pressure coefficient at different building zones, and gust-effects factors. In a wind event, the structural response of the MWFRS is designed to remain elastic (e.g., no permanent deformations) for design wind loads. However, ASCE 7 (2021a) Risk Category criteria pertain only to the basic wind speed; the standard does not address other issues such as drift control or envelope toughness that are necessary to achieve a desired functional level of building performance (ASCE 2019). Wind-induced building failures often occur in connections between members rather than member failure or in exterior C&C. Load combinations in Chapter 2 of ASCE 7 address wind loads in combination with dead, live, flood, and roof live or rain or snow loads.

Information and maps with 10-yr, 25-yr, 50-yr, and 100-yr MRIs are provided in ASCE 7 Appendix C Commentary. The selection of deflection limits for associated wind MRIs is typically at the discretion of the design professional and owner, based on building occupancy type and performance goals. A building's lateral drift limitations may be dictated by the building enclosure and any adjacent obstructions in addition to the performance criteria and owner requirements. ASCE 7 Appendix CC also contains additional information regarding drift, vibration, and deflection limits and considerations (ASCE 2021a).

Wind-borne debris is addressed for glazed opening in ASCE 7 that are within 1 m (1.6 km) of the coast where the basic wind speed is equal to or greater than 130 mph (58 m/s) and for all areas where the basic wind speed is equal to or greater than 140 mph (63 m/s). Glazing more than 60 ft (18.3 m) above grade and more than 30 ft (9.2 m) above ballasted roofs do not need to resist debris impact (ASCE 2021a).

ASCE 7 Tornado Criteria

Criteria for storm shelters and tornado shelters are provided by the ICC 500 (2020a) *Standard for the Design and Construction of Storm Shelters*.

ASCE 7 (2021a) chapter 32 for tornado loads addresses wind loads for buildings and other structures located in designated tornado-prone regions designated as Risk Category III or IV. They shall be designed and constructed to resist the greater of the tornado loads or the wind loads determined in accordance with Chapters 26 through 32, using the load combinations provided in Chapter 2 (Levitan et al 2021). The new requirements include the main wind force resisting system (MWFRS) and all components and cladding (C&C).

Prestandard for PBWD

The *Prestandard for Performance-Based Wind Design* (PBWD, ASCE 2019) presents recommended alternatives to the prescriptive procedures for wind design of buildings contained in ASCE 7 and IBC. The Prestandard's recommendations address the design of engineered buildings and the building envelope (or C&C) and select internal systems that require enhanced performance beyond that provided by codes and standards. Performance objectives and acceptance criteria are identified for performance levels of occupant comfort, operational, and continuous occupancy with limited interruption. For a continuous occupancy performance level, the Prestandard has performance objectives and related acceptance criteria for the inelastic response of specific elements or components of the structural system, given that the structural system withstands a design wind event with a low probability of partial or total collapse. Guidance is also provided for building envelope and nonstructural systems.

Resilience Summary

The use of Risk Categories in wind design helps to classify buildings according to their role in the community with regards to their functional importance and the societal consequences of failure. However, Risk Categories cannot be used to directly address functional requirements in design; rather, the increased design requirements are implicitly assumed to achieve the desired performance.

In general, mitigation efforts collectively improve the pre-event performance level of existing buildings and help reduce damage, functional loss, and time to recover functionality. The Prestandard provides a methodology to more directly address performance objectives beyond those in ASCE 7 and the IBC. However, consideration of damage consequences and the corresponding loss and repairs for recovery of function remains a challenge for designers.

2.4.2 Resilience Concepts

The resilience of a community directly depends upon the pre-event condition of its building and infrastructure. For communities to improve their resilience, adoption and enforcement of current building codes for new and existing construction is a key factor. Additional performance requirements may be needed to address local hazards or improve existing building stock. While some of these requirements will be common to all communities, there are others that will vary between community (NIST 2016).

Current practice for building design primarily focuses on withstanding load effects and limiting member failure to a specified location and manner (e.g., local ductile failure without structural instability). However, a more comprehensive approach is needed to achieve building functionality—designing for performance during and recovery after hazard events—that can be aligned with a community's resilience goals.

The concept of functional recovery is intended to improve the design of individual buildings and infrastructure systems to serve community resilience goals through building codes and industry standards supplemented by additional performance objectives. Addressing the interdependency between buildings and infrastructure systems is also essential to achieving building functionality.

Full recovery of buildings and the community depends on many factors, including public policies (NIST 2020). Model building codes may be modified when adopted and enforced at the community level; the modifications my increase or decrease the performance of a building. Other factors, such as insurance for hazard related losses and federal/state requirements for grants and loans often influence the funds available for repairs and reconstruction after events (McAllister et al 2019).

2.4.2.1 Planned Recovery

Model building codes address the design of individual buildings, whereas community resilience addresses the collective performance of all buildings and infrastructure systems, and how they support the recovery of social institutions. The default assignment of a Risk Category and associated design requirements may not fully address community resilience goals. For example, treatment facilities (e.g., dialysis and cancer) are typically located in Risk Category II buildings, while hospitals are Risk Category IV buildings. The treatment facilities may sustain more damage than hospitals for the same hazard event. Both healthcare functions are essential to community healthcare. Another example is power-generating stations not required as emergency backup facilities are classified in IBC (2020) as Risk Category III, but these stations may need to be classified as a Risk Category IV based on their role in community recovery needs.

Model building codes do not explicitly address damage levels or the recovery of functionality. Risk Categories focus on the probability of structural member or system failure based on a target reliability for design level hazard events. Functionality for Risk Category IV facilities is defined in ASCE 7-22 Section 1.3.3 in qualitative terms: "structural systems and designated nonstructural systems shall have adequate strength and stiffness to limit deflections, lateral drift, or other deformations so that function of the facility is supported immediately following any design level hazard events in the standard". Including functionality in design and assessment requires clear definitions of functional recovery goals, damage limit states, and repair needs to support time to recovery of function.

Across a community, recovery occurs in phases, with critical buildings prioritized for the first short-term phase of recovery. The level of damage and time to recovery of function for a given hazard event is expected to be less for critical facilities designed for Risk Category

are needed that address the entire building—structural system, foundation, envelope—and the corresponding performance of nonstructural and mechanical systems. To improve the resilient performance of buildings, further research on predicting the damage to structural and nonstructural systems and the role of aging or degradation is needed to inform design solutions that enhance building performance and recovery. Additionally, design professionals, building officials, owners/operators, and communities need to understand current limitations of building performance provided by codes and standards.

For existing buildings, the substantial improvement criteria defined by IEBC do not address performance and recovery levels. Currently, under IEBC existing buildings may be restored to the pre-event conditions, which may not align with the current building code or climate change considerations as part of the community resilience goals. ASCE 41 does establish building performance objectives and associated performance levels for the seismic evaluation and retrofit of existing buildings to withstand seismic events. Similar standards for existing buildings are needed for flood and wind hazards.

Maintaining or restoring building functionality after a hazard event is a foundational element of community resilience. Model building codes have minimum requirements for safety and structural stability and integrity that provide a minimum baseline for building performance and their impact on community resilience. Currently, Risk Categories are used for prescriptive design provisions to provide structural safety, stability, and integrity, with varying levels of post-event damage to be expected. Performance-based design methods are used to address additional performance requirements to withstand hazard events and other owner-defined criteria; however, the time for a building to recover its functions is not explicitly addressed.

Recovery of functions depends on many factors. As a starting place, a baseline set of quantitative limit states for functional performance levels and associated probabilities of failure and damage levels is needed to inform evaluation of repair and recovery processes and associated times. These baseline criteria can them be used to advance resilience in design and assessment tools for the building design process, enabling informed comparison of design alternatives to meet the performance objectives. Guidance should also be developed to assist design professionals with communicating resilience options to owners and the public.

The following list identifies gaps and potential areas of improvement for building design practice:

- Model building codes and standards have minimum requirements for structural stability, integrity, and life safety. Resilient buildings need to address the performance of the entire building, including the structural system and foundation, building envelope (e.g., components and cladding), nonstructural components (e.g., electrical and mechanical systems), non-building structures (e.g., roof-top structures) and contents (e.g., sensitive medical equipment, hazardous materials). ***Design methods are needed that address the performance of the entire building as an integrated system—the structural system, building envelope, nonstructural systems, , and essential building contents.***

- Building codes provide minimum requirements for design and construction that are based on target reliabilities for component or system performance but do not explicitly address the corresponding post-event damage or recovery of function. Additionally, performance based on Risk Category requirements may not adequately align with community resilience goals. For example, treatment facilities (e.g., dialysis and cancer) are typically classified as Risk Category II buildings, while hospitals are Risk Category IV buildings. The treatment facilities will likely sustain more damage than hospitals for the same hazard event. Both healthcare functions are essential to the community. The assignment of Risk Category should consider a building's role within the community social functions as part of a building cluster. ***Functional performance goals and design criteria for buildings need to better address their role in the community, expected levels of damage, subsequent impact on building functionality, repairs required to achieve recovery of function within a specified timeframe, and potential impacts on community recovery.***
- Performance-based design (PBD) guidance documents provide performance objectives and design criteria for buildings that exceed code requirements in some areas. The *Prestandard for Performance-Based Wind Design* (ASCE 2019) provides qualitative performance objectives and acceptance criteria, as well as dependencies on other systems that may cause service interruptions and that can inform project-specific functional recovery times. Industry groups, such as the Structural Engineers Association of California (SEAOC), are developing guidance for establishing recovery times for building functions based on the guidance provided by the NIST *Community Resilience Planning Guide* (NIST 2016). Such documents provide a starting point for design practice that may lead to design criteria in consensus standards. ***Best practice guidance is needed for all hazards with appropriate performance objectives, design and assessment methods and quantitative criteria that address building functionality, dependencies, and community impacts.***
- Performance objectives for resilient buildings should promotes recovery of functionality by addressing occupancy and use during repairs. A set of baseline performance objectives that support common community resilience goals can advance resilient design practice. Baseline performance objectives for buildings will provide a foundation for model codes and standards and performance-based design (PBD) methods. A starting point may be review of the performance levels for seismic hazards—operational, immediate occupancy, life safety, and collapse prevention—with additions for functional recovery objectives and adjustments for application to all hazards. ***Performance objectives for buildings that include damage levels and corresponding***

recovery of function are needed to provide a common foundation for individual projects and model codes and standards.

- Functional recovery time depends on damage levels. ASCE 7 (2022) Section 1.3.3 defines functionality for Risk Category IV facilities in qualitative terms: "Structural systems and members and connections thereof assigned to Risk Category IV shall be designed with reasonable probability to have adequate structural strength and stiffness to limit deflections, lateral drift, or other deformations such that their behavior would not prevent function of the facility immediately following any of the design level environmental hazard events specified in this standard". Quantitative engineering parameters are needed for inclusion of functionality in design. ***A core set of damage limit states are needed to support quantitative assessment of time to recover functionality.***
- Data on repair costs and downtime for buildings are available in a few analysis tools and publications, but further development of repair and recovery data for buildings is needed to support analyses for all hazard types. Resilient community assessment tools strategies (e.g., Hazus [FEMA 2020b], IN-CORE [NIST-CoE 2020], SimCenter [NHERI 2020]) are advancing the capability to simulate aspects of building damage, losses, and recovery to inform community resilience. Such models may also inform building design methods and policies relative to model building code requirements to better support community resilience. ***Data to characterize typical repair costs and functional recovery times for a range of damage levels are needed, as well as data on related impacts to community function.***
- Community resilience goals are hazard agnostic in that a building should provide resilient performance for all expected hazards; the level of functional building performance should not substantially differ between hazards. For example, all emergency care centers should be located and designed to provide continuous services during and after all expected hazard events. The designer needs to determine if a new or existing building can meet the resilient performance criteria for specified hazards. The degree to which a building may meet the resilience goals may vary between hazards, particularly for older existing buildings. ***Guidance is needed to identify performance objectives for building response to design hazard events that support community resilience goals.***
- Flood design hazards for buildings in codes and standards are based on NFIP Flood Insurance Rate Maps (FIRMs), which were developed for floodplains and insurance risk purposes. While NFIP and related programs have improved design practices for flood events, many locations still experience damage from flood events. For example, flood damage may also be caused by flash floods, inadequate stormwater systems, or an increase in impervious surfaces. The design flood hazard may need to be increased from code requirements, based on local conditions and the intended function of the building within the community. ***Guidance is needed for determining flood risks that include***

flood zones and other local conditions and to identify design flood criteria for community and building resilience goals.

There are multiple organizations and committees studying community resilience, including the ICC Alliance for National and Community Resilience, ASCE/SEI Board of Governors Resilience Committee, NIBS reports and webinars, and the NCSEA Resilience Committee, to name a few. Effort to implement effective community resilience measures are being addressed by federal, state, and local governments; industry researchers and practitioners; and members of the community.

2.5 Conclusions

Model building codes and standards provide minimum requirements to address life safety and structural stability and integrity; however, these provisions do not fully address community resilience considerations. Consistent performance criteria are needed for design hazards to support resilience, understanding that they may be varied in meeting community resilience goals.

There is limited data and guidance about post-event functional requirements and the time to recovery of function for a building after a hazard event. Building resilience objectives should consider the entire building's performance and functionality, including its performance and continued occupancy during repairs. Performance objectives for buildings in terms of damage levels and levels of functionality need to be developed in a quantitative format to provide a common foundation for individual projects and SDOs moving forward to address the gap between the current objectives of model building codes and achieving community-level resilience.

Current design criteria for building importance factors and Risk Category may or may not be aligned with a community's resilience goals. A community needs to understand its current vulnerabilities to the hazard events and properly address them by implementing design criteria in building codes. Guidance that develops a baseline set of community resilience goals and associated building performance objectives to support assessment of functional recovery would help bridge the gap between building performance and community resilience.

A broader understanding of interdependencies between buildings and infrastructure systems is needed. The impacts of variations between building and infrastructure codes and standards on community resilience also needs to be evaluated to identify any critical topics that need to be addressed.

2.6 References

ACI, 2017. *ACI 369.1-17: Standard Requirements for Seismic Evaluation and Retrofit of Existing Concrete Buildings and Commentary.* American Concrete Institute, Farmington Hills, MI.

ACI, 2019. *ACI 318-19: Building Code Requirements for Structural Concrete.* American Concrete Institute, Farmington Hills, MI.

AISC, 2016. *AISC 341-16: Seismic Provisions for Structural Steel Buildings*. American Institute of Steel Construction, Chicago, IL.

AISC, 2021. *AISC 360-16: Specification for Structural Steel Buildings. Errata to ANSI/AISC 360-16, March 2017. Errata to ANSI/AISC 360-16, Revised June 2018*. American Institute of Steel Construction, Chicago, IL.

AISI, 2015. *AISI S240-15: North American Standard for Cold-Formed Steel Structural Framing*. American Iron and Steel Institute, Washington, DC.

AISI, 2015b. *AISI S230-15: Standard for Cold-Formed Steel Framing – Prescriptive Method for One and Two-Family Dwellings*. American Iron and Steel Institute, Washington, DC.

AISI, 2015c. *AISI S400-15: North American Standard for Seismic Design of Cold-Formed Steel Structural Framing Systems*. American Iron and Steel Institute, Washington, DC.

ANSI/AMCA, 2015. *Test Method For Louvers Impacted By Wind Borne Debris*, ANSI/AMCA 540-2015, The Air Movement and Control Association International, Inc. (Content Provider).

ANSI/DASMA, 2017. *Standard Method for Testing Sectional Garage Doors, Rolling Doors and Flexible Doors: Determination of Structural Performance Under Missile Impact and Cyclic Wind Pressure*, ANSI/DASMA 115-2017, Door & Access Systems Manufacturers' Association, International (Content Provider).

ASCE, 2015. ASCE 24-14: *Flood Resistant Design and Construction*. American Society of Civil Engineers, Structural Engineering Institute, Reston, VA.

ASCE, 2017. ASCE 41-17: *Seismic Evaluation and Retrofit of Existing Buildings*. American Society of Civil Engineers, Structural Engineering Institute, Reston, VA.

ASCE, 2018. *Climate-Resilient Infrastructure: Adaptive Design and Risk Management.* MOP 140, American Society of Civil Engineers, Structural Engineering Institute, Reston, VA.

ASCE, 2019. *Prestandard for Performance-Based Wind Design.* American Society of Civil Engineers, Structural Engineering Institute, Reston, VA.

ASCE, 2021a. ASCE 7-22: *Minimum Design Loads and Associated Criteria for Buildings and Other Structures.* American Society of Civil Engineers, Structural Engineering Institute, Reston, VA.

ASCE, 2021b. ASCE 49-21: *Wind Tunnel Testing for Buildings and Other Structures.* American Society of Civil Engineers, Structural Engineering Institute, Reston, VA.

ASCE, 2022. *Sustainability & Resilience*. American Society of Civil Engineers. https://www.asce.org/topics/sustainability-resilience.

ASTM, 2014. *Standard Specification For Performance Of Exterior Windows, Curtain Walls, Doors, And Impact Protective Systems Impacted By Windborne Debris In Hurricanes*, ASTM E1996-14a, ASTM International, West Conshohocken, PA.

ASTM 2022. Standardization News: 5 Standards that Support Resilience, ASTM International, West Conshohocken, PA. https://sn.astm.org/?q=features/5-standards-support-resilience-.html

ATC, 2009. *Design Guide 2, Basic Wind Engineering for Low-Rise Buildings.* Applied Technology Council, Redwood City, CA.

AWC, 2018a. *2018 National Design Specification (NDS) for Wood Construction*. American Wood Council, Leesburg, VA.

AWC, 2018b. *2018 Wood Frame Construction Manual (WFCM) for One and Two-Family Dwellings*. American Wood Council, Leesburg, VA.

AWC, 2018. *2018 National Design Specification (NDS) for Wood Construction*. American Wood Council, Leesburg, VA.

AWC, 2021. *ANSI/AWC 2021 Special Design Provisions for Wind and Seismic (SDPWS)*. American Wood Council, Leesburg, VA.

Buckalew J, Lang A, Mayes R, Wade K, 2019. *SEAOC Resilience Committee Update and Report to the Membership*. https://www.iccsafe.org/wp-content/uploads/SEAOC-Resilience-Committee-Update-and-Report-to-the-Membership.pdf.

California, 2019. *The 1989 Loma Prieta Earthquake.* Department of Conservation. https://www.conservation.ca.gov/cgs/earthquakes/loma-prieta.

Celebi, M., 1998. *The Lorna Prieta, California, Earthquake of October 17, 1989-Building Structures*, U.S. Geological Survey Professional Paper 1552-C, US Government Printing Office, Washington, DC.

CBS News, 2012. *NYC hospital successfully evacuates 300 patients after Superstorm Sandy*. https://www.cbsnews.com/news/nyc-hospital-successfully-evacuates-300-patients-after-superstorm-sandy/.

CFR, 2019. *Title 44 – Emergency Management and Assistance*. Code of Federal Regulations. https://www.govinfo.gov/app/details/CFR-2019-title44-vol1/CFR-2019-title44-vol1-sec59-1.

.

FEMA, 2006. *Homebuilders' Guide to Earthquake Resistant Design and Construction*. FEMA 232, Federal Emergency Management Agency, Washington, DC.

FEMA, 2007a. *Design Guide for Improving Critical Facility Safety in Earthquakes, Floods, and High Winds*. FEMA 543, Risk Management Series, Federal Emergency Management Agency, Washington, DC.

FEMA, 2007b. *Risk Management Series: Design Guide for Improving Hospital Safety in Earthquakes, Floods, and High Winds*. FEMA 577, Federal Emergency Management Agency, Washington, DC.

FEMA, 2009a. *Recommended Residential Construction for Coastal Areas: Building on Strong and Safe Foundations.* FEMA P-550, Federal Emergency Management Agency, Washington, DC.

FEMA, 2009b. *Engineering Guideline for Incremental Seismic Rehabilitation,* FEMA P-420, Federal Emergency Management Agency, Washington, DC.

FEMA, 2009c. *Quantification of Building Seismic Performance Factors,* FEMA P-695, Federal Emergency Management Agency, Washington, DC.

FEMA, 2015. *NEHRP Recommended Seismic Provisions for New Buildings and Other Structures,* FEMA P-1050, Federal Emergency Management Agency, Washington, DC.

FEMA, 2018. FEMA Fact Sheet: Mitigation Assessment Team Results – Hurricane Sandy. Federal Emergency Management Agency, Washington, DC.

FEMA 2019. *Seismic Performance Assessment of Buildings: Volumes 1-7,* FEMA P-58, Federal Emergency Management Agency, Washington, DC.

FEMA, 2020a. *The National Flood Insurance Program*. Federal Emergency Management Agency, Washington, DC. https://www.fema.gov/national-flood-insurance-program.

FEMA, 2020b. *Hazus-MH*. Federal Emergency Management Agency, Washington, DC. https://www.fema.gov/flood-maps/products-tools/hazus

FBC, 2020. *Florida Building Code,* Florida Department of Business & Professional Regulation. https://floridabuilding.org/.

FIU, 2019*. Potential Implications of Sea-Level Rise and Changing Rainfall for Communities in Florida using Miami-Dade County as a Case Study,* Sea Level Solutions Center (SLSC), Florida International University, Miami, FL. https://environment.fiu.edu/_drafts/projects-emily/_assets/fbc_fiu_finalreport_22aug2019.pdf.

IBC, 2021. *International Building Code*. International Code Council, Washington, DC.

IEBC, 2021. *International Existing Building Code*. International Code Council, Washington, D.C.

IRC, 2021. *International Residential Code for One- and Two-Family Dwellings*. International Code Council, Washington, DC.

ICC, 2019. *About the International Code Council*. International Code Council, Washington, D.C. https://www.iccsafe.org/about/who-we-are/.

ICC, 2020a. *ICC 500-2020: ICC/NSSA Standard for the Design and Construction of Storm Shelters*. International Code Council, Washington, DC.

ICC, 2020b. *ICC 600-2020: Standard for Residential Construction in High-Wind Regions*. International Code Council, Washington, DC.

Mehta, K. C., D. L. Kriebel, G. J. White, and D. A. Smith. 1998. *An investigation of load factors for flood and combined wind and flood*. Report prepared for FEMA. Washington, DC.

Levitan, M., Twisdale, L., and Phan, L., 2021. *New Tornado Risk Maps for Engineering Design*. NRC Regulatory Information Conference RIC 2021. https://ric.nrc.gov/docs/abstracts/levitanm-t11-hv.pdf

Lew, editor, 1990. *Performance of Structures During the Loma Prieta Earthquake of October 17, 1989*. NIST SP-778, National Institute of Standards and Technology, Gaithersburg, MD. https://nvlpubs.nist.gov/nistpubs/Legacy/SP/nistspecialpublication778.pdf.

McAllister, T., Clavin, C., Ellingwood, B., van de Lindt, J., Mizzen, D., and Lavelle, F. 2019. *Data, Information, and Tools Needed for Community Resilience Planning and Decision-Making*, NIST Special Publication 1240, National Institute of Standards and Technology (NIST), Gaithersburg, MD, https://nvlpubs.nist.gov/nistpubs/specialpublications/NIST.SP.1240.pdf

NCSEA, 2020. *Resilience and What it Means to the Structural Engineer* [Webinar]. National Council of Structural Engineers Association, Chicago, IL. https://www.pathlms.com/ncsea/courses/16580/webinars/796.

NEHRP, 2016. *About Us Background & History,* National Earthquake Hazard Reduction Program. https://www.nehrp.gov/about/history.htm.

NEHRP, 2018. *The National Earthquake Hazards Reduction Program (NEHRP): Issues in Brief*, Congressional Research Service, updated December 13, 2018, https://sgp.fas.org/crs/misc/R43141.pdf

NHERI, 2022*. SimCenter Computational Modeling and Simulation Center*. DesignSafe-CI, National Science Foundation. https://simcenter.designsafe-ci.org/

NIBS, 2019. *National Hazard Mitigation Saves 2019 Report.* https://cdn.ymaws.com/www.nibs.org/resource/resmgr/reports/mitigation_saves_2019/mitigationsaves2019report.pdf.

NIST, 2016. *Community Resilience Planning Guide for Buildings and Infrastructure Systems, Volume 1*. NIST SP-1190. National Institute of Standards and Technology, Gaithersburg, MD. http://dx.doi.org/10.6028/NIST.SP.1190v1.

NIST, 2016. *Community Resilience Planning Guide for Buildings and Infrastructure Systems, Volume 2*. NIST SP-1190. National Institute of Standards and Technology, Gaithersburg, MD. http://dx.doi.org/10.6028/NIST.SP.1190v2.

NIST, 2018. *Research Needs to Support Immediate Occupancy Building Performance Objective Following Natural Hazard Events*. NIST SP-1224. National Institute of Standards and Technology, Gaithersburg, MD. http://dx.doi.org/10.6028/NIST.SP.1224 .

NIST-CoE. 2022. *IN-CORE: Interdependent Networked Community Resilience Modeling Environment*, Center for Risk-Based Community Resilience Planning, a NIST-funded Center of Excellence, Colorado State University. http://resilience.colostate.edu/in_core/

NIST/FEMA, 2021. *Recommended Options for Improving the Built Environment for Post-Earthquake Reoccupancy and Functional Recovery Time*, NIST SP-1254/FEMA P-2090, National Institute of Standards and Technology, Gaithersburg, MD. https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1254.pdf.

NOAA, 2017, *Global and Regional Sea Level Rise Scenarios for the United States*, NOAA Technical Report NOS CO-OPS 083, National Oceanographic and Atmospheric Administration, Washington, DC. https://tidesandcurrents.noaa.gov/publications/techrpt83_Global_and_Regional_SLR_Scenarios_for_the_US_final.pdf.

NYC, 2014. *Coastal Climate Resiliency: Retrofitting Buildings for Flood Risk*, Department of City Planning, New York City, NY. https://www1.nyc.gov/site/planning/plans/retrofitting-buildings/retrofitting-buildings.page.

NYC, 2019. *Lower Manhattan Climate Resilience Study*. Economic Development Corporation, Mayor's Office of Recovery and Resiliency, New York City, NY. https://edc.nyc/sites/default/files/filemanager/Projects/LMCR/Final_Image/Lower_Manhattan_Climate_Resilience_March_2019.pdf.

NYC, 2021. *Zoning for Coastal Flood Resiliency*. New York City Department of City Planning. NY. https://www1.nyc.gov/site/planning/plans/flood-resilience-zoning-text-update/flood-resilience-zoning-text-update.page.

NIBS, 2018. *Whole Building Design Guide: Building Resilience*. National Institute of Building Sciences, Washington, D.C. https://www.wbdg.org/resources/building-resiliency.

PCI, 2017. *PCI Design Handbook: Precast and Prestressed Concrete, 8th Edition*. Precast/Prestressed Concrete Institute, Chicago, IL.

PEER, 2017. *Guidelines for Performance-Based Seismic Design of Tall Buildings*, Pacific Earthquake Engineering Research Center, Tall Buildings Initiative (TBI), Report No. 2017/06, Version 2.03, https://peer.berkeley.edu/sites/default/files/final_tbi_report_10.9.2017_0.pdf.

TMS, 2016. *TMS 402/602-16: Building Code Requirements and Specification for Masonry Structures*. The Masonry Society, Longmont, CO.

Virginia, 2018. *Executive Order 45: Virginia Flood Risk Management Standard*, Virginia Department of Conservation and Recreation, Richmond, VA. https://www.dcr.virginia.gov/crmp/flood-freeboard-standard

3 Water Infrastructure

3.1 Overview

Water infrastructure systems in the U.S. are essential for sustaining community life, safety, and sanitation. U.S. water infrastructure systems are complex, with the major types of systems comprising potable water, wastewater, and stormwater. Flood risk management on a whole system level involves the control of water and managing the risk to property, assets and life from potential inundation. Flood risk management interacts with the potable water, wastewater, and stormwater systems through (1) the natural water supply above and below ground prior to its use in drinking water and other supply source waters, (2) everything after effluent leaves a wastewater facility back to the natural environment, and (3) the collection, treatment, and return of urban stormwater runoff back to the natural environment.

Water infrastructure systems, which serve many different functions, are parallel and interacting systems. There are approximately 153,000 public drinking water systems in the United States, which treat and provide potable water for more than 80% of the U.S. population (DHS and EPA 2015). There are more than 16,500 publicly owned wastewater treatment systems in the United States, which treat sanitary sewerage for about 75% of the U.S. population (DHS and EPA 2015). The United States has over 90,000 dams and an estimated 100,000 miles of levees, both of which have an average infrastructure age of over 50-yr old and were designed using criteria that no longer meet the needs of current environmental threats (ASCE 2017a).

Uses of water include agricultural, industrial, household, recreational, and environmental activities. The average water consumption in the U.S. is 98 gal (446 l) per person per day, for activities such as drinking, cooking, personal hygiene, flushing toilets, and laundry (Aubuchon and Morley 2013). In addition to personal water consumption provided by the potable water system, most businesses and industries are dependent on wastewater disposal and stormwater management. Communities can generally accommodate short-term disruptions in water and wastewater services resulting from hazard events. However, longer-term outages are highly disruptive to community functions and hazard event recovery itself. Drivers for increased resilience in water infrastructure include public safety, aging infrastructure with compromised system condition and capacity—particularly in the case of dams and levees—and ability to accommodate more extreme hazard events associated with climate change.

This chapter assesses water infrastructure regulatory bodies and design criteria in nationally recognized codes, standards, and best practices related to seismic, flood, and wind hazards, for an understanding of current water infrastructure state of practice and expected performance from a community resilience perspective. This overview section provides a description of the different major water infrastructure.

3.1.1 Potable Water Systems

Potable water systems provide safe drinking water, which is central to individual and community life. Drinking water is sourced from the environment, treated to satisfy public health standards, stored, and distributed to end users. Potable water systems can also be used for purposes other than just drinking water, such as firefighting, industrial use, and irrigation.

Potable water systems consist of four general infrastructure subcategories:

1. **Supply.** Potable water systems are sourced from groundwater, surface water, saltwater, and harvesting of rainwater. Hazard events may reduce, cut off, or contaminate the source, and resiliency concepts include the ability to utilize alternate sources or share sources (supply) with adjacent water utilities. Stressed water supplies may have reduced availability due to increased demand and hazard events such as drought, precipitation, and wind events (such as reversed flow in rivers).
2. **Treatment.** Facilities to treat source water to meet potable water standards set by the U.S. Environmental Protection Agency (EPA) typically provide redundancy in unit processes such as screening, filtration, chemical treatment, and disinfection. Unit redundancy allows one or more-unit processes to be taken out of service for repair after a hazard event and maintain treatment to meet permit compliance.
3. **Transmission.** Conveyance infrastructure includes intake structures, pipelines, and culverts to move source water to treatment facilities. They also include movement of bulk treated water between treatment sources and pressure zones to areas of distribution. Redundancy in transmission lines and interconnections with isolation capabilities can provide alternate routes to transfer flow.
4. **Distribution.** Delivery systems, such as piping networks that deliver water to service areas and end users, can incorporate parallel or looped systems so that segments can be isolated while repairing damage and maintaining service to areas outside the isolated segment. This involves strategic location of isolation equipment and interconnections.

Pumping and storage systems are also part of supply, treatment, transmission, and distribution systems. Pumping systems convey water where gravity flow is not feasible, such as to higher elevations or over long distances, and provide adequate pressure for intended uses. Redundancy (N+1) is typically provided in mechanical systems that convey water to allow one or more units to be out of service for repair and maintain pumping capacity. Because repair or major maintenance may take several months for larger equipment, increased resilience is provided by implementing an N+1+1 configuration. In this case, a unit can be out for repair or maintenance, and the pumping system still has a standby unit available for service if a duty unit fails or is damaged by a hazard event. Unit redundancy is useful for flood control or pump outage but is less effective for extensive damage to a facility due to flood, wildfire, or an earthquake. However, having redundant methods for moving water improves water system resilience, even if an individual facility is inoperable.

Storage systems include vessels such as reservoirs or tanks that provide a buffer or manage flow to account for differences between rate of supply and rate of use of water. Multiple storage units, in different geographic locations if possible, can improve system operability so that a damaged storage unit can be taken out of service for repair and another storage system can provide baseline services.

Loss of service to one or more of these four general infrastructure subcategories may impact the associated potable water system depending on a given system's robustness, redundancy, and rapidity of recovery. Process unit redundancy allows one or more-unit processes to be taken out of service for repair after a hazard event and maintain treatment to meet permit compliance. However, unit redundancy may not help in cases with extensive damage, such as floods inundating a treatment plant or an earthquake impacting many components within the treatment system.

Much of U.S. potable water infrastructure is aging and in need of upgrades to maintain function through and rapidly recover from a hazard event. A number of service authorities that operate and maintain these assets have instituted programs to extend asset life and raise the level of the system's robustness, redundancy, and rapidity of recovery. Short service interruptions in hours or days are inconvenient, whereas longer disruptions can be detrimental to the populations served.

The ability to rapidly restore potable water service is a critical aspect of system resilience and sustainability. Improving resiliency across a potable water system as well as its transfer capabilities (i.e., transferring water treated in one community or region to another community or region whose potable water system is impacted by hazard events) allows water systems to provide service to more areas. Demand-side resilience concepts such as rationing may also be employed. Pipe networks that are designed to accommodate damage with the ability to continue providing water services or limit outage times are needed to support community recovery (Davis 2018).

To increase the resilience of potable water systems, mechanisms are needed to better predict availability, reliability, and allocation of potable water for use. These mechanisms include system modeling and use of real-time monitoring devices in strategic locations to provide feedback regarding status and inform decisions on how to best manage the system before, during, and after a hazard event.

3.1.2 Wastewater Systems

Apart from a small number of private facilities (at industrial plants, etc.), wastewater in the U.S. is treated primarily by publicly owned treatment works (DHS and EPA 2015). Wastewater systems gather domestic and industrial liquid waste products and convey them to treatment plants through collection and conveyance systems and pump stations. After separation of solids, biological processing, and disinfection, treated wastewater may be discharged as effluent into a receiving body of water, reclaimed for groundwater recharge, or reused for irrigation or other purposes. Some utilities have separate collection systems for wastewater and stormwater; other utilities have collection systems that combine collected wastewater and stormwater in the same pipelines. These systems, which are under stress from more extreme hazard events and increasing urban development, pose a growing threat to wastewater system resilience. Pipeline system failure can discharge raw sewage into basements, onto city streets, or into receiving waters, resulting in public health issues and environmental contamination.

Standard wastewater systems are comprised of four general subcategories of infrastructure:

1. **Collection.** Collection systems capture sewage from drains and buildings that connect to a conveyance system, or on-site disposal systems that collect sewage from a local area.
2. **Conveyance.** The system of gravity and pressurized pipes that convey sewage from the collection area to the treatment facility can become damaged during a hazard event. Conveyance systems and interconnections with isolation capabilities allow the transfer of flow to alternate routes.
3. **Treatment.** Facilities that treat sewage to meet regulated discharge or end use standards consist of screening, grit removal, gravity separation, biological and/or chemical treatment, and disinfection. These processes typically have unit redundancy to allow process units to be taken out of service for repair and maintain treatment to meet permit compliance.
4. **Discharge.** Discharging of treated water to a receiving body of water, recharge groundwater, or for reuse can be impacted by a hazard event. Provisions to pump treated water to higher discharge elevations with installed pumps or portable pumps with a redundant power source improves operating capabilities during hazard events.

Pumping systems are part of collection, conveyance, treatment, and discharge systems. They convey sewage where gravity flow is not feasible and provide adequate scouring velocities to keep solids in suspension along the route.

Disruption of a wastewater system can cause flooding, economic impacts, and severe public health and environmental impacts. Publicly owned wastewater treatment works in the

United States collectively provide wastewater service and treatment to more than 227 million people and are generally designed to treat domestic sewage (DHS and EPA 2015).

As with potable water systems, much of U.S. wastewater infrastructure is aging and needs to be upgraded. Wastewater system authorities perform condition assessments and implement capital improvement programs to extend asset life and prioritize upgrades of critical assets with the highest risk of failure and consequences.

Redundancy in collection systems and the ability to isolate damaged infrastructure for repair helps maintain service for the remaining collection systems. However, unit redundancy may not help in cases with extensive damage, such as floods inundating a treatment plant or an earthquake impacting many components within the treatment system.

3.1.3 Stormwater Systems

Stormwater systems collect, store, and convey rain and snow runoff from land and impervious surfaces to minimize flooding and mitigate impacts on water quality and catchment areas. Conventional stormwater systems include grading and sloping of runoff areas to a collection point that can accommodate the flow from a hazard event. If management of runoff by gravity alone is not possible, then use of site runoff pump stations are typically used to convey flow away from a collection area to a discharge location that can handle the flow from hazard events.

Managing increases in stormwater volumes and peak flows, due to increase in impervious surfaces or precipitation, may require development activities. Reviews and upgrades of existing systems should address stormwater quality, pollution, and volume control consistent with regulatory guidelines. Designs may provide for or augment existing systems to meet future capacity for anticipated changes or future stormwater control requirements.

Green infrastructure is also used for stormwater management and comprises "the range of measures that use plant or soil systems, permeable pavement or other permeable surfaces or substrates, stormwater harvest and reuse, or landscaping to store, infiltrate, or evapo-transpirate stormwater and reduce flows to sewer systems or to the surface waters" as defined by Section 502 of the Clean Water Act (EPA 2020). There is an increased interest in green infrastructure to provide sustainable, low-impact stormwater management solutions that incorporate natural vegetation and systems to filter pollutants out of water and reduce flooding.

3.1.4 Dams and Levees

Dams and levees are major components of potable water, wastewater, and stormwater systems. Dams serve many different functions, including flood control, water supply, irrigation, recreation, and energy supply through hydropower. There are many different types of dams, although the two most common types of dams are embankment dams and concrete dams. Embankment dams are generally earthfill, rockfill, or a combination of both. Three of the most common types of concrete dams are gravity, buttress, and arch dams. All dams, regardless of the type, provide some method for retaining water and passing water from the reservoir to the downstream side of the dam. This is typically accomplished through outlet works, one or more spillways, or allowing water to flow overtop the dam. Various types of spillways include concrete chutes, gated structures, a riser structure with a pipe, or a vegetated earth or rockcut spillway typically located at either abutment of the dam. There are over 90,000 dams in the United States which have an average age of over 50 yr (ASCE 2021a). These dams vary greatly in size and hazard levels, ranging from high hazard structures, which would likely cause loss of human life if they were to fail, to low hazard structures, where failure or mis-operation would result in no probable loss of human life and low economic and environmental losses.

Levees are embankments or walls made from earth or concrete primarily intended to contain or divert water and reduce flood hazard (ASCE 2021b). A small percentage of levees are also used in potable water and wastewater systems for various aspects of water flow control. The U.S. contains an estimated 100,000 miles of levees, totaling an estimated $1.3 trillion in property, protecting homes, businesses, colleges and universities, and farmlands from flooding, across every state and the District of Columbia (ASCE 2021b). The average age of levees in the U.S. is more than 50 yr and a large number are approaching 100 yr. In addition to the deteriorating structural integrity of existing levees, many of the older levees were not designed to withstand the severity of present-day hazard events due to climate change (ASCE 2021b).

Many dams and levees provide a life sustaining resource by directing flow and containing rising levels in bodies of water that would otherwise inundate low-lying areas during flooding hazard events. Dams and levees in the U.S. vary in size, from hydroelectric dams or coastal levees that cover entire regions to privately owned systems that protect individual property (DHS 2015). Dams and levees also provide storage for water supplies (raw and treated) and containment of wastewater (raw and treated). With rising sea levels and aging infrastructure and given that over half of the U.S. population lives within 50 mi (80 km) of coastline (ASCE 2021b), dam and levee resilience is critical for the wellbeing of many U.S. communities. Dam and levee performance criteria currently focus on minimizing risk and preventing a catastrophic release of water. A reservoir critical to system operations may remove all ability to provide water supply after a major flood or earthquake hazard strike.

3.2 Literature Review and Data Collection

3.2.1 Regulatory Environment

U.S. water infrastructure is regulated by multiple governing authorities, all of whom share in the mission to protect public health, the environment, and security and resilience activities. Water sector regulatory authorities include EPA, state agencies, and other federal agencies such as the U.S. Department of Agriculture (USDA), Federal Energy Regulatory Commission (FERC), and USACE.

EPA establishes requirements for drinking water quality under authority of the Safe Drinking Water Act (SDWA) in 1974 (CFR 1974) and for wastewater effluent quality under authority of the Federal Water Pollution Control Act or Clean Water Act (CWA) (CFR 1972). EPA's National Combined Sewer Overflow (CSO) Policy [EPA 1994] coordinates planning, selection, design, and implementation of CSO management practices and controls to meet requirements of the CWA. A state agency that meets certain criteria may be granted primacy to oversee and implement these requirements.

Buildings and structures for water infrastructure are designed according to the criteria for buildings and structures in Chapter 2 and for electric power systems in Chapter 4.

3.2.1.1 Water and Wastewater

Water and wastewater systems abide by federal regulations such as established by the EPA, USDA, and USACE. States can be consistent with or more stringent than federal regulations for water and wastewater systems. Water and wastewater planning and design requirements are generally controlled by states, regional regulatory agencies, and local governments. States typically require that water and wastewater system owners prepare comprehensive plans on a regular basis to assess future system needs (e.g., capacity and level of treatment) and how those needs will be met. The elements of those comprehensive plans are defined by the state, typically by state departments of environment that meet or exceed federal agency regulations. Often, these plans include requirements to identify the hazards that the system could produce or be subjected to and how the utility will address those hazards. These comprehensive plans are typically quite general and reference national design standards such as ANSI, American Water Works Association (AWWA), ASCE, and NFIP for detailed requirements.

3.2.1.2 Stormwater

Stormwater quality, pollution, and volume control is regulated by the federal government as well as individual states and is an important aspect of development and redevelopment planning. Urban and suburban population growth and development coupled with more extreme hazard events has put mounting pressure on stormwater infrastructure capacity. To address this, ASCE will begin in 2021 providing a national infrastructure report card on

U.S. stormwater systems to point out weaknesses and areas for improvement in the systems (they currently already provide report cards for bridges, dams, and levees, among other infrastructure) (ASCE 2019).

Stormwater management infrastructure was developed to move a vast volume of water from a site as quickly as possible through a network of surface runoff collection, storage, and pumping systems. Urban and suburban runoff impacts water quality, erodes channels, and reduces groundwater recharge. While intense flows from large rainstorms erode stream channels, degrade aquatic conditions, and may cause flooding, it is the more frequent smaller to medium-sized storms (i.e., "nuisance flooding") that convey the highest pollutant loads over time. Stormwater quantity (i.e., peak flow) for nuisance flood control is generally regulated by local city, county, and drainage district authorities. Local ordinances often require new land development and redevelopment activities to maintain peak flow rates from a site to be equal to or less than a defined predevelopment condition. To meet these laws, peak runoff flow rates from a design storm, or series of design storms, are specified.

Stormwater quality, pollution, and volume control regulations generally result from the CWA of 1972 and the Clean Water Act Amendments of 1987. Although the federal regulations provide the basis for stormwater pollution control, there are differences stipulated by each state. Some states are more aggressive in stormwater pollution control requirements, and others only meet the minimum federal criteria.

Stormwater regulations in many states mandate decreased runoff volume from storm events to reduce pollutant loads and restore a more natural hydrologic regime to urban watersheds. Numerous states also require land development projects—both new and redevelopment—to incorporate Low Impact Development (LID) and green infrastructure (GI) practices. In addition, federal properties across the nation need to comply with similar requirements.

3.2.1.3 Dams and Levees

Dams in the U.S. are owned, operated, and regulated by many different entities at all levels of government. With close to two-thirds of all U.S. dams privately owned, most dams rely on state dam safety programs for permitting, inspection, and enforcement (ASCE 2021a, 2021b). State governments have regulatory responsibility for 70% of the approximately 90,000 dams within the National Inventory of Dams (USACE 2020). Each state, with the exception of Alabama, has its own dam safety program that establishes and enforces regulations for dam safety. The state's dam safety programs are established and governed by a set of statutes passed by that state's legislature and a set of regulations promulgated by the department that administers the program. These regulations include specific definitions and classifications related to dams, rules for dam permitting and approval processes, inspection requirements, emergency measures for incidents or owner's non-compliance, and the review and approval of emergency action plans (ASDSO 2020).

Approximately 14% of dams in the U.S. are owned or regulated by federal agencies. FEMA does not own or regulate dams itself but administers the National Dam Safety Program, which coordinates all federal dam safety programs and assists states in improving their dam safety regulatory programs. Federal agencies involved with dam safety, as owners or regulators, include the following (DHS and EPA 2015):

- U.S. Department of Agriculture
    - Natural Resources Conservation Service (NRCS)
    - Agriculture Research Service
- Department of Defense
    - USACE
        - Engineer Research and Development Center
        - Hydrologic Engineering Center (HEC)
- Department of the Interior
    - Bureau of Indian Affairs
    - Bureau of Land Management
    - U.S. Bureau of Reclamation (USBR)
    - U.S. Fish and Wildlife Service
    - National Park Service
    - Office of Surface Mining
- Federal Energy Regulatory Commission (FERC)
- International Boundary and Water Commission (U.S. Section)
- Mine Safety and Health Administration
- Nuclear Regulatory Commission (NRC)
- Tennessee Valley Authority

The USACE regulates work and structures that are located in, under, or over navigable waters of the United States under Section 10 of the Rivers and Harbors Act of 1899. This has been expanded to include tributaries to navigable waters, wetlands adjacent to those waters, and isolated wetlands that have a demonstrated interstate commerce connection. USACE regulates the discharge of dredged or fill materials into waters of the United States under Section 404 of the Clean Water Act and regulates the transportation of dredged materials for the purpose of disposal in the ocean under Section 103 of the Marine Protection, Research, and Sanctuaries Act. Agencies such as the NRCS and USBR have published many design manuals on the various components of dam engineering that are used for the dams that fall under their respective jurisdictions. Some of these design manuals have also been adopted by many state dam safety programs as state of practice standards to be followed.

Dams that are part of hydroelectric plants are regulated by the Federal Energy Regulatory Commission (FERC), which is an independent agency within the U.S. Department of Energy (DOE). FERC was created through the Department of Energy Organization Act on October 1, 1977 and derives its authority from the 1920 Federal Power Act (FPA), which is the primary statute governing the regulation of non-federal hydropower projects throughout the United States. Section 10(c) of the FPA forms the basis of FERC's mission related to dam safety, and states that the licensee (i.e., Owner) of a hydropower dam "shall conform to such rules and regulations as FERC may from time to time prescribe for protection of life, health, and property." At times the FERC regulations overlap with other regulations such as state-mandated dam safety regulations. In the event that there are different regulations regarding a specific design criterion, the dam should be designed to the more conservative of the two design criteria to satisfy both sets of criteria.

FERC authorizes construction and operation of hydroelectric projects through its dam safety program and outlines dam safety requirements and guidelines in FERC regulations (FERC 2020), which requires that the water-retaining features of hydropower projects be designed, constructed, operated, and maintained using current engineering standards that meet federal guidelines for dam safety. Part 12 applies not only to licensed projects but also to existing unlicensed projects that FERC has determined require licensing, as well as to certain exempted projects if FERC conditions the exemption on compliance with any particular provision of Part 12.

Levees may protect an area from flooding from bodies of water by acting as a barrier, or they may support water conveyance. Currently, there is no national policy related to the safety and regulation of levees. The responsibility for levee safety is often assigned to various agencies and different levels of government in an uncoordinated and incomplete manner. Federal and state agencies have varying policies and criteria concerning many aspects of levee design, construction, operation and maintenance. However, there are no national policies, standards, or best practices that are comprehensive to the issues of levee safety that can be adopted broadly by governments at all levels. Surveys by the Association of State Dam Safety Officials (ASDSO) and the Association of State Floodplain Managers (ASFPM) found that only 10 states keep any listing of levees within their borders, and only 23 states have an agency with some responsibility for levee safety (USACE 2021).

The USACE has a Levee Safety Program that works with local levee sponsors and stakeholders to make sure the levees within the program provide their intended benefits. However, only a small portion of levees within the U.S. are registered in the USACE Levee

Safety Program. Figure 3-1 depicts the approximate mileage of levees maintained by the USACE Levee Safety Program (USACE 2021).

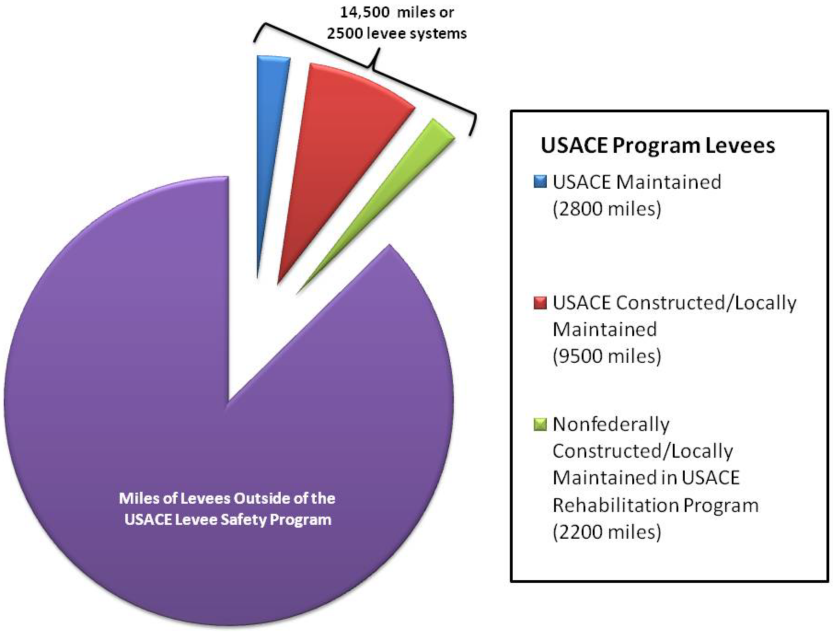


Figure 3-1: Miles of Levees Maintained by the USACE Levee Safety Program

3.2.2 National Codes

CFR Title 40: *Protection of Environment* deals with EPA's mission of protecting human health and the environment. Water and wastewater infrastructure systems are governed by this and other national codes in conjunction with the type of infrastructure. Title 40 of the CFR regulates a range of categories with Subchapter D – Water Programs (Parts 100 to 149) encompassing standards and regulations of the CWA and SDWA.

National Fire Protection Association Standard 820 *Standard for Fire Protection in Wastewater Treatment and Collection Facilities* (NFPA 2020) provides requirements for protection against fire and explosion hazards specific to wastewater treatment facilities and their associated collection systems. This includes combustible and toxic substances contained in or released from sewage or chemicals used in the treatment process.

The related buildings and structures such as treatment plants and pump stations are regulated consistent with codes found in Chapter 2. For example, water/sewer separation requirements are contained in the IBC (2021). The related electric power infrastructure is regulated by codes found in Chapter 4. Related transportation infrastructure is regulated by codes found in Chapter 5. National standards (see Section 3.2.3) for potable water and wastewater infrastructure systems are adopted by various levels of government and regulatory agencies.

3.2.3 National Standards

There are two major organizations that develop design standards relevant to natural hazard impacts on water infrastructure:

- American Concrete Institute (ACI) develops standards addressing concrete treatment process tanks, such as ACI 350-06: *Code Requirements for Environmental Engineering Concrete Structures* (ACI 2006).
- American Water Works Association (AWWA) develops standards addressing design of water storage tanks, seismic design of water storage tanks, risk and resilience management, and performance of water and wastewater systems when subjected to natural and human-caused hazards; AWWA also develops standards addressing pipeline design and water quality, but none of these standards address natural hazards:
    - AWWA D100 (2011a): Welded Carbon Steel Tanks for Water Storage
    - AWWA D110 (2013): Wire- and Strand-Wound, Circular-Prestressed Concrete Water Tanks
    - AWWA D115 (2020): Circular-Prestressed Concrete Water Tanks with Circumferential Tendons
    - AWWA J100 (2010): Risk and Resilience Management of Water and Wastewater Systems

Design of new aboveground structures (treatment plant office and laboratory buildings, pump stations, process tanks, water storage tanks and reservoirs, etc.) is typically governed by local building codes or design standards (see related discussion provided in Chapter 2), with the exception of large-scale federal water infrastructure investments, such as the USACE hurricane protection system in New Orleans, Louisiana (U.S. Army 2015). State and local governments adopt model building codes, such as the IBC (2021), which rely heavily on standards such as ASCE 7 (2021c): *Minimum Design Loads for Buildings and Other Structures*. In many cases, a state will adopt these model codes; in some cases, local jurisdictions adopt modified versions to suit their specific needs. Chapter 2 provides detailed discussion of building standards and codes.

Water infrastructure should have redundant power sources to protect against loss of use if the primary power source is lost. This can be accommodated through use of two separate utility power supplies or through one utility power supply coupled with on-site power generation.

Water infrastructure design loads for buildings and similar structures are prescribed by ASCE 7. This standard uses the concept of Risk Categories to increase design loads for more important structures. Typical buildings are designed for Risk Category II. Water and wastewater treatment facilities are assigned to Risk Category III, which includes facilities that may disrupt civilian life or potentially cause public health risks. Water storage facilities and pump stations required to maintain water pressure for fire suppression systems are assigned to the highest category, Risk Category IV.

Although building codes include design standards for Risk Category III or IV structures, major water infrastructure systems remain vulnerable to damage from a hazard event of this magnitude. The code, for example, does not provide design levels for permanent ground movements associated with lateral spreading, landslides, fault rupture, or erosion in flooding. These types of hazards have a significant impact on buried conduits within the water and wastewater systems. The resiliency of the water infrastructure system is dependent on the interconnectivity between the building, electrical, and transportation sectors. The ability to continue operation during or rapidly restore functionality following a hazard event is dependent on a given system's resourcefulness, rapidity, and redundancy.

Large-scale federal investments use their own guidance for design, which varies depending on the agency (e.g., USACE and DoD each has its own construction and engineering design standards). Otherwise, design standards are often developed according to an ANSI-based consensus process and voluntarily adopted by various organizations. In some cases, design standards are referenced by the building code. In other cases, they can be used by utilities on a project-by-project basis.

3.2.4 Codes, Standards, and Guidelines for Natural Hazards

National standards and guidelines for water infrastructure for general hazard events are listed in Table 3-1, and primary hazard are listed in Table 3-2 and discussed below. Refer to Table 2-1 for facilities and other structures that are part of water systems.

Table 3-1: Codes, Standards, and Guidelines for Natural Hazards

General Hazard

- AWWA J100-10 Standard for Risk and Resilience Management of Water and Wastewater Systems (2010)
- ASME B31.3-2020 Code for Pressure Piping (2020)
- AWWA G440-11, Emergency Preparedness Practices (2011b)
- AWWA M19, Emergency Planning for Water Utilities (2001)
- Business Continuity Planning for Water Utilities: Guidance Document (WRF, 2013)
- Emergency Planning, Response, and Recovery (WEF, 2013)
- Critical Assessment of Lifeline System Performance: Understanding Societal Needs in Disaster Recovery (NIST 2016a)

Table 3-2: Codes, Standards, and Guidelines by Primary Hazard

Flood

- EPA Flood Resilience Checklist (EPA 2014a)
- FEMA P-94: Selecting and Accommodating Inflow Design Floods for Dams (2013a)
- FEMA 543: Design Guide for Improving Critical Facility Safety from Flooding and High Winds (2007)
- FERC Engineering Guidelines, Chapter 2: Selecting and Accommodating Inflow Design Floods for Dams (2015)
- NFIP requirements (FEMA 2005a)

Seismic

- ISO 16134:2020 Earthquake and Subsidence Resistant Design of Ductile Iron Pipes (ISO 2020)
- ASME B31.3-2020 Code for Pressure Piping (ASME 2020)
- ASME B31E-2008 Standard for the Seismic Design and Retrofit of Above-Ground Piping Systems (ASME 2008)
- ASTM E2026−16a Standard Guide for Seismic Risk Assessment of Buildings (ASTM 2016)
- AWWA D103-09 Standard for Factory-Coated Bolted Carbon Steel Tanks for Water Storage (AWWA 2009)
- AWWA D100-11 Standard for Welded Carbon Steel Tanks for Water Storage (AWWA 2011a)
- ALA Guidelines for the Design of Buried Steel Pipe (ALA, 2001a)
- ALA Seismic Design and Retrofit of Piping Systems (ALA, 2002)
- ALA Seismic Fragility Formulations for Water Systems (ALA, 2001b)
- ALA Seismic Guidelines for Water Pipelines (ALA, 2005b)
- ASCE Technical Council on Lifeline Earthquake Engineering (TCLEE) Monograph 15, Guidelines for the Seismic Evaluation and Upgrade of Water Transmission Facilities (ASCE, 1999)
- FERC Engineering Guidelines, Chapter 3: Gravity Dams (2016)
- FERC Engineering Guidelines Chapter 4, Embankment Dams (2006)
- NIST GCR 97-730, Reliability and Restoration of Water Supply Systems for Fire Suppression and Drinking Following Earthquakes (NIST, 1997)

Wind

- ASME B31.3-2020 Code for Pressure Piping

3.2.4.1 Flood

EPA has made available *Flood Resilience: A Basic Guide for Water and Wastewater Utilities* (EPA 2014b). For the water sector, “flood resilience” refers to the ability of water and wastewater utilities to withstand a flooding event, minimize damage, and rapidly recover from disruptions to service. Utilities can build resilience by implementing mitigation measures. A mitigation measure can be an emergency planning activity, equipment modification/upgrade, or new capital investment/construction project. Examples of mitigation measures include:

- Emergency response plan
- Barriers around key assets

- Elevated electrical equipment
- Emergency generators
- Bolted down chemical tanks

Implementing these mitigation measures requires financial investment by the utility; however, flood mitigation could prevent costly damage and enable the utility to provide more reliable service to customers during a disaster. To help pay for flood mitigation measures, a utility can also apply for federal disaster mitigation funds.

AWWA G440-11 (2011b) is a management standard providing minimum requirements to establish and maintain an acceptable level of emergency preparedness based on the identified and perceived risks facing utilities in the water sector.

FEMA 543, *Design Guide for Improving Critical Facility Safety from Flooding and High Winds: Providing Protection to People and Buildings* (FEMA 2007) concentrates on critical facilities (hospitals, schools, fire and police stations, and emergency operation centers). It is based on the performance of critical facilities during Hurricane Katrina and makes recommendations on the Occupational Safety and Health Administration (OSHA) Flood Preparedness and Response website. It includes a Resources page with Response/Recovery QuickCards™ and Fact Sheets that provide details about hazards present in flooded areas. The information below provides a brief summary of some of the most common secondary hazards associated with floods, such as electrical hazards, mold, and fire, as well as precautions that can be taken to protect against secondary hazards, Tree and debris removal

The following documents provide information concerning the flood resistance provisions of the 2018, 2015, 2012, and 2009 International Codes® (ICC codes): the referenced standard ASCE 24 (2015), *Flood Resistant Design and Construction*, and FEMA NFIP requirements.

- For Flood Design Class 4 buildings, the minimum lowest floor elevation (or floodproofing level of protection) is required to be the higher of the Base Flood Elevation plus freeboard specified in Chapters 2, 4, and 6, the Design Flood Elevation, or the 500-yr flood elevation.
- Well-established design standards, such as the 10 State Standards developed by The Great Lakes-Upper Mississippi River Board developed in 1951 for the states of Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, New York, Ohio, Pennsylvania, and Wisconsin, Manual TR-16, *Guides for the Design of Wastewater Treatment Works* developed in 1998 by the New England Interstate Water Pollution Control Commission, have updated these respective standards multiple times and adopted them as widely accepted guidelines for wastewater facilities (Great Lakes 2014). These standards provide guidance on design protection against flood events, including the 4% and 1% annual chance of occurrence flood levels, impacts on floodplains and floodways, and compliance with applicable regulations regarding construction in flood-prone areas.

3.2.4.2 Seismic

Water infrastructure is composed of many elements that fall under associated primary hazard standards and guidelines, such as water support system buildings addressed under Chapter 2, electric power distribution infrastructure addressed under Chapter 4, and roadway related systems infrastructure addressed under Chapter 5.

Primary hazard standards and guidelines specific to water infrastructure focus on water storage and conveyance structures and interconnecting piping and equipment that include:

- Seismic restraint of tanks, piping, equipment, and appurtenances to control movement and sway in response to a seismic event.
- Flexible connections for piping, especially at construction joints and connection to equipment to account for seismic movement. This includes pipe fittings and connections to structures and equipment. If structures are designed to move, then piping crossing construction joints also needs support systems to allow movement along with the structure.
- Adequate freeboard in open tanks and conveyance structures to account for seismic oscillations of liquid. Compartmentalized tank baffles are to resist forces from oscillating liquid in response to a seismic event.
- American Lifeline Alliance (ALA) provides guidelines for design integrity of steel buried pipe for a range of loads, seismic design, and retrofit of piping systems in essential facilities, including new or existing aboveground piping systems, and detailed procedures for water transmission systems to assess the probability of damage from earthquake hazards to various components of the system.
- International Organization for Standardization (ISO) 16134 (2020) includes design standards for earthquake and subsidence-resistant ductile iron pipes and provides means of determining and checking resistance of buried pipelines applicable to buried ductile iron pipes and fittings with joints with expansion/contraction and deflection capabilities.
- AWWA J100 (2010) notes that most natural hazards do not result in total destruction of the assets they encounter. Rather, partial damage is incurred, so repair and restoration are more frequent than replacement. For example, experience has shown that piping systems are quite robust and will survive a seismic event, in most cases. The piping systems used in chemical plants and refineries are generally well-supported, welded systems constructed of ductile metals. A seismic event may cause large deflections, loss of hangers and snubbers, etc., but the basic piping, valves, and pumps are not severely damaged. However, underground pipe may be severely damaged. It is assumed that large, heavy-walled vessels will be reusable. The cost is primarily the repair and replacement of the plant equipment. To maintain comparability, general damage factors are provided that can be used for several hazards.

- AWWA J100 (2020) also states that buildings will generally suffer more damage due to a seismic event than equipment and piping. Frame structures are normally flexible and will deform significantly. This causes damage to masonry, veneer, internal walls, etc. Normally, the damage can be repaired, but the cost is a higher percentage of the total replacement cost. Newer buildings, presumably built to modern standards, should fare better than older buildings. Structures with seismic upgrades should be considered recent for costing purposes. Buildings not designed to code and portable buildings are expected to incur the greatest damage.

3.2.4.3 Wind

Primary hazard standards and guidelines specific to water infrastructure focus on water storage and conveyance structures and interconnecting piping and equipment that include:

- Wind protection of aboveground storage tanks to protect against flying debris that may include screen walls and/or improved tank construction.
- Securing exposed liquid storage tanks, conveyance structures, piping, equipment, and appurtenances to resist high wind events. Empty tanks and support systems are to resist wind loads. In advance of a high wind event, exposed tanks that are empty can be filled with water or intended liquid to provide better resistance to high wind loads.
- Providing adequate freeboard in open tanks and conveyance structures to account for wind-driven oscillations of liquid. Compartmentalized tank baffles resist wind-driven water forces and empty tank wind loads on exposed wall surface areas.
- Wind protection of electric power substations with screen walls to provide a barrier from flying debris as well as hurricane shutters and doors to protect electric power buildings from flying debris and high wind events.

AWWA J100 (2010) notes that wind loads seldom exceed the design basis in the Uniform Building Code (UBC), except for hurricanes and tornadoes, and that most, if not all, critical infrastructure up to code, do not suffer damage unless there is a hurricane or strong wind that exceeds the design basis for that region. AWWA J100 states that open space-frame type structures, like piping and slab-mounted equipment, pipe racks, beam and column frames, freestanding pressure vessels, and machinery, will be affected by the high-velocity winds, but the pressure differential does not typically cause damage. Closed structures are much more likely to be demolished. However, blast-resistant structures, such as control rooms for refineries, underground storage for water treatment facilities, bunkers used for storing explosives and military equipment, etc., have the capability to survive tornadoes.

3.2.5 Best Practices

3.2.5.1 Water and Wastewater Best Practices

Lessons learned from hazard events are typically incorporated into infrastructure best practices, which often drive updates to codes and standards. Best practices are implemented to help protect critical water infrastructure from future similar hazard events and restore service more rapidly. Water infrastructure best practices include:

Planning

- Emergency response plans with periodic updates and drills to confirm essential staff awareness of plan and implementation.
- Business continuity planning and periodic updates and drills to confirm essential staff awareness of power reserves, adequate and accessible essential supplies and replacement equipment, emergency center operation coordination, and disaster preparedness checklists.

Design

- Robust design of water facilities and networks to withstand hazard load effects is a primary resilience strategy for infrastructure. This includes increasing design hazard levels appropriate for critical infrastructure, such as Risk Category III for structures.
- Materials should be compatible with exposure to fluids, gases, and processed matter; materials should be corrosion-resistant and resist microbial and erosion sources.
- Surge and storage capacity with self-regulation to minimize upsets and interaction between various process units.
- Avoid single points of failure by including distributed control systems, check valves to prevent reverse flow, material compatibility of all interconnected fluids, and looped systems to allow isolation of a break and continued service to remainder of system.
- System equipment should be able to withstand hazard events and operating environments such as freezing temperatures, operating conditions such as equipment cycling, and characteristics of matter being processed, conveyed, or pumped.
- Use electric hydraulic actuators with a self-contained hydraulic cylinder that can move an actuated valve in the event electric power is lost.
- Provide on-site redundant power supplies, such as a generator and fuel or other independent power source, to continue operation of critical pumping systems when utility power is lost.
    - Provide alternate power sources for sump pumps to keep subgrade facilities and tunnels dry and operational until electric power is restored.
    - Provide means to connect portable pumping systems to a wet well and discharge piping system in the event installed pumps are disabled.

Redundancy

- Water systems often plan for certain levels of redundancy to allow service to continue despite outages due to planned or unplanned events. This includes spatial redundancy to serve large areas and bypass damaged infrastructure or to reallocate water resources to impacted communities.

- Redundancy (N+1+1) for critical equipment with stocked spare units so that a standby unit is available for service if a duty unit fails to reduce the time needed to restore capacity.
- Stock adequate supplies and equipment at strategic locations to rapidly restore the functionality of distributed water systems during and following a hazard event.

Temporary Measures

- Standby power to restore functionality to critical equipment such as pumps, process air blowers, disinfection; on-site power generation with adequate fuel storage to span utility power outage following a hazard event; portable generators with readily available connections to critical equipment.
- Emergency pumping capability is needed unless system overflow prevention is provided by adequate storage capacity. Emergency pumping capability can be accomplished by connecting to at least two independent utility substations, by providing portable or in-place equipment for electrical or mechanical energy, or by providing portable pumping equipment. Such emergency standby systems should have sufficient capacity to start up and maintain the total rated running capacity of the station. Regardless of the type of emergency standby system provided, rapid connection capabilities and appropriate valves should be provided outside the dry well and wet well. Ten states have standards that provide guidance for emergency pumping.

Operations

- Remote operational capabilities improve responsiveness of decision making and implementation; where remote capabilities are not possible (for cybersecurity or technical reasons), provisions for access and staffing of remote facilities is needed to manage and respond to hazard events.
- Instrumentation that provides equipment protection, monitoring, and control.
- Capability to operate critical equipment and systems in manual to reduce impact of environmental hazards, equipment failure, pipe breaks, and loss of monitoring or control systems.
- Safe accessibility for employees to service, repair, and replace equipment, especially if equipment is needed during or following a hazard event to maintain or restore capacity.

Flood, Wind, and Seismic Hazards

EPA Flood Resilience Checklist (EPA 2014a) helps existing water and wastewater utilities become more resilient through the following concepts:

- Understand the threat.
- Identify vulnerable assets and determine consequences that may include loss of service.
- Identify and evaluate mitigation measures to protect assets, reduce risk and consequence, and quickly restore service.

- Develop a plan to implement mitigation measures.

Flooding hazards may be due to an adjacent water body, surface runoff, or process failure within the system. Relocating water infrastructure out of FEMA-mapped Flood Zones reduces vulnerability and risk; however, this is not feasible in many cases, and other mitigation strategies can be implemented. If a critical facility is located in a flood hazard area, it should be designed to a higher flood standard for critical infrastructure (e.g., 500-yr MRI flood). This can include relocation, elevation, installing barrier protection, or implementing submersible systems (Figure 3-2 through Figure 3-6). Where possible, remote operation capabilities can improve responsiveness for decision making and implementation. Otherwise, provisions for access and staffing of remote facilities are needed to manage and respond to a hazard event.

Flood performance can be improved by elevating critical equipment above the flood level or selecting equipment that continue to function when submerged, Examples include specifying submersible rated motors and ancillary equipment, power, and controls for dry pits and elevating pump motors and ancillary equipment above the design flood level for wet pits; locating electrical controls and panels above flood level if possible or else relocate electrical equipment above design flood levels. To reduce facility vulnerability to flood events: set or elevate entrances and electrical and mechanical equipment above flood levels where possible; where infrastructure cannot be relocated or elevated, provide flood walls or barriers; locate submarine doors between split drywell areas to isolate the extent of flood damage. To address potential facility flooding conditions due to pipe leak or breaks, use failsafe actuators for isolation valves, increase sump pump capacity, and provide pump room water level indicators.

Wind events can cause damage from flying debris or inadequate structural integrity to withstand a wind event. Wind performance can be improved by securing exposed components, providing wind barriers, and installing roofing, windows, and doors rated for design wind events.

Seismic events can cause damage from inadequate stiffness, ductility, or anchorage. Seismic performance can be improved by restraining or anchoring equipment and interconnected piping, conduit, and ductwork; using flexible connections at pipeline interfaces with structures and differential ground movements; designing systems to withstand damage or have ability to be rapidly repaired for all potential earthquake hazards (ground shaking, fault rupture, liquefaction, differential settlement, lateral spreading), and upgrading buildings and structures to current seismic code.

Figure 3-2: Example of Raising Vulnerable Infrastructure Above Floodplain Elevation

Figure 3-3: Hurricane Door Outside Double Door to Electric power Building / Tank Fill Guidelines

Figure 3-4: Barriers for Flood Protection Where Assets Cannot Be Raised

Figure 3-5: Flood Protection Barrier with Removable Gates Across Roadway

3.2.5.2 Figure 3-6: Raised Gate Access Above Conduit Flood Surcharge ElevationStormwater Best Practices

Best practices for stormwater systems focus on low impact development (LID) and green infrastructure (GI) which integrate multiple vegetated management features into a stormwater system. The goal is for the hydrology to closely mimic that which would exist for the site under natural land cover conditions. This type of development incorporates features such as grass swales, biofilters, rain gardens, green roofs, and porous pavement, to reduce impervious surfaces and buffer the drainage system from runoff.

LID and GI objectives typically consist of the following elements:

- Constructible – make use of readily available materials that can be successfully installed with techniques that are easily implementable by contractors.
- Durable – design systems to withstand common urban stresses including vandalism, heavy traffic, snow, and erosion; create systems with overflow drain and outlet redundancies to provide longevity; select materials with reasonable lifecycle expectations.
- Maintainable – develop protocols for inspection, cleaning, repair, and replacement; quantify maintenance of LID/GI elements; quantify anticipated maintenance costs and establish budgets to implement these protocols; use native or non-invasive species to reduce maintenance burden.
- Compatible – locate, size, and detail LID/GI systems to support community needs in addition to stormwater management; these needs may include Americans with

Disabilities Act accessibility, vehicular or pedestrian circulation, and accessibility for recreation, beautification, and community events.

- Replicable – catalogue performance results to set standards and baseline expectations for future iterations of LID/GI work, including testing and maintenance protocols.

Nonstructural best management practices (BMPs) focus on preserving open space, protecting natural systems, and incorporating existing landscape features such as wetlands and stream corridors into a site plan to manage stormwater at its source. Examples of BMPs include:

- High-efficiency street cleaning and catch basin cleaning.
- Reducing fertilizer use.
- Increasing urban tree cover and grass buffers.
- Stabilizing outfalls.
- Restoring floodplains.
- Restoring and stabilizing eroded streams.
- Watershed planning to maximize the environmental benefits of future development.
- Public education to reduce discharge of fertilizers, pet wastes, and other substances from private land.

Sustainable stormwater management captures water closer to the source, reducing flooding and water quality impacts and using rainwater and snowmelt as an asset to improve the environment. Many communities develop short- and long-term policies with the following goals:

- Achieve balanced land use decisions.
- Manage resources in a sustainable manner.
- Protect or restore water quality.
- Provide for flood and drought resilience.
- Build a regional framework for green infrastructure.

Municipalities evaluate the flooding and stormwater drainage issues identified by local citizens or observed by municipal staff to identify stormwater upgrade projects. The scale of these projects varies from simple pipe repairs and replacements to complex drainage improvement projects that may require culvert replacements under roads. Prioritizing these projects by the probability and consequence of drainage infrastructure failure and considering the effects of deferring maintenance or repair and replacement enables the most efficient allocation of available capital improvement funds.

3.2.5.3 Dam and Levee Best Practices

Improving the structural safety of existing dams/reservoirs extends the service life of infrastructure that is difficult or impossible to replace. Vulnerabilities and improvements can be determined with the following steps:

- Conduct dam assessments including deterministic and probabilistic seismic hazard analyses (DSHA and PSHA) to develop ground motions for a seismic structural analysis.
- Develop an Interim Operation Restriction Plan until further studies are completed on the seismic and hydrologic risks of a dam.
- Prepare a Remediation Options Report to present options and costs for remediating the seismic and hydrologic hazards. Remediation options included dam buttressing, dam notching, spillway modifications, and a new labyrinth spillway.
- Create an Operations and Maintenance Manual to describe the normal operation of the dam and appurtenances.
- Conduct a seismic structural analysis to select the remediation option to upgrade dams and spillways.
- Conduct a slope stability and seepage analysis of dam and levee earthen embankments.
- Conduct a watershed analysis including probable maximum flood (PMF) evaluations to help identify the spillway design flood (SDF) to be routed through a dam's spillway(s).
- Conduct a hydraulic analysis of spillway(s) to determine the dam's spillway capacity and freeboard.
- Conduct a dam breach analysis.
- Prepare and update Emergency Action Plans, including a new inundation map, tailoring the emergency guidance to a specific dam type and site aspects.

Comprehensive assessments can include the following elements:

- Dam safety management and risk assessment
    - Potential failure mode analysis
    - Estimation of dam failure consequences, including potential loss of life, and economic and environmental consequences
    - Geotechnical investigations and assessments
    - Flooding assessments, dam break analysis, and consequence assessment
    - Surveillance
    - Design of upgrades and mitigation embankment design
    - Structure design and modeling
    - Fish passage design
    - Mechanical and electrical design

- Constructability and construction risk
- Upgrade options development and options evaluation

Monitoring of existing dams and levees includes construction of piezometers, survey monuments, strong motion accelerographs, and an automated data acquisition system to measure and store collected data and transmit data to an operations center for analysis. Periodic visual inspections and record keeping are essential best practices.

3.3 Case Studies

3.3.1 Infrastructure Performance in Hazard Events

Flood *– 2012 Superstorm Sandy, NJ and NY*

Wastewater Treatment Plants (WWTP) are typically built next to bodies of water to allow return of large volumes of treated water. This also facilitates moving treated water primarily by gravity flows, thus reducing power needs and operating costs. The FEMA Mitigation Assessment Team report (2013b) reviewed the performance of three WWTP: Yonkers WWTP in Yonkers, NY; Passaic Valley WWTP, in Newark, NJ (one of the largest sewage treatment facilities in the nation); and Bay Park WWTP in East Rockaway, NY.

All three sites have utility tunnels and galleries beneath the facilities and due to their proximity to rivers and bays. Facility preparations were similar to those for Hurricane Irene and included plans for breaching, evacuation, and de-energizing plant systems as floodwater gradually rose. Preparation activities included staging emergency generators from other locations at the WWTP site, sandbagging, and installing barrier covers to protect air intakes, switchgear, and other critical systems.

All three WWTPs were in a Zone AE with a BFE between 7 and 9 ft (2.1 to 2.7 m). A 12-ft (3.6 m) storm surge, which exceeded the 100-yr flood elevation in many locations, traveled up the Hudson River and inundated both the Passaic Valley and Yonkers WWTP facilities. The storm surge rapidly inundated all three of the WWTP sites. The rapid rise prevented some of the planned actions, such as de-energizing plant systems at two of the WWTPs. The treatment plants had submerged power distribution systems, motors, pumps, blowers, and support systems. It took months to implement measures to make repairs, many of which were temporary, to recover treatment services.

EPA's *Adaptation Strategies Guide for Water Utilities* (EPA 2013) reported that Superstorm Sandy significantly challenged the operations of New York City's Department of Environmental Protection (NYC DEP), which provides drinking water, wastewater treatment, and stormwater management services to over 9 million people. NYC DEP was able to continue to provide drinking water services throughout the storm, but 10 of the 14 wastewater treatment plants and 42 out of 96 pumping stations were damaged or lost power, resulting in the release of untreated or partially treated wastewater into local waterways.

Since the storm event, many water and wastewater infrastructure systems were evaluated for opportunities to incorporate resilience and improve responsiveness for a more rapid return to service following a flood event. Improvements recommended by agencies such as New England Interstate Water Pollution Control Commission's *Preparing for Extreme Weather at Wastewater Utilities: Strategies and Tips* (NEIWPCC 2016) and EPA's *Flood Resilience: A Basic Guide for Water and Wastewater Utilities* (EPA 2021a) include:

- Erect flood barriers adjacent to water bodies to protect the water infrastructure against the 0.2% annual exceedance storm event.
- Relocate/raise electrical substations and motor control centers above the 0.2% annual exceedance storm event elevation.
- Locate on-site back-up power generation systems above the 0.2% annual exceedance event elevation.
- Use submersible equipment for flood events so that it may continue to operate.
- Raise access points to outfalls such as gate openings to prevent back-flooding from receiving waters.
- Secure and seal access points to surcharged conduits to withstand surcharging due to back-flooding from receiving waters.
- Increase site runoff pump station capacity to accommodate more severe rain intensity and duration events, as well as to provided redundancy and standby power.
- Expand storage capacity of chemicals, consumables, spare parts, and provisions for staff to span the expected duration of blocked access to site or inability to get material goods from suppliers. This could span 10 to 30 days, depending on how remote or vulnerable access is to the site.
- Prior to hazard events, identify temporary equipment for rapid recovery of operation, such as temporary clarifiers, aeration systems and pump stations.
- Prepare a hazard response plan so staff is knowledgeable and trained on what to do in preparation for, during, and following a hazard event.

Earthquake *– 1989 Loma Prieta Earthquake, San Francisco, CA*

The 1989 Loma Prieta Earthquake was a major seismic event that impacted infrastructure across all categories. Water and wastewater systems were impacted in terms of loss of electric power and damaged power distribution equipment, broken or separated interconnecting piping between structures, and damaged water-carrying and support structures.

In May 2002, the San Francisco Public Utilities Commission (SFPUC) adopted a capital improvement program (CIP), later called the Water System Improvement Program (WSIP), to rebuild and retrofit the regional water system to improve system reliability, especially to ensure seismic safety (BAWSCA 2021). Many parts of the regional water system are 75 to 100 yr and do not meet today's seismic codes. As reported in one SFPUC study commissioned in 2000, a major earthquake could cripple the system to such an extent that service might not be restored for 2 to 30 days or longer.

The following practices for seismic events have been incorporated into water infrastructure systems, including:

- Incorporate pipe joint flexibility to withstand ground motions in seismic events and prevent separation.
- Use pipe supports with seismic restraints to control pipe movement associated with a seismic event.
- Add on-site power generation equipment to temporarily restore utility power (electric and gas) that may be damaged or interrupted as a result of a seismic event.
- Develop and maintain capability to connect portable pumping systems to existing wet wells in the event the installed pumps are damaged.
- Develop and maintain capability to connect temporary overland piping from pump stations in the event that interconnecting buried piping is damaged.
- Prepare hazard response plans and ensure that staff is knowledgeable and trained on what to do in preparation for, during, and following a hazard event.

Wind *– 2017 Hurricane Irma, Miami Dade County, FL*

On September 10, Hurricane Irma made landfall on Cudjoe Key, FL, as a Category 4 storm with maximum sustained winds near 130 mph. Later that day, Hurricane Irma made a second landfall near Marco Island as a Category 3 hurricane with maximum sustained winds of 115 mph. As Hurricane Irma hit Florida, tropical storm force winds extended up to 400 miles from the center, and hurricane force winds extended outward 80 miles (FEMA 2018).

South Florida faces water challenges due to its low elevation near the ocean, its aging infrastructure and its porous limestone rock. After Hurricane Irma, sewage and other wastewater posed the most immediate problem in Florida, raising the risk of disease and triggering algae blooms. The low-lying sewage systems are unable to process the additional flow of water an Irma-like storm brings. With its flat terrain, WWTP rely on lift stations with pumps to move sewage, and the pumps rely on electric power (Mufson and Dennis, 2017).

Hurricane Irma imparted significant damage to water and wastewater infrastructure. Storm damage was caused by projectiles, such as trees and wind-driven debris, as well as floodwater and loss of electric power. The following improvements are planned (Miami Dade 2017):

- Develop automation plan for sewer and water plants should they need to be evacuated.
- Increase damage assessment teams to expedite repairs.
- Increase the number of portable generators with appropriate support staff.
- Replace satellite phones with county radios to remedy difficulty communicating with cellular phones.
- Identify field staff that will mobilize quickly to address main breaks, low pressure issues, and plant issues.
- Increase communication with support staff to establish clear lines of responsibilities for action steps and redundancy should key personnel not be available.
- Increased hardening of projects (e.g., wind and debris resistance) through Capital Improvement Plan.
- Elevate electrical components.
- Provide direct support and communication to state Department of Health for testing of potable water and surface water.
- Increase communication for residents that rely on private wells as a source of water.
- Increased communication with regulatory agencies as FDEP and EPA.

3.3.2 Infrastructure Adaptation to Flooding due to Climate Change

For existing water and wastewater infrastructure systems, the main focus related to climate change is on adapting the existing facilities to protect against associated risks. Precipitation intensity, duration, and location can affect the runoff and flood potential of each locality, as well as pre-existing conditions such a saturated soils, wildfires, or drought. Runoff and rising water in bodies such as rivers, lakes, and oceans need to be considered when evaluated water infrastructure performance and impacts.

Several resources provide input in this regard, including *Community Resilience Planning Guide for Buildings and Infrastructure Systems* (NIST 2016b), *Adaptation Strategies Guide for Water Utilities* (EPA 2013), *Implications of Climate Change for Adaptation by Wastewater and Stormwater Agencies* (WERF, 2009), and *Preparing for Extreme Weather at Wastewater Utilities: Strategies and Tips (*NEIWPCC, 2016).

Adaptation considerations for water infrastructure have unique challenges beyond those mentioned for buildings. Water and wastewater infrastructure need to integrate the functionality of older systems and plans for updates or expansions, and the interconnected nature of water infrastructure networks.

  - Higher discharge levels impact the hydraulic flow path through the treatment facility and may require increasing freeboard levels in tanks and channels, which can be done by, for example, raising sidewalls and weir levels. This cascade effect would also require lift pumps to raise flow to a higher elevation at the head end of the treatment facility.
  - Rising rivers and bays may impede discharge systems that operate by gravity. To address this, effluent pumping is required to raise the discharge head and to avoid backflows. An effluent pump station can be added, or the plant effluent system can be configured to allow connection of temporary pumping equipment that can be set in place with an approaching hazard event.
  - Stormwater management systems may need to be enhanced to accommodate more extreme rain intensity and duration to avoid flooding.
  - Rising water tables may also affect system structures and require stabilization from buoyancy effects on foundations.

The WERF (2009) study on implications of climate change for wastewater and stormwater agencies found that many multipurpose storage reservoirs are designed to provide flood protection during the winter and spring and supply water in the summer and fall, consistent with historical patterns of snow and rain. Under altered precipitation conditions resulting from climate change, meeting both collection or supply objectives might become difficult.

Unified Facilities Criteria and USACE Publications

DoD established the use of Unified Facilities Criteria (UFC) documents to provide “planning, design, construction, sustainment, restoration, and modernization criteria” for locations managed by DoD and the military (WBDG 2022). These documents effectively act as supplemental design requirements and guidance for the special considerations of DoD facilities and their associated infrastructure.

In 2016, DoD issued *Directive 4715.21: Climate Change Adaptation and Resilience*, which established responsibilities in DoD agencies to incorporate climate change considerations into future assessments and planning to manage “risks that develop as a result of climate change to build resilience” (DoD 2018). This led to the development of resources to address specific aspects of climate change impacts to DoD facilities and infrastructure, with the primary focus on coastal and inland flooding changes. In 2018, UFC 1-200-02: *High Performance and Sustainable Building Requirements* was updated to include and strengthen climate considerations (WBDG 2022). In the recent 2019 DoD report, *Report on Effects of a Changing Climate to the Department of Defense*, the main hazards of concern listed were recurrent flooding, drought, desertification, wildfire, and thawing permafrost (DoD 2019).

In general, these documents do not mention any special considerations for hurricane wind changes due to climate change. Wind design consideration are listed in UFC 3-310-01 *Structural Engineering* (WBDG 2022) and UFC-4-023-10 *Safe Havens* (WBDG 2022). The main type of wind design standard changes from the minimum relate to certain types of facilities, such as limits on the types of airport hangar doors in high wind areas.

For coastal flooding, there are a number of additional documents related to sea level rise (SLR) and inland flooding. For SLR, there are some additional specific publications of concern. A summary of how DoD addresses SLR can be found in the *Military Installations and Sea-Level Rise* (Congressional Research Service 2019). One of the primary publications with SLR information for DoD sites comes from the DoD's Strategic Environmental Research and Development Program in the report, *Regional Sea Level Scenarios for Coastal Risk Management: Managing the Uncertainty of Future Sea Level Change and Extreme Water Levels for Department of Defense Coastal Sites Worldwide* (DoD 2016). These sources provide guidance, but not minimum design standards for SLR.

Inland flooding is also beginning to be addressed in USACE publications. This includes the USACE Engineering and Construction Bulletin (ECB) No. 2018-14 titled *Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Designs, and Projects* (USACE 2018). This bulletin details both qualitative and quantitative approaches assessing how inland flooding may change over a project's lifetime and addressing that uncertainty as part of design and planning. This includes recommendations for how to determine when a statistically significant change is detected in precipitation patterns (such as the depth-duration-frequency profile for a location) and how to incorporate those changed into design. The ECB also specifically mentions that designs for features like dams based on PMF and related statistics do not have current compelling evidence of changes from climate change and should be calculated by existing approaches. Like SLR, there are no minimum design standards that have been adjusted to directly address climate change-induced inland flood changes.

Currently, none of the SLR or inland flood documents directly incorporate climate change considerations into the design process for DoD facilities and infrastructure. The UFC documents make use of a higher freeboard standard as the current approach to address future flooding uncertainty. Specifically, in UFC 3-201-01 (2010 revision) *Civil Engineering* in Chapter 2 (WBDG 2022), the minimum freeboard requirement for the four ASCE Flood Design Classes have been revised, so Class 2 (moderate risk) and Class 3 (high risk, non-mission critical) remain at 2.0 ft (0.6 m), but Class 3 (high risk, mission critical) and Class 4 (essential facilities) have 3.0 ft (0.9 m) of freeboard. This freeboard is added to a base flood elevation (BFE, based on the 1% annual probability of exceedance event) for a design flood elevation (DFE) to be used for new infrastructure. In addition to the elevation aspect of the DFE, the horizontal flooding extent beyond the BFE is also a critical consideration for site planning and design.

3.4 Assessment of Codes, Standards, Regulations, and Best Practices

3.4.1 Hazard Design Criteria and Performance Levels

Table 3-3 summarizes the design hazard levels and expected performance for various water infrastructure categories, based on a review of codes, standards, and best practices.

The flood, seismic, and wind design criteria for buildings and structures in water infrastructure are addressed in Chapter 2. In ASCE 7, buildings and structures associated with utilities required to protect the health and safety of a community, including water-treatment and wastewater treatment plants, are identified as Risk Category III for design purposes. Failure of water and wastewater treatment facilities can disrupt community life and potentially cause large-scale public health risks (ASCE 7 2021c).

3.4.1.1 Flood

Buildings and structures follow the flood criteria in ASCE 7 (2021c) and ASCE 24 (2015), as described in Chapter 2.

Stormwater systems are primarily regulated by EPA and state requirements or guidance that focus on volume, conveyance, channel protection, water quality, and flood control. Flood control criteria varies from 10 to 100-yr storms (rainfall events). A summary of state stormwater programs is given by EPA (2011).

Dam guidelines and regulations address multiple levels of flood hazard design criteria, based on the dam hazard classification (FEMA 2004):

- Low hazard potential - Dams assigned the low hazard potential classification are those where failure or mis-operation results in no probable loss of human life and low economic and environmental losses. Losses are principally limited to the owner’s property.
- Significant hazard potential - Dams where failure or mis-operation results in no probable loss of human life but can cause economic loss, environmental damage, disruption of lifeline facilities, or can impact other concerns. These dams are often located in predominantly rural or agricultural areas but could be located in areas with population and significant infrastructure.
- High hazard potential - Dams where failure or mis-operation will probably cause loss of human life.

Dams and levees are designed with freeboard to ensure that wave runup due to a reservoir’s fetch do not overtop the embankment. They are also designed to ensure waves do not erode the structures over time. There are exceptions for dams that are constructed with overtopping protection such as a constructed spillway or sections of the dam armored with roller compacted concrete, articulated concrete blocks, a secant pile wall, etc. A basic performance requirement for dams is to withstand the design flood without failure, even if there is no apparent downstream hazard involved; the design flood should be selected to have virtually no chance of exceedance during the service life of the dam (FEMA 2004).

Dam safety guidelines generally require that dams having a low hazard potential should be designed to at least meet a minimum standard to protect against the risk of damage or loss. The spillway design flood (SDF) for low hazard potential dams is typically the 1% annual probability of exceedance flood. Therefore, the dam is required to safely pass the associated floodwaters through the outlet works and spillway(s).

Dam safety guidelines by federal agencies and states can vary on the requirements of the spillway design flood. The SDF for significant hazard dams varies from the 1% annual chance of occurrence flood to the PMF depending on state and regulatory agency guidelines. A flood less than the PMF may be used if an incremental damage assessment (IDA) hazard evaluation shows no further damage would result from a SDF less than the PMF.

The SDF for high hazard dams is generally the probable maximum flood (PMF). Dam safety guidelines generally require that, for dams containing the potential for loss of human life (high hazard), the spillway should be designed for the PMF, unless an IDA demonstrates the safety of a lesser flood design criteria. The minimum SDF is the 1% annual chance of occurrence flood.

Levee systems can be accredited by FEMA, if appropriate documentation demonstrates appropriate design, construction, maintenance, and operation standards that provide protection from the 1% annual chance flood (FEMA 2020). However, many levees are not regularly maintained and do not meet the design standards set forth by FEMA for accreditation. Levee performance criteria include resisting overtopping and erosion during a design flood. (FEMA 2020).

The use of ASCE 7 and ASCE 24 flood design criteria for buildings and structures in water infrastructure support community resilience through consistent design and performance criteria across infrastructure sectors. Water infrastructure that is based on other design criteria, such as stormwater systems, dams, and levees, may have criteria the result in varying performance relative to buildings and structures.

Table 3-3: Summary of Hazard Design Criteria and Expected Performance Levels for Various Water Infrastructure

Water Infrastructure	**Flood**		**Seismic**		**Wind**	
	Hazard Design Criteria	**Performance Levels**	**Hazard Design Criteria**	**Performance Levels**	**Hazard Design Criteria**	**Performance Levels**
Potable Water Supply Water & Wastewater Treatment, Transmission, Distribution (ASCE 7, ASCE 24) RC III	**ASCE 7** Design Flood **ASCE 24** FDC 3: BFE + 1 ft (0.3 m); BFE + 2 ft (0.61 m) in coastal areas; or DFE	**ASCE 7** Performance levels for buildings.	**ASCE 7** Design EQ Response Accel. parameters for Seismic Design Category.	**ASCE 7** Performance levels for buildings.	**ASCE 7** Design Wind 1700-yr MRI	**ASCE 7** Performance levels for buildings.
Stormwater (ASCE 7 for structures, EPA, state) RC III	**ASCE 7** Design Flood **State** Varies for green and natural systems based on local requirements.	**State** Move water quickly from site without local flooding.	**ASCE 7** Design EQ	**ASCE 7** Performance levels for structures.	Not Applicable.	Not Applicable.
Levees (federal, state, local) RC III	Varies by **federal, state, local agency.**	**FEMA** Mitigate flooding by containing and directing flows. Transport potable and treated water to designated location.	Varies by **federal, state, local agency**.	**FEMA** Mitigate flooding by containing and directing flows Transport potable and treated water to designated location	Not Applicable.	Not Applicable.
Dams (federal/state) RC III-IV	**Federal/state** Varies between PMF and 100-yr flood based on Dam Hazard Classification**.**	**FEMA** Withstand the design flood without failure. Safely pass spillway design flood.	**Federal/state** Design EQ ground motions by dam safety authority.	**FEMA** Minimize risk of a catastrophic release of water based on design-level EQ hazards	Not Applicable.	Not Applicable.

1. Design flood hazard may be defined as a 100-yr flood (1% probability of annual exceedance; 39% probability of occurrence in 50 yr), a 500-yr flood (0.2% probability of annual exceedance; 10% probability of occurrence in 50 yr), or the flood hazard defined on a Flood Hazard Map (FHM).
2. There are four Flood Design Categories (FDC) defined by ASCE 24-14; the greatest elevation of the listed options is used for design.
3. Seismic Design Categories (SDC) and Importance Factor (Ie) modify the Design Response Acceleration parameters by Risk Category. Risk Category I, II, or III structures located where the mapped spectral response acceleration parameter at 1-s period, S1, is greater than or equal to 0.75 shall be assigned to Seismic Design Category E. Risk Category IV structures located where the mapped spectral response acceleration parameter at 1-s period, S1, is greater than or equal to 0.75 shall be assigned to Seismic Design Category F. All other structures shall be assigned to a Seismic Design Category based on their Risk Category and the design spectral response acceleration parameters, SDS and SD1.
4. PMF is a probable maximum flood based on data and meteorological models.

3.4.1.2 Seismic

For water storage tanks, the AWWA (2009, 2011a, 2013) provides standards for design earthquake ground motion derived from ASCE 7 and based on a maximum considered earthquake ground motion. ACI (ACI 2006, 2016a, 2016b) references ground motions from ASCE 7-05 (2006).

Seismic hazard design criteria for gravity dams can be found in FERC Engineering Guidelines Chapter 3, Gravity Dams (FERC 2016). FERC acceptance criteria are based on the dam's stability under post-earthquake static loading considering the damage likely to have resulted from an earthquake.

Seismic hazard design criteria for embankment dams can be found in FERC Engineering Guidelines Chapter 4, Embankment Dams (FERC 2006). The Guidelines in sections 4-6.9 and 4.7 provide details for seismic evaluation of embankment dams. FERC references FEMA guidance (FEMA 2005b) for the earthquake analysis and design of dams. The performance criteria of these guidelines are intended to prevent a catastrophic release of water. Meeting these criteria does not ensure that the dam can operate at any level following an event other than hold water.

The use of ASCE 7 seismic design criteria for buildings and structures, and AWWA and ACI design criteria that reference ASCE 7, for water infrastructure support community resilience through consistent design and performance criteria across infrastructure sectors. In general, seismic design criteria for dams are addressed by hazard classification and federal and state regulations and guidelines. At present, there is no national consensus design criteria for dams and levees.

3.4.1.3 Wind

The use of ASCE 7 wind design criteria for buildings and structures, and AWWA design criteria, for water infrastructure support community resilience through consistent design and performance criteria across infrastructure sectors. Primary wind design considerations for dams and levees address wind generated wave runup and wave loads.

AWWA (AWWA 2009, 2011a, 2013) provides design criteria and performance for aboveground storage tanks that follow ASCE 7 procedure for determining wind loads. AWWA design criteria note that in special wind regions, tanks may be exposed to wind speeds that exceed those shown in maps. In such cases, the basic wind speed is specified for the project.

Wind loads are generally not considered in levee or dam design. However, the height of waves and associated runup due to wind may be important factors for determining the freeboard of a dam. Wave height and forces depend on the fetch, or the horizontal distance of water over which wind acts to produce waves and runup (USACE 1995; FloodSafe California 2012).

3.4.2 Resilience Concepts

Water systems are considered critical infrastructure, and resilience concepts can increase long-term operational reliability (i.e., uninterrupted or minimally disrupted operations). Wind, flood, and seismic hazards are primarily addressed with structural design standards. Climate adaptation strategies encourage protection of critical water and wastewater assets from hazards such as sea/lake/river level rise, storm surge, precipitation, landslides, drought, and wildfire. Other climate effects may also be considered, such as extreme heat and changing groundwater levels. For example, emerging operational risks may include changing groundwater elevations or increased salinity may necessitate use of non-corrosive pipeline materials or less buoyant hydraulic structures.

Federal, state, or local requirements, building codes and standards, and guidance for water facilities typically address structural performance, process and water flow management, water quality, cybersecurity, and emergency plans. However, the complexity and uniqueness of water systems and operations creates a challenge for integrating resilience across the range of codes, design standards, and best practices.

Primary resilience concepts include robust and redundant system design and rapid recovery of services. These concepts help critical infrastructure systems to meet performance objectives, long-term asset management, and resilience goals.

3.4.2.1 Planned Recovery

Most state-level regulatory agencies require potable water and wastewater facilities to prepare and keep current operation and maintenance (O&M) manuals. These manuals contain scenarios for normal operation, maintenance requirements, and various modes of operation, including during and after an emergency such as a damaging hazard event. For many water facilities, the severity of the recovery effort may depend on how well a facility was operated during an event. For example, limited interior flooding of a wastewater facility may be managed in such a way as to allow for rapid recovery if plant personnel are trained for and implement emergency operating procedures in time. Some O&M manuals incorporate recovery planning and training for plant personnel, although there is not a consistent industry practice or standard.

Though no current design standards or criteria are formally available or adopted throughout the water infrastructure industry, there are emerging standards (e.g., AWWA 2010), guidance (EPA 2021b; Morley 2018), and principals of design.

Due to the localized nature and types of hazards and operational challenges facing each facility, it is often local municipalities that adopt such principles of design as policy or standards. As some larger municipal governments incorporate dedicated resilience staff into the planning and policy decision making, these policies and standards are becoming more common, though not necessarily consistent with one another. These may range from having treatment trains that can operate independently and therefore provide a minimum level of post-event service. Alternatively, there are some local standards that have established instrumentation and control backups or manual operation procedures and staffing post-event.

NEIWPCC (2016) published *Preparing for Extreme Weather at Wastewater Utilities: Strategies and Tips* as a supplement to the eleventh edition of *Guides for the Design of Wastewater Treatment Works*. This supplement includes recommended the following procedures for preparing for hazard events:

- Top-off all emergency generators that use diesel fuel.
- Check all pump systems and level indicators.
- Clear facilities of all loose items and tarps. Make sure outdoor trash cans are secured so they don't smash through windows during a flood.
- Remove hazardous materials from flood-prone areas.
- Clear preliminary treatment systems, such as screens and grinders at head works.
- Empty primary treatment systems of solids. If possible, drain at least one unit to be used as a surge buffer.
- Check all inlet and outlet gates and valves for operational function.
- Initiate pre-event communication and operational procedures with staff, local emergency responders, and appropriate state officials.

3.4.2.2 Interdependencies

Water infrastructure largely depends on other infrastructure systems, both for day-to-day operation and for restoration following a hazard event. Likewise, water sector is critical for community resilience and key for the buildings and structures, electric power, and transportation sectors.

Buildings and structures are fundamental to conveying and treating water and wastewater, as well as supporting stormwater systems, dams, and levees. Water and wastewater utilities rely on buildings and structures to contain water, chemicals, equipment, and control/administrative functions. A level of redundancy in pumping and treatment assets is typically provided for water and wastewater systems such as standby treatment units, process blowers and pumps; however, interconnecting structures and those without mechanical systems such as interconnecting channels and piping may not have redundancy. Buildings and water storage and conveyance structures, if damaged, are not typically able to be repaired quickly, and portable/temporary means may be necessary to restore vital functionality. Building and structures are covered in detail in Chapter 2.

Electric power is necessary for maintaining powered equipment and controls such as pumping and treatment operations. Typically, two sources of power are required for critical water infrastructure to provide a level of redundancy. This can be in the form of two independent utility feeds or one utility feed and on-site generator. If a hazard event were to disable utility power to water infrastructure, it can result in loss of use for water and wastewater systems, loss of pumping or delivery of water to end users, and upstream flooding for wastewater and stormwater systems, with contamination of impacted areas. In some cases, the on-site generator is only sized to restore basic functions such as pumping and disinfection. Loss of power to dams and levees may render control gates non-functional and not able to respond to changing conditions, which may result in flooding and damage to impacted areas. Guidance for power resilience for water and wastewater facilities is available from EPA (2019).

Following a hazard event that takes out power supply, critical power needs for items such as pumping, and disinfection and control of water are prioritized to be restored first. If on-site power generation is not available or it is damaged, portable generators and adequate fuel supplies should be readily accessible and connected to return powered systems to service until the utility power is restored. Power supply and distribution are covered in detail in Chapter 4.

Transportation systems provide access for operation and maintenance of critical water and wastewater infrastructure, as well as enabling the supply chain necessary to deliver chemicals and equipment for operation. Interruption in access to critical infrastructure may limit the ability to treat water and wastewater if supplies run out. Restoring access to critical infrastructure following a hazard event is needed to enable inspection and repairs, as well as portable generators, pumps, equipment, and personnel to restore service and limit damage. Transportation systems are covered in detail in Chapter 5.

Conversely, buildings and other infrastructure systems are also dependent on water, wastewater, and stormwater systems to continue to provide services to the community. Without water, other community services and critical facilities cannot operate.

Buildings need water systems for flood control, and water supply with adequate flow and pressure for fire suppression as well as sanitation. Industrial facilities need functional water and wastewater systems for developing, processing, and manufacturing materials and products. Agriculture relies on water supply, conveyance and distribution to meet needs of crops and livestock. The public relies on water and wastewater services for the overall health of the community. Water supply is also critical to agriculture and farming. Hazard events can damage buildings and structures and disrupt functionality that may take a significant amount of time to restore.

Electric power systems need water for cooling and hydroelectric power, and require water, wastewater, stormwater, dams, and levees to function to protect electric power systems from flooding. Failure of water systems to function or related damage from a hazard event could result in flooding that could result in cascading impacts that damage or take out electric power systems such as generation and transmission systems. Seismic events can damage electric power systems and require a significant amount of time to repair and restore service. Wind events can damage exposed electric power systems with projectiles, downed trees, etc. that may take significant time to restore functionality.

Transportation systems need depend on water systems for river navigation, flood control, and construction, and need water, wastewater, stormwater, dams, and levees to function to protect transportation systems from flooding. Failure of water systems to function or that result in related damage from a hazard event could result in flooding that could damage or take out transportations systems such as roads, bridges, and tunnels. Seismic events can damage transportation systems and require a significant amount of time to restore functionality. Wind events can render roadways impassible when trees and debris block access, that may take several days to clear.

3.4.2.3 Gaps and Areas for Improvement

Water systems infrastructure typically rely on buildings (Chapter 2), electric power infrastructure (Chapter 4), and transportation infrastructure (Chapter 5). Resilience requirements should address vulnerability to hazard events and how rapidly the impacted water system can be restored to service. Vulnerability assessments should identify risk and consequence of hazard to the system and the community. For water systems, including water, wastewater, and stormwater, this would include vulnerabilities for access, repair, restoration of power, on-site storage of supplies necessary to provide service to the community; accommodations for staffing of facilities, and the ability to remotely monitor and control critical functions. While best practices exist that strive for redundancy, specific guidance on redundancy is lacking in codes, standards, and guidelines.

The following is a summary list of the identified gaps and areas of improvement:

- Existing design standards for water infrastructure rely heavily on codes and standards intended for buildings, which focus on life safety objectives. In addition to life safety objectives, performance objectives that are specific to water infrastructure systems are needed. Design criteria for community resilience also need to be further developed. ***The design criteria and performance goals in building standards focus on life safety objectives and may not meet the desired performance goals for water infrastructure, which typically target reliability of service during normal operations.***
- Minimum criteria for design level hazards and performance goals are currently guidelines only and need to be incorporated into design standards to be effectively

implemented. This is a necessary step but is insufficient to achieve system resilience. For resilience, design criteria for functional performance for flood, seismic, and wind hazards are needed. ***Consensus design standards for water infrastructure need to specifically address design level hazards for flood, seismic, and wind hazards.***

- The advancement of modern in-plant electrical, instrumentation, and control systems may outpace formal design guidelines and may pose a potential single point of failure or inhibit recovery if not implemented to consistent best practice or standards. ***Design standards for water infrastructure need to address the role of individual components in a system to address complex interdependencies.***
- While there have been some advances with performance-based design methods for buildings, similar quantitative performance criteria need to be developed for water infrastructure, both structural and nonstructural components, to resist design hazard loads and provide continuity of service. While some initial steps have been taken to develop performance-based design for water systems (e.g., Davis 2019), significant additional work is needed. ***Structural and nonstructural components of water infrastructure, such as electrical, instrumentation, and control systems that affect resilience performance objectives need consensus minimum or baseline performance criteria developed for use in practice and consideration for design standards.***
- While the review of codes, standards, and best practices for existing infrastructure is beyond the purview of this document, it should be noted that aging infrastructure, and interdependencies of other infrastructure, is a critical vulnerability of water infrastructure. Guidance should, at a minimum, help evaluate the likely gap between the level of service existing systems can provide if a hazard event occurred today and the desired community performance goals. ***Resilience guidance is needed for evaluating and updating existing infrastructure.***
- Resilient design is currently based on specific system components or assets, such as a building or a length of pipe. However, for a water system to be resilient, the system itself needs to provide services to users when needed. ***Resilience standards are needed to identify system-level performance criteria from which component or asset level performance can be defined to ensure the system performs as intended.***
- Community resilience can be enhanced through an improved understanding of how potable water, wastewater, and stormwater systems are expected to perform in various hazard events for routine, design, and extreme events. This includes the extent of potential loss of services and the time to recovery of functions. ***Guidance is needed on how to conduct resilience assessments of water sector systems and communicate the results to service users.***
- Users should identify effective actions to undertake during the absence of services being provided through the network. ***Guidance is needed on how service users should prepare for loss of water service.***

Dam and levee performance criteria currently focus on minimizing risk and preventing a catastrophic release of water. A reservoir critical to system operations that is damaged may remove all ability to provide water supply after a major flood or earthquake hazard event.

3.5 Conclusions

Water infrastructure systems are dependent in large part on building, electric power, and transportation systems to function during normal operations and to recover from hazard events. Likewise, building, electric power, and transportation systems are dependent on water infrastructure systems. Even within the water sector, water and wastewater systems are dependent on each other.

Water infrastructure operates dynamically and continually changes to respond to conditions. It is inherently designed to operate under a range of design conditions and is dependent on the training and preparedness of the operations staff to recover post-event. This dependency on personnel further emphasizes the interdependence with overall community building, electric power, and transportation systems to ensure staff are not affected by external factors that would prevent them from working.

Building, electric power, and transportation systems continually update codes, standards, and guidelines to provide resilient systems that help protect associated infrastructure systems from hazard events. Water systems lack a consistent set of guidelines regarding resilience and would benefit from more dialogue and establishment of guidelines to protect them from climate change and recover from a hazard event. FEMA's Public Assistance Grant Program provides funds for communities to upgrade damaged facilities and structures to current adopted codes and standards to build community resilience. These processes for upgrading older facilities and systems are detailed in FEMA's Public Assistance Program and Policy Guide.

Drivers for increased resiliency include aging infrastructure, stressed systems due to densification of service areas, and ability to accommodate more intense hazard events due to climate change. Vulnerability assessments identify high risk elements of water infrastructure systems. Hazard recovery plans and proper training would position agencies to prepare for and react to hazard events to restore critical services in a timeframe that would minimize impact to the community.

3.6 References

ACI, 2006. ACI 350-06: *Code Requirements for Environmental Engineering Concrete Structures*, American Concrete Institute, Farmington Hills, MI.

ACI, 2016a. ACI 371R-16: *Guide for the Analysis, Design, and Construction of Elevated Concrete and Composite Steel-Concrete Water Storage Tanks*, American Concrete Institute, Farmington Hills, MI.

ACI, 2016b. ACI 372R-13: *Guide to Design and Construction of Circular Wire- and Strand Wrapped Prestressed Concrete Structures*, American Concrete Institute, Farmington Hills, MI.

ALA, 2001a. Guidelines for the Design of Buried Steel Pipe, American Lifelines Alliance, https://www.americanlifelinesalliance.com/pdf/Update061305.pdf.

ALA, 2002. Seismic Design and Retrofit of Piping Systems, American Lifelines Alliance, https://www.americanlifelinesalliance.com/pdf/Seismic_Design_and_Retrofit_of_Piping_Systems.pdf.

ALA, 2001b. Seismic Fragility Formulations for Water Systems, American Lifelines Alliance, https://www.americanlifelinesalliance.com/pdf/Part_1_Guideline.pdf.

ALA, 2005. Seismic Guidelines for Water Pipelines, American Lifelines Alliance, https://www.americanlifelinesalliance.com/pdf/SeismicGuidelines_WaterPipelines_P1.pdf.

ASCE, 1999. *Guidelines for the Seismic Evaluation and Upgrade of Water Transmission Facilities*, Technical Council on Lifeline Earthquake Engineering (TCLEE) Monograph 15, American Society of Civil Engineers, Structural Engineering Institute, Reston, VA.

ASCE, 2006, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, ASCE 7-05, American Society of Civil Engineers, Reston, VA.

ASCE, 2015. ASCE 24-14: *Flood Resistant Design and Construction*. American Society of Civil Engineers, Structural Engineering Institute, Reston, VA.

ASCE, 2019. *American Society of Civil Engineers to Grade Stormwater for First Time in 2021 Infrastructure Report Card*.

ASCE, 2021a. *2017 Infrastructure Report Card: Dams*. American Society of Civil Engineers, Structural Engineering Institute, Reston, VA.

ASCE, 2021b. *2017 Infrastructure Report Card: Levees*. American Society of Civil Engineers, Structural Engineering Institute, Reston, VA..

ASCE, 2021c. ASCE 7-22: *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*. American Society of Civil Engineers, Structural Engineering Institute, ASDSO, 2020. Reston, VA.

ASDSO, 2022. *Dam Safety Resource Center*. Association of State Dam Safety Officials. Lexington, KY. https://www.damsafety.org/resource-center

ASME, 2008. *Standard for the Seismic Design and Retrofit of Above-Ground Piping Systems,* B31E-2008, American Society of Mechanical Engineers, New York, NY.

ASME, 2020. *Code for Pressure Piping*, B31.3-2020, American Society of Mechanical Engineers, New York, NY.

ASTM, 2016. Standard Guide for Seismic Risk Assessment of Buildings, ASTM E2026-16a, ANSI, Washington, DC.

AWWA, 2001. M19 *Emergency Planning for Water Utilities*, Fourth Edition, American Water Works Association, Denver, CO.

AWWA, 2009. Factory-Coated Bolted Carbon Steel Tanks for Water Storage, AWWA D103-09, American Water Works Association, Denver, CO.

AWWA, 2010. *Risk and Resilience Management of Water and Wastewater Systems*, J100-10, American Water Works Association, Denver, CO.

AWWA, 2011a. *Welded Carbon Steel Tanks for Water Storage*, D100-11, American Water Works Association, Denver, CO.

AWWA, 2011b. *Emergency Preparedness Practices,* G440-11, American Water Works Association, Denver, CO.

AWWA, 2013. *Wire- and Strand-Wound, Circular, Prestressed Concrete Water Tanks*, D110-13, American Water Works Association , Denver, CO.

AWWA, 2020. *Circular-Prestressed Concrete Water Tanks with Circumferential Tendons*, D115-20, American Water Works Association, Denver, CO.

ASDSO, 2020. Summary of State Laws and Regulations on Dam Safety. Association of State Dam Safety Officials. https://damsafety-prod.s3.amazonaws.com/s3fs-public/files/FINAL%20-%202020%20Update%20State%20Laws%20and%20Regulations%20Summary_0.pdf.

Aubuchon, C.P. and K.M. Morley, 2013. "The Economic Value of Water: Providing Confidence and Context to FEMA's Methodology." https://www.semanticscholar.org/paper/The-Economic-Value-of-Water%3A-Providing-Confidence-Aubuchon-Morley/850e88d210244758f54acaffd3e05a0323683899.

BAWSCA, 2021. Water System Improvement Program, Bay Area Water Supply and Conservation Agency, Bay Area Water Supply & Conservation Agency, San Mateo, CA.

CFR, 1972. *Clean Water Act*. 33 U.S.Codes. et seq. 1251–1387, https://www.epa.gov/laws-regulations/summary-clean-water-act

CFR, 1974. *Safe Drinking Water Act*, 42 U.S.Codes. §300f et seq., https://www.epa.gov/sdwa/title-xiv-public-health-service-act-safety-public-water-systems-safe-drinking-water-act-0

Congressional Research Service, 2019. "Military Installations and Sea-Level Rise" in *In Focus*. https://crsreports.congress.gov/product/pdf/IF/IF11275.

Davis, C. A., 2018. “Creating a seismic resilient pipe network for Los Angeles.” In Utility Engineering and Survey Institute Pipelines 2018 Conf., Paper 384423. Reston, VA: ASCE.

Davis, C.A., 2019, *Infrastructure System Resilience: Functionality and Operability*, *Proceedings*, 2nd International Conference on Natural Hazards & Infrastructure (ICONHIC 2019), Chania, Greece.

DoD, 2016. *Report on Regional Sea Level Scenarios for Coastal Risk Management*. Department of Defense, 04/25/2016. https://www.serdp-estcp.org/News-and-Events/News-Announcements/Program-News/DoD-Report-on-Regional-Sea-Level-Scenarios.

DoD, 2018. *DoD Directive 4715.21: Climate Change Adaptation and Resilience*. Department of Defense. https://www.esd.whs.mil/Portals/54/Documents/DD/issuances/dodd/471521p.pdf?ver=2018-09-25-081059-330.

DoD, 2019. *Report on Effects of a Changing Climate*. Department of Defense. https://media.defense.gov/2019/Jan/29/2002084200/-1/-1/1/CLIMATE-CHANGE-REPORT-2019.PDF.

DHS, 2015. *Dams Sector-Specific Plan: An Annex to the NIPP 2013*. Department of Homeland Security, Washington, DC. https://www.cisa.gov/sites/default/files/publications/nipp-ssp-dams-2015-508.pdf.

DHS and EPA, 2015. *Water and Wastewater Systems Sector-Specific Plan*. Department of Homeland Security and Environmental Protection Agency, Washington, DC. https://www.cisa.gov/sites/default/files/publications/nipp-ssp-water-2015-508.pdf.

EPA, 1994. National Pollutant Discharge Elimination System (NPDES) Combined Sewer Overflow (CSO) Policy. Environmental Protection Agency, Washington, DC.

EPA, 2011. *Summary of State Stormwater Standards*, Draft, Office of Wastewater Management, Environmental Protection Agency, Washington, DC. https://www3.epa.gov/npdes/pubs/sw_state_summary_standards.pdf

EPA, 2013. *Adaptation Strategies Guide for Water Utilities.* EPA 817-K-13-001. Environmental Protection Agency, Washington, DC.

EPA, 2014a. Flood Resilience Checklist, Environmental Protection Agency, Washington, DC. https://www.epa.gov/sites/default/files/2014-07/documents/flood-resilience-checklist.pdf.

EPA, 2014b. *Flood Resilience: A Basic Guide for Water and Wastewater Utilities*. Environmental Protection Agency, Washington, DC. https://www.epa.gov/sites/default/files/2015-08/documents/flood_resilience_guide.pdf

EPA. 2019. *Power Resilience – Guide for Water and Wastewater Utilities*. EPA 800–R–19–001. Environmental Protection Agency, Washington, DC.

EPA, 2020. *What is Green Infrastructure?* Environmental Protection Agency Website. https://www.epa.gov/green-infrastructure/what-green-infrastructure#:~:text=Section%20502%20of%20the%20Clean,reduce%20flows%20to%20sewer%20systems.

EPA, 2021a. *Flood Resilience: A Basic Guide for Water and Wastewater Utilities*. EPA 817-B-14-006. Environmental Protection Agency, Washington, DC. https://www.epa.gov/sites/production/files/2015-08/documents/flood_resilience_guide.pdf.

EPA, 2021b. *Drinking Water and Wastewater Resilience*. Environmental Protection Agency, Washington, DC. https://www.epa.gov/waterresilience

FEMA, 2004. *Federal Guidelines for Dam Safety, Hazard Potential Classification System for Dams*. Federal Emergency Management Agency, Washington, DC. https://www.fema.gov/sites/default/files/2020-08/fema_dam-safety_P-93.pdf.

FEMA, 2005a. National Flood Insurance Program (NFIP) Floodplain Management Requirements, FEMA 480, Federal Emergency Management Agency, Washington, DC.

FEMA, 2005b. *Federal Guidelines for Dam Safety Earthquake Analyses and Design of Dams*, Federal Emergency Management Agency, Washington, DC. https://www.ferc.gov/sites/default/files/2020-04/fema-65.pdf.

FEMA, 2007. *Design Guide for Improving Critical Facility Safety from Flooding and High Winds: Providing Protection to People and Buildings*. FEMA 543, Risk Management Series, Federal Emergency Management Agency, Washington, DC.

FEMA, 2013a. *Selecting and Accommodating Inflow Design Floods for Dams*. FEMA P-94. Federal Emergency Management Agency, Washington, DC.

FEMA, 2013b. *Mitigation Assessment Team Report: Hurricane Sandy in New Jersey and New York, Building Performance Observations, Recommendations, and Technical Guidance*, FEMA P-942, Federal Emergency Management Agency, Washington, DC.

FEMA, 2018. Mitigation Assessment Team Report: Hurricane Irma in Florida, *Building Performance Observations, Recommendations, and Technical Guidance*, FEMA P-2023, Federal Emergency Management Agency, Washington, DC.

FEMA, 2020. *Guidance for Flood Risk Analysis and Mapping: Levees*. Federal Emergency Management Agency, Washington, DC. https://www.fema.gov/sites/default/files/documents/fema_levee-guidance.pdf

FEMA, 2021. *National Flood Insurance Program (NFIP)*. Federal Emergency Management Agency, Washington, DC. https://www.fema.gov/flood-insurance.

FERC, 2006. *Chapter 4 Embankment Dams. Engineering Guidelines for the Evaluation of Hydropower Projects*. Federal Energy Regulatory Commission, Washington, DC. https://www.ferc.gov/industries-data/hydropower/dam-safety-and-inspections/eng-guidelines.

FERC, 2015. *Chapter 2 Selecting and Accommodating Inflow Design Floods for Dams. Engineering Guidelines for the Evaluation of Hydropower Projects*. Federal Energy Regulatory Commission, Washington, DC. https://www.ferc.gov/industries-data/hydropower/dam-safety-and-inspections/eng-guidelines.

FERC, 2016. *Chapter 3 Gravity Dams. Engineering Guidelines for the Evaluation of Hydropower Projects*. Federal Energy Regulatory Commission, Washington, DC. https://www.ferc.gov/industries-data/hydropower/dam-safety-and-inspections/eng-guidelines.

FERC, 2020. *Safety of Waterpower Projects and Project Works*. 172 FERC 61,061. 18 CFR Part 12, Federal Energy Regulatory Commission, Washington, DC.

FloodSafe California, 2012. Urban Levee Design Criteria, FloodSafe California, Department of Water Resources, The Natural Resources Agency, State of California.

Great Lakes, 2014. *Recommended Standards for Wastewater Facilities*. Great Lakes-Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers, http://www.healthresearch.org/store/ten-state-standards.

IBC, 2021. International Building Code. International Code Council, Washington, DC.

ISO, 2020. *Earthquake and Subsidence Resistant Design of Ductile Iron Pipes*. ISO 16134:2020, International Organization for Standardization (ISO)

Miami Dade, 2017. *Miami-Dade County Hurricane Irma Preliminary Report*, https://www.miamidade.gov/mayor/library/memos-and-reports/2017/09/09.28.17-Miami-Dade-County-Hurricane-Irma-Preliminary-Report.pdf

Morley, 2018. *Water Sector Approach to Manage Risk & Resilience*, Presentation by K. Morley, American Water Works Association. https://www.waterrf.org/sites/default/files/file/2020-03/IWN-Morley.pdf.

Mufson, S. and Dennis, B., 2017. *In Irma's wake, millions of gallons of sewage and wastewater are bubbling up across Florida*, Washington Post, https://www.washingtonpost.com/news/energy-environment/wp/2017/09/15/in-irmas-wake-millions-of-gallons-of-sewage-and-wastewater-are-bubbling-up-across-florida/.

NEIWPCC, 2016. *Preparing for Extreme Weather at Wastewater Utilities: Strategies and Tips,* New England Interstate Water Pollution Control Commission. https://www.neiwpcc.org/neiwpcc_docs/9-20-2016%20NEIWPCC%20Extreme%20Weather%20Guide%20for%20web.pdf.

NFPA, 2020. *Standard for Fire Protection in Wastewater Treatment and Collection Facilities,* NFPA 820, National Fire Protection Association, Quincy, MA.

NIST, 1997. *Reliability and Restoration of Water Supply Systems for Fire Suppression and Drinking Following Earthquakes*, NIST GCR-97-730, National Institute of Standards and Technology, Gaithersburg, MD.

NIST, 2016a. *Critical Assessment of Lifeline System Performance: Understanding Societal Needs in Disaster Recovery*, NIST GCR 16-917-39, National Institute of Standards and Technology, Gaithersburg, MD.

NIST, 2016b. *Community Resilience Planning Guide for Buildings and Infrastructure Systems, Volume 2*. NIST SP-1190. National Institute of Standards and Technology, Gaithersburg, MD.

U.S. Army, 2015. *Engineers take protecting New Orleans personally*. https://www.army.mil/article/153971/engineers_take_protecting_new_orleans_personally.

USACE, 1995. Gravity Dam Design. EM 1110-2-2200, 30 June 1995. US Army Corps of Engineers.

USACE, 2018. Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Designs, and Projects. ECB 2018-14. 09-10-2018..

USACE, 2020. National Inventory of Dams, https://nid.sec.usace.army.mil/ords/f?p=105:1.

USACE. 2021. *Levee Safety Program*. U.S. Army Corps of Engineers Headquarters Website. https://www.usace.army.mil/Missions/Civil-Works/Levee-Safety-Program/.

WBDG, 2022. *Unified Facilities Criteria*, Whole Building Design Guide, National Institute of Building Science, Washington, DC. https://www.wbdg.org/ffc/dod/unified-facilities-criteria-ufc

WEF. 2013. *Emergency Planning, Response, and Recovery*. Water Environment Federation, Alexandria, VA. https://news.wef.org/wef-emergency-planning-book-provides-real-world-case-studies-to-model/.

WERF, 2009. Implications of Climate Change for Adaptation by Wastewater and Stormwater Agencies. Water Environment Research Foundation. Stratus Consulting Inc. and MWH Global Inc. CC2R08.

WRF, 2013. Business Continuity Planning for Water Utilities: Guidance Document, Web Report #4319, Water Research Foundation, Denver, CO. https://www.waterisac.org/system/files/Business+Continuity+Planning+for+Water+Utilities.pdf.

4 Electric Power Infrastructure

4.1 Overview

The U.S. electric power grid supports our communities and daily lives, providing electricity both for comfort and for critical equipment and processes. Without electricity, key functions of our communities (e.g., hospitals, grocery stores, data centers) cannot operate, unless those functions have backup generation or on-site microgrid or generation capabilities. The electric power grid is closely interconnected with all other major infrastructure systems—buildings, water and wastewater, and transportation—and is becoming increasingly so as more buildings and vehicles are electrified. While these systems are interconnected functionally, the codes, standards, and guidelines that govern their design and performance are developed independently by authorities and organizations unique to the individual systems. This siloed approach to codes and standards development can inhibit the resilience of overall community infrastructure (e.g., design hazard loads can differ for electric power and water infrastructure that are dependent on each other).

This chapter provides a summary and analysis of electric power infrastructure regulatory bodies, codes, standards, and best practices for increased resilience, primarily to flood, seismic, and wind hazards, for five major subcomponents of the U.S. national electric grid: generation, transmission, distribution, substations, and microgrids. Electric power infrastructure codes and standards have historically focused on electric power system safety through the National Electrical Safety Code (NESC 2017) and reliability to provide intended service with minimal functional disruption; there has been less focus on grid resilience as the ability to withstand and recover from damaging hazard events (Hansen 2016). Under current standards, a component could meet reliability requirements but lack resilience (e.g., an electric power system could have adequate baseload measures in place, but insufficient redundant infrastructure to maintain or quickly recover electricity demand in the event of a major disruption) (Lu et al. 2018). To date, there are no nationally accepted electric power infrastructure resilience standards.

More frequent high-intensity weather events, electrification of urban transportation and building sectors, and decentralization of the utility system are changing the national electric grid. National design practices are evolving to meet these challenges. The National Electrical Code is incorporating practices for large scale photo-voltaic electric supply stations, energy storage systems, stand-along systems, and direct-current microgrids (Butterfield 2021). A report by GridWise Alliance, a consortium of electric grid stakeholders, recognized the impact of ‘very large-scale events’ on multiple utilities requires coordination and collaboration at federal, regional, state, and local levels. It produced a set of recommendations to advance grid reliability and resilience, including grid modernization, hardening (increased capacity to withstand events), and distributed generation technologies (GridWise Alliance 2013). This evolution needs to continue to ensure a more reliable and resilient national electric grid.

4.1.1 Generation

Historically, the national grid has been managed in a vertically integrated approach, beginning with utilities generating electricity at power plants (Figure 4-1). Most plants today burn fossil fuels to produce steam to operate turbines to generate electricity for transmission and distribution across the grid. Other methods of generation include nuclear power plants (which made up 20% of the national generation mix in 2019), hydroelectric plants (7%), and non-hydroelectric renewables such as solar photovoltaics, geothermal, biomass, and wind (10%) (EIA 2020). As on-site and decentralized generation (e.g., residential solar panels) grow, the grid is becoming a linear chain from generation to distribution, but with additional generation points beyond the traditional sources.

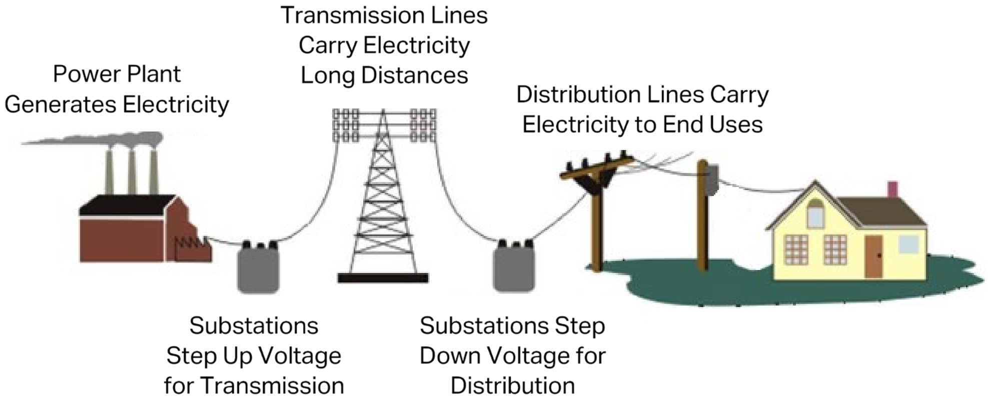


Figure 4-1: Traditional, Vertically Integrated Electric Power Grid (EIA)

4.1.2 Transmission

Once electricity is generated and transformed to high-voltage (generally 69 kilovolts [kV] and above), utility transmission lines carry the electricity over long distances. At higher voltage, electricity can be transmitted at greater efficiency (i.e., less energy loss). With recent developments in high-voltage, direct-current technology, transmission lines can carry electricity at either direct current or alternating current.

4.1.3 Distribution

As electricity nears its final destination, substations step down the voltage to 35 kV or lower to carry electricity on structurally and electrically smaller components (towers, lines, and other equipment) at a voltage closer to that of its end users. Pad-mounted overhead or underground feeders, or pole-mounted transformers in many residential neighborhoods, then further step down the voltage for customer use. The distribution system also uses reclosers, which function like circuit breakers in residential homes, to automatically switch off electric power in the event of a short circuit or hazard.

4.1.4 Substations

Electric substations control the voltage of electricity from the point of generation to transport across high-voltage transmission networks and convert high-voltage electricity to medium- or low-voltage electricity across distribution systems (DOE 2015). Substation equipment has traditionally been air-insulated, but there is a recent trend to shift to gas-insulated substations (GIS), which insulate equipment using sulfur hexafluoride (SF_6) gas instead of air. GIS systems are more resilient to weather impacts, require less maintenance (visual inspection once every 4 years, as opposed to every year for air-insulated substations), and reduce the risk of arc flash (Beta Engineering 2020); however, SF_6 gas does have a global warming potential over 20,000 times that of carbon dioxide, and can cause negative climate implications if not properly contained (Shadle 2019).

4.1.5 Microgrids

Microgrids are combinations of distributed energy resources (DERs) for local power generation or storage that can run connected to or islanded from the electricity grid. Microgrids allow more dynamic control of on-site energy demand and consumption and greater resilience to hazards since they are less reliant on the grid. Microgrid architecture continues to rapidly evolve with a wide variety of control system hardware available from numerous manufacturers (NIST 2014).

4.2 Literature Review and Data Collection

4.2.1 Regulatory Environment

States regulate permitting, construction, inspection, and maintenance (including vegetation management) of electric power infrastructure often via Public Service Commissions (PSC) or equivalent. In addition to state infrastructure regulations, federal and interstate entities regulate the licensing, emissions, reliability, sales, and bulk-power transmission of certain grid components as outlined below.

4.2.1.1 Generation

Most power generation facilities (75%) are licensed and regulated at the state and local levels, while hydropower and nuclear power generation facilities are licensed and regulated by FERC and the NRC, respectively (Lazar 2016). Some states require a certificate of public convenience and necessity and/or an integrated resource planning process to approve proposed power plants (Lazar 2016). Following state PSC or equivalent approval, state departments of the environment regulate and monitor air, water, and waste associated with construction and operation for pollutant-emitting power generation facilities (DOE 2015). There are three types of electric utilities in the United States:

1. Investor-owned utilities, which serve almost three-quarters of U.S. electricity customers, primarily in urban areas, and which bought and consolidated municipal utilities as 20th century technology developments made smaller generation plants uneconomical,
2. Publicly owned utilities, which are resident-owned utility non-profits, in many cases run by city or county government, and
3. Cooperatives, which are member-owned utility non-profits, mainly in rural areas (EIA 2019).

Power generation itself is primarily managed by utilities, groups of utilities, or independent suppliers, with one notable exception: federal Power Market Administrations (e.g., the Tennessee Valley Authority, Bonneville Power Administration, Western Area Power Administration, Southeastern Power Administration, and Southwestern Power Administration) (Marston 2018). States may mandate utility renewable electricity generation via renewable portfolio standards (RPS). For example, Hawaii's RPS requires 100% of electricity generation to come via renewable energy, whereas South Carolina mandates a renewable portfolio standard of 2% (Marston 2018). In addition to mandatory, enforceable RPS, some states have voluntary renewable targets beyond the mandatory minimums (EPA 2018).

4.2.1.2 Transmission

Wholesale interstate electric power sales and interstate electricity transmission are regulated by FERC, an independent agency within the U.S. DOE whose five members are Presidential appointees (DOE 2015) (Figure 4-2). FERC coordinates energy reliability in natural disasters and emergency events with DHS and FEMA. FERC's authority is granted in the Federal Power Act of 1920, codified in 16 U.S.C. §§ 791 to 823d and amended in 1935 to include interstate electricity transmission regulation (Vann 2010). In 1977, the Department of Energy Organization Act (codified in 42 U.S.C. § 7134) renamed the Federal Power Commission as FERC, which was maintained as an independent regulatory body. Following several national electricity reliability crises, including Enron deliberately shutting down California power plants to increase prices and the 2003 Northeast Blackout in which poor vegetation management and lack of employee training led to 50 million people in the northeast U.S. losing power for up to two weeks, the Energy Policy Act of 2005 charged FERC with the additional responsibility of enforcing bulk-power system reliability regulation. FERC delegated this responsibility to the North American Electric Reliability Corporation (NERC) and designated them as the U.S. government Electrical Reliability Organization (ERO).

NERC, the ERO authority and non-profit private sector counterpart to FERC, develops and mandates reliability standards and imposes financial penalties for non-compliance (DOE 2015). Additionally, NERC trains and certifies industry personnel (e.g., System Operator Certification) and operates the Electric Sector Information Sharing and Analysis Center, the electric power industry's primary communications channel.

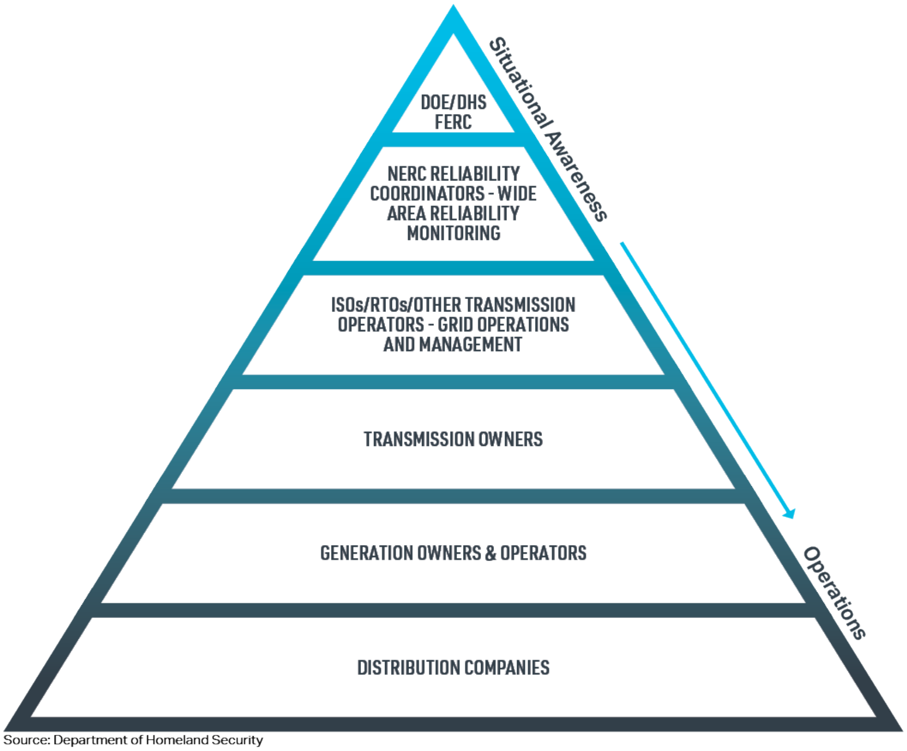


Figure 4-2: Hierarchy of Electric Reliability Monitoring (Source: U.S. Department of Homeland Security)

FERC and NERC regulate Regional Transmission Organizations (RTOs) and Independent System Operators (ISOs) (DOE 2015). ISOs operate, administer wholesale electricity for, and provide reliability planning to their region's grid. There are currently seven ISOs in North America. RTOs perform the same functions as ISOs but have greater responsibility through FERC for the transmission network. As shown in Figure 4-3, there are four North American RTOs: Western Interconnection, Electric Reliability Council of Texas (ERCOT), Eastern Interconnection, and Quebec Interconnection. In areas without RTOs or ISOs (predominantly in the Southeast and West), utilities coordinate and develop their own transmission plans and are subject to FERC rules.

While states are responsible for regulating transmission infrastructure construction and maintenance, FERC can influence certain situations. FERC can alter transmission rates in specific areas to incentivize transmission line construction in those locations, and FERC has siting authority (as granted through the Energy Policy Act of 2005) in specific cases involving federal lands, multi-state projects, or eminent domain (FERC 2022). In addition, the DOE can designate certain high-congestion geographic areas as “national interest electric transmission corridors” through its triennial electric transmission constraints study; however, national corridor designation does not automatically trigger transmission infrastructure upgrades, as federal appeals courts have overturned past national corridor designations (DOE 2021).

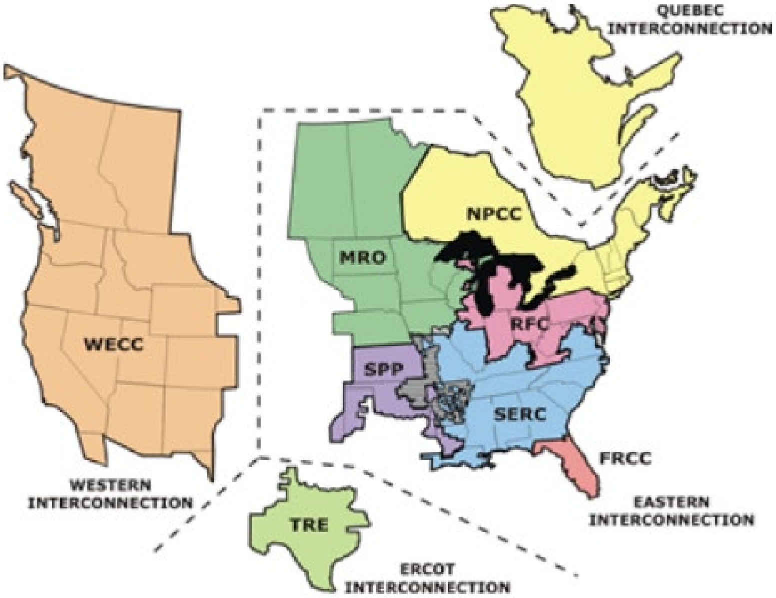


Figure 4-3: North American Regional Transmission Operators (NERC)

4.2.1.3 Distribution

Electricity distribution, which delivers electricity from the transmission network to the end users, is regulated at the state level, while operation, maintenance, and planning of distribution infrastructure is managed by local utilities (Warwick et al. 2016). State regulators establish the construction standards for distribution facilities (Lazar 2016). While there are state construction standards for distribution infrastructure, there are no distribution-level reliability standards and no federal oversight of the distribution system (Warwick et al. 2016); 90% of electrical outages in the United States occur at the distribution level (Bie et al. 2017).

4.2.1.4 Substations

Substations fall under both transmission and distribution systems, with the determining factor being the voltage level that the substation is handling (Figure 4-1). As with transmission and distribution infrastructure, substation infrastructure itself is regulated at the state level; however, transmission substation performance is regulated by FERC, and transmission reliability is regulated by NERC.

4.2.1.5 Microgrids

Microgrids can be considered as part of generation or distribution, and their regulation depends on the size and purpose of the system. Larger microgrids designed to serve multiple facilities can be considered legally as "electrical distribution utilities," which triggers state PSC regulation of service rates and construction approval, and, in some cases, FERC regulation requirements (Hirsch et al. 2018).

Smaller microgrids constructed "within the end customer's rights-of-way" are regulated by the local municipality, which is the case for most microgrids in the United States (Oueid 2019). Regardless of size or purpose, all microgrids are regulated by state departments of the environment for air and waste emission levels (Hirsch et al. 2018).

4.2.2 National Codes

While regulatory bodies differ by grid subcomponent, electric power infrastructure codes are more standard across subcomponents. In the U.S., it is the responsibility of states or, in some states, local jurisdictions to set their own electric power codes for construction, operation, and maintenance of electric power infrastructure. There are two primary electric power codes adopted into law by states or municipalities:

1. The **National Electrical Safety Code (NESC)**, also known as IEEE C2 (NESC 2017), published by the Institute of Electrical and Electronics Engineers (IEEE), which is a set of guidelines for safe installation, operation, and maintenance of substations and overhead and underground lines for voltages over 1,000 volts, and
2. The **National Electrical Code (NEC)**, or NFPA 70, published by the NFPA, which offers guidance and requirements on safe installation of building wiring, grounding, and equipment for voltages of 1,000 volts and less (NFPA 2017).

Historically, the NESC has pertained to grid-side electric power generation, transmission, and distribution codes and the NEC to customer-side, low-voltage distribution and building code, including installation and wiring requirements for electric vehicle chargers and backup power hookups at the building level—transfer switches, interlock devices, or quick connect tap boxes—and alternate power source requirements via on-site generator for all essential electric power systems in healthcare facilities (NFPA 2017, IEEE 2018a). As the grid becomes increasingly distributed, however, the two codes have overlapped. The 2017 edition of the NEC, for example, includes articles on large (minimum 5 megawatts) solar photovoltaic systems, direct-current microgrids, and electric power storage systems (NFPA 2017). States can either adopt electric power code into law for the entire state, grant local jurisdictions authority to adopt electric power code into law, or a combination of the two (e.g., the state of Alabama adopted the NEC in 2016 for all schools, hotels, movie theaters, and state-owned buildings, but not all cities or counties in the state have adopted the NEC into law) (IAEI 2019).

In addition, for nuclear power plants specifically, Appendix A to Part 50 of 10 CFR outlines general design criteria that proposed nuclear power plants need to meet to obtain a construction permit.

4.2.3 National Standards

There are three primary standard development organizations of electric power technical standards:

1. American National Standards Institute (ANSI)/IEEE Standard C2 (NESC 2017)
2. American Society of Civil Engineers (ASCE) standards for structural design of transmission and substation infrastructure
3. Institute of Electrical and Electronics Engineers (IEEE) standards for seismic and short-circuit loads for substations, construction, erection, and related areas

In addition, all U.S. electric power infrastructure projects are required to meet OSHA Electrical Standards 1910.137 (protective equipment) and 1910.269 (electric power generation, transmission, and distribution), which are based on the NFPA 70E standard for electrical safety in the workplace (OSHA 2021). Note that the NEC is also aligned with the work safety practices outlined in the NFPA 70E standard.

As with regulatory bodies, several grid subcomponents have specific electric power infrastructure standards outside of those mentioned above. Some key standards by grid subcomponent are described here.

- **Transmission**
    - NERC All Reliability Standards (NERC 2017) mandate Regional Transmission Operators (RTO) and Independent System Operators (ISO) have Reliability Coordinators. They also impact reporting on extreme weather events, operating plans, emergency preparedness plans, and restoration plans in place to prevent or mitigate the effects of potential outages.
    - NERC Reliability Indicators (NERC 2020) assess transmission reliability and set minimum system metrics (e.g., frequency limits) that RTOs and ISOs are required to meet. Two of the most common metrics used to measure electricity reliability are System Average Interruption Duration Index (SAIDI), which measures the duration of sustained customer interruptions greater than 5 minutes divided by number of customers served, and System Average Interruption Frequency Index (SAIFI), which measures the frequency of sustained customer interruptions greater than 5 minutes divided by number of customers served (Eto 2018). SAIDI and SAIFI are factored into several NERC reliability indices, including the Severity Risk Index. IEEE developed both the SAIDI and SAIFI metrics in 1998 as part of IEEE 1366 *Guide for Electric Power Distribution Reliability* (IEEE 2015a), to provide a uniform approach to calculate and compare reliability nationwide (Eto 2018).

        While SAIDI and SAIFI were developed to measure reliability of the bulk power system, these metrics do not consider voltage levels and, thus, do not explicitly differentiate if an outage occurs at the transmission or distribution level (Eto et al. 2019).

        - Electric Power Research Institute (EPRI) Transmission Line Reference Books (EPRI 2017) provide is an industry standard for transmission line design, with reference books for design for 345 kV transmission lines and above, 115 to 138 kV (compact line design), and alternating current for 200 kV and above.
        - Center for Energy Advancement through Technology Innovation (CEATI International 2020) has technical reports on design, loading, maintenance, failure recovery, etc. of the electric power generation and delivery systems. CEATI is a collaboration of 140+ participating organizations (including 40+ major U.S. electric utility members as well as gas utilities, governmental agencies, and provincial and state research bodies) with topic-focused programs on generation, transmission, and distribution systems.

- **Distribution**
    - IEEE C37.60 High-Voltage Switchgear and Controlgear - Part 111: Automatic circuit reclosers and fault interrupters for alternating current systems up to 38 kV. (IEEE 2019).
- **Substations**
    - IEEE C37.60 High-Voltage Switchgear and Controlgear - Part 111: Automatic circuit reclosers and fault interrupters for alternating current systems up to 38 kV. (IEEE 2019).
    - International Electrotechnical Commission (IEC) 61850-90-1 Technical Report, Communication Networks and Systems for Power Utility Automation - Part 90-1: Use of IEC 61850 for the communication between substations (IEC 2010). This report defines substation communication and automation and integration with distributed energy resources.
- **Microgrids**
    - IEEE 1547 Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces (IEEE 2018d).
    - IEEE 1547.4 Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems (IEEE 2011a) addresses safe and intentional islanding.
    - UL 1741 Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources (UL 2021).
    - NERC Critical Infrastructure Protection Standards (NERC 2021) are a set of standards used to derive smart grid cybersecurity requirements.

- California Rule 21 Interconnection (CPUC 2021) are rules set by the California Public Utilities Commission for streamlined microgrid permitting, review, interconnection, testing, and validation (Hirsch et al. 2018).

4.2.4 Codes, Standards, and Guidelines for Natural Hazards

The electric power industry can be characterized as having three levels of design: safety, reliability, and resiliency. Reliability and resiliency address extreme events (e.g., high-impact, low frequency events), where the difference in design practice is based on the number of system components that are expected to fail. In the electric power industry, this is referred to by the number of failed components, such as N-1 or N-2. The loss of one or two components is considered for reliability-based design and system operation. For a resilient design, a larger number of component failures is considered, such as 5+ transmission lines or 3+ substations, as the basis of design.

Natural hazards are the most common cause of electricity outages in the United States, often induced by flood, seismic, and wind events (DOE 2015). This section discusses national electric power infrastructure standards and guidelines for each hazard, with standards and guidelines listed in Table 4-1.

4.2.4.1 Flood

Except for nuclear and hydroelectric power plants, and buildings or structures, there are no national requirements for electric power systems that specifically address flood hazard protection or mitigation. For new generation plants, plant upgrades, and substation design, flood hazard criteria is generally based on FEMA flood zones.

If a proposed site is within a flood zone, the systems should be elevated or protected from flood damage. Per 44 CFR § 9.4, design to the 500-yr flood is required for critical facilities (e.g., power generating plants or “other principal points of utility lines” such as transmission towers) that are located within flood zone (e.g., Zone X) and that receive funding from the federal government (FEMA 2013a). Authorities having jurisdiction (typically state or city departments of environmental protection or of natural resources) often prohibit transmission towers or substations from being constructed within the flood zones or require more stringent structural requirements. Communities that choose not to participate in the NFIP do not receive official FEMA flood maps; however, flood hazard zones in these communities can be determined using NOAA or USGS flood maps.

A shortfall in the resilience of electric power systems is the lack of national standards or guidance for their performance and subsequent recovery of functions for damaging flood events. In particular, such guidance needs to be compatible with design criteria for buildings and other structures, as electric power is critical to the functionality of other infrastructure.

Table 4-1: Codes, Standards, and Guidelines for Natural Hazards

Flood

- ANSI / American Nuclear Society (ANS)-2.8-1992, Determining Design Basis Flooding at Power Reactor Sites (ANSI, 1992)
- Federal Guidelines for Dam Safety (FEMA, 2004)
- Regulatory Guide 1.102: Flood Protection for Nuclear Power Plants (NRC, 1976)
- Nuclear Regulatory Commission (NUREG) tsunami hazard analysis and design recommendations, including NUREG/CR-6966 – Tsunami Hazard Assessment at Nuclear Power Plant Sites in the United States of America (NRC 2009)

Seismic

- 10 CFR Part 50, Appendix S: Earthquake Engineering Criteria for Nuclear Power Plants (NRC 2017a)
- 10 CFR § 50.155, Mitigation of Beyond Design Basis Events (Post-Fukushima Safety Enhancements)
- NUREG seismic hazard analysis and design recommendations, including NUREG/CR-6372 – Recommendations for Probabilistic Seismic Hazard Analysis
- ASCE 7-22, Minimum Design Loads for Buildings and Other Structures (ASCE, 2022), including for offshore substation seismic loads; calls for design per USGS seismic design maps, which are updated at least once a decade (NIBS Building Seismic Safety Council, 2015)
- IEEE 693, Recommended Best Practice for Seismic Design of Substations (2018b)
- IEEE 1527, Recommended Practice for the Design of Flexible Buswork Located in Seismically Active Areas (2018c)
- Rural Utility Service (RUS) Bulletin 1724E-300, Design Guide for Rural Substations (including seismic evaluation and loading guidelines) (USDA 2001)
- Seismic Design Classification for Nuclear Power Plants (NRC, 1976)

Wind

- ASCE MOP 113, Substation Structure Design Guide – design guidelines for wind loading on substation structures, equipment, and rigid bus systems (2008)
- ASCE MOP 74, Guidelines for Electrical Transmission Line Structural Loading – applies reliability-based methodology for determining design structural loads (2020)
- Det Norske Veritas (DNV-ST-0145, Offshore Substations (DNV 2021)
- EPRI Transmission Line Reference Books (including design guidelines on wind-induced overhead line vibration) (2008)
- IEEE 605, Guide for Bus Design in Air-Insulated Substations – wind load design guidelines for outdoor substations (2008)
- IEEE C37.30.2, Guide for Wind-Load Evaluation of High-Voltage (>1000 V) Air-Break Switches (2015b)
- NERC FAC-003-4, Transmission Vegetation Management – developed in response to the 2003 Northeast Blackout, which was caused in large part by poor vegetation management; references ANSI A300 tree care standards (2016)
- Pennsylvania, Jersey, Maryland (PJM) Regional Transmission Organization (RTO) Design and Application of Overhead Transmission Lines (69 kV and above) – wind load criteria (PJM 2017)
- RUS Bulletin 1724E-200, Design Manual for High Voltage (230 kV and less) Transmission Lines (including for extreme wind) (USDA 2009)
- RUS Bulletin 1724E-300, Design Guide for Rural Substations (including wind calculation and concept guidelines for tubular bus structure and lattice tower structural design) (USDA 2001)
- ANSI/American Petroleum Institute Recommended Practice 2MET, Derivation of Metocean Design and Operating Conditions (including wind loads for offshore wind turbines/farms in water depth 10 meters or more) (Moffatt and Nichol, 2015)

NEC requirements dictate the location of some electrical service components so that emergency personnel can safely de-energize power to buildings and structures. However, in flood prone areas, additional guidance is needed to ensure that such equipment is designed and located to prevent water damage during flood events (FEMA 2012).

4.2.4.2 Seismic

Electric power infrastructure standards and guidelines for seismic hazards are available for generation plants, some components, and substations, based on ASCE 7 ground motion parameters or USGS seismic maps (see Table 4-2). However, transmission and distributions systems are lacking specific guidance beyond that available through ASCE documents for structures.

An assessment in the late 1990s of electric power systems after California earthquakes found that parts of electric power systems were particularly vulnerable to damage. Most damage was due to the failure of porcelain elements in high-voltage substation equipment, although performance was also strongly influenced by specific equipment designs and installation practices. ASCE Manual of Practice (MOP) 96, *Guide to Improved Earthquake Performance of Electric Power Systems* (ASCE 1999), was issued to improve the earthquake response of electric power systems. It addresses power generating stations, transmission and distribution lines, substations, system communications and control, and ancillary facilities and functions.

Similar issues continue to exist for electric power systems. For example, as documented by Kempner et al (2018), the design of transmission line structures is commonly governed by wind/ice combinations and broken wire loads and earthquake effects are not commonly considered in transmission line structural design, even in high-risk seismic areas.

4.2.4.3 Wind

Electric power infrastructure standards and guidelines largely refer to ASCE 7 for wind loading requirements (see Table 4-2). Kempner (2009) discusses application of ASCE MOP 74, IEC 60826, and NESC (Rule 250C) extreme wind load methodologies to transmission line towers and conductors. The application of these methods can result in varying loads for towers and conductors. ASCE MOP 74 (2020) for transmission line loading has updated its references for wind and ice maps to those in ASCE 7-16 (ASCE 2017) for design criteria. The MOP now distinguishes between the design provisions and serviceability provisions.

While there are a number of standards and guidelines for wind hazards, including vegetation management to prevent wind hazard impacts via fallen tree limbs, there is little guidance for distribution systems. For instance, the NESC (2017) allows for structures and supported facilities that are less than 60 ft (18.3 m) above ground to be exempt from loading conditions for “extreme wind loading” (NESC Rule 250C) and “extreme ice with concurrent wind loading” (NESC Rule 250D). This exclusion results in most distribution systems being designed to a lesser performance level than transmission systems. Additionally, the design wind speeds for NESC are based on wind maps from ASCE 7-05 (2006).

4.2.5 Best Practices

Guidelines offer best practices and may become standards if the practice or technology in question is widely adopted. Most transmission and substation standards reference ASCE MOP 74 (2020) and ASCE 113 (2008) guidelines for design load requirements, which in turn reference standards ASCE 7 (2006, 2017), IEEE 693 (2018b), and IEEE 1527 (2018c) for seismic and wind criteria. The following electric power infrastructure guidelines are frequently used in design of subsystems.

Transmission Systems.

- ASCE MOP 74 – Guidelines for Electrical Transmission Line Structural Loading (2020)
- IEEE 1366 – Guide for Electric Power Distribution Reliability, including explanation and approach for calculating SAIDI, SAIFI, and Customer Average Interruption Duration Index (CAIDI) reliability metrics (2015a)
- U.S. Department of Agriculture Rural Utility Service (RUS) Bulletins (USDA 2022) – guidance on transmission infrastructure design in rural areas
- CEATI Transmission Line Program Knowledge Base (2022) – database of best practices for the analysis, design, structural loads, maintenance, and structural failure recovery for transmission lines

Distribution Systems.

- IEEE 1366 – Guide for Electric Power Distribution Reliability, including SAIDI, SAIFI, and CAIDI metrics; while the distribution system is not held by law to national reliability standards like the transmission system, most distribution utilities still use these metrics to measure their service reliability (2015a)
- U.S. Department of Agriculture RUS Bulletins (USDA, Rural Development 2020) – guidance on distribution infrastructure design in rural areas

Substations.

- ASCE 113 – Substation Structure Design Guide (although refers to IEEE 693 for seismic design requirements and ASCE MOP 74 and ASCE 7 for wind design requirements, and does not mention flood design) (ASCE 2008, IEEE 2018b, ASCE 2020, ASCE 2006)
- U.S. Department of Agriculture RUS Bulletins (USDA 2022) – guidance on substation infrastructure design in rural areas
- RUS Bulletin 1724E-300 – Design Guide for Rural Substations (USDA 2001)

Microgrids.

- IEEE 2030 – Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), End-Use Applications, and Loads (IEEE 2011b)

Asset Management

There are several industry best practices for increasing electric power infrastructure resilience. While there are no national codes or standards for when to replace electric power infrastructure equipment, utilities typically follow asset management as a best practice for upgrades and replacements (Warwick, et al. 2016). Asset management considers both the age and usage intensity of equipment, as opposed to a replacement schedule, which only considers equipment age (Warwick, et al. 2016). For example, Pepco, an Exelon utility in the Washington, DC, area, maintains a distribution reliability enhancement plan, which includes annual assessments and upgrades of priority electrical feeders, and installation of new feeders or non-wires alternatives (e.g., energy efficiency or demand response software or programs) to reduce load on existing feeders with growing customer usage (Pepco 2022). Many utilities conduct risk-based asset management or sustainability return on investment analyses to compare the cost of equipment maintenance or enhanced sustainability design features versus the cost to restore services following hazard-induced failure (Anguelov and Stiolov 2016). Implementation of risk-based analysis and asset management allows utilities to reduce the number of emergency or end-of-life equipment replacements.

Redundancy and Backup

Another best practice for improved electric power infrastructure resilience can include equipment redundancy**,** backup generation, and distributed energy generation, as well as increased battery storage, demand-side management (e.g., charging electric vehicle chargers during high solar or wind production), and flexible transmission line routes for renewable generation systems (Cleary and Palmer 2019). Below are a few alternative resilience strategies by hazard, which can be incorporated through or in addition to planning and design (Bie et al. 2017).

Flood Hazards.

Elevating substations and locating facilities well above base flood elevation is a best practice. For example, a private company found in a study of substations damaged by Hurricane Sandy that raising all substation equipment at least 1 ft (0.3 m) above the highest design elevation as established by FEMA, using post-Sandy Advisory Based Flood Elevation (FEMA 2013b), offered higher resilience and longer-term performance of the substation, despite the higher upfront capital cost. Building flood walls and gates to protect equipment that cannot be elevated above design flood levels, or to provide additional protection, is also a best practice.

Seismic Hazards.

Stronger pole materials and reinforcements for overhead transmission and distribution lines can reduce damage levels in low mass structures. The addition of isolation systems or dampers to buses, wires, or plant equipment, can help absorb ground vibrations and protect infrastructure (NRC 2019).

Wind Hazards.

Stronger pole materials and reinforcements for overhead transmission and distribution lines. For example, with increasing wind and flood conditions, there is increasing use of steel and concrete pole line materials, improving pole line foundation stability in floodplains and tidal wetlands, and replacing air-insulated substation equipment with gas-insulated equipment, which is more weather-resistant and requires less maintenance (Reed 2013).

Underground/buried transmission and distribution lines in areas not subject to flood or seismic events, although initial construction is more expensive than overhead lines, can be cost effective if damage and repairs are reduced (EPRI 2013).

Smart Grid Technology.

Inclusion of smart grid technology is becoming a best practice for real-time, location-based monitoring of system operation and efficient restoration of electricity outages. Though they can introduce the potential of cybersecurity vulnerability, strategic installation of microgrids (which can run in island mode off the grid) near hospitals and critical facilities (NASEM 2017), advanced controls and automation, and sophisticated demand-side management and metering are all methods for increasing system resilience through smart technology (EPRI 2013). For example, to improve electric reliability in Borrego Springs, California, San Diego Gas & Electric installed a community microgrid for the town through a pilot project funded by the U.S. DOE and California Energy Commission (Navigant 2015). Borrego Springs was previously tied to the grid via a single transmission line that frequently lost power in severe storms. The new microgrid allowed the town to reduce peak load of local feeders, shift load as needed, and improve overall reliability. During a storm in September 2013 that took out the grid power, the town was able to island from the grid, drop critical loads, and shift power to “cool zones” for vulnerable residents during the three days before the grid power could be restored. This project had significantly less regulatory and interconnection hurdles than traditional end-user-owned microgrids, since it was utility-owned and state and federally funded. The Borrego Springs community microgrid demonstrates how coordinated smart grid technology can increase community resilience to multiple hazards and save resident lives.

4.3 Case Studies

The following case studies demonstrate electric power infrastructure performance in major hazard events, and example projects that implemented system mitigation and smart grid best practices to increase resilience to storm hazards.

4.3.1 Infrastructure Performance in Hazard Events

Hurricane Sandy – Hazards: Wind and Flood

In October 2012, Hurricane Sandy brought 80 mph (129 kph) winds and up to 14 ft (4.3 m) of flooding from storm surge and tide to the Northeast United States, causing at least 131 fatalities, knocking out electric power to 8.66 million customers, and damaging assets in 24 states, primarily in New Jersey, New York, and Connecticut (DOE 2013). A nor'easter storm hit the same affected areas just over a week later, exacerbating existing damage and further delaying restoration activities; power restoration to 95% of affected customers was completed in 10 days (DOE 2013). Strong winds knocked out transmission and distribution lines, and flooding affected 69 electric power plants, 102 substations (including underground substations), and eight nuclear reactors (three of which were shut down, and five of which were operated at reduced load due to equipment damage or reduced power demand from customer outages) (DOE 2013). In addition, the storm knocked out 25% of cellphone towers in 10 states, reducing the effectiveness of a key information sharing and disaster recovery tool (IEEE 2013).

A key lesson learned from Hurricane Sandy is that critical electrical equipment (e.g., breaker boxes, building connections, elevator service, backup generators, etc.) should not be located in basements or on the ground floor of buildings; many buildings' electrical equipment was inaccessible because of the flooding as well as damaged by the water (DOE 2012). Since Hurricane Sandy, many authorities having jurisdiction, including New York City, have updated building codes to require any mechanical, electrical, or plumbing equipment to be located above the base flood elevation, which has increased resilience to future hazard events by reducing damage potential and improving recovery access (NYC 2021).

Another lesson learned is the effectiveness of distributed energy resources (DER) and microgrids: many colleges and universities, including New York University and Princeton University, were able to maintain power to facilities and provide shelter and electricity to neighboring communities because of combined heat, power, and microgrid systems that could "island," or disconnect and continue to operate independently from the grid and supply on-site generation and power (IEEE 2013). Recovery activities were aided in large part by the federal government sharing 100% of restoration costs and designating utility workers as first responders so they could have priority access to roads and fuel, as well as mutual assistance groups of partner utility companies and volunteer electric power workers sharing resources and technical labor for relief (DOE 2012).

Hurricane Sandy underscored the threat of changing climate conditions, the need to update electric power codes accordingly, and the benefits of a flexible electric power system and recovery plan.

Joplin Tornado – Hazards: Wind

An EF-5 tornado with 250 mph (402 kph) winds hit Joplin, Missouri in May 2011, causing 159 fatalities, tearing down more than 4,000 wood and steel poles, destroying one of the two hospitals in the area, knocking out a substation to the surviving hospital, and damaging 100 miles of distribution lines, including underground equipment (T&D World 2012). The tornado compromised Empire District Electric Company's communications and damage assessment system. The utility had to coordinate response primarily in person among their 150 linemen and 250 mutual assistance agreement workers (Penning 2012). A particular challenge was that much of the equipment to connect backup generation to buildings was also destroyed, so workers had to repair transmission, distribution, and building connection infrastructure (Breslin 2011). Response workers prioritized restoring power to the surviving hospital to care for tornado victims and established a new connection to the other hospital since its substation was destroyed (Breslin 2011).

NIST conducted a comprehensive study of the event and worked with Applied Research Associates (ARA) to develop tornado risk maps, which were published in 2020 (NIST 2020). The ICC has adopted stricter storm shelter design standards of up to EF-5 winds for schools and high-occupancy buildings in tornado-prone areas (NIST 2016), ASCE 7-22 incorporated ARA tornado risk maps into a new chapter for wind structural loading design criteria (NIST 2021).

While the restoration of electric power infrastructure to existing codes in 2011 did not benefit from this new guidance for buildings, it is now available to support new design and maintenance practices for electric power and other infrastructure systems.

4.3.2 Infrastructure Adaptation to Climate Change

Addressing climate change effects for electric power infrastructure has some unique considerations not addressed for buildings and water infrastructure.

Electric power codes and standards are being adapted or developed for distributed resources to address renewable energy and energy efficiency (IEEE 2021). For microgrids and local renewable generation systems, IEEE 2030 (2011b) – *Guide for Smart Grid Interoperability of Energy and Information Technology Operation with the Electric Power System* defines specifications among power systems and distributed energy resources. For energy efficiency, IEEE 1801 (2018e) - *Standard for Design and Verification of Low-Power,* *Energy-Aware Electronic Systems* improves the management and control of energy use of data servers and power-managed systems. While design and construction beyond code minimum may increase upfront costs, return-on-investment and risk-based asset management analyses show that communities can save money in the long term on hazard recovery by proactively adapting to climate change.

For long-term climate adaptation, electric power systems will need to increase the use of clean, renewable energy as demand grows from other sectors, such as transportation become increasingly electrified. The following case studies present examples of adapting electric power infrastructure to climate change. The first case study presents a recent Canadian publication specific to electric power infrastructure and climate change. The second case study focuses on Consolidated Edison (Con-Ed) in New York, the impacts of Superstorm Sandy on its electric power infrastructure, and the utility's efforts to address climate change.

Canada

The National Research Council Canada and Infrastructure Canada supported the Canadian Standards Association Group to develop the report titled *Development of Climate Change Adaptation Solutions Within the Framework of the CSA Group Canadian Electrical Code Parts I, II, and III* (CSA Group 2019). This report focused on climate change impacts to the Canadian electric power infrastructure from flooding, extreme weather, winter storms (ice, wind, snow), wildfires, and permafrost and associated land movement. Climate risks were highest across Canada for winter-storms. Flooding and extreme weather were also seen as a high risk for many locations in Canada. Wildfire and land movement were considered to be lower risk in general, though they might be primary risks in specific locations of the country.

The main concern for winter storms focused on the combined effect of ice/snow loads with higher wind speeds that may cause severe damage to above ground lines. While current design standards specify loads based on historical data, criteria are needed for future changes in storm patterns and temperatures that may bring winter storm loads locations not accustomed to these issues. Similar concerns may apply to the U.S. Northeast and Midwest. Adaptation for increased ice loads include improved line monitoring, use of line types that tend to inhibit ice formation, limiting long straight runs of line without geometry change, or stronger towers and poles, and better tree maintenance along rights-of-way.

Canada does not have a national flood mapping program, so first steps include identifying current floodplains and then modeling future impacts of changing flood conditions. Adaptation measures include elevating electrical panels above flood elevations, locating substations and other critical equipment outside the floodplain or elevating equipment above specified flood elevations (including freeboard), and providing standards for waterproofing or submersible equipment such as sump pumps. Comparing climate challenges and adaptation approaches between Canada and the U.S. offers additional insight into shared best practices for increasing resilience in similar geographies.

Consolidated Edison of New York

Con-Ed was severely impacted by Superstorm Sandy in 2012 (Con-Ed 2013). The storm brought coastal flooding from storm surge and sustained high winds. Con-Ed decided to provide greater protection from flooding for electrical assets and make overhead systems more resistant to high winds and tree damages. One part of that response was working with Columbia University to develop the *Climate Change Vulnerability Study* (Con-Ed 2019). The study identified climate variables of concern as temperature, humidity, precipitation, sea level rise, and extreme events, which include hurricanes, nor'easters, and long-term heat waves. The study also focused on energy supply and demand, how climate change will impact heating and cooling needs, and how changes in code and standards for energy usage can influence the scale of these changes. Similar to the report from Canada, wind loads were examined within the larger context of future changes to extreme events. For the New York City Metro area, the study considered increased wind speeds and power line damage and more severe nor'easters and wind-on-ice issues.

Proposed climate adaption measures were grouped in categories of Withstand, Absorb, and Recover. Withstand measures included physical adaption of certain assets, such as reinforcing transmission structures, expanded the number of compression fittings for weak points in overhead transmission lines, retrofitting distribution poles and lines, and moving critical sections of distribution system underground in more vulnerable locations. Absorb measures included increasing spare pole inventories between major events. Recover measures included expanded system redundancy through deployment of hybrid energy generation and storage systems and use of resilience hubs. These hubs would support community resilience by creating sites with basic energy services to support residents and to coordinate resources before, during, and after hazard events.

The study included measures that focused on coastal and SLR-influenced flooding and inland flooding from increased precipitation. For coastal locations, new infrastructure would use a minimum design elevation related to the base flood elevation (BFE based on 1% annual probability of exceedance), add 1.0 ft (0.3 m) for short-term SLR, and then an additional 2.0 ft (0.6 m) of freeboard. This would align Con-Ed design practices with New York City's Climate Resilience Design Guidelines (detailed in Chapter 5) for critical infrastructure. For existing assets, the study conducted site-specific analyses based on a long-term estimate of 3.0 ft (0.9 m) of SLR and developed a range of time-based options for each site. For example, an electric substation may have current protections up to BFE + 3 ft (0.9 m). As SLR occurs over time, and the flood hazard exceeds the level of protection, other measures could be deployed, such as enhanced sump pump capacity, a flood barrier, or relocation. For inland flooding, the study developed new design rainfall levels based on climate models. Adaptation measures included elevating substation transformer moats and use of trash pumps behind flood walls, relocating critical transmission and distribution lines underground, and installing more submersible equipment. The study that Con-Ed produced with Columbia University will help the utility adapt to climate change and improve its asset resilience to future extreme wind and precipitation events.

4.4 Assessment of Codes, Standards, Regulations, and Best Practices

4.4.1 Hazard Design Criteria and Performance Levels

This section outlines hazard design criteria and expected performance levels by electric power infrastructure component, as summarized in Table 4-2.

Table 4-2: Summary of Hazard Design Criteria and Expected Performance Levels by Electric Power Infrastructure Component

Electric Power Infrastructure	Flood		Seismic		Wind	
	Hazard Design Criteria	Performance Levels	Hazard Design Criteria	Performance Levels	Hazard Design Criteria	Performance Levels
Nuclear plants (CFR, FERC, ASCE) RC IV	**CFR** Design Basis Flood Level[(a)]	**CFR** Safe plant shut down. Prevent damage or failure causing loss of function.	**CFR** EQ Ground Motion used for Safe Shutdown EQ (**ASCE 7** Design EQ)	**CFR** Safe plant shut down. Prevent damage or failure causing loss of function.	**ASCE 7** Design Wind	**ASCE 7** Withstand Design Wind. Prevent damage or failure causing loss of function.
Hydroelectric plants (FERC, NFIP, ASCE) RC III	**FERC** Probable Maximum Flood (PMF). **NFIP** 100-yr flood minimum	**FERC** Withstand PMF; meet specified risk to downstream life and property. **NFIP** performance requirements.	**FERC** Earthquake ground motion parameters with MCE or PSHA	**FERC** Withstand Design EQ. Meet specified risk to downstream life and property.	**ASCE 7** Design Wind	**ASCE 7** Withstand Design Wind. Prevent damage or failure causing loss of function.
Other structures [(c)] (ASCE) RC III/IV	**ASCE 7** Design Flood **ASCE 24** FDC 3/4	**ASCE 7** Performance levels for buildings.	**ASCE 7** Design EQ	**ASCE 7** Performance levels for buildings.	**ASCE 7** Design Wind 1700-3000 MRI.	**ASCE 7** Performance levels for buildings and structures.
Transmission (NFIP, ASCE, NESC) RC III	**NFIP** 100-yr flood, or as specified by AHJ	**NFIP** performance requirements.	Not specified.	Not specified.	**ASCE MOP 74:** 100-yr MRI **NESC** Extreme Ice & Wind Maps	**ASCE MOP 74** Withstand design loads; contain cascading failures.
Distribution (NFIP, ASCE, NESC) RC III	**NFIP** Same as above.	**NFIP** performance requirements.	**IEEE 693** 0 g to 1 g PGA for low, med, or high seismic qualification level.	**IEEE 693** No significant damage, maintain functionality.	**ASCE 7** Design Wind	**ASCE 7** Performance levels for structures.
Substations (NFIP, ASCE, NESC) RC III	**NFIP** 100-yr flood, or as specified by AHJ	**NFIP** performance requirements.	Not specified.	Not specified.	**ASCE MOP 74:** 100-yr MRI **NESC** Extreme Ice & Wind Maps	**ASCE MOP 74** Withstand design loads; contain failures.
Substations Rural (NFIP, RUS, ASCE) RC III	**NFIP** 100-yr flood, or as specified by AHJ	**NFIP** performance requirements.	**RUS**: UBC 1997 Seismic Zone Maps < 3 g PGA; **IEEE 693/ASCE 7** criteria for > 3 g PGA	**ASCE 7** Performance levels for structures.	**ASCE 7-95** Basic Wind Speed Maps	**ASCE 7** Performance levels for structures.

Electric Power Infrastructure	Flood		Seismic		Wind	
	Hazard Design Criteria	Performance Levels	Hazard Design Criteria	Performance Levels	Hazard Design Criteria	Performance Levels
Offshore wind turbines	Not Applicable.	Not Applicable.	Not Applicable.	Not Applicable.	**API RP 2MET**	**API** Not specified.
Offshore substations	Not Applicable.	Not Applicable.	Not Applicable.	Not Applicable.	**DNV-ST-0145**	**DNV** Life safety from electrical hazards

a) Considers most severe recorded natural phenomenon on site.
(b) Determined via local building code, deterministic seismic hazard analysis, or probabilistic seismic hazard analysis; MCE = Maximum Credible Earthquake; PSHA = Probabilistic seismic hazard analysis.
(c) Based on RC III/IV structures; See Table 2-3 for facilities that support generation and operations (e.g., hydropower plant administrative buildings).
(d) PGA = peak ground acceleration.

4.4.1.1 Flood

Apart from nuclear and hydropower generation facilities, flood design criteria are established by guidelines, instead of codes or standards. FEMA guidelines recommend the 500-yr flood as the design event for critical emergency response facilities and the 1% annual chance of occurrence flood as the design event for all other infrastructure. However, for infrastructure systems that support critical facilities, the 500-yr flood criteria are more relevant.

- **Hazard Design Criteria**
  - Nuclear Plants. The Design Basis Flood Level considers the most severe recorded natural phenomena that has occurred on the site, with sufficient margin added for limitations during the time period of data collection (10 CFR Part 50, Appendix A) (NRC 2011). While the was evaluated, The NRC did not update design criteria after the Fukushima Daiichi nuclear disaster (NRC 2019).
  - Hydroelectric Plants. The Probably Maximum Flood (PMF) sets the upper limit for design and the 100-yr flood sets the lower limit. The PMF is determined by modeling inflow from runoff and outflow for the maximum reservoir dam elevation (FERC 2021)
  - Other Electric Structures. The 100-yr flood is used unless more stringent criteria are established by the Authority Having Jurisdiction. The 100-yr flood is based on FEMA guidelines and NFIP requirements. The 500-yr flood is strongly recommended in FEMA guidelines for critical facilities (FEMA 2007, 2013b). Local and state agencies can impose more stringent flood requirements. For example, the Port Authority of New York and New Jersey imposed criteria greater than the 100-yr flood for construction at Newark Liberty International Airport. Austin, Texas and other cities with high flood exposure have designated their 500-yr floodplain as their design-basis floodplain to account for rising sea levels and changing environmental conditions (Austin, Texas 2019).
  - Underground Lines. There are no specific design criteria for underground lines. However, routes should avoid “unstable soil such as mud, shifting soils, corrosive soils, or other natural hazards” and, if unavoidable, protect installations from such hazards using measures that are “compatible with other installations in the area” (NESC 2017).
- **Expected Performance Levels**
  - Nuclear plants. Sufficient time to safely shut down a nuclear plant when a Design Basis Flood Level occurs is required (10 CFR Part 50, Appendix A).
  - Hydroelectric plants. The facility needs to withstand Probable Maximum Flood loading condition, or flood condition where failure would not cause a downstream hazard to life and property (FERC 2021). The hazard potential is classified as low (no

loss of human life expected, low economic or environmental damage), significant (no loss of human life expected, economic or environmental damage expected), or high (probable loss of human life). Designers should define consequences of dam failure by reviewing NFIP flood maps for the site and conducting dam failure studies using USACE HEC's River Analysis System model or similar, approved methods.

  - All other energy structures. NFIP performance requirements include (FEMA 2013a):
    - Being reasonably safe from flooding.
    - Having adequate site drainage.
    - Not locating structures in floodways, unless engineering analysis can prove there will be no increase in flood levels.
    - Using flood-resistant materials below the design flood elevation.
    - Preventing water from entering or accumulating in electrical areas.

4.4.1.2 Seismic

Ground motion design criteria for most electric power infrastructure are set through a combination of ASCE 7 ground motion parameters, USGS seismic design maps, and UBC Seismic Zone Factor Maps (specifically for rural substations per RUS Bulletins), depending on the structure and its geographic location. Chapter 11 of ASCE 7 exempts transmission towers from its design seismic loading requirements, because most large utilities consider combinations of location-specific design loads including extreme ice and wind, broken wires, heavy vertical construction loads, etc. to design towers resilient to seismic inertia loading (ASCE 2021). Nuclear reactors, likewise, are designed to much higher seismic loads than ASCE 7 minimum requirements, as outlined below.

- **Hazard Design Criteria**
  - Nuclear Plants: Safe Shutdown Earthquake Ground Motion
    - Ground motion for which reactor coolant pressure boundary remains intact and all system equipment related to reactor can remain functional to provide adequate time for safe shutdown; design must factor in seismically inducted floods and waves, as well as normal operating loads (10 CFR Part 50, Appendix S, NRC 2017a)
    - Must "evaluate all siting factors and potential causes of failure" (10 CFR Part 50)
    - Standards for seismic design of nuclear facilities; ASCE 43 (2019) and DOE-STD_1020 (2016) invoke ASCE 7 for Seismic Design Categories 1 and 2 (Malushte 2016).
    - U.S. designs are required to be evaluated to beyond design-basis earthquake ground motions. Current standard plants require applicants to demonstrate High Confidence of Low Probability of Failure (HCLPF) margin of 1.67 times design (NRC, 2017b).

- Hydroelectric Plants: Earthquake ground motion parameters
    - Seismic design parameters can be determined with the local building code, deterministic seismic hazard analysis, or probabilistic seismic hazard analysis (FERC 2021). The traditional standards-based (deterministic) approach is typically performed by selecting an earthquake scenario that can reasonably be expected to produce the largest seismic demand (ground motion) on the dam, referred to as the Maximum Credible Earthquake (MCE). The PSHA involves an element of time and uses all possible earthquake scenarios and probability levels as inputs to the seismic load for the dam. The probabilistic approach also incorporates the uncertainties in earthquake locations, earthquake size and ground motion models (FERC 2020).
- Substations and Buswork, and Power Transformers and Reactors: 0.0 g, 0.5 g, or 1.0 g peak ground acceleration (PGA) based on low, medium, or high seismic qualification level, per USGS seismic maps (IEEE 2018b)
    - Designed per IEEE 693 seismic requirements, based on USGS seismic maps
    - IEEE 693 offers two qualification approaches: design level qualification (see design criteria above) or performance level qualification through testing
    - IEEE 1527 (2018c) and ASCE 113 (2008) both reference IEEE 693 for seismic design criteria and performance levels
    - IEEE 1527 adds that substation buswork in seismically active areas "must allow the interconnected equipment to displace without sudden impact due to loss of all available slack." For flexible conductors, the slack must equal at least the maximum differential displacement, or elongation demand, during a seismic event; for rigid buses, the slack should "allow for the differential displacement to take place without sudden impact"
- Rural Substations: Ground motion parameters based on UBC Seismic Zone Factor Maps
    - Design parameters provided for < 0.3 g PGA (RUS Bulletin 1724E-300, USDA 2001)
    - Substation rigid and flexible isolated support structures in Zones 3 (0.3 g PGA) or 4 (0.4 g PGA) must be designed to IEEE 693, which sets performance objectives of 0.5 g moderate to 1.0 g high, referring to ASCE 7 ground motion parameters and using USGS seismic design maps (RUS Bulletin 1724E-300)
- Other structures: ASCE 7 ground motion parameters based on USGS seismic design maps (IEEE 693, IEEE 2018b)
    - Many seismic guidelines for other electric power infrastructure (e.g., gas-insulated substations, outdoor substations, etc.) refer to IEEE 693

    - Transmission tower and structural pole design refers to ASCE MOP 74 (2020) for design loads, which refers to ASCE 7 for wind and seismic design loads; ASCE MOP 74 notes that most transmission structural vibration issues are wind-induced (ASCE 10 (2015), ASCE 48 (2019))
    - Distribution poles and lines are designed
- **Expected Performance Levels**
  - Nuclear Plants: As with flood hazard, must allow for sufficient time to safely shut down plant (10 CFR Part 50, Appendix S, NRC 2017a)
  - Hydroelectric Plants: Must be able to withstand earthquake ground motion parameter loading condition, or up to condition where failure would not cause hazard downstream to life and property (FERC 2021)
    - Hazard potential classified as low (no loss of human life expected, low economic or environmental damage), significant (no loss of human life expected, economic or environmental damage expected), or high (probable loss of human life)
    - Designers must define consequences of dam failure by reviewing USGS seismic design maps, and conducting site-specific seismic hazard analysis
  - Substations and Buswork, and Power Transformers and Reactors: Must survive the design earthquake without significant damage and maintain electric power functionality at nominal operating conditions during and after an event (IEEE 693, IEEE 2018b)
  - Rural Substations: Design should minimize damage, even if some damage will most likely be sustained (RUS Bulletin 1724E-300, USDA 2001)
  - Other Structures: Provide life safety and controlled deformation in selected members, maintain structural stability and integrity, and a limited probability of collapse at the risk-based maximum considered earthquake hazard (MCE_R, ASCE 2021).

4.4.1.3 Wind

Wind design criteria for electric power infrastructure are established by ASCE 7 basic and extreme wind speed maps. Though it is a safety code and not intended for design, the NESC exempts infrastructure less than 60 ft (18.3 m) tall (i.e., most distribution poles) from ASCE 7 extreme wind or extreme ice with concurrent wind loading requirements.

- **Hazard Design Criteria**
  - Transmission Lines and Other Structures: ASCE MOP 74 (2020), ASCE 7-95 (1996) for RUS
    - 3-s gust wind speed at 33 ft (10 m) above ground in flat/open country terrain with 100-yr MRI recorded at National Weather Service stations (ASCE MOP 74, 2020)

        - Adjust design wind speeds for elevations above 33 ft (10 m) for tall structures
        - ASCE 7-95 wind design criteria referred to for rural substations (RUS Bulletin 1724E-300), air-insulated substations (IEEE 605, 2008), RTO substations (e.g., PJM 2017), and high-voltage air-break switches (C37.30.2, IEEE 2015b)
    - Rural and RTO High-Voltage Transmission Lines: NESC Extreme Ice and Wind Maps
        - Consider concurrent extreme ice and wind loads with 50-yr MRI (RUS Bulletin 1724E-200 (USDA 2009), PJM 2017); note that there is a proposal for the upcoming revised edition of NESC (2017) to apply a 100-yr MRI for extreme ice with concurrent wind
    - Offshore Substations: Sustained 1-min wind speed at 10 m (33 ft) above the ground (DNV-ST-0145, 2021)
    - Offshore Wind Turbines: Sustained and gust wind speeds at 10 m (33 ft) above mean sea level
        - Conduct wind data analysis on local, gust wind actions and fatigue limit state structural assessment on sustained and time variable wind conditions (ANSI/American Petroleum Institute (API) Recommended Practice 2MET, Moffatt & Nichol 2015)
- **Expected Performance Levels**
    - Transmission Lines and Other Structures: Reliability to design load, as well as failure containment through rigid inspection and anti-cascade structures or load-limiting devices (ASCE MOP 74, 2020)
    - Rural High-Voltage Transmission Lines: Withstands ice and wind loads associated with Uniform Ice Thickness and Concurrent Wind Speed specified by NESC (RUS Bulletin 1724E-200, 2009)
    - RTO High-Voltage Transmission Lines: Withstands ice and wind loads associated with Uniform Ice Thickness and Concurrent Wind Speed specified by NESC if 138 kV or less, 25 psf (1.2 kpa) or NESC Extreme Wind (whichever greater) for lines greater than 138 kV (NESC 2017, PJM 2017)
    - Offshore Substations: Ensure safety of personnel from electrical hazards (DNV-ST-0145, 2021)
    - Offshore Wind Turbines: Meet design parameters for extreme, abnormal, and operationally relevant wind conditions for structure type and nature (ANSI/API Recommended Practice 2MET, Moffatt & Nichol 2015)

ASCE MOP 74 (2020) addresses wind and ice loads, but not flood or seismic loads. The MOP discusses earthquakes from the perspective that transmission tower structural performance has not been an issue from inertial loads, but earth related failures (landslides, liquefaction, lateral spreading, fault offsets, rock falls, etc.) have caused tower damage. Traditional extreme event loads (wind, ice, combined wind and ice, broken conductor/wire tensions, construction loads, etc.) provide adequate seismic capacity, along with the tower/wire dynamic system.

Resilience concepts, such as redundancy or planned recovery, could be better incorporated and defined in national standards and guidelines. Additional factors beyond weather-related hazards can cause stress to the reliability and resilience of the electric grid. For example, the Northeast Blackout of 2003, which knocked out power to 50 million people for two weeks, was caused by overgrown vegetation near electric power infrastructure, faulty alarm systems, and inexperienced operators (DOE 2015). While it is important to prioritize the most common hazards, it is also necessary to consider all hazards to improve the overall design and performance of the electric grid.

4.4.2 Resilience Concepts

There are two primary elements of resilience: (1) preparing for and withstanding hazard events, and (2) recovering system functionality following damaging hazard events. While the former element is addressed by current national electrical codes, standards, and guidelines through design loads, performance levels, and reliability standards, the latter is not. For example, NERC Reliability Standards require all bulk electric transmission systems (RTOs, ISOs, etc.) to develop and maintain an Operating Plan to prepare for and mitigate extreme weather impacts, a System Model to simulate weather event impacts, and an Outage Coordination Process, as well as to report all outages and resulting levels of damage. These requirements primarily apply to planning and mitigation prior to hazard events rather than recovery from them (NERC 2017). While RTOs, ISOs, and utilities have detailed regional recovery plans for responding to hazard outages, resilience is not uniformly regulated at the national code or standard level. Resilience concepts need to be standardized for design and recovery for greater overall electric power infrastructure resilience.

4.4.2.1 Planned Recovery

Restoration of power following hazard events begins with utilities mapping the location of infrastructure damages, determining restoration priorities based on critical needs for electric power, and dispatching crews and resources accordingly (NASEM 2017). To speed restoration activities, utilities often rely on mutual assistance agreements with other utility companies to share and temporarily re-allocate workforce and equipment resources (NASEM 2017). During outages, system operators control switching and load reduction to reroute power where needed in interconnected areas, and utilities may coordinate operations using DERs to provide power in key areas while the grid is being restored (NASEM 2017). Following immediate power restoration, investigations to identify the root cause of failure are essential to determine what additional investments are needed to fully recover load or what procedures are needed to prevent or mitigate future disruptions

(NASEM 2017). The duration of a hazard event itself is short compared to the disaster preparedness activities involved before and after (Figure 4-4); however, time to partial and full recovery is not accounted for in any reliability metrics or infrastructure standard requirements and is a key component of resilience (Preston et al. 2016).

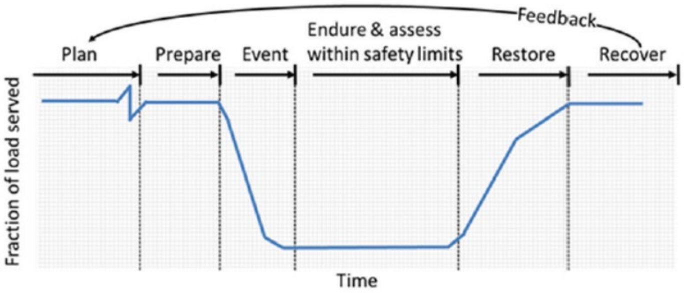


Figure 4-4: Notional Time Series of a Major Power Outage by Stage (Source: The National Academies of Sciences, Engineering, and Medicine)

Planned recovery is important for efficient restoration of power following hazard events, and increasingly involves the use of smart technology to help personnel more quickly identify damaged infrastructure and restore service. Utilities could maintain electricity in outages for critical operations while personnel repair the identified damaged equipment by using optimization software and other methods to accurately identify fault locations and optimization software to automatically switch load through islanded distributed generation, backup systems, or alternate distribution routes, (Bie et al. 2017). This may involve coordination with and access to DERs that are not necessarily owned by the utility (NASEM 2017). As the Borrego Springs community example illustrated, planned recovery that uses microgrids can provide critical electricity for community-wide resilience.

Communities can also help local businesses and organizations improve critical infrastructure recovery and decision-making in the aftermath of a hazard event. For example, following a series of devastating earthquakes in 2010 and 2011, Christchurch, New Zealand, developed an educational program to aid private businesses and schools in assessing their assets for potential infrastructure weaknesses (PwC 2013).

Flexible electric power system and load configurations as well as shared resources through mutual assistance agreements are already widely used for recovery. Standardized guidance for recovery prioritization and associated times could also improve the variability that occurs between providers.

4.4.2.2 Interdependencies

Apart from a few general references (e.g., suggestion in the NESC to route underground electricity supply and communications lines separately where practical to mitigate potential hazard impacts), codes and standards for the five electric power infrastructure subcomponents included in this analysis (generation, transmission, distribution, substations, and microgrids) do not address interdependencies with other infrastructure systems. One notable exception is the National Electrical Code (NFPA 70, 2017), which explicitly covers installations in buildings that are not integral to generation or substations, and details how electric power infrastructure and buildings are interconnected. For example, NFPA 70 states that for service conductors that pass over buildings, structural support should be provided that is independent from the building itself. While there is some existing overlap between building and electric power codes and standards, external system interdependencies could be more comprehensively articulated and codified, particularly given the cascading effects that electric power system infrastructure failure can have on other systems (e.g., loss of power to elevators in buildings, pumps for water and wastewater distribution systems, or light rail trains), and as building and transportation electrification increases system interconnectivity.

Electric power subcomponent infrastructure itself is highly internally interdependent, given the historically linear design of the electric grid. Failures upstream in generation or substation systems can cause chain reaction outages in transmission and distribution systems. DERs help mitigate this linear reliance and add resilience in the form of redundancy and backup generation (e.g., microgrids maintaining power to universities during Hurricane Sandy); however, they are not as well-regulated because not all DERs are covered by the NESC, which until recently outlined consistent safety requirements for all grid-side interdependent electric power infrastructure (generation, transmission, substations, and distribution). The NESC includes requirements for solar photovoltaic and wind turbine generation systems, for example, but it does not cover DERs such as microgrids or ground source heat pumps. Flexibility in how electric power lines are routed and managed and introduction of DERs can reduce interdependency cascading hazard effects but can introduce confusion from a codes and standards perspective because they blur the line between NESC and NEC scope.

While microgrids can improve resilience and reduce linear grid interdependence, regulatory barriers inhibit their expanded adoption or financial viability. There is a lack of consistent regulation on behind-the-meter microgrids, which raises concerns of reliability, worker safety, and operations and maintenance relative to generation and transmission systems. In addition, grid interconnection requirements and current electrical tariff structures are skewed toward utility business models that are based on one-way energy flow—from generation to transmission to distribution—rather than two-way flow between the grid and "prosumers," or customers who produce energy through on-site generation and consume energy from the grid. This introduces challenges in microgrid design, implementation, and return on investment, particularly since the ancillary market (i.e., revenue streams from selling electricity back to the grid, turning on power to critical facilities during grid outage via "black start" capabilities, supporting voltage regulation, etc.) is not available to all microgrids (Wood 2014). Finally, utility rate cases for microgrids are difficult to get approved except in particular circumstances (e.g., microgrids could help mitigate potential forest fire risks in California during transmission line forced outages), since microgrids offer localized benefits yet all rate payers bear the cost burden. While there is promising activity in this area among the U.S. House of Representatives (Roberts 2020) and certain public service commissions, regulatory barriers will need to be lifted for broader implementation of microgrids as a resilience strategy.

4.4.2.3 Gaps and Areas for Improvement

A significant gap in electric power infrastructure design practices from a hazard design perspective is flood regulation (see Table 4-1). There are national flood mitigation and protection requirements for nuclear and hydroelectric power plants, but not for other electric power subcomponents. While FEMA offers guidelines based on NFIP FIRMs, risk-based national codes and standards for flood could help improve electric power infrastructure resilience, particularly as sea levels rise continues.

Current national electric power infrastructure codes, standards, and guidelines address withstanding wind and seismic hazards. However, guidance for these hazard events and the impacts of changing climate conditions could be improved. Current electric power infrastructure requirements that refer to ASCE 7 wind or seismic maps are often based on older versions of ASCE 7. The NESC exemptions for structures less than 60 ft (18 m) in height primarily excludes community distribution systems from design criteria consistent with the rest of the electric power infrastructure.

An area for improvement from a subcomponent regulation perspective is distribution systems, as most electric power outages originate at this level of the grid. Distribution systems would benefit from reliability and resilience criteria to standardize grid performance and associated metrics (e.g., requiring voltage levels to be reported along with SAIDI and SAIFI metrics to pinpoint the subsystem origin of outages). In addition, distribution could incorporate smart grid technology for greater visibility into fault locations, utilization of DERs, and more efficient planned recovery.

The following is a summary list of the identified gaps and areas of improvement:

- Electric power codes and standards, often through ASCE MOP 74, point to older versions of ASCE 7 for wind design criteria, and flood design criteria are established using NFIP flood maps. There is a lack of structural reliability and functional recovery criteria for electric power systems and their subcomponents to support community resilience. ***Codes, standards, and guidelines need minimum requirements for the structural reliability and functional recovery of individual components and systems*, *including temporary measures that enable recovery of services, to meet typical community needs, particularly essential services.***
- Recovery time and designing for recovery (beyond failure containment) are not addressed by electric power codes, standards, or best practices. To advance resilience, guidance is needed to address recovery of electric power system functionality. ***Design***

methods and criteria need to support designing for recovery, as resilience goes beyond failure containment, are needed to address how design and expected damage affect the recovery process.

- Electric power distribution systems could incorporate smart grid technology for greater visibility into fault locations, utilization of distributed energy resources (DER) as backup generation sources, and to support more efficient and flexible planned recovery. ***Electric power line routes need to be designed more dynamically for added redundancy and automated or simplified rerouting in the event of outages.***
- The NEC requires all healthcare facilities to have on-site backup generators to meet critical electric power loads in the event of outage; however, DERs are not required for critical facilities. The role of DERs in meeting resilience performance requirements of critical facilities needs to be clarified, including minimum requirements, technology options, and challenges and solutions related to their use. ***Distributed energy resources (DERs) or microgrids (combinations of DERs) should be incorporated for critical facilities***.
- As floodplains and extreme precipitation events increase with climate change, improved requirements for safe design and operations of electric power infrastructure will be needed. ***Risk-based flood hazard design requirements for electric power infrastructure need to be developed.***

Addressing these major areas for improvement would strengthen the electric power grid and render communities less susceptible to impact from flood, seismic, or wind hazards. Design criteria to minimize damage and recovery time to ensure functionality after an event need to be addressed for greater resilience in electric power infrastructure.

4.5 Conclusions

The national electric grid is an infrastructure system critical to community resilience as well as to the resilience of other infrastructure systems. While current national electric power infrastructure codes, standards, and guidelines generally cover reliability and withstanding hazards to the design criteria, there are several areas for improvement that could increase the overall resilience and reliability of the system, including:

- Improving flood hazard codes and standards
- Updating design criteria to address changing climate and hazard events
- Updating ASCE MOP 74 guidelines (which establish wind design loads for most transmission and substation infrastructure) wind criteria
- Establishing distribution reliability and resilience guidance and standards

As the electric power system becomes more flexible with alternate power sources and renewably sourced, and as more external systems rely on electric power infrastructure, this is an opportune time for strengthening design practices and increasing system resilience.

4.6 References

ANSI, 1992. *Determining Design Basis Flooding at Power Reactor Sites*, (ANS)-2.8-1992, American Nuclear Society, American National Standards Institute, Washington, DC.

ASCE, 1996, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, ASCE 7-95, American Society of Civil Engineers, Reston, VA.

ASCE, 1999. *Guide to Improved Earthquake Performance of Electric Power Systems,* MOP 96, Edited by AJ Schiff, American Society of Civil Engineers, Reston, VA.

ASCE, 2005. *Design of Steel Transmission Pole Structures*, ASCE 48-05. American Society of Civil Engineers, Reston, VA.

ASCE, 2006, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, ASCE 7-05, American Society of Civil Engineers, Reston, VA.

ASCE, 2008. Substation Structure Design Guide, ASCE MOP 113, Edited by L. Kempner, American Society of Civil Engineers, Reston, VA.

ASCE, 2015. *Design of Latticed Steel Transmission Structures*, ASCE 10-15. American Society of Civil Engineers, Reston, VA.

ASCE, 2017. *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, ASCE 7-16. American Society of Civil Engineers, Reston, VA.

ASCE, 2019. *Seismic Design Criteria For Structures, Systems, And Components In Nuclear Facilities*, ASCE 43-2019. American Society of Civil Engineers, Reston, VA.

ASCE, 2020. *Guidelines for Electrical Transmission Line Structural Loading*. ASCE MOP 74, 4th Edition. American Society of Civil Engineers, Reston, VA. https://ascelibrary.org/doi/10.1061/9780784479414.013

ASCE, 2021. *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*. ASCE 7-22. American Society of Civil Engineers, Reston, VA.

Anguelov, K. & Stiolov, D., 2016. *Risk based asset management of electrical distribution network*. 2016 19th International Symposium on Electrical Apparatus and Technologies (SIELA), DOI:10.1109/SIELA.2016.7542971

Austin, Texas, 2019. *Flood Risk and Atlas 14*, Watershed Development, Codes and Regulations, Austin, TX. https://www.austintexas.gov/department/flood-risk-and-atlas-14.

Beta Engineering, 2022. *Five Differences Between Air Insulated Substations and Gas Insulated Substations*. Beta Engineering, Pineville, LA. https://www.betaengineering.com/news/5-differences-between-air-insulated-substations-and-gas-insulated-substations

Bie, Z., Lin, Y., Li, G., & Li, F., 2017. *Battling the Extreme: A Study on the Power System Resilience*. IEEE, 105 (7): 1253-1266. https://ieeexplore.ieee.org/document/7893706.

Breslin, M., 2011. *Restoring Power in the Wake of the Joplin Disaster*, Electrical Contractor Magazine, Washington, DC. https://www.ecmag.com/section/miscellaneous/restoring-power-wake-joplin-disaster.

Butterfield, J, 2021. 4 *Changes to 2017 National Electric Code for Renewable Energy Systems*, Hallam-ICS Blog, https://www.hallam-ics.com/blog/medium-voltage-systems-0

CEATI International, 2022. Center for Energy Advancement through Technology Innovation. https://www.ceati.com/

Cleary, K and Palmer, K,, 2019. *Planning for Resilience in a Renewable-Dominated World*, Resources, Resources for the Future, ISSN: 0048-7376.

Con-Ed, 2013. *Post Sandy Enhancement Plan,* Consolidated Edison Company of New York, Orange and Rockland Utilities, New York, NY. https://www.coned.com/-/media/files/coned/documents/services-outages/post_sandy_enhancement_plan.pdf

Con-Ed, 2019. *Our Climate Change Resiliency Plan*. https://www.coned.com/en/our-energy-future/our-energy-vision/storm-hardening-enhancement-plan

CPUC, 2021. *Rule 21 Interconnection*, California Public Utilities Commission, State of California. https://www.cpuc.ca.gov/Rule21/.

CSA Group, 2019. *Development of Climate Change Adaptation Solutions Within the Framework of the CSA Group Canadian Electrical Code Parts I, II and III*. https://www.csagroup.org/wp-content/uploads/CSA-RR_CEC-ClimateChange.pdf.

DNV, 2021. *Offshore Substations,* DNV-ST-0145, Det Norske Veritas, Oslo, Norway. https://www.dnv.com/energy/standards-guidelines/dnv-st-0145-offshore-substations.html#

DOE, 2012. *Hurricane Sandy and Our Energy Infrastructure*, Department of Energy, Washington, DC. https://www.energy.gov/articles/hurricane-sandy-and-our-energy-infrastructure.

DOE, 2013. *Comparing the Impacts of Northeast Hurricanes on Energy Infrastructure*. Office of Electricity Delivery and Energy Reliability, Department of Energy, Washington, DC. https://www.energy.gov/sites/prod/files/2013/04/f0/Northeast%20Storm%20Comparison_FINAL_041513b.pdf.

DOE, 2015. *United States Electricity Industry Primer*. Department of Energy, Washington, DC. https://www.energy.gov/sites/prod/files/2015/12/f28/united-states-electricity-industry-primer.pdf].

DOE, 2016. *Natural Phenomena Hazards Analysis and Design Criteria for DOE Facilities*. DOE-STD-1020-2016, Department of Energy, Washington, DC.

DOE, 2021. *Electricity 101*. Office of Electricity. Department of Energy, Washington, DC. https://www.energy.gov/oe/information-center/educational-resources/electricity-101#sys2.

EIA, 2019. *Investor-owned utilities served 72% of U.S. electricity customers in 2017*. U.S. Energy Information Administration, Washington, DC. https://www.eia.gov/todayinenergy/detail.php?id=40913

EIA, 2020. *Electricity explained: Electricity generation, capacity, and sales in the United States*. U.S. Energy Information Administration, Washington, DC. https://www.eia.gov/energyexplained/electricity/electricity-in-the-us-generation-capacity-and-sales.php

EPA, 2018. *The Benefits and Costs of Green Power*, Chapter 3, Guide to Purchasing Green Power, Environmental Protection Agency, Washington, DC. https://www.epa.gov/sites/default/files/2018-08/documents/guide-purchasing-green-power-3.pdf

EPRI, 2009. *EPRI Transmission Line Reference Book: Wind-Induced Conductor Motion (Orange Book) Revision*, Report 1018554, Electric Power Research Institute, Palo Alto, CA.

EPRI, 2013. *Enhancing Distribution Resiliency: Opportunities for Applying Innovative Technologies*. Electric Power Research Institute, Palo Alto, CA. https://www.epri.com/#/pages/product/000000000001026889/?lang=en-US.

EPRI, 2017. *EPRI Transmission Line Reference Book—200 kV and Above, Third Edition: The "Red Book"*, Electric Power Research Institute, Palo Alto, CA

Eto, J., LaCommare, K., Caswell, H., & Till, D., March 2019. *Distribution system versus bulk power system: identifying the source of electric service interruptions in the US.*, Energy Analysis and Environmental Impacts Division, Lawrence Berkeley National Laboratory, Berkeley, CA. https://eta-publications.lbl.gov/sites/default/files/dist_system_vs._bulk_power_journal_article.pdf.

Eto, J., 2018. *Reliability Metrics and Reliability Value-Based Planning*, Presentation, Lawrence Berkeley National Laboratory, Berkeley, CA. https://emp.lbl.gov/sites/default/files/6._170928_necpuc_training_reliability_metrics_and_rvbp.pdf.

FEMA, 2004. *Selecting and Accommodating Inflow Design Floods for Dams*, FEMA P-94, Federal Emergency Management Agency, Washington, DC.

FEMA, 2007. *Design Guide for Improving Critical Facility Safety from Flooding and High Winds: Providing Protection to People and Buildings*. FEMA 543, Risk Management Series, Federal Emergency Management Agency, Washington, DC. https://www.hsdl.org/?abstract&did=817800.

FEMA, 2012. *Minimizing Flood Damage to Electrical Service Components*. https://s3-us-gov-west-1.amazonaws.com/dam-production/uploads/20130726-1859-25045-5831/fema_isaac_ra_2.pdf.

FEMA, 2013a. *Making Critical Facilities Safe from Flooding*, FEMA 543, Risk Management Series. Federal Emergency Management Agency, Washington, DC.

FEMA, 2013b. *New York/New Jersey Coastal Advisory Flood Hazard Information Development, Final Report,* Federal Emergency Management Agency, Washington, DC.

FERC, 2020. *FERC Engineering Guidelines: Risk-Informed Decision Making, Chapter R20: Probabilistic Seismic Hazard Analysis*, Federal Energy Regulatory Commission, Washington, DC. https://www.ferc.gov/sites/default/files/2020-04/chapter-R20.pdf

FERC, 2021. *Engineering Guidelines for the Evaluation of Hydropower Projects*, Federal Energy Regulatory Commission, Washington, DC. https://www.ferc.gov/industries-data/hydropower/dam-safety-and-inspections/eng-guidelines.

FERC, 2022. *Electric Transmission*, Federal Energy Regulatory Commission, Washington, DC. https://www.ferc.gov/electric-transmission

GridWise Alliance, 2013. *Improving Electric Grid Reliability and Resilience: Lessons Learned from Superstorm Sandy and Other Extreme Events*, https://www.energy.gov/sites/prod/files/2015/03/f20/GridWise%20Improving%20Electric%20Grid%20Reliability%20and%20Resilience%20Report%20June%202013.pdf.

Hansen, T., 2016. *Reliability vs. Resiliency*, PowerGrid International, Distributech International, Dallas TX.. https://www.power-grid.com/td/reliability-vs-resiliency/#gref.

Hirsch, A., Parag, Y., and Guerrero, J., 2018. *Microgrids: A review of technologies, key drivers, and outstanding issues*. Renewable and Sustainable Energy Reviews, July 2018, 90, 402-411. https://doi.org/10.1016/j.rser.2018.03.040.

IAEI, 2019. *U.S. Electrical Codes and Regulations by State*, International Association of Electrical Inspectors, Richardson, TX. https://iaeimagazine.org/magazine/nec-code-adoption/united-states/

IEC, 2010. *Communication networks and systems for power utility automation – Part 90-1: Use of IEC 61850 for the communication between substations*, Technical Report, IEC/TR

61850-90-1, International Electrotechnical Commission, Geneva, Switzerland. https://webstore.iec.ch/preview/info_iec61850-90-1%7Bed1.0%7Den.pdf

IEEE, 2008. *Guide for Bus Design in Air-Insulated Substations – wind loading design guidelines for outdoor substations*, IEEE 605, Institute of Electrical and Electronic Engineers, Piscataway, NJ.

IEEE, 2011a. *Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems*, IEEE 1547.4-2011, Institute of Electrical and Electronic Engineers, Piscataway, NJ.

IEEE, 2011b. *Guide for Smart Grid Interoperability of Energy and Information Technology Operation with the Electric Power System*, IEEE 2030, Institute of Electrical and Electronic Engineers, Piscataway, NJ.

IEEE, 2013. *One Year Later; Superstorm Sandy Underscores Need for a Resilient Grid*, Spectrum, Institute of Electrical and Electronic Engineers, Piscataway, NJ. https://spectrum.ieee.org/energy/the-smarter-grid/one-year-later-superstorm-sandy-underscores-need-for-a-resilient-grid.

IEEE, 2015a. *Draft Guide for Electric Power Distribution Reliability Indices*, IEEE P1366, Institute of Electrical and Electronic Engineers, Piscataway, NJ.

IEEE, 2015b. *Guide for Wind-Load Evaluation of High-Voltage (>1000 V) Air-Break Switches*, IEEE C37.30.2, Institute of Electrical and Electronic Engineers, Piscataway, NJ.

IEEE, 2018a. *Working with Electricity: How the NESC Differs From the NEC*, Institute of Electrical and Electronic Engineers, Piscataway, NJ. https://innovationatwork.ieee.org/how-the-nesc-differs-from-the-nec/

IEEE, 2018b. *Recommended Best Practice for Seismic Design of Substations*, IEEE-693-18, Institute of Electrical and Electronic Engineers, Piscataway, NJ. https://standards.ieee.org/standard/693-2018.html.

IEEE, 2018c. *Recommended Practice for the Design of Buswork Located in Seismically Active Areas*, IEEE 1527-2018, Institute of Electrical and Electronic Engineers, Piscataway, NJ. https://standards.ieee.org/ieee/1527/4976/

IEEE, 2018d*. Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces*, IEEE 1547-2018, Institute of Electrical and Electronic Engineers, Piscataway, NJ. https://standards.ieee.org/standard/1547-2018.html.

IEEE, 2018e. *Standard for Design and Verification of Low-Power, Energy-Aware Electronic Systems*, IEEE 1801, Institute of Electrical and Electronic Engineers, Piscataway, NJ. https://standards.ieee.org/standard/1801-

2018.html?utm_source=ieeeorg&utm_medium=the-institute&utm_campaign=sustainable-development-2021

IEEE, 2019. *High-voltage switchgear and controlgear – Part 111: Automatic circuit reclosers for alternating current systems up to and including 38 kV*, IEEE C37.60, Institute of Electrical and Electronic Engineers, Piscataway, NJ. https://standards.ieee.org/standard/C37_60-2012.html.

IEEE, 2021. *9 Standards for a More Sustainable Future in Honor of Earth Day*, Spectrum, IEEE Standards Association, 22 April, Institute of Electrical and Electronic Engineers, Piscataway, NJ. https://spectrum.ieee.org/9-standards-for-a-more-sustainable-future-in-honor-of-earth-day.

Kempner, L., 2009. *Wind Load Methodologies for Transmission Line Towers and Conductors*, Electrical Transmission and Substation Structures 2009, November 8-12, 2009, Fort Worth, Texas. https://doi.org/10.1061/41077(363)19.

Kempner, L., Schleter, S., and Haldar, A., 2018. Seismic Effects on Transmission Lines and Their Major Components, Electrical Transmission and Substation Structures 2018, November 4–8, 2018, Atlanta, Georgia. https://ascelibrary.org/doi/10.1061/9780784481837.012.

Lazar, J., 2016. *Electricity Regulation in the US: A Guide (Second Edition),* The Regulatory Assistance Project, Montepelier, VT. https://www.raponline.org/knowledge-center/electricity-regulation-in-the-us-a-guide-2.

Levitan, M., Twisdale, L., and Phan, L., 2021. New Tornado Risk Maps for Engineering Design. NRC Regulatory Information Conference RIC 2021. https://ric.nrc.gov/docs/abstracts/levitanm-t11-hv.pdf

Lu, J., Guo, J., Jian, Z., Yang, Y., & Tang, W., 2018. *Resilience Assessment and Its Enhancement in Tackling Adverse Impact of Ice Disasters for Power Transmission Systems*. Energies 2018, 11 (9), 2272. https://doi.org/10.3390/en11092272.

Malushte, 2016. *Comparison of ASCE 7 and ASCE 43 for Informed Adoption of ASCE 7 for Seismic Design of SDC-1 SSCs*, Presentation, 2-16 DOE Natural Phenomena Hazards (NPH) Meeting. https://www.energy.gov/sites/prod/files/2016/11/f34/2_Sanj_Malushte_Comparison_of_ASCE_7_and_ASCE_43_for_Informed_Adoption_of_ASCE_7__Tuesday_18_2016%5B1%5D.pdf

Marston, T., 2018. *The US Electric Power System Infrastructure and Its Vulnerabilities*, The Bridge, National Academy of Engineering, Washington, DC. https://www.nae.edu/183133/The-US-Electric-Power-System-Infrastructure-and-Its-Vulnerabilities.

Moffatt & Nichol, 2015. *Offshore Substation Design Development of Standards*, Study for Bureau of Safety and Environmental Enforcement & Bureau of Ocean Energy Management, Baltimore, MD. https://www.boem.gov/sites/default/files/renewable-energy-program/Studies/TAP/723AA.pdf.

NASEM, 2017. *Enhancing the Resilience of the Nation's Electricity System*. The National Academies Press, National Academies of Sciences, Engineering, and Medicine Washington, DC. https://www.nap.edu/read/24836/chapter/1.

Navigant, 2015. *Community Microgrid Case Study and Analysis Report*, Prepared for: New York State Smart Grid Consortium, Navigant Consulting, Inc., Burlington, MA. http://nyssmartgrid.com/wp-content/uploads/CommunityMicrogridCaseStudyandAnalysisReport_2015-08-133.pdf.

NERC, 2016*. Transmission Vegetation Management*, FAC-003-4, North American Electric Reliability Corporation, Atlanta, GA. https://www.ferc.gov/sites/default/files/2020-04/fac-003-4.pdf

NERC, 2017. *All Reliability Standards*. North American Electric Reliability Corporation, Atlanta, GA. https://www.nerc.com/pa/Stand/Pages/AllReliabilityStandards.aspx.

NERC, 2020. *Reliability Indicators*. North American Electric Reliability Corporation, Atlanta, GA. https://www.nerc.com/pa/RAPA/ri/Pages/default.aspx.

NERC, 2021. *Critical Infrastructure Protection (CIP) Standards*, North American Electric Reliability Corporation, Atlanta, GA. https://www.nerc.com/pa/Stand/Pages/CIPStandards.aspx.

NESC, 2017. *National Electrical Safety Code*, IEEE C2-2017, Institute of Electrical and Electronic Engineers, Piscataway, NJ. https://standards.ieee.org/standard/C2-2017.html.

NFPA, 2017. *NFPA 70: National Electric Code,* National Fire Protection Association, Quincy, MA. https://catalog.nfpa.org/NFPA-70-National-Electrical-Code-NEC-C4022.aspx

NIBS, 2015. *Project 17- Developing Next-Generation Seismic Design Value Maps*. Building Seismic Safety Council, National Institute Building Sciences (NIBS), Washington, DC. https://www.nehrp.gov/pdf/Project17PlanningReport.pdf

NIST, 2014. NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 3.0, National Institute of Standards and Technology, Gaithersburg, MD. https://www.nist.gov/system/files/documents/smartgrid/NIST-SP-1108r3.pdf.

NIST, 2016. *Community Resilience Planning Guide for Buildings and Infrastructure Systems.* NIST Special Publication 1190 Volume I and II. National Institute of Standards and Technology. Gaithersburg, MD. http://dx.doi.org/10.6028/NIST.SP.1190v1, http://dx.doi.org/10.6028/NIST.SP.1190v2.

NRC, 1976. *Regulatory Guide 1.102: Flood Protection for Nuclear Power Plants, Revision 1*, Nuclear Regulatory Commission, Washington, DC. https://www.nrc.gov/docs/ML0037/ML003740308.pdf

NRC, 2009. *Tsunami Hazard Assessment at Nuclear Power Plant Sites in the United States of America*, US Nuclear Regulatory Commission, Washington, DC. https://www.nrc.gov/docs/ML0915/ML091590193.pdf

NRC, 2011. *Design-Basis Flood Estimation for Site Characterization at Nuclear Power Plants in the United States of America*, U.S. Nuclear Regulatory Commission, Washington, DC. https://www.nrc.gov/docs/ML1132/ML11321A195.pdf.

NRC, 2017a. *Seismic Design Standards and Calculational Methods in the United States and Japan*, NUREG/CR -7230, US Nuclear Regulatory Commission, Washington, DC. https://www.nrc.gov/docs/ML1713/ML17131A127.pdf

NRC, 2017b. *Appendix S to Part 50—Earthquake Engineering Criteria for Nuclear Power Plants*. U.S. Nuclear Regulatory Commission, Washington, DC. https://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-apps.html

NRC, 2019. *Post-Fukushima Safety Enhancements*. U.S. Nuclear Regulatory Commission, Washington, DC. https://www.nrc.gov/reactors/operating/ops-experience/post-fukushima-safety-enhancements.html].

NYC 2021. Climate Resiliency Initiatives – Frequently Asked Questions. Department of City Planning, New York City. https://www1.nyc.gov/site/planning/plans/climate-resiliency-faq.page.

OSHA, 2021. *Electrical Standards*. Occupational Safety and Health Administration, Washington, DC.. https://www.osha.gov/electrical/standards.

Oueid, R. K., 2019. Microgrid finance, revenue, and regulation considerations. The Electricity Journal, June 2019, 32 (5), 2-9. https://doi.org/10.1016/j.tej.2019.05.006.

Penning, M, 2012. *Linemen Rebuild Joplin After Twister's Destruction*. T&D World, Overland Park, KS. https://www.tdworld.com/overhead-distribution/article/20961296/linemen-rebuild-joplin-after-twisters-destruction

Pepco, 2022. *Reliability Improvements,* Potomac Electric Power Company. https://www.pepco.com/SmartEnergy/ReliabilityImprovements/Pages/default.aspx

PJM, 2017. *Overhead Transmission Lines, V. Design, Application, Maintenance & Operation Technical Requirements*, PJM, Audubon, PA. https://www.pjm.com/-/media/planning/design-engineering/maac-standards/20020520-va-general-criteria.ashx

Preston, B, SN. Backhaus, M Ewers, JA Phillips, CA Silva-Monroy, JE Dagle, Alfonso G. Tarditi, J Looney, and TJ King, Jr., 2016. *Resilience of the U.S. Electricity System: A Multi-Hazard Perspective*, Department of Energy, Washington, DC. https://www.energy.gov/sites/prod/files/2017/01/f34/Resilience%20of%20the%20U.S.%20Electricity%20System%20A%20Multi-Hazard%20Perspective.pdf

PwC, 2013. *The mantra in Christchurch: prepare, prepare, prepare*. PwC Rebuilding for Resilience. https://www.pwc.com/gx/en/capital-projects-infrastructure/disaster-resilience/assets/pdf/interview-bob-parker.pdf.

Reed, C., 2013. *Challenges Impacting Critical Electrical Infrastructure in the Floodplain and Flood Prone Areas due to Storm Events and Sea-level Rise*. https://static1.squarespace.com/static/527154c0e4b09a993f80e460/t/5277a615e4b0ffc77a65e655/1383573013727/3-1-Reed.pdf.

Roberts, M, 2020. *Congressional Proposal Recognizes Microgrid Role in US Climate Strategy*, Microgrid Knowledge. https://microgridknowledge.com/microgrids-climate-strategies.

Shadle, D., 2019. *SF6: Does its Impact Outweigh its Benefits*?, T&D World, Overland Park, KS. https://www.tdworld.com/substations/article/21118852/sf6-does-its-impact-outweigh-its-benefits

UL, 2021. *Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources*, UL 1741, Underwriter Laboratories, Northbrook, IL. https://standardscatalog.ul.com/ProductDetail.aspx?productId=UL1741.

USDA, 2001. *Design Guide for Rural Substations*, Bulletin 1724-300, Rural Utilities Service, U.S. Department of Agriculture, Washington, DC. https://www.rd.usda.gov/sites/default/files/UEP_Bulletin_1724E-300.pdf

USDA, 2009. *Design Manual for High Voltage Transmission Lines*, Bulletin 1724-200, Rural Utilities Service, Electric Staff Division. U.S. Department of Agriculture, Washington, DC. https://www.rd.usda.gov/files/UEP_Bulletin_1724E-200.pdf

USDA, 2022. *Electric Programs*, Rural Development, U.S. Department of Agriculture, Washington, DC. https://www.rd.usda.gov/programs-services/electric-programs

Vann, A, 2010. *The Federal Government's Role in Electric Transmission Facility Siting*, Congressional Research Service, Washington, DC. https://fas.org/sgp/crs/misc/R40657.pdf.

Warwick, WM, TD Hardy, MG Hoffman, JS Homer. July 2016. *Electricity Distribution System Baseline Report*, PNNL-25178, Pacific Northwest National Laboratory, Richland, WA. https://www.energy.gov/sites/prod/files/2017/01/f34/Electricity%20Distribution%20System%20Baseline%20Report.pdf

Wood, E, 2014. *How Microgrids Earn Revenue and Serve the Central Grid*, Microgrid Knowledge. https://microgridknowledge.com/microgrids-earn-revenue-serve-central-grid.

5 Transportation Infrastructure

5.1 Overview

The U.S. transportation system is composed of interconnected modes, including roads, rail, transit, air, and maritime, that transport people, food, water, medicines, fuel, and other commodities essential to the public health, safety, security, and economic wellbeing of our communities. The infrastructure supporting these transportation modes include road and highways, bridges, tunnels, railways, airports, and maritime ports that provide services vital to our life and communities.

People use transportation systems to travel to and from work and school, visit family and friends, and manage their health. Businesses use multi-modal transportation (trucks, ships, trains, and airplanes) to efficiently transport goods from the point of production to the point of use or consumption. The critical role that transportation infrastructure plays in community resilience is highlighted by both its complex intermodal organization, and its complex interdependencies in supporting services and other infrastructure systems (NIST 2016). This large, diverse U.S. transportation network also make intermodal transportation a key consideration for communities. While the different modes of transportation are highly interconnected, the codes, standards, and guidelines that govern their design and performance are typically developed independently of each other, which can create gaps in performance and community resilience.

This chapter provides a summary and analysis of transportation infrastructure regulatory bodies, codes, standards, and best practices for increased resilience, primarily to flood, seismic, and wind hazards, for four major subcomponents of the U.S. national transportation network: roads, rail, and ports (air and maritime). It is important to note that individual components such as surface roads, bridges, and tunnels together makeup a network of roads and highways in communities. Bridges and tunnels are also a part of the rail and transit network, which may have different regulations and standards. Table 5-1 provides a description and comparison of the different transportation modes and infrastructure evaluated in this chapter.

Table 5-1: Overview of Transportation Modes, Functions, and Interdependencies

Mode	Functions	Infrastructure	Interdependencies
Roads and Highways	Primary means of transportation for people at local and regional levels. National Highway System provides national surface transportation system.	• Surface roads • Bridges • Tunnels	• Primary access to other infrastructure (buildings, water, wastewater, electric power) • Utilities are usually co-located with roadways • Bridges and tunnels can be critical nodes or access points for communities • Intermodal passenger transportation (with transit, aviation, and maritime) • Intermodal freight transportation (with rail, aviation, and maritime)
Rail	Passenger and freight transport regionally and nationally. Mass transit systems transport people locally.	• Tracks • Bridges • Tunnels • Stations • Rail yards • Operation centers • Power systems	• Primary access to urban and rural areas • Intermodal freight transportation (with road, aviation, and maritime)
Air	Provides transport of people and goods long distances in short time periods nationally and internationally.	• Terminal and parking buildings • Traffic control • Hangers and maintenance facilities • Runways and taxiways	• Primary access to urban and rural areas • Intermodal freight transportation (with road, rail, and maritime)
Maritime	Provides import and export of freight internationally and distributes them inland.	• Ports • Harbors • Waterways	• Intermodal freight transportation (with road, rail, and aviation)

5.1.1 Roadways

The large network of roads and highways in the United States serves as the primary transportation infrastructure used by most people and businesses. Infrastructure for roads includes bridges and tunnels. Roads and highways encompass more than four million miles of public roadways that carry vehicles including automobiles, buses, light rail, motorcycles, and all types of trucks, trailers, and recreational vehicles (ASCE 2021a). The network includes local streets, county routes, state highways, and interstate highways. Roads also serve as evacuation and emergency access routes. Loss of a road can dramatically increase the time required for emergency responders to reach an area or reduce the ability for individuals to evacuate after a hazard event. Roads and highways also may have essential utilities that transmit, distribute and deliver services alongside, above, or below roads.

Bridges traverse significant geological features such as canyons, rivers, and other bodies of water, as well as other roads. Temporary closure of a bridge may lead to significant detour travel distances. Tunnels serve a similar purpose to bridges in road networks. They connect links of the networks by passing under water; through mountains; or under other roads, highways, or railways.

Roads, bridges, and tunnels are susceptible to damage from flood, earthquake, and wind hazards. The forces of earthquakes can cause roads to split, or secondary effects such as landslides can cause damage. Flooding can temporarily cut off the roadways until floodwaters recede but can also cause failure of the road from scour or erosion of the foundation bedding. Failure or loss of service of individual roads does not always cause a major disruption for a community because redundancy is often built into the road network. Major disruptions occur when a significant portion or critical component of a road/highway network fails, such that people and goods cannot travel to their destinations. Failure of a bridge or tunnel can put additional stress on other parts of a local road network, causing people to avoid certain areas and thus businesses.

5.1.2 Rail

Rail systems in the U.S. consist of transit systems, such as subways and elevated trains, that operate within large, high-density cities; regional commuter rail systems, which connect suburban communities to the city core; intercity passenger rail systems; freight rail systems that transport cargo both regionally and across the nation; and light rail systems that operate within cities and airports. Components of railway transportation systems include tracks, track beds, bridges, tunnels, stations, and power, dispatch and maintenance facilities.

Freight rail systems in the U.S. play a particularly important role in the intermodal transportation of containerized cargo from ports on both coasts to points in the Midwest. Containers may be double stacked on rail cars and transported to interior distribution hubs, and then transferred to trucks that take the cargo to its final destination (NIST 2016).

The U.S. railway network is similar to road and highway infrastructure in that both rely on bridges and tunnels. However, the railway network is not as redundant as local road networks. Thus, disruptions in the railway network can have a more significant impact.

5.1.3 Airports

Airport infrastructure includes control towers, runways, terminal buildings, parking structures, fuel facilities, and maintenance and hangar facilities. The nation’s air infrastructure provides the fastest way for freight and people to travel long distances. U.S. airports serve more than two million passengers a day and are a key component of the supply chain for commerce activities (ASCE 2021a). Online purchases result in tons of overnight air cargo transferred to trucks at airports and delivered to communities (ASCE

2021a). There is a strong dependency between airports and roadway systems for timely delivery of high-priority and perishable goods as well as transportation of passengers. Airport closures cause re-routing to other airports with longer truck travel times, thus delaying delivery of goods (NIST 2016).

When airports experience damage or disruptions, goods or people are typically re-routed to road and rail networks. Disruption of airports after a hazard event has a major impact on community resilience, as federal and state aid is most quickly administered by transporting resources by aviation.

5.1.4 Maritime (Ports, Harbors, and Waterways)

Maritime transportation systems such as ports, harbors, and inland waterways consist of waterfront structures, cranes/cargo handling equipment, terminal buildings, warehouses, and fuel facilities. Ports, harbors, and waterways are primarily used for import and export of goods and materials. The 926 ports in the United States are essential to the nation's economic competitiveness, responsible for $4.6 trillion in economic activity and serving as the gateway through which 99% of overseas trade passes (ASCE 2021a). The U.S. has 25,000 miles of inland waterways and 239 locks (to raise and lower watercraft) that form the freight network's water highway (ASCE 2021a). Unlike road and rail networks, there is little redundancy in the inland waterways network. Loss of use on a single inland waterway is not easily addressed within the marine transportation system. The use of railway and roadway systems as replacements is less efficient due to the orders of magnitude differences in load carrying capacities between containers and ships.

Maritime infrastructure offers another important component of domestic trade: waterborne transportation of passengers and vehicles (NIST 2016). Ferries transport commuters across metropolitan waterways where tunnels and bridges are not available or in areas with heavy road or rail traffic (NIST 2016). In addition, ferries can support emergency evacuations of urban areas when other transportation networks are congested or inoperable (NIST 2016).

5.2 Literature Review and Data Collection

5.2.1 Regulatory Environment

Regulatory bodies at federal, state, and local levels of government have authority over the transportation infrastructure sector. State, local, and regional agencies are largely responsible for regulating the design, construction, and maintenance of transportation systems in their jurisdictions.

Federal regulations typically apply on interstate projects and those that involve federal funding. CFR Title 23, Part 650, prescribes FHWA policies and procedures for the location and hydraulic design of highway encroachments on floodplains, including federal highway projects administered by the FHWA. The base flood is a 100-yr flood, or a flood having a 1% chance of being exceeded in any one year. The design flood is defined as “the peak discharge, volume if appropriate, stage or wave crest elevation of the flood associated with the probability of exceedance selected for the design of a highway encroachment. By definition, the highway will not be inundated from the stage of the design flood.” (FHWA 2022).

Regional coalitions in large metropolitan areas, known as metropolitan planning organizations (MPOs), have responsibility for planning, programming, and coordinating federal highway and transit investments. MPOs coordinate partnerships at the state and local levels to enhance the safe and secure transportation of goods and people; MPOs do not cover all geographies.

Federal regulatory agencies oversee transportation networks and methods of transportation. These agencies promulgate policies and regulations to maintain the safety and security of the infrastructure and its operations. Federal agencies dealing with transportation include the U.S. Department of Transportation (USDOT) and its components, including the Federal Highway Administration (FHWA), Federal Motor Carrier Safety Administration (FMCSA), Federal Transit Administration (FTA), Federal Railroad Administration (FRA), Federal Aviation Administration (FAA), and Maritime Administration (MARAD). Other federal agencies are the Transportation Security Administration (TSA), Federal Emergency Management Agency (FEMA), the United States Coast Guard (USCG), and the US Army Corps of Engineers (USACE).

In addition, transportation industry organizations provide industry-wide support and guidance. Industry organizations include American Association of State Highway and Transportation Officials (AASHTO), American Railway Engineering and Maintenance-of-Way Association (AREMA), American Public Transportation Association (APTA), and American Association of Port Authorities (AAPA).

Table 5-2 summarizes the typical ownership (private or public) and regulatory oversight authorities by method of transportation. A summary of transportation system federal regulatory agencies and their roles and responsibilities is provided in Table 5-3.

Table 5-2: Transportation Infrastructure Ownership and Governing Regulatory Agencies (Source: NIST 2016)

Industry	Infrastructure	Type	Method of Transportation	Public	Private	Oversight Authority												
						DHS	FEMA	NTSB	USDOT	FRA	FTA	TSA	FMCSA	FHWA	USCG	EPA	FAA	1+ state agencies
Surface Transport	Rail	Passenger	Inter-City Rail (Amtrak)	X		X	X	X	X	X		X						X
			Commuter Rail	X		X	X	X	X	X	X	X	X					X
			Subway	X		X	X	X	X		X	X						X
			Light Rail	X		X	X	X	X		X	X						X
			Inclined Plane	X		X	X	X	X		X	X						X
			Trolley/ Cable Car	X		X	X	X	X		X	X						X
		Freight	Class 1 Freight Carriers		X	X	X	X	X	X		X						X
	Roads, Bridges and Tunnels	Passenger	Inter-City Motor coach	X	X	X	X	X	X			X	X					X
			Intra-City Bus/Motor coach	X	X	X	X	X	X		X	X	X	X				X
			Paratransit/ Jitneys	X	X	X	X	X	X		X	X	X	X				X
			Taxis	X	X	X	X	X	X			X	X	X				X
			Personal Cars		X				X									X
		Freight	Commercial Trucking		X	X		X	X			X	X	X				X
	Maritime	Passenger	Ocean Lines		X			X	X			X			X	X		X
			Ferries	X		X	X	X	X		X	X		X	X	X		X
			Commercial Boats		X			X	X			X			X	X		X
			Personal Boats		X			X	X			X			X	X		X
		Freight	Freighters		X	X	X	X	X			X			X	X		X
			Barges		X	X	X	X	X			X			X	X		X
Air	Air	Passenger	Commercial Airplanes		X			X	X			X				X	X	X
			Blimps		X			X	X			X				X	X	X
			Drones	X	X			X	X			X				X	X	X
		Freight	Commercial Air Freight		X			X	X			X				X	X	X

Table 5-3: Federal Regulatory Agency Roles

Agency	Role
U.S. Department of Transportation (USDOT)	Responsible for ensuring a safe, efficient, and accessible transportation system. It includes operating administrations such as FHWA, FTA, FRA, FAA, and MARAD. (https://www.transportation.gov/administrations)
Federal Highway Administration (FHWA)	Responsible for ensuring that America's roads and highways remain safe, technologically up-to-date, and environmentally friendly by providing financial and technical support to state, local, and tribal government highway owners. The Administration works to improve the efficiency by which people and goods move throughout the nation and improve the efficiency of connections to other modes of transportation. (DHS 2010). (https://highways.dot.gov/)
Federal Transit Administration (FTA)	Assists in developing improved mass transportation systems for cities and communities nationwide through financial and technical support. (https://www.transit.dot.gov/)
Federal Railroad Administration (FRA)	Oversees heavy rail freight, commuter and inter-city passenger rail systems to enable the safe, reliable, and efficient movement of people and goods. Responsible for ensuring railroad safety throughout the nation in compliance with federally mandated safety standards. (https://railroads.dot.gov/)
Federal Aviation Administration (FAA)	The FAA regulates commercial service airports under the Code of Federal Regulations (CFR), Title 14 Part 139, Certification of Airports. This regulation prescribes rules governing the certification and operation of airports in any U.S. state, the District of Columbia, or any U.S. territory or possession providing scheduled passenger service. Advisory Circulars (ACs) contain methods and procedures that certificate holders use to comply with the requirements of Part 139. (https://www.faa.gov/)
Federal Motor Carrier Safety Administration (FMCSA)	The FMCSA regulates and provides safety oversight of commercial motor vehicles (CMVs), FMCSA partners with industry, safety advocates, and state and local governments to keep our nation's roadways safe and improve CMV safety through regulation, education, enforcement, research, and technology. (https://www.fmcsa.dot.gov/)
Transportation Security Administration (TSA)	Prevents the intentional destruction or disablement of all transportation modes. Imposes security oversight and regulation in aviation, highway, mass transit, passenger and freight rail, pipelines, and maritime. (https://www.tsa.gov/)
Maritime Administration (MARAD)	Promotes development and maintenance of an adequate, well-balanced, United States merchant marine, sufficient to carry the nation's domestic waterborne commerce and a substantial portion of its waterborne foreign commerce, and capable of serving as a naval and military auxiliary in time of war or national emergency. (https://www.maritime.dot.gov/)
Federal Emergency Management Agency (FEMA)	Coordinates the response to a disaster that has occurred in the United States and that overwhelms the resources of local and state authorities and supports planning to reduce vulnerabilities. (https://www.fema.gov/)
United States Coast Guard (USCG)	Oversees safety and security of national waterways, including commercial freight and passenger service, and public transportation such as municipal ferry service, boaters, and kayakers. (https://www.uscg.mil/)
United States Army Corps of Engineers (USACE)	Provides support in the emergency operation and restoration of inland waterways, ports, and harbors under the supervision of Department of Defense (DoD)/USACE, including dredging operations, and assists in restoring the transportation infrastructure. (https://www.usace.army.mil/)

5.2.2 National Codes

The FHWA is responsible for approving the design of highways on the National Highway System and has adopted AASHTO standards that apply to such facilities. AASHTO is a national, nonprofit association representing highway and transportation departments in the 50 states, the District of Columbia, and Puerto Rico. It represents all transportation modes including air, highways, public transportation, active transportation, rail, and water. Its primary goal is to foster the development, operation, and maintenance of an integrated national transportation system (AASHTO 2021).

The FAA regulates commercial service airports under 14 CFR Part 139, Certification of Airports (FAA 2022a). This regulation prescribes rules governing the certification and operation of airports in any U.S. state, the District of Columbia, or any U.S. territory or possession providing scheduled passenger service of an aircraft configured for more than nine passenger seats. Advisory Circulars (ACs) contain methods and procedures that certificate holders use to comply with the requirements of Part 139.

Marine structures vary widely in nature, from buildings to coastal engineering infrastructure, and have specific standards and guidelines (Farmer 2018). ASCE develops wind, flood, and seismic standards for piers, wharfs, and structures, as well as manuals of practice for mooring and waterfront facilities. In addition, the Department of Defense (DoD) produces Unified Facilities Criteria (UFC) for DoD coastal facilities and USACE develops the Coastal Engineering Manual (USACE 2002).

Each transportation system has building facilities such as stations, terminals, maintenance facilities, substations, cargo storage facilities, and other buildings that support its functions. These buildings are governed by adopted building codes, which are often based on the International Building Code. More information on codes and applicable standards is found in Chapter 2, Buildings.

5.2.3 National Standards

Each mode of transportation—road, rail, air, and maritime—has specific standards and specifications that typically govern the design of construction of supporting infrastructure. A summary of national consensus standards is provided in this section.

5.2.3.1 Roads

AASHTO standards are typically adopted and enforced by each state’s Department of Transportation (DOT). AASHTO publishes specifications, test protocols, and guidelines used in highway and bridge design and construction throughout the United States. AASHTO design specifications have been widely accepted for road, bridge, and tunnel design. The standards are used by the state highway departments and by other transportation authorities and agencies in the United States. However, not all transportation agencies accept the AASHTO code in its entirety. State DOTs and local government agencies regularly issue amendments to the AASHTO code. These amendments offer additional requirements or exceptions to certain design criteria.

The primary AASHTO standards applied to surface roads and highways include:

- A Policy on Design Standards – Interstate System, 6th Edition (AASHTO, 2016a)
- A Policy on Geometric Design of Highways and Streets, 7th Edition (AASHTO, 2018a)

These documents primarily focus on geometric and traffic safety design standards for construction of roadways and highways.

The design and construction of bridges that are a part of road and highway networks are typically governed by:

- Load and Resistance Factor Design (LRFD) Bridge Design Specifications, 9th Edition (AASHTO, 2020a)
- LRFD Bridge Construction Specifications, 4th Edition (AASHTO, 2020b)

The provisions of these standards are intended for the design, evaluation, and rehabilitation of both fixed and movable highway bridges. The documents define minimum design-level hazard events for flood, wind, and seismic with varying performance levels. The criteria are based on prescriptive requirements where satisfactory performance is assumed if the requirements are met. The basis of the prescriptive requirements is life safety with limited considerations for operational classification. Provisions are not included for bridges used solely for railway, rail transit, or public utilities, or for mechanical, electric power, and special vehicular and pedestrian safety aspects of movable bridges. Bridges that are part of the rail network are typically governed by the AREMA *Manual for Railway Engineering* (MRE) discussed in Section 5.2.3.2.

The design and construction of tunnels that are a part of road and highway network are typically governed by the following standards:

- LRFD Road Tunnel Design and Construction Guide Specifications (AASHTO, 2017)
- Technical Manual for Design and Construction of Road Tunnels (AASHTO, 2010)
- NFPA 502, Standard for Road Tunnels, Bridges, and Other Limited (NFPA, 2020)

Tunnel standards are similar to bridge design specifications in that the criteria are based on prescriptive requirements where satisfactory performance is assumed if the requirements are met. The basis of the prescriptive requirements for tunnels is life safety. Tunnels that are part of the rail network are typically governed by the MRE, discussed in Section 5.2.3.2.

5.2.3.2 Rail

Within the rail industry, AREMA was established in 1997 as a merger of the American Railway Bridge and Building Association, Roadmaster and Maintenance of Way Association, and Communications and Signals Division of the Association of American Railroads

(AREMA 2020). The Association of American Railroads (AAR) develops standards and guidelines specifically for freight railroads (AAR 2020).

AREMA publishes recommended practices for the design, construction, and maintenance of railway infrastructure. A primary guidance document is the:

- Manual of Railway Engineering (MRE) (AREMA, 2021).

The manual includes design of the tracks, structures (bridges and tunnels), infrastructure, and passenger facilities. The MRE contains principles, data, specifications, plans, and economics pertaining to the engineering, design, and construction of the fixed plant of railways (except signals and communications), and allied services and facilities. The MRE is updated annually with new design standards for fixed railway.

5.2.3.3 Airports

Airports will typically be governed by local ordinances and building codes (see Chapter 2) adopted by the Authority Having Jurisdiction. The applicable codes and standards for buildings and structures include:

- International Building Code (IBC 2020)
- ASCE 7, Minimum Design Loads for Buildings and Other Structures (2021b)
- ASCE 24, Flood Resistant Design and Construction (2015)

The FAA can accept state standards for construction materials and methods for airports. Under certain conditions, the use of state dimensional standards that differ from the standards in FAA Advisory Circulars (AC) are acceptable for federally obligated or certified airports.

The FAA issues ACs that govern engineering, design, and construction standards for various airport-related equipment, facilities, and structures. FAA Series 150 AC Library (FAA 2022b) has a complete listing of current ACs. If a project is funded wholly or partly through the FAA, these requirements must be used. ACs cover standards for general airport design, specifying construction, design and installation of visual aids, drainage design, approach path systems, runway and taxiway pavement and lighting design, and planning and design guidelines for airport terminals and facilities. ACs define design criteria for most details of an airport’s facilities, including terminal buildings, lighting, and navigational aids. These documents define standard criteria for design and construction, but do not specifically address extreme weather events beyond drainage construction for a 2% annual exceedance storm.

5.2.3.4 Maritime

The standards that control maritime design include applicable codes and standards for buildings and structures adopted by the AHJ:

- IBC (for land-based structures supporting ports, harbors, and waterways) (2021)
- ASCE 7, Minimum Design Loads for Buildings and Other Structures (2021b)
- ASCE 24, Flood Resistant Design and Construction (2015)
- ASCE 61, Seismic Design of Piers and Wharves (ASCE 2014a)

A variety of standards and guidelines are commonly used in maritime infrastructure design and construction from organizations such as AASHTO, the World Association for Waterborne Transport Infrastructure (PIANC), ASCE, ACI, DoD, and USACE. In the United States, the DoD's UFCs are widely referenced by the marine design community even for non-military projects (Gaythwaite 2016).

Unlike traditional land-based structures, which are designed based on criteria established by building codes, marine structures are most often designed to hazard, and their performance criteria established by the designer in concert with facility owner and operator requirements (Gaythwaite 2016).

The design of land-based structures supporting ports, harbors, and waterways—such as terminal buildings or civil engineering site works—is the same as for any other land-based construction with consideration to environmental conditions. See Chapter 2, Buildings, for codes, standards, and guidelines governing resilience design of such structures.

5.2.4 Codes, Standards, and Guidelines for Natural Hazards

Codes, standards, and guidelines that typically govern the design hazard levels for transportation infrastructure is provided in Table 5-4.

5.2.4.1 Flood

AASHTO standards do not specify minimum flood hazard requirements for roads, bridges, and tunnels. AASHTO (2018a), in *A Policy on Geometric Design of Highways and Streets* states:

> "Hydraulic capacities and locations of such structures should be designed to take into consideration damage to upstream and downstream property and to reduce the likelihood of traffic interruption by flooding consistent with the importance of the road, the design traffic service needs, Federal and state regulations, and available funds. While drainage design considerations are an integral part of highway geometric design, specific drainage design criteria are not included in this policy."

Table 5-4: Codes, Standards, and Guidelines for Natural Hazards

Flood Hazards:

Roads and Highways:

- 23 CFR Title 23 Part 650 (CFR 2022)
- AASHTO Drainage Manual (2014)
- AASHTO Highway Drainage Guidelines, 4th Edition (2016b)
- AASHTO LRFD Bridge Design Specification, 9th Edition (2020a)
- AASHTO LRFD Road Tunnel Design and Construction Guide Specifications (2017)
- AASHTO Guide Specifications for Bridges Vulnerable to Coastal Storms (2008)
- FHWA HEC 17, Highways in River Environment- Floodplains, Extreme Events, Risk and Resilience, 2nd Edition (2016)
- FHWA HEC 25, Highways in Coastal Environment (2020)

Rail:

- AREMA Manual for Railway Engineering (2021)

Airports:

- International Building Code (IBC 2021)
- ASCE 7, Minimum Design Loads for Buildings and Other Structures (2020)
- ASCE 24, Flood Resistant Design and Construction (2015)
- FAA Advisory Circulars Series 150 (2022b)

Ports, Harbors, and Waterways:

- International Building Code (IBC 2021)
- ASCE 7, Minimum Design Loads for Buildings and Other Structures (2020)
- ASCE 24, Flood Resistant Design and Construction (2015)
- Design of Marine Facilities (Gaythwaite 2016)

Seismic Hazards:

Roads and Highways:

- AASHTO LRFD Bridge Design Specification, 9th Edition (2020a)
- AASHTO Specifications for LRFD Seismic Bridge Design (2011a)
- AASHTO LRFD Road Tunnel Design and Construction Guide Specifications (2017)
- FHWA Seismic Retrofitting Manual for Highway Structures: Part 1- Bridges (2006)
- FHWA Seismic Retrofitting Manual for Highway Structures: Part 2 – Retaining Structures, Slopes, Tunnels, Culverts, and Roadways (2004)
- FHWA LRFD Seismic Analysis and Design of Bridges Reference Manual (2014)
- FHWA Technical Manual for Design and Construction of Road Tunnels — Civil Elements (2009)

Rail:

- AREMA Manual for Railway Engineering (2021)

Airports:

- International Building Code (IBC 2021)
- ASCE 7, Minimum Design Loads for Buildings and Other Structures (2020)

Ports, Harbors, and Waterways:

- International Building Code (IBC 2021)
- ASCE 7, Minimum Design Loads for Buildings and Other Structures (2020)
- ASCE 61, Seismic Design of Piers and Wharves (2014a)
- PIANC Seismic Design Guidelines for Port Structures (2005)
- USACE EM 1110-2-1100, Coastal Engineering Manual (2002)

Wind Hazards:

Roads and Highways:

- AASHTO LRFD Bridge Design Specification, 9th Edition (2020a)
- FHWA LRFD for Highway Bridge Superstructures, Reference Manual.(2014)

Rail:

- AREMA Manual for Railway Engineering (2021)

Airports:

- International Building Code (IBC 2021)
- ASCE 7, Minimum Design Loads for Buildings and Other Structures (2020)

Ports, Harbors, and Waterways:

- International Building Code (IBC 2021)
- ASCE 7, Minimum Design Loads for Buildings and Other Structures (2020)
- Design of Marine Facilities (Gaythwaite 2016)

Many standards that provide recommended policy and guidance for hydraulic considerations (including design flood hazards) reference the AASHTO Drainage Manual and AASHTO Highway Drainage Guidelines. The criteria for the flood hazard design storm (10-yr, 25-yr, 50-yr, 100-yr, etc.) is typically established by the state or local agency and depends on the type and criticality of the drainage structure. Facilities designed for higher frequency storms (e.g., 10-yr) are acknowledged to have a higher potential for inundation when subjected to lower frequency storm events (e.g., 100-yr).

5.2.4.2 Seismic

Typically, seismic design criteria are specified for structures, such as bridges, tunnels, and retaining walls, but not for roadways, runways, and rails on the assumption that these components can be quickly repaired. For bridges, a 75-yr service life is assumed for design, and the design seismic event has a 7% probability of exceedance in 75 yr, corresponding to a 1000-yr event (FHWA 2014). For tunnels, the collapse of a modern transportation tunnel (particularly for mass transit purpose) during or after a major seismic event could have catastrophic effects as well as profound social and economic impacts (FHWA 2009). It is typical therefore for modern and critical transportation tunnels to be designed to withstand seismic ground motions with a return period (or mean recurrence interval, MRI) of 2,500 yr, (corresponding to 2% probability of exceedance in 50 yr, or 3% probability of exceedance in 75 yr) (FHWA 2009). The main objectives of AREMA performance criteria for railways are to ensure the safety of trains and to minimize the costs of damage and loss of use caused by potential earthquakes (AREMA 2021). A three-level ground motion and performance criteria approach is employed with ground motion levels specified for serviceability (less than design), ultimate (design), and survivability (greater than design) performance criteria. The corresponding ground motion levels are 200 to 475 yr MRI for the ultimate performance criteria and 1000-2475 yr MRI for the survivability performance criteria (AREMA 2021). AASHTO and AREMA have no seismic standards for surface roads and rail tracks.

FAA has a number of guides for airport design, but they say little about seismic performance. In general, transportation standards and guidance documents reference ASCE 7 for the seismic design of structures.

For ports, specific seismic design criteria are provided by ASCE 61. ASCE 7 may be used for public-access structures. PIANC (2005) publishes international seismic design guidelines for maritime structures.

5.2.4.3 Wind

Transportation infrastructure standards and guidelines largely refer to ASCE 7 for wind load requirements.

For bridge design, the base design wind speed is 100 mph (161 kph) for a 30 ft (9 m) elevation. Adjustments are made for variations in elevation of structural components greater than 30 ft (9 m) (FHWA 2015).

AREMA (2021) specifies wind loads for railway structures, where 30 psf (1.4 kpa) is applied to loaded structures, including girder and truss spans, towers and bents, and columns and tower bracing. For unloaded structures, the wind load is taken as 50 psf (2.4 kpa).

5.2.5 Best Practices

Best practices documents published as guidelines and manuals of practice are available for all transportation systems and are developed based on industry expertise. These documents may prescribe design hazard levels, performance levels, and resilience objectives that supplement the consensus codes and standards. These documents may be adopted by state and local agencies. Commonly used best practice documents are listed below by subcomponent.

Roads and Highways:

- AASHTO Guide for Design of Pavement Structures, 4th Edition (1993)
- AASHTO Highway Drainage Guidelines, 4th Edition (2007)
- AASHTO Guidelines for Geometric Design of Low-Volume Roads, 2nd Edition (2019)
- AASHTO Drainage Manual (2014)
- AASHTO Roadside Design Guide, 4th Edition (2011b)
- FHWA HEC 17, Highways in River Environment- Floodplains, Extreme Events, Risk and Resilience (2016)
- FHWA HEC 25, Highways in Coastal Environment (2020)

- FHWA Seismic Retrofitting Manual for Highway Structures (2004)

Bridges:

- AASHTO Guide Specifications for LRFD Seismic Bridge Design (20011a)
- AASHTO Guide Specifications for Bridges Vulnerable to Coastal Storms (2008)

Tunnels:

- NCHRP Best Practices for Roadway Tunnel Design, Construction, Maintenance, Inspection, and Operations (2011)
- FHWA Technical Manual for Design and Construction of Road Tunnels — Civil Elements (2009)

Ports, Harbors, and Waterways:

- ACI 357.3R-14, Guide for Design and Construction of Waterfront and Coastal Concrete Marine Structures (2014)
- ASCE 61 Seismic Design of Piers and Wharves (2014a)
- ASCE MOP 50, Planning and Design Guidelines for Small Craft Harbors (2012)
- ASCE MOP 129, Mooring of Ships to Piers and Wharves (2014b)
- ASCE MOP 130, Waterfront Facilities Inspection and Assessment (2014c)
- USACE EM 1110-2-1100, Coastal Engineering Manual (2002)
- USACE Design of Coastal Revetments, Seawalls, and Bulkheads (1995)
- PIANC Seismic Design Guidelines for Port Structures (2005)
- PIANC Resilience of the Maritime and Inland Waterborne Transport System (2020)
- UFC 4-152-01 Design: Piers and Wharves (2017)

5.3 Case Studies

The following case studies demonstrate transportation infrastructure performance in major hazard events, adaptation to changing climate, and example projects that implemented best practices to increase infrastructure resilience.

5.3.1 Infrastructure Performance in Hazard Events

2011 Tropical Storm Irene – Vermont

In 2011, Vermont was hit by Tropical Storm Irene, which poured as much as 11 in. (28 cm) of rain in some areas and caused about $733 million in total damages (AASHTO 2018b). The tropical storm was considered a 1,000-yr event. The heavy downpour caused flooding events around the state and washouts of buildings, roads, and bridges/culverts. More than 2,400 roads, 800 homes and businesses, 300 bridges, and a half dozen railroad lines were destroyed or damaged. This damage to infrastructure left 11 communities in the state stranded without means of access or egress.

The Vermont Agency of Transportation (VTrans) was responsible for coordinating with key partners to streamline infrastructure recovery. Immediately after the event, VTrans worked with mutual aid partners and began rebuilding the washed-out roadways. Most of the damaged roadways were addressed within a month of Tropical Storm Irene and all roadways were repaired within four months.

VTrans created an Irene Innovation Task Force after the event to identify what went well during the event and what needed to be improved. Examples of changes made to address resilience within the DOT based on the lessons learned from Tropical Storm Irene included (VTrans 2012):

- The VTrans Hydraulics Manual was updated to be brought up to date with the current VTrans bridge manual and include considerations of bridge abilities to withstand flooding.
- River channeling had a direct influence on the severity of the event, which was outside of VTrans' control. Moving forward, VTrans is supporting streambed stabilization as part of its design procedures, by increasing use of rip rap and other river stabilization design options.
- An Accelerated Bridge Program is now well-established and adopted by VTrans and the industry, making Vermont even better prepared for rapid bridge replacements.
- VTrans worked with FEMA to develop standards that would ensure structures such as culverts are built wide enough to handle debris.

2012 Hurricane Sandy – New York, New Jersey, and Connecticut

In October 2012, Hurricane Sandy brought 80 mph (129 kph) winds and up to 14 ft (4.3 m) of flooding from storm surge and tides to the Northeast United States. Many critical transportation facilities were inundated (some tunnels from floor to ceiling), and transit and roadway facilities were shut down, some for weeks.

Hurricane Sandy's storm surge caused coastal flooding, with extensive washouts and bridge damage along the Jersey Shore and the south shore of Long Island. The storm surge also led to inundation of tunnels crossing the Hudson and East Rivers, and low-lying mechanical and electric power equipment were inundated when water levels rose in coastal and near-coastal areas around the region. As water flowed into and out of major channels, bridge piers and foundations were compromised due to scouring of sediment and rocks from channel bottoms. Hurricane Sandy also caused extensive wind-related damage to roadway appurtenances like signs, guardrails, fences, and lights throughout the region, either due to direct wind related structural failure or due to damage from wind-blown trees and other debris (FHWA 2017).

The transit system experienced damage similar to area roadways but was most heavily impacted by Hurricane Sandy's storm surge. Rail and subway tunnels and stations were flooded and aboveground tracks, rail yards, signals, and switches were inundated or washed out in three states. New Jersey Transit and Metro-North Railroad also experienced severe wind-related damage, with trees and other debris destroying overhead rail lines west and north of New York City.

In addition to closures of roadway infrastructure, much of the region experienced a shortage of diesel and gasoline in the days after the storm. New York Harbor was closed to navigation by the U.S. Coast Guard for 6 days from October 30 to November 4, 2012. Due to storm surge flooding that impacted three of the region's largest refineries and several fuel storage facilities, the region's fuel distribution system could not transport enough fuel to the region's gas stations to meet demand. Motorists and truck drivers in New Jersey, New York City, and Long Island waited in hours-long lines to refuel in the days after the storm (FHWA 2017).

The impacts of Hurricane Sandy on transportation systems in New York, New Jersey, and Connecticut illustrated the need for implementing resilience measures that exceed minimum requirements in current codes and standards. Post-Sandy, all three states addressed climate change and adaptation in their planning and project development processes. The Federal Highway Administration led a Hurricane Sandy Resiliency Study to inform ways to improve resilience of the tri-state New York - New Jersey - Connecticut region's transportation system and to inform disaster recovery efforts. The study, which began in 2013 and was completed in late 2017, involved a detailed assessment of the impacts and disruption caused by Hurricane Sandy as well as from several other extreme weather events occurring in the area in 2011, and analyzed vulnerability and risk to the tri-state transportation system at three different scales: regional (entire study area), subarea (corridor/small network), and facility. The study was completed in partnership with state departments of transportation from New York, New Jersey, and Connecticut, and metropolitan planning organizations (MPOs) in the region: the New York Metropolitan Transportation Council, the North Jersey Transportation Planning Authority, and the South Western Region MPO and the Greater Bridgeport and Valley MPO in Connecticut (Adaptation Clearinghouse 2021).

5.3.2 Infrastructure Adaptation to Climate Change

Climate change considerations for transportation need to address a wider range of flood and wind events than most other infrastructure. The two case studies in this section from the New York City area provide a level of detail to highlight these requirements.

New York City Climate Resiliency Design Guidelines

NYC Climate Resilience Design Guidelines (NYC 2019) address increasing heat, precipitation, and SLR. The guidelines consider big picture approaches for planning for an uncertain future with anticipated changes to flood elevations. Unlike many of the climate change case studies described in the other chapters, these resiliency guidelines are specifically meant to incorporate climate change modeling results directly into the design process, as shown in Figure 5-1. To incorporate climate change projections, the guidelines take a number of different approaches specific to hazard and infrastructure type.

For wind hazards, the climate literature and projections indicate that the intensity and frequency of storms like hurricanes and nor'easters are expected to increase. However, there are no firm projections on how future wind conditions will change and how that would affect current design standards. Therefore, NYC made the decision to conduct research to assess projected changes from all types of wind hazards and identify risks to city infrastructure.

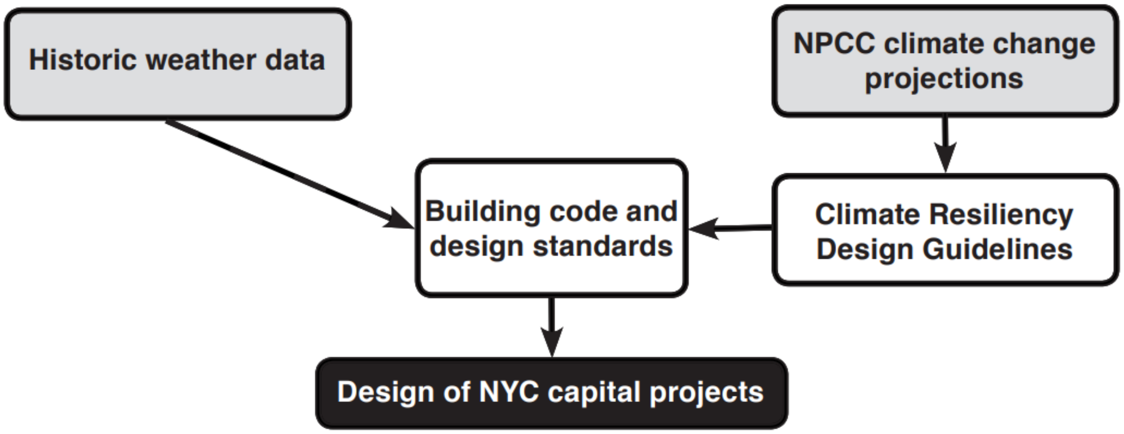


Figure 5-1: Updating the Design Process in NYC (Source: Figure 1 of NYC 2019)

One aspect of the guidelines that is unique is coupling the service life of capital projects with periods of climate projections. Typically, the service life of infrastructure is based on the infrastructure type, location, and materials. The NYC Guidelines break infrastructure and other assets into four time periods. The first time period—from the 2020s through 2039—includes temporary and rapidly replaced components such as asphalt pavement, green infrastructure, and temporary facilities. The design of these assets would use climate projections from the 2020s timeframe as their basis of design. The second time period—centered in the 2050s and covering 2040 to 2069—includes facility improvements and components on a regular replacement cycle. These include mechanical systems (electric, HVAC, etc.), concrete paving, outdoor recreational facilities, and stormwater detention systems. The third time period—centered in the 2080s and covering 2070 to 2099—includes new buildings and infrastructure such as most buildings, port facilities, and retaining walls. Lastly, the fourth time period is 2100+ and includes assets with long service periods, such as major infrastructure like tunnels, bridges, major roads, and subgrade sewer infrastructure.

For SLR considerations, this leads to a tiered approach for assigning flood freeboard values based on the following:

1. Located in area susceptible to SLR (NYC mapping is available)
2. Critical or non-critical facility (as defined by the Guidelines)
3. Service period (based on asset type)

For example, the DFE for a major road elevation in an area susceptible to SLR, assuming it is considered a critical asset and would use the 2100+ useful lifetime period, would be calculated as DFE = current FEMA 1% BFE + 2.0 ft (0.6 m) of freeboard + 3.0 ft (0.9 m) of SLR = BFE + 5.0 ft (1.5 m). The amount of design flood freeboard and SLR increases based on the criticality and time period, so the overall adjustment to BFE in the example above can be as low as 1.5 ft (0.5 m) and as high as 5.0 ft (1.5 m).

For flooding caused by precipitation, which includes inland flooding and stormwater management, the climate projections address increased intensity and frequency of rainfall events. For stormwater systems, which are expected to have a 50+ yr service life, the current design 5-yr storm event should include a rainfall intensity values for the years 2070 to 2099. The guidelines have tables with the projected changes for different precipitation statistics (by time period), including annual precipitation and number of days per year with rainfall at or above thresholds of 1, 2, and 4 in (2.5, 5.1, and 10.2 cm). The design guidance includes conducting a sensitivity analysis and benefit-cost analysis to look at possibly addressing larger events as well.

In term of designing transportation infrastructure to accommodate changing climate conditions, especially in areas susceptible to SLR, the guidelines include a section on managing uncertainty, with strategies for changing flood-protection elevations over time. The recommendations address how to design individual components of a system through the use of flood barriers or the installation of additional height to systems in the future.

Port Authority of New York and New Jersey, Engineering Department Climate Resilience Design Guidelines, v 1.2, 2018

The Port Authority of New York and New Jersey (PANYNJ) developed Guidelines that focus specifically on the facilities that the Port Authority manages (PANYNJ 2018a). These guidelines include a number of approaches for specific types of transportation infrastructure for sea level rise (SLR) and coastal inundation.

For SLR, the PANYNJ Guidelines use a similar approach to the NYC Guidelines, where a design flood elevation (DFE) is calculated based on a base flood elevation (BFE) plus a freeboard that is a function of asset location in the floodplain, criticality, and service life. The PANYNJ Guidelines use the 500-yr (or 0.2% annual chance event) floodplain for the BFE. The PANYNJ uses its own definition of criticality, which includes all Flood Design Class 3 and 4 structures. For service life, three time periods are specified: 2021 to 2050, 2051 to 2080, and 2080+. These options are used to determine the freeboard to add to the BFE. For example, the entrances for tunnels are considered critical assets, so the 2080+ requirements are applicable. The DFE = BFE + 5.0 ft (1.5 m) is similar to the value from the NYC Guidelines for 2100+ requirements.

Some specific climate change design requirements from the Port Authority's Civil Design Guidelines (PANYNJ 2018b) include using the DFE, not the BFE, as the basis for the roadway elevation for all public roadways within a flood hazard area when feasible. Drainage design is also required to account for future climate change when the water table is impacted by increases in average precipitation or sea level rise. Designs that have pipes with tidal outfalls also need to account for sea level rise changes to mean high water.

5.4 Assessment of Codes, Standards, Regulations, and Best Practices

5.4.1 Hazard Design Criteria and Performance Levels

This section characterizes the hazard design criteria and corresponding expected performance levels for each category of transportation based on assessment of the codes, standards, and best practices documents identified in the literature review, as summarized in Table 5-5.

Table 5-5: Summary of Hazard Design Criteria and Expected Performance Levels for Transportation System

Transportation Infrastructure	Flood		Seismic		Wind	
	Hazard Design Criteria	**Performance Levels**	**Hazard Design Criteria**	**Performance Levels**	**Hazard Design Criteria**	**Performance Levels**
Roadways (AASHTO, CFR, FHWA) RC II/III	**State or local requirements.** **AASHTO** 5-yr to 50-yr MRI flood depending on roadway classification**.** **CFR** 50-yr to 100-yr MRI flood.	**AASHTO** No inundation or overtopping of roadways. **CFR** Minimize damage to upstream and downstream property. Reduce the likelihood of traffic interruption.	Not Specified.	Not Specified.	Not Applicable	Not Applicable
Bridges (AASHTO, FHWA) RC III	**AASHTO** Recommends design floods for waterway, bridge overtopping, scour.	**AASHTO** No inundation or overtopping of the bridge. Structural damage may occur, but structural integrity is maintained.	**AASHTO** Recommended Design EQ (1000-yr MRI) for essential/other bridges. Large EQ (1000-2500 MRI) for essential and critical bridges.	**AASHTO** Small EQ – elastic performance without significant damage. Design/Large EQ – maintain structural stability without collapse, operational for emergency vehicles.	**AASHTO** Design wind criteria from **ASCE 7-10** for RC II structures.	**ASCE 7** Performance levels for buildings.
Tunnels (AASHTO, FHWA) RC III	**AASHTO** Consider flood and tsunami effects. **FHWA** Design flood (500-yr flood).	**AASHTO** Prevent flood inundation of tunnel. Ensure structural survival of tunnel during a design flood or tsunami event.	**AASHTO** Safety Eval EQ (SEE) MRI 1000–2500 yr). Functional Eval EQ (FEE) Risk level specified by Owner.	**AASHTO** SEE: No collapse or inundation with danger to life. Repairable damage. FEE: No collapse, minimal damage, remain operational immediately after design EQ.	Not Applicable	Not Applicable
Rail (AREMA) RC II/III	**AREMA** State regulations or engineering judgment (typical floods are 25- to 100-yr MRI for floodplains)	**AREMA** Control flood flows. Protection of roadway and structures for safety, economy, and continuity of operation.	**AREMA** Design EQ (Level 2): 200- to 475-yr MRI. MCE (Level 3): 1,000- to 2,475-yr MRI.	**AREMA** Ensure safety of trains. Minimize damage to railway structures and loss of use.	**AREMA** Max 30 psf (1.4 kpa) wind load for train operations. Max 50 psf (2.4 kpa) wind load for railroad structures.	Not specified.

Transportation Infrastructure	**Flood**		**Seismic**		**Wind**	
	Hazard Design Criteria	**Performance Levels**	**Hazard Design Criteria**	**Performance Levels**	**Hazard Design Criteria**	**Performance Levels**
Airports (FAA, IBC, ASCE 7) RC III/IV	**ASCE 7** Design Flood for structures. **FAA AC 150/5320-5D** Design criteria for airport drainage (up to 50-yr MRI).	**ASCE 7** Performance levels for buildings.	**ASCE 7** Design EQ for structures.	**ASCE 7** Performance levels for buildings.	**ASCE 7** Design Wind for structures.	**ASCE 7** Performance levels for buildings.
Ports, harbors, and waterways (Regulations, UFC, ASCE 61, ASCE 7) RC II/III	**State, local, or Port Authority requirements** **UFC 4-152-01**	**UFC** Avoid overtopping of wharves and piers. Resist currents and waves forces.	**ASCE 61-14** design criteria per **ASCE 7-05.**	**ASCE 61-14** Maintain overall structural integrity for Design EQ. Allow for egress. No loss of containment presenting a public hazard.	**ASCE 7** Design Wind for structures.	**ASCE 7** Performance levels for structures.

5.4.1.1 Flood

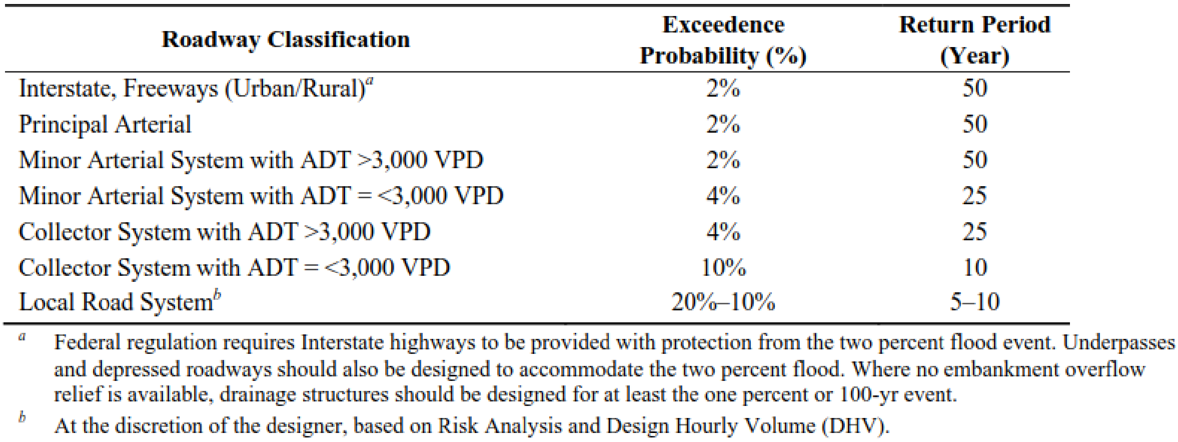
Roadways

AASHTO's *A Policy on Geometric Design of Highways and Streets* (2018a) does not specify minimum flood hazard levels for roads and highways. When describing road drainage the document states "Hydraulic capacities and locations of such structures should be designed to take into consideration damage to upstream and downstream property and to reduce the likelihood of traffic interruption by flooding consistent with the importance of the road, the design traffic service needs, Federal and state regulations, and available funds. While drainage design considerations are an integral part of highway geometric design, specific drainage design criteria are not included in this policy."

This leaves hazard specifications up to state regulations and engineering judgment. The AASHTO *Drainage Manual* (2014) and AASHTO *Highway Drainage Guidelines* (2007) are referenced for recommended hydraulic policy and guidance for the design of roads and highways.

The performance criteria for roads and highways is no overtopping or inundation of the roadway during a design flood. Recommended design frequencies from AASHTO based on roadway classification are shown in Table 5-6.

Table 5-6: Design Storm Selection Guidelines (Source: AASHTO 2014)



Roadway Classification	Exceedence Probability (%)	Return Period (Year)
Interstate, Freeways (Urban/Rural)[a]	2%	50
Principal Arterial	2%	50
Minor Arterial System with ADT >3,000 VPD	2%	50
Minor Arterial System with ADT = <3,000 VPD	4%	25
Collector System with ADT >3,000 VPD	4%	25
Collector System with ADT = <3,000 VPD	10%	10
Local Road System[b]	20%–10%	5–10

[a] Federal regulation requires Interstate highways to be provided with protection from the two percent flood event. Underpasses and depressed roadways should also be designed to accommodate the two percent flood. Where no embankment overflow relief is available, drainage structures should be designed for at least the one percent or 100-yr event.

[b] At the discretion of the designer, based on Risk Analysis and Design Hourly Volume (DHV).

AASHTO hydrologic and hydraulic analysis guidelines of highway encroachments in floodplains evaluate several types of floods:

- <u>Base flood</u> – The flood having a 1% chance of being equaled or exceeded in any given year, also referred to as the 100-yr flood. The base flood is commonly used as the standard flood in FEMA's flood insurance studies and has been adopted for flood hazard analysis by many agencies to comply with NFIP regulatory requirements.

- Super Flood – A flood greater than the Base Flood (e.g., 0.2% annual exceedance or 500-yr flood).
- Overtopping Flood – The flood at which flow occurs over the highway, over the watershed divide, or through structure(s) provided for emergency relief. This flood is of particular interest to highway engineers as it may be the threshold where the highway acts as a flood relief structure for upstream backwater.
- Design Flood – The peak discharge, volume, stage or wave crest elevation of the flood associated with the probability of exceedance selected for the design of a highway encroachment. By definition, the highway will not be inundated by the design flood.
- Maximum Historical Flood – The maximum flood that has been recorded or known to have occurred at or near a highway location.
- Probable Maximum Flood – The maximum flood that may reasonably be expected, accounting for the most adverse flood-related conditions based on geographic location, meteorology, and terrain. The effects of this flood should be considered if the highway embankment is designed to serve as a dam or other critical flood control facility where failure may result in catastrophic consequences. Pertinent information for determining the probable maximum flood may be obtained from the USACE, Bureau of Reclamation, USGS, and state water resource agencies. Although the probable maximum flood can be considered as a super flood, it is generally of a greater magnitude than super floods used in hydrologic or hydraulic analysis.

The AASHTO *Highway Drainage Guidelines* (2007) discuss two alternatives to establish the hazard level (flood frequency) for the design at a specific site: the Policy Alternative and the Economic Assessment Alternative. These alternatives can be applied exclusively or jointly at a given site.

- The Policy Alternative specifies a design flood frequency by policy. The policy of a highway agency may require that a flood frequency be adopted as the design flood. CFR Title 23 Part 650A specifies that the design flood for encroachment through lanes of interstate highways shall not be less than a flood with a 2% chance of being equaled or exceeded in any given year (50-yr flood). The factors that should be considered in selecting the design flood frequency are highway classification and flood hazard criteria (e.g., sensitivity in flood elevations relative to loss of life, property damage, traffic interruption, and economic constraints). Recommended design flood frequencies are provided in Table 5-6.
- The Economic Assessment Alternative is a quantitative practice for establishing a design flood frequency. This evaluation provides a detailed analysis of alternative designs to determine which one provides the greatest flood hazard avoidance for the least total expected cost to the public.

23 CFR Title 23 Part 650A requires all highways that encroach on floodplains, bodies of water, or streams to be designed to permit conveyance of the 100-yr flood without

significant damage to the highway, stream, body of water or other property. The design flood for encroachments for interstate highways shall not be less than a 50-yr flood. No minimum design flood is specified for Interstate highway ramps and frontage roads or for other highways. Freeboard shall be provided, where practicable, to protect bridge structures from debris- and scour-related failure.

Bridges

AASHTO requires bridge designers to evaluate the waterway opening of the bridge and scour of the foundation for design flood hazards. The design hazard level may vary for each. The AASHTO *Drainage Manual* (2014) and FHWA *Federal Lands Highway Project Development and Design Manual* (2012) recommends the following floods be investigated, as appropriate, in the hydrologic studies:

- Base Flood to assess flood hazards and floodplain management requirements
- Overtopping Flood or Design Flood to assess risks to highway users and for bridge scour, damage to the bridge, and its roadway approaches
- Design Flood for evaluating flow through the waterway opening and bridge scour to satisfy agency design policies and criteria for the various functional classes of highways
- Historical Floods to calibrate water surface profiles and to evaluate the performance of existing structures
- Design Flood or Check Flood (flow rate exceeds Design Flood; does not exceed 500-yr flood) for evaluating the adequacy of bridge foundations to resist scour

AASHTO does not specify a minimum flood hazard level for the design flood for waterway openings. The design flood for a waterway opening is determined on the basis of the engineer′s judgment of the hydrologic and hydraulic flow conditions at the site. Guidance for selection is provided in the AASHTO Drainage Manual (2014). The waterway opening performance for a design flood is that the highway or bridge will not be inundated or overtopped. Inundation is typically defined as water within the travel lanes of roadways or above the bottom of the superstructure (bottom chord/flange) on bridges.

The design flood for bridge scour is based on the flood flow equal to or less than the 1% annual chance of occurrence flood. AASHTO states in its commentary that the majority of bridge failures in the United States are a result of scour. The performance level at the design flood for bridge scour is the strength limit state where structural damage may occur, but overall structural integrity is maintained. The highway or bridge may be inundated with the design flood for bridge scour.

The check flood for bridge scour is the flood resulting from storm, storm surge, tide, or some combination thereof having a flow rate in excess of the design flood for scour, but not exceeding a 500-yr MRI. The check flood for bridge scour is used in the investigation and assessment of a bridge foundation to determine whether the foundation can withstand that flow and its associated scour and remain stable. The performance level for the check flood is evaluated at the extreme limit state for structural stability where severe operational impacts are expected but the superstructure will not collapse.

Tunnels

Tunnels are inherently susceptible to flooding. AASHTO and FHWA recommend that tunnel approaches provide a positive means of protection against flooding when the access portals are located in low-lying areas, such as adequate elevation or flood gates.

AASHTO *LRFD Road Tunnel Design and Construction Guide Specifications* (2017) address floods and tsunami-related flooding. The Specifications state that tsunami and floodwater design levels (referred to as extreme events) shall be determined from historical data and/or modeling. The effects of flood loads (including scour, hydrostatic pressures, and soil effects) shall be considered in the design. FHWA *Technical Manual for Design and Construction of Road Tunnels – Civil Elements* (2009) recommends using a 500-yr MRI for flood design and a minimum 100-yr service period. The performance level at the extreme event limit state shall be taken to ensure the structural survival of a tunnel during a design flood or tsunami event.

Rail

The AREMA *Manual for Railway Engineering* notes that properly designed openings, control of flood flows, and protection of roadway and structures are of vast importance from the standpoints of safety, economy, and continuity of operation during flood periods (AREMA 2021). The manual does not, however, specify the design hazard level for flood; instead it provides guidance on how rail systems should be developed leaving hazard specification up to state regulations or engineering judgment. Specifically, "The design flood frequency to be used is a matter of engineering judgment, jurisdictional requirements and cost/benefit analysis." The commentary states that railroad drainage openings are typically designed for floods in the range of 25- to 100-yrs. If the rail system encroaches a floodplain as identified by criteria established by the FEMA NFIP, the 100-yr BFE is the most commonly regulated stormwater elevation associated with rivers, streams, and concentrated flow areas. Any change to the floodplain will generally result in extensive studies and computer modeling to be submitted for approval.

Airports

Airport terminals, hangars and ancillary buildings are typically governed by adopted state and local building codes (see Chapter 2, Buildings). The Risk Category assigned will determine the design hazard level and performance level. Airports are generally considered critical or essential facilities and assigned Risk Category III or IV per the IBC and ASCE 7. The FAA AC does not specifically address design hazard levels for flood, seismic, and wind for pavement (runways, taxiways, roadways) and airfield control lighting. FAA AC

150/5320-5D (2013) provides design criteria for airport drainage. It states that the drain system will be designed based on a selected design storm and will perform without damage to facilities, undue saturation of the subsoil, or significant interruption of normal traffic. The degree of protection to be provided by the drain system depends largely on the importance of the facility as determined by the type and volume of traffic to be accommodated, the necessity for uninterrupted service, and similar factors. It states in some designs, portions of the drainage system have been based on as high as a 50-yr design frequency to reduce the likelihood of flooding a facility essential to operations and to prevent loss of life (FAA 2013).

Ports, Harbors, and Waterways

Ports, harbors, and waterways are usually evaluated based on several water datums. The datum normally used for waterfront structures is mean lower low water, mean sea level, or mean low water. Using this datum allows easy reference to dock construction clearances during construction, utility clearances, and ship deck elevations for operational considerations. This dimension depends on the exposure of the pier or wharf to the wave climate, current forces on structure, tidal variations, sea bottom conditions, height of the ship's deck, and type of ship-to-pier transfer facilities. The air gap should consider flood elevations and maximum river stages to keep the dock out of flood plains or design for flood current loads.

The extreme high water (EHW) and extreme low water are not usually associated with extreme astronomical tides alone, but rather with a combination of large astronomical tides and storm-surge effects. FEMA FISs and FIRMs for most U.S. coastal communities give extreme still water levels associated with 10-, 50-, 100-, and sometimes 500-yr MRI. The FIRMs give a base flood elevation, which is the maximum wave crest or run-up elevation associated with a 100-yr event.

UFC 4-152-01 (2017) was developed for military facilities and recommends avoiding overtopping, deck elevations should be set at a distance above mean higher high-water level equal to two-thirds of the maximum wave height, if any, plus a freeboard of at least 3 ft (0.9 m). Bottom elevation of deck slab should be kept at least 1 ft (0.3 m) above EHW level.

5.4.1.2 Seismic

Surface Roads

AASHTO does not specifically address seismic hazard levels for surface roadways in codes and standards. Roads are susceptible to damage from earthquakes as ground deformations can cause roads to split, as seen after the Loma Prieta earthquake (Duwadi 2010).

Bridges

Seismic design hazard and performance levels for bridges are based on an expected service life of 75 yr for the structure. Bridges are generally designed to have a low probability of collapse but may suffer significant damage and disruption to service when subject to earthquake ground motions that have a 7% probability of exceedance in 75 yr (approximately a 1,000-yr MRI).

AASHTO *LRFD Bridge Design Specifications* (2017) address serviceability, fatigue, strength and extreme event limit states. The strength limit state addresses structural integrity and stability for design loads and load combinations. The extreme event limit state addresses the structural survival of the bridge during an earthquake, blast, ice, or collision event with an MRI that exceeds those used for design.

AASHTO (2017) identifies three operational categories: Critical, Essential, and Other. The basis of classification includes social/survival and security/defense requirements. The operation classification is used to determine the response modification factors (R-factors) used in the design. In classifying a bridge, consideration should be given to possible future changes in conditions and requirements.

- Critical bridges must remain open to all traffic after the design earthquake and be usable by emergency vehicles and for security/defense purposes immediately after a large earthquake (e.g., a 2,500-yr MRI event, or 3% probability of exceedance in 75 yr).
- Essential bridges should, as a minimum, be open to emergency vehicles and for security/defense purposes immediately after the design earthquake (typically a 1,000-yr MRI event).
- Other Bridges should maintain structural stability without collapse, significant damage, or disruption in service for the design earthquake.

Each class of bridge determines the performance level and whether partial or complete replacement may be required. The following design philosophy is widely accepted for the seismic design of highway bridges (FHWA 2014):

- Small-to-moderate earthquakes should be resisted within the elastic range of the structural components without significant damage.
- Realistic seismic ground motion intensities should be used to determine the seismic demands on the structural components for the design earthquake'.
- Exposure to shaking from moderate-to-large earthquakes should not cause collapse of all or part of the bridge. However damage is accepted provided it is ductile in nature, readily detectable and accessible for inspection and subsequent repair if necessary.

Tunnels

Seismic design for tunnel structures is based primarily on soil-structure interactions due to ground deformation rather than inertial forces (FHWA 2009). AASHTO *LRFD Road Tunnel Design and Construction Guide Specifications* (2017) identifies two design earthquakes:

Safety Evaluation Earthquake (SEE) and Functionality Evaluation Earthquake (FEE). The tunnel structure shall provide a high level of assurance for protection of life safety during and after an SEE and for continued operation during and after an FEE.

The SEE is a design earthquake event for structural safety and integrity that has a small probability of exceedance during the service life of the facility. The structure is designed with adequate strength and ductility to survive loads and deformations imposed on the structure, which may include inelastic deformation, and prevent structural collapse and maintain life safety. Structural damage is controlled and limited to the elements that are repairable. Following the SEE, some interruption in service is permitted.

The FEE is used to evaluate continuity of operations for more frequent earthquake events. There is minimal interruption in service during or after the FEE. For the FEE, the structure is designed to respond in an elastic manner with no collapse, and only minimal damage to structural elements that is repairable. The structure should remain fully operational immediately after the earthquake, allowing a few hours for inspection.

The MRI for the SEE and FEE design earthquakes are selected based on the risk acceptable to the Owner. A minimum design life of 100 yr shall be used to evaluate the design earthquake MRI unless otherwise specified by the Owner. For the SEE level event, infrastructure owners have used MRI varying from 1,000 yr to 2,500 yr. A design earthquake with a 2,500-yr MRI corresponds to approximately a 4% probability of exceedance in 100 yr.

To avoid lengthy down time and to minimize costly repairs, a more frequent seismic event is selected for a FEE level analysis. In high seismic areas (e.g., western United States), a FEE event with a 100-yr MRI (corresponding to an approximately 65% probability of exceedance in 100 yr) is generally defined. In areas where earthquake occurrence is much less frequent (e.g., eastern United States) or when the consequence of disruption to the operation of the system is grave, an earthquake event with a MRI greater than 100 yr (up to a 500-yr MRI or an event corresponding to a 20% probability of exceedance in 100 yr) is selected for FEE level analysis.

If the Owner determines that the tunnel is not a critical structure, a single-level performance criterion may be used. For these non-critical structures, the target performance shall be established by the Owner.

Rail

The AREMA *Manual for Railway Engineering* (MRE; 2021) addresses seismic design criteria for railway structures including track, roadbed, bridges, drainage structures, retaining walls, and other structures. The main objective of the performance criteria is stated as to ensure safety of trains and to minimize the costs of damage and loss of use caused by potential earthquakes. AREMA outlines a framework for seismic criteria that uses a three-level ground motion and performance criteria approach consistent with railroad post-seismic event response procedures. The three levels of ground motion are defined as:

- Level 1 – Motion that has a reasonable probability of being exceeded during the life of the bridge.
- Level 2 – Motion that has a low probability of being exceeded during the life of the bridge.
- Level 3 – Represents a very rare or maximum credible event with a very low probability of being exceeded during the life of the structure.

The MRI for each ground motion level is determined based on seismic risk considerations and structure importance classifications. The ground motion levels correspond to operational response levels and performance levels. The three performance levels are:

- Serviceability Limit State – At this level, only moderate damage that does not affect the safety of trains at restricted speeds is allowed. The structure shall not suffer any permanent deformation due to deformations or liquefaction of the foundation soil.
- Ultimate Limit State – At this level, the structure is expected to maintain the overall structural integrity of the bridge during a Level 2 ground motion. The damage that should occur is intended in design and should be readily detectable and accessible for repair. The structure shall not suffer any damage that threatens the overall integrity of the bridge due to deformations or liquefaction of the foundation soil.
- Survivability Limit State – At this level, extensive structural damage, short of bridge collapse, may be allowed. The individual railroad may allow irreparable damage for the survivability limit state and opt for new construction.

The manual states that seismic design loads for railroad buildings and support facilities should be governed by the local building code or other applicable local, state, or federal regulations. The commentary states that railroad bridges historically have performed well in seismic events with little or no damage. Contributing factors include bridge structures are traversed by a track structure that functions as a restraint against longitudinal and lateral movement during earthquakes. Additionally, the controlled operating environment permits different seismic performance requirements for railroad bridges compared to highway bridges. Table 5-7 and Table 5-8: list the seismic performance criteria and ground motion levels published in the AREMA MRE.

Table 5-7: Seismic Performance Criteria (Source: AREMA 2018)

Railroad Response Level	Ground Motion Level	Performance Criteria Limit State
II	1	Serviceability
III	2	Ultimate
III	3	Survivability

Table 5-8: Ground Motion Levels (Source: AREMA 2018)

Ground Motion Levels	Frequency	MRI (Yr)
1	Occasional	50–100
2	Rare	200–475
3	Very Rare	1,000–2,475

Airports

Airports are generally considered critical or essential facilities and assigned Risk Category III or IV per the IBC and ASCE 7. The FAA AC does not specifically address design hazard levels for flood, seismic, and wind for pavement (runways, taxiways, roadways) and airfield control lighting. See Section 5.4.1.1, Flood.

Ports, Harbors, and Waterways

The most severe damage typically occurs in high seismicity zones with soft and liquefiable soils (common in coastal environments), which generally results in large ground deformations caused by lateral spreading and liquefaction (Gaythwaite 2016). As a result, most port structures fail because of excessive deformations as distinguishable from the collapse mode of failure more typical of buildings and bridges.

Displacement-based design methods are typically used for design, unless the structure is located in a low seismic hazard zone then force-based design similar to buildings is used. Port and harbor facilities are typically governed by adopted state and local building codes. See Chapter 2, Buildings.

ASCE 61 (2014a) specifies the design seismic hazard level as the ground motions in ASCE 7. The minimum performance level for the seismic design event (DE) hazard level is life safety protection. The post-earthquake damage state is such that the structure continues to support gravity loads, damage that does occur does not prevent egress, and there is no loss of containment of materials in a manner that would pose a public hazard. The standard states the Authority Having Jurisdiction should assign a design classification**.** The DE is equivalent to two -thirds of the maximum credible earthquake (MCE) having a 2,475-yr MRI. Higher performance goals for critical facilities can include design in for minimal damage with continued operation after the MCE. Additional criteria include the smaller Contingency Level Earthquake (CLE) with a 475-yr MRI and the Operating Level Earthquake (OLE) with a 72-yr MRI, where the performance required is controlled and repairable damage for CLE and minimal damage for the OLE.

The Marine Oil Terminal Engineering and Maintenance Standards (MOTEMS 2005) are building standards (California Building Code, Chapter 31F – Marine Oil Terminals) that apply to all marine oil terminals in California and are often referenced outside of California for seismic performance criteria levels which are similar to ASCE 61. In addition, MOTEMS provides operational planning and post event inspection and recovery guidance. Other post event inspection and recovery guidance are provided in ASCE MOP 130, Waterfront Facilities Inspection and Assessment (ASCE 2014c).

5.4.1.3 Wind

Surface Roads

AASHTO does not specifically address wind hazards for surface roadways in codes and standards. Wind hazard is not typically a significant design consideration for surface roadways; however, they could be affected by falling objects such as trees and poles (supporting highway signs, luminaires, traffic signals, utilities, etc.) that temporarily block the travel way or uproot foundations.

Bridges

AASHTO *LRFD Bridge Design Specifications* (2020a) wind design criteria use the 3-s gust wind speed maps for RC II structures from ASCE 7-10 (2013) to determine design wind loads on bridges. Wind speeds for RC II structures correspond to approximately a 7% probability of exceedance in 50 yr (700-yr MRI). Where records, experience, or site-specific wind studies indicate wind speeds higher than reflected in the maps are possible at the bridge location, the wind speeds are to be increased. Wind loads are evaluated for the fatigue and strength limit states to ensure that structural integrity and stability of the bridge are maintained, with some local damage that may occur.

Tunnels

Tunnel structures are not exposed to the environment, so it will not be subjected to wind loads when in service.

Rail

The AREMA MRE (2021) specifies design hazard levels for wind as an arbitrary magnitude that varies based on the construction material of timber, steel, and concrete structures. The loading conditions assume wind action on both the bridge and the train. It is assumed that the maximum wind velocity under which train operations would be attempted would produce a force of 30 psf (1.4 kPa). Hurricane winds, under which train operations would not be attempted, would produce a wind force of 50 psf (2.4 kPa). There is no specific performance level specified; however, the commentary states that historically, lateral forces developed in the AREMA MRE have worked well when combined with wind loads to produce adequate lateral resistance.

Airports

Airports are generally considered critical or essential facilities and assigned Risk Category III or IV per the IBC and ASCE 7. The FAA AC does not specifically address design hazard levels for flood, seismic, and wind for pavement (runways, taxiways, roadways) and airfield control lighting. See Section 5.4.1.1, Flood.

Ports, Harbors, and Waterways

Wind loads are usually calculated based on local building code criteria. Other standards, such as ASCE 7, are generally used if no local code is applicable. Wind loads act on the pier/wharf structure, as well as on stored material, buildings, and movable equipment.

5.4.2 Resilience Concepts

The current codes and standards for transportation systems support resilience by specifying minimum design hazard levels for seismic, flood, and wind. Two key criteria evaluated to gage resilience planning status within the sector are (1) how design hazard events align within the sector and with interdependent sectors (2) how design criteria consider loss and recovery time and cost.

As portrayed in Sections 5.3 and 5.4.1, the design hazard levels for the various transportation modes (road, rail, air, maritime) are significantly different from each other and from ASCE 7. One exception is of airport facilities which use ASCE 7 for the terminals and other support structures. In terms

Loss, recover time, and cost are also a mixed bag in terms of the code provisions.

For roadway, airports, and marine transportation systems, no specific criteria for recovery levels are identified in codes or standards. However, at state and local levels there are operational and in some cases performance goals in coordination with emergency planning and operation centers that have extensive communications and safety protocols which provide some regard to recovery of function. There is minimal description of required recovery levels for airports. Current emphasis is on regional resourcing via the FAA Logistics Center supporting 24/7 the National Airspace System in identifying recovery needs to allow continuity of critical resource supply to disaster areas.

AREMA includes Post-Seismic Event Operation Guidelines within its design manual, including guidance on operations, response levels, and post-event inspections.

- Operations – The guidelines note that railroads shall subscribe to a notification system that supplies continuous real-time notification of seismic events, with magnitude and epicenter. Utilizing the notification systems immediately after an earthquake, all trains and engines within a 100-mile radius of reporting area shall be notified and instructed to run at a restricted speed. Inspection of the track, structures, signal and communication systems would be initiated.
- Response Levels – The magnitude and epicenter of the earthquake correspond to response levels that govern operations within the specified radius from the epicenter.

Table 5-9 lists the response radii for earthquakes of different magnitudes. Table 5-10 defines the response levels, and Table 5-11 explains the damage criteria.

- Post-Earthquake Inspection – Inspection procedures and modifications of facilities to expedite the inspection process should be established before the seismic event. The track and roadbed, bridges, culverts, retaining walls, tunnels, and signal and communication facilities should all be inspected as part of the inspection procedure.

Table 5-9: Specified Response Radii

Earthquake Magnitude (Richter Scale)	Response Level	California and Baja California	Remainder of North America
0.0–4.99	I	As directed	As directed
5.0–5.99	II	50 miles	100 miles
6.0–6.99	III	100 miles	200 miles
	II	150 miles	300 miles
7.0 or greater	III	As directed, but not less than for 6.0–6.99	
	II	As directed, but not less than for 6.0–6.99	

Table 5-10: Response Levels

Response Levels	
I	Resume maximum operating speed. The need for the continuation of inspections will be determined by the proper authority.
II	All trains and engines will run at restricted speed within the specified radius of the epicenter until inspections have been made and appropriate speeds established by the proper authority.
III	All trains and engines within the specified radius of the epicenter must stop and may not proceed until proper inspections have been performed and appropriate speed restrictions established by the proper authority. For earthquakes of 7.0 or greater, operations shall be as directed by the proper authority, but the radius shall not be less than that specified for earthquakes between 6.0 and 6.99.

Table 5-11: Damage Criteria

Response Level	Ground Motion Level	Expected Damage to Track, Structure, Signal and Communications
I	0	Very low probability of damage or speed restrictions.
II	1	Moderate damage that may require temporary speed restrictions.
III	2	Heavy damage that can be economically repaired. Track or structures may be out of service for a short period of time.
III	3	Severe damage or failure requiring new construction or major rehabilitation. Track or structures may be out of service for an indefinite period of time.

5.4.2.1 Planned Recovery

Transportation systems play a critical role in community recovery following a hazard event. The community relies on the transportation systems to provide the following recovery needs:

- Access for emergency responders to reach people in need
- Access for workers to restore critical facilities and infrastructure (water, wastewater, and electricity)
- Access to facilities for shelter, medical care, banks, commerce, and food
- Egress or evacuation from a community during or immediately after a hazard if needed
- Ingress of goods and supplies immediately after event to provide aid

For the community to reach full recovery and pre-hazard functionality, the transportation systems are required to recover their own basic functionality to provide:

- Ability for community members to get to work, school, medical facilities, sports and entertainment venues, and places to gather for religious or cultural events
- Access to businesses (both small and large), banks, retail, manufacturing, and similar facilities so they can receive supplies and serve their customers
- Access to key transportation facilities (airports, ports/harbors, railway stations) so goods can be transported, and the supply chain restored

The current performance levels in codes and standards for transportation systems primarily are focused on life safety objective and do not specifically incorporate acceptable recovery times. Although AASHTO does describe that design objectives other than structural survival for an extreme event maybe required, these operational objectives are left to the discretion of the Owner. Both AASHTO and AREMA incorporate importance classification into the design criteria which implicitly includes some functional recovery.

A popular transportation strategy is to design bridges, their abutments and approaches to remain operational following a design event and allow certain amounts of failure to the connecting embankments with planned rapid reconstruction which can be done more effectively than for bridge structures and approaches. This allows for a more economical solution and stretches mitigation dollars to cover a larger number of bridges.

5.4.2.2 Interdependencies

Nearly every other infrastructure sector is dependent to some degree on the transportation system (Figure 5-2). All sectors rely on transportation service for access, supplies, and emergency services. Key dependencies are those that, if interrupted, could significantly impact the performance and overall resilience of the transportation system. Understanding these dependencies and addressing them is critical to aspects of community resilience.

Examples of specific dependencies on the transportation system include:

- The electric power sector relies on bulk shipments of fuel and supplies via barge, freight rail, and truck routes for power plant operations.
- The defense industry depends on air, maritime, rail, and highway networks to move material in support of military operations.
- The agriculture and food industry depend on the security of the transportation portion of the food supply chain to ensure safety and security of food shipments.
- Communications and public utility infrastructure collocate much of its networking equipment (routers, fiber-optic cable, electric, gas, water, etc.) along existing transportation routes (rail lines, highways, tunnels, and bridges).
- Manufacturing industries ship goods and services across the entire transportation system utilizing all transportation modes.
- Emergency services depend on the resilience of the transportation network to respond effectively to emergencies.

Specific interdependencies of transportation systems with the other infrastructure systems include:

- The transportation system depends on the power and electric power grid. Gas stations need electricity for vehicle owners to access fuel. Electric power is necessary for traffic signals to function. Airports, rail stations, moveable bridges, vehicular tunnels, and ports rely on electric energy.
- Buildings are rendered useless if people cannot reach them. Transportation systems allow people to travel to critical facilities, businesses, and to other homes and facilities to check on the safety of friends, family, and vulnerable populations. When transportation systems are not available to get community members to buildings and facilities, such structures also cannot contribute to the recovery.
- Water, wastewater, and gas lines are often located underneath roads. Leaks and failures of this infrastructure can damage or destroy road foundations. Sinkholes forming due to leaks often result in roadway collapses which in turn cause breaks in the leaking and adjacent utilities leading to disruptions in service.
- Due to the nature of our large, diverse transportation network and how it is used today, intermodal transportation is a key consideration for communities.

Figure 5-2: Transportation Cross-Sector Dependencies (Source: DHS 2015)

The current codes, standards, and best practices documents do not specifically address interdependencies between the different infrastructure systems of the built environment, nor do they address dependencies within the transportation sector itself. The codes and standards within the different physical components appear to be for the most part independently developed within each system.

5.4.2.3 Gaps and Areas for Improvement

An assessment of codes, standards, and best practices for transportations systems identified the following technical gaps and areas where improvements are needed to increase the resilience of these systems and support community resilience:

- The codes and standards that generally govern the design and construction of transportation systems are focused on the performance of individual components that make up each system. For example, the highway/road transportation system comprises individual components including roads, bridges, and tunnels. Each individual component has a separate AASHTO standard that addresses hazard and performance criteria (which may have differences in themselves) for the individual component, but none of the standards address the role of the individual component in the system or the performance of the highway system in its entirety. The same was observed for port structures (air and marine). The performance of the components and the system in its entirety are necessary to achieve community resilience. There is a lack of guidance on planning and designing an entire transportation network to maintain its function of transporting people and goods immediately after a natural hazard event. Marine and aviation do not have a clearly defined set of standards, but guidance is provided by FAA ACs and ASCE guidance. ***Future development of codes and standards for transportation systems, including AASHTO, FHWA, and AREMA standards, should***

consider performance of the entire transportation network in addition to the individual components.

- Hazard design criteria for transportation systems are generally intended to protect structures (bridges, tunnels, etc.) and accept damage to roadways, runways, and rail tracks on the basis that these components can be quickly repaired or restored after an event. For instance, the governing codes and standards for roadway, rail tracks, and airport runways do not address seismic performance, although the pavement can be split/cracked from ground deformations and their foundation subgrade can cause further damage from settlements, liquefaction, or landslides. Flood hazards are only addressed in terms of evaluating the impact of the component on the floodplain and in terms of drainage capacity or preventing overtopping. Runways are a critical component to the functionality of airports; however, there is little guidance on minimizing damage to design level hazards. This approach may be acceptable depending on the recovery time objectives, level of redundancy built into the system, operational and maintenance capabilities, and the criticality/importance of the component. ***Further guidance is needed to make adequate determination of the resilience performance requirements for these surface components (roadways, tracks, and runaways).***
- Design hazard levels specified in codes, standards, and best practices vary between the different transportation systems and individual components. In some instances, such as flood hazards for roadways, the design hazard levels are left up to engineering judgment or selection by the owner. The variation in design level events does not support community resilience, as differences in performance can be expected during the same level of hazard event. This is especially important due to the highly interconnected and intermodal nature of transportation systems. ***Minimum design hazard levels in codes and standards should be specified for flood, seismic, and wind that support consistent performance across the different transportation systems to address interdependencies within the various modes of transportation and between different infrastructure sectors.***
- The FAA issues advisory circulars (ACs) that govern engineering, design, and construction standards for various airport-related equipment, facilities, and structures; however, they do not address resilience concepts such as design hazard levels, recovery time objectives, climate change, or adaptation, and interdependencies with other transportation systems. The ACs do not specify minimum hazard levels with the exception of drainage construction. ***The ACs would be improved by incorporating resilience concepts and specifying design criteria for hazard levels and recovery time objectives.***
- The current codes and standards for transportation are primarily based on life safety objectives. Future updates to codes and standards should consider both life safety and functional recovery objectives in establishing performance levels. ***Methods and***

guidance for determining functional recovery objectives at both the component and system level are needed.

- Current codes and standards for transportation systems are predominantly prescriptive in nature. ***Performance-based design methods are available but should be more predominantly incorporated in standards of practice to address community resilience goals that exceed code requirements.***

5.5 Conclusions

The current codes and standards used in the design of transportation systems provide minimum requirements to address life safety; however, these provisions are not extensive enough to address community resilience considerations. There are no consistent performance-based criteria for flood, seismic and wind hazards and there is very limited information about post-event functional requirements for specific transportation infrastructure or recovery time after a hazard event. Many of the documents do not specify minimum hazard levels and leave their selection up to engineering judgment.

5.6 References

AAR, 2020. *Association of American Railroads: About Us.* Association of American Railroads. https://www.aar.org/about-us/.

AASHTO, 1993. *Guide for Design of Pavement Structures, 4th Edition*, American Association of State Highway and Transportation Officials. Washington, DC.

AASHTO, 2007. *Highway Drainage Guidelines, 4th Edition*. American Association of State Highway and Transportation Officials. Washington, DC.

AASHTO, 2008, *Guide Specifications for Bridges Vulnerable to Coastal Storms,* American Association of State Highway and Transportation Officials, Washington, DC.

AASHTO, 2010. *Technical Manual for Design and Construction of Road Tunnels*, American Association of State Highway and Transportation Officials. Washington, DC. https://store.transportation.org/Item/CollectionDetail?ID=7

AASHTO, 2011a. *Guide Specifications for LRFD Seismic Bridge Design* (2nd edition). American Association of State Highway and Transportation Officials. Washington, DC.

AASHTO, 2011b. *Roadside Design Guide, 4th Edition*, American Association of State Highway and Transportation Officials. Washington, DC.

AASHTO, 2014. *Drainage Manual.* American Association of State Highway and Transportation Officials. Washington, DC.

AASHTO, 2016a. *A Policy on Design Standards – Interstate System, 6th Edition.* American Association of State Highway and Transportation Officials. Washington, DC. https://store.transportation.org/Item/PublicationDetail?ID=2624

AASHTO, 2016b. *Highway Drainage Guidelines, 4th Edition.* Washington, DC: American Association of State Highway and Transportation Officials.

AASHTO, 2016c. *Highways in the River Environment - Floodplains, Extreme Events, Risk, and Resilience, 2nd Edition,* American Association of State Highway and Transportation Officials, Washington, DC.

AASHTO, 2017. *LRFD Road Tunnel Design and Construction Guide Specifications,* American Association of State Highway and Transportation Officials. Washington, DC. https://store.transportation.org/Item/PublicationDetail?ID=3742

AASHTO, 2018a. *A Policy on Geometric Design of Highways and Streets, 7th Edition.* American Association of State Highway and Transportation Officials. Washington, DC. https://store.transportation.org/item/collectiondetail/180

AASHTO, 2018b. *Resiliency Case Studies: State DOT Lessons Learned*. American Association of State Highway and Transportation Officials, Washington, DC.

AASHTO, 2019. *Guidelines for Geometric Design of Low-Volume Roads, 2nd Edition*, American Association of State Highway and Transportation Officials, Washington, DC.

AASHTO, 2020a. *LRFD Bridge Design Specifications (9th ed.)*, American Association of State Highway and Transportation Officials, Washington, DC.

AASHTO, 2020b. *LRFD Road Tunnel Design and Construction Guide Specifications, 4th Edition, Interim Revisions.* Washington, DC: American Association of State Highway and Transportation Officials.]

AASHTO, 2021. *AASHTO Overview,* American Association of State Highway and Transportation Officials. Washington, DC. https://www.transportation.org/home/organization/.

ACI, 2014. *Guide for Design and Construction of Waterfront and Coastal Concrete Marine Structures*, ACI 357.3R-14, American Concrete Institute. Farmington Hills, MI.

Adaptation Clearinghouse 2021. *Post Hurricane Sandy Transportation Resilience Study in New York, New Jersey, and Connecticut*, Georgetown Climate Center, Washington, DC. https://www.adaptationclearinghouse.org/resources/post-hurricane-sandy-transportation-resilience-study-in-new-york-new-jersey-and-connecticut.html

AREMA, 2020. *American Railway Engineering and Maintenance-of-Way Association: What is AREMA?* American Railway Engineering and Maintenance-of-Way Association. Lanham, Maryland. https://www.arema.org/AREMA_MBRR/About.

AREMA, 2021. *Manual for Railway Engineering.* American Railway Engineering and Maintenance-of-Way Association. Lanham, Maryland. https://publications.arema.org/Publication/MRE_2021

ASCE, 2013. *ASCE 7-10: Minimum Design Loads and Associated Criteria for Buildings and other Structures, Third Printing*. American Society of Civil Engineers, Reston, VA.

ASCE, 2012. *Planning and Design Guidelines for Small Craft Harbors Third Edition*. ASCE MOP 50, American Society of Civil Engineers. Reston, Virginia.

ASCE, 2014a. *ASCE 61-14: Seismic Design of Piers and Wharves*. American Society of Civil Engineers, Reston, VA.

ASCE, 2014b. *Mooring of Ships to Piers and Wharves,* MOP 129, American Society of Civil Engineers, Reston, VA.

ASCE, 2014c. *Waterfront Facilities Inspection and Assessment,* MOP 130, American Society of Civil Engineers, Reston, VA.

ASCE, 2015. *ASCE 24-14: Flood resistant Design and Construction*. Reston, Virginia: American Society of Civil Engineers.

ASCE, 2021a. *America's Infrastructure Report Card: Aviation, Bridges, Inland Waterways, Ports, Rail, Roads, Transit*, American Society of Civil Engineers, Reston, VA. https://infrastructurereportcard.org/

ASCE, 2021b. *ASCE 7-22: Minimum Design Loads and Associated Criteria for Buildings and other Structures*. American Society of Civil Engineers, Reston, VA.

CFR, 2022. *Title 23 Highways, CFR Title 23 Part 650*, Code of Federal Regulations, National Archives. https://www.ecfr.gov/current/title-23/chapter-I/subchapter-G/part-650?toc=1

DHS, 2010. *Transportation Systems Sector-Specific Plan an Annex to the National Infrastructure Protection Plan,* Department of Homeland Security, Washington, DC.

DHS, 2015. *Transportation Systems Sector-Specific Plan,* Department of Homeland Security, Washington, DC.

Duwadi, SR, 2010. *Hazard Mitigation R&D Series: Article 1: Taking a Key Role in Reducing Disaster Risks*, FHWA-HRT-10-004, United States Department of Transportation (DOT)/Federal Highway Administration (FHWA), Vol. 73 No. 6, May/June,

FAA, 2013. *Airport Drainage Design.* FAA Advisory Circular, AC 150/5320-5D. Federal Aviation Administration (FAA), Washington, DC.

FAA, 2022a. *Part 139 Airport Certification.* Federal Aviation Administration (FAA), Washington, DC. https://www.faa.gov/airports/airport_safety/part139_cert/

FAA, 2022b. *Series 150 Advisory Circulars (ACs) for Airport Projects.* FAA Advisory Circulars. Federal Aviation Administration (FAA), Washington, DC. https://www.faa.gov/airports/resources/advisory_circulars/

Farmer, A., 2018. *Waterfront Facilities. Whole Building Design Guide*, National Institute of Building Sciences, Washington, DC. https://www.wbdg.org/building-types/waterfront-facilities.

FHWA, 2004. *FHWA Seismic Retrofitting Manual for Highway Structures: Part 2 – Retaining Structures, Slopes, Tunnels, Culverts, and Roadways*, Federal Highway Administration, U.S. Department of Transportation, Washington, DC.

FHWA, 2006. *FHWA Seismic Retrofitting Manual for Highway Structures: Part 1- Bridges*. Federal Highway Administration, U.S. Department of Transportation, Washington, DC.

FHWA, 2009. *Technical Manual for Design and Construction of Road Tunnels — Civil Elements,* Publication No. FHWA-NHI-10-034. Federal Highway Administration, U.S. Department of Transportation, Washington, DC. https://www.fhwa.dot.gov/bridge/tunnel/pubs/nhi09010/tunnel_manual.pdf

FHWA, 2012. *Federal Lands Highway Project Development and Design Manual, Chapter 7: Hydrology and Hydraulics*. Federal Highway Administration, U.S. Department of Transportation, Washington, DC.

FHWA, 2014. *LRFD Seismic Analysis and Design of Bridges Reference Manual*, Publication No. FHWA-NHI-15-004. Federal Highway Administration, U.S. Department of Transportation, Washington, DC.

FHWA, 2015. *Load and Resistance Factor Design (LRFD) for Highway Bridge Superstructures*, Reference Manual, Publication No. FHWA-NHI-15-047. Federal Highway Administration, U.S. Department of Transportation, Washington, DC.

FHWA, 2016. *Highways in River Environment- Floodplains, Extreme Events, Risk and Resilience, 2nd Edition*, Hydraulic Engineering Circular (HEC) 17, Federal Highway Administration, U.S. Department of Transportation, Washington, DC.

FHWA, 2017. *Post Hurricane Sandy Transportation Resilience Study in New York, New Jersey, and Connecticut*. Federal Highway Administration, U.S. Department of Transportation, Washington, DC.

FHWA, 2020. *Highways in the Coastal Environment Third Edition*, Hydraulic Engineering Circular (HEC) 25, Federal Highway Administration, U.S. Department of Transportation, Washington, DC.

FHWA, 2022. *Subpart A - Location and Hydraulic Design of Encroachments on Flood Plains,* Subchapter G – Engineering and Traffic Operations, Part 650 - Bridges, Structures, and Hydraulics, Federal Highway Administration, Washington, DC.

Gaythwaite, JW, 2016. *Design of Marine Facilities: Engineering and Design of Port and Harbor Structures Third Edition*, American Society of Civil Engineers, Reston, VA.

IBC, 2021. International Building Code. International Code Council, Washington, DC.

MOTEMS (2005). *Marine Oil Terminal Engineering & Maintenance Standards (MOTEMS)*, California State Lands Commission, Sacramento, CA. https://www.slc.ca.gov/motems/

NCHRP, 2011. *Best Practices for Roadway Tunnel Design, Construction, Maintenance, Inspection, and Operations*, NCHRP Project 20-68A, National Cooperative Highway Research Program, Transportation Research Board, Washington DC.

NFPA, 2020. *Standard for Road Tunnels, Bridges, and Other Limited Access Highways*, National Fire Protection Association, Quincy, MA. https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=502

NIST, 2016. *Community Resilience Planning Guide for Buildings and Infrastructure Systems.* NIST Special Publication 1190 Volume I and II. National Institute of Standards and Technology. Gaithersburg, MD. http://dx.doi.org/10.6028/NIST.SP.1190v1, http://dx.doi.org/10.6028/NIST.SP.1190v2.

NYC, 2019. *Climate Resiliency Design Guidelines, Version 4*. New York City Mayor's Office of Recovery and Resilience. New York, NY. https://www1.nyc.gov/assets/orr/pdf/NYC_Climate_Resiliency_Design_Guidelines_v4-0.pdf

PANYNJ, 2018a. *Civil Design Guidelines*. Engineering Department Manual, The Port Authority of New York and New Jersey, New York, NY

PANYNJ, 2018b. *Climate Resilience Design Guidelines (v1.2)*, Engineering Department Manual, The Port Authority of New York and New Jersey, New York, NY.

PIANC, 2005. *MarCom WG 34: Seismic Design Guidelines for Port Structures (2001-2005),* PIANC, The World Association for Waterborne Transport Infrastructure.

PIANC, 2020. *Resilience of the Maritime and Inland Waterborne Transport System, EnviCom TG193,* PIANC, The World Association for Waterborne Transport Infrastructure.

UFC, 2017. *Design: Piers and Wharves*, UFC 4-152-01, United Facilities Criteria, Department of Defense. https://www.wbdg.org/ffc/dod/unified-facilities-criteria-ufc/ufc-4-152-01

USACE, 1995. *Design of Coastal Revetments, Seawalls, and Bulkheads*, EM 1110-2-1614, United States Army Corps of Engineers. Washington, DC.

USACE, 2002. *Coastal Engineering Manual*, Engineer Manual 1110-2-1100, United States Army Corps of Engineers. Washington, DC.

VTrans, 2012. Adapting Vermont's Transportation Infrastructure to the Future Impacts of Climate Change, Vermont Agency of Transportation, Barre, VT. https://vtrans.vermont.gov/sites/aot/files/planning/documents/planning/VTrans%20Climate%20Change%20Adaptation%20White%20Paper%202012.pdf

6 Discussion and Summary

The performance of the built environment depends on the codes, standards, regulations, and best practices that are adopted and enforced. Community resilience planning efforts require, as a foundational element, that communities adopt and implement codes and standards to improve the performance of their built environment for natural hazards. However, even if a community adopts and enforces all current codes and standards, there will be inconsistencies between sectors of the built environment as well as within individual sectors that may result in cascading damage to other sectors. While each sector has its own design issues and goals beyond the minimum criteria of life safety, such as design issues related to vehicle loads, water pressure, or voltage, a better understanding of how these sectors will perform for the same hazard event is needed. Knowledge of their relative performance will help identify changes needed to improve their relative performance during hazard events. Additionally, this information will provide a basis for developing minimum performance objectives and criteria to support the community resilience goals.

Design criteria in regulations, codes, standards, and best practices were examined to improve understanding of current design criteria and expected performance for the built environment. This included exploring the similarities and differences between building and infrastructure design criteria, limitations in addressing system interdependency issues, and available methods to address the impact of changing environmental conditions on infrastructure.

Codes and standards for buildings and infrastructure are generally developed independently through different industry organizations with varying design criteria and expected performance. Many codes and standards provide prescriptive requirements with the assumption that if the requirements are met, satisfactory (minimum) performance is obtained. Regulations or mandates by government bodies may incorporate codes and standards but can also include additional requirements that may be either more strict or less stringent. The regulations for the different systems and subsystems of the built environment differ due to multiple regulatory bodies at various levels of government (federal, state, and local). In addition to the codes, standards, and regulations, each system typically has specific best practices that may or may not exceed the minimum requirements of the codes and standards governing the design. Best practices maybe published as guidelines, manuals of practices, or prestandards.

Even if a community enforces and adopts all current codes and standards, the performance of the built environment is not expected to result in a resilient community. This is because prescriptive and performance requirements in current codes and standards primarily focus on life safety objectives for buildings and transportation, and on reliability for electric and water. The existing regulations, codes, and standards for the built environment inherently include some resilience concepts through defining minimum design hazard levels, concepts to mitigate damage, and recognizing the relative importance of certain buildings and infrastructure (through the use of Risk Categories and Importance Factors), but overall they require additional criteria to achieve community resilience such uniform hazard levels, recovery of function, adaptation, and addressing interdependencies.

Despite being subjected to the same hazards, the systems and components of the built environment are largely not designed to a comparable hazard level; therefore, varying levels of performance for the built environment are expected if subjected to the same hazard event. Furthermore, performance goals currently do not fully address functionality or recovery of buildings and infrastructure systems following a design-level hazard event. Best practice documents (guidelines and manual of practice) are available that address recovery of function to a certain extent. Performance-based design procedures have been developed for buildings for both seismic and wind that include recovery time objectives.

Adaptation and interdependency concepts are largely not addressed within the codes and standards for all branches of the built environment. Several guidelines are available that address adaptation concepts, including information on evaluating and retrofitting existing buildings and infrastructure systems. There are several guidelines from USACE and FHWA that offer guidance on evaluating and planning for climate change.

Chapters 2 through 5 provided a review and assessment that focused on each infrastructure system of the built environment: buildings, water, electric power, and transportation. A comparison and assessment are provided of the differences and common identified gaps. Areas for improvement to increase the resilience of these systems at a community scale are also presented.

6.1 Hazard Design Criteria and Expected Performance

Many of the independent codes and standards for buildings, water, electric power, and transportation specify minimum design-level hazard requirements for flood, seismic, and wind; however, there are gaps where minimum hazard levels have not been defined. Where minimum design-level hazards are not defined, hazard specification is addressed by state/local regulations and engineering judgment. In some instances, guidance may be provided on how hazard levels should be developed. For example, the AASHTO Drainage Manual does not specify the minimum design flood for overtopping of the road but provides guidance for recommended practices based on the roadway classification.

This report identified similarities and differences for design hazard levels between infrastructure and subcomponents. Differences in design criteria can lead to varying performance during the same hazard event, which could affect the ability of a community to respond and recover from an event. Performance criteria for buildings and transportation primarily focus on life safety objectives. Electric and water have performance criteria that emphasize reliability (no interruptions to customer service). A comparison of the design criteria for flood, seismic, and wind hazard events is provided below.

6.1.1 Flood

With the exception of buildings, minimum design-level flood hazards and performance goals for infrastructure are not well defined for infrastructure systems. Flood hazard characterization may be specified by state or local regulations; otherwise it is left to engineering judgment. Buildings that are located within flood hazard areas are generally subject to the NFIP requirements, toward which the codes and standards for buildings are tailored. Typically, FEMA's FIRMs delineate the SFHAs of the community. In flood hazard areas, the minimum design flood is the 100-yr MRI or 500-yr MRI (for critical/essential buildings). State or local regulations may specify more stringent requirements by adding freeboard to the design flood elevation. The expected performance depends on the Risk Category but generally involves withstanding the hazard load and preventing inundation of the lowest floor elevation to minimize damage.

Water, wastewater, electric power, and transportation infrastructure have less clear minimum design-level hazards and performance goals. Water, wastewater, and electric power infrastructure typically use design criteria consistent with the NFIP and with the design-level hazard based on the 1% annual chance of occurrence flood defined on the FIRM. Transportation infrastructure provides guidance for selecting the design-level flood hazards for different components. This includes site-specific analysis and use of the NFIP FIRMs. For roads, general guidance for selection of the design flood is provided with a performance goal of not being inundated or overtopped. Performance goals generally do not address damage to road bedding or pavement from scour or erosion during a flood. For bridges, the design flood for overtopping, scour protection, and size of the waterway opening are all different. The structural integrity of the bridge for scour is checked using the 100-yr MRI. Railways, airports, and marine ports do not have minimum requirements and will typically be defined based on best practice guidance.

6.1.2 Seismic

Design-level seismic hazards are generally well defined for the built environment; however, the minimum requirements vary quite significantly among infrastructure systems as well as between components within a system. Where no specific design criteria exist, common practice is to use seismic design criteria established in ASCE 7.

For buildings, design-level seismic hazards and performance levels vary based on the Risk Category applied to the structure. The primary performance objective for buildings is life safety; however, the codes and standards acknowledge that critical or essential buildings need to perform at a higher level and remain functional after a seismic event. Critical or essential buildings are typically assigned the highest Risk Category. Recovery objectives are not explicitly considered in the design process; however, the use of the Risk Categories addresses the performance of some nonstructural systems, which helps minimize damage and improve the likelihood that the building remains functional during a design level event. Design criteria for resilience, particularly recovery, need to address all building uses, not just those deemed essential. Design-level seismic events tend to have a probability of exceedance on the order of 10% over a 50-yr period for ordinary structures and corresponds with Risk Category II design criteria for buildings (an MRI of approximately 475 yr). The design hazard level for a specific building or infrastructure component may be greater, based on its occupancy and Risk Category classifications. Building code provisions for essential facilities assigned to the highest Risk Category thus have a greater opportunity to remain operational by designing for an event that exceeds the design level hazard. ASCE 7 permits the use of performance-based seismic design methods, which are addressed in guidance documents that can be used to address performance objectives beyond the minimum requirements of codes and standards.

Regulations, codes, and standards for water and wastewater systems focus on reliability of service. Most of the standards do not address minimum design-level seismic hazards or seismic design, though some address particular subcomponents. For example, ASCE is currently developing a manual of practice for the seismic design of water and wastewater pipelines that incorporates four performance levels, but it does not address functional recovery times.

Electric power infrastructure standards and guidelines are well developed for seismic hazard mitigation and draw on ASCE 7 ground motion parameters; however, none of the federal regulatory bodies, including FERC and the NRC, or state regulatory commissions adopt specific seismic design criteria that establish recovery times, and in general the performance goals are not well defined. At the state and local levels, regulators may adopt codes or standards for design and construction, but there is wide variation in the level of design guidance.

For transportation, AASHTO and AREMA establish minimum design-level seismic hazard criteria for structures such as bridges and tunnels. Typically, the criteria are intended to protect the structures and accept damage to roadways, runways, and rails on the assumption that these components can be quickly repaired.

The design hazard and performance levels for road and highway bridges are generally designed to have a low probability of collapse, but they may suffer significant damage and disruption to service when subject to the design level earthquake. The design level earthquake for bridges is based on ground motions that have a 7% probability of exceedance in 75 yr (approximately a 1,000-yr MRI). Partial or complete replacement may be required. AASHTO acknowledges the importance of higher levels of performance and allows that they may be used with the authorization of the bridge owner.

Seismic design criteria by AREMA specify a three-point performance objective intended to provide for serviceability, structural integrity, and collapse prevention at three different hazard levels (occasional, rare, and very rare). The specified hazard levels vary with the importance of the bridge. Any consideration of functional recovery time is implicit in the importance classification.

6.1.3 Wind

Design-level wind hazards for all sectors are generally consistent with, or specifically refer to, the design criteria established in ASCE 7; however, many standards do not use or reference the most recent version of ASCE 7. In some circumstances, such as the AREMA Manual for Railway Engineering, they modify the design wind speed or wind loads. The wind design criteria are based on basic wind speed maps with risk adjustments corresponding to the Risk Category selected for the given structure. The magnitude or intensity of the wind speed is based on a probability of exceedance established in ASCE 7 for the given Risk Category.

Despite the relative uniform and consistent use of wind design criteria from ASCE 7 among the different sectors, historical evidence shows that the built environment is affected by high wind events. Varying levels of performance can be expected based on the engineering judgment used in selection of the Risk Categories, which may not align with community resilience objectives. Furthermore, climate change is leading to more routine and intense high-wind-speed events. Design criteria for wind hazards will generally not address extreme wind events such as tornadoes.

6.2 Adaptation and Climate Change

Current codes and standards for the built environment do not specifically incorporate adaptation planning or climate change; however, several guidance documents are available that provide related best practices. Furthermore, several communities have taken initiatives to produce adaption plans and guidelines. Several case studies are discussed throughout this report illustrating how adaptation is being incorporated in design of the built environment such as the Virginia Flood Risk Management Standard, the Florida Building Code, and the Port Authority of New York and New Jersey Engineering Department Climate Resilience Design Guidelines. Best practices and lessons learned from these case studies can be used to inform incorporation of climate change and adaptation into codes, standards, and best practices. Some examples of how communities are addressing adaptation and climate change in planning include:

- The Virginia Flood Risk Management Standard requires a mandatory adoption of 1.0 ft (0.3 m) of freeboard statewide for localities, especially single-family residential buildings. Additionally, Virginia issued Executive Order 45, which established a state-level series of requirements based on climate change considerations for design flood elevations for state-owned property. Currently, all state-owned buildings proposed within Virginia's SFHA must obtain a variance from state officials. This was established to discourage construction in floodplains (mapped SFHAs) in general. If the variance is permitted for these structures, then the minimum freeboard for all SFHA construction is 3.0 ft, 1 ft (0.9 m, 0.3m) higher than the current freeboard requirement for IBC (2020) Flood Design Class 4 structures. This applies to both riverine and coastal floodplain areas outside of a designed SLR Inundation Area. The SLR area is based on the NOAA (2017) Intermediate-High scenario curve for 2100. Within that SLR area, all state-owned structures not in a currently mapped SFHA require 5.0 ft (1.5 m) of freeboard, and if within a mapped SFHA require 8.0 ft (2.4 m) of freeboard.
- The FBC includes the special hurricane protection standards for the HVHZ for Miami-Dade County, Broward County, and coastal Palm Beach County. Not only do structures in the HVHZ have higher design wind speeds standards (and the associated requirements of structural elements designed for those wind speeds), but the FBC also includes higher standards for building components, attachments, and equipment. The HVHZ requirements act as a model for higher standards for various communities in Florida and other states with high hurricane wind hazards.
- The Port Authority of New York and New Jersey Engineering Department Climate Resilience Design Guidelines evaluate sea level rise by determining the design flood elevation based on the base flood elevation plus a freeboard that is a function of asset location in the floodplain, criticality, and useful lifetime. The Port Guidelines use the existing 500-yr (or 0.2% annual chance event) floodplain as the initial basis of the floodplain location.

6.3 Recovery of Function

Recovery is not explicitly addressed in the design of the built environment. All codes and standards acknowledge to some degree that there are critical or essential buildings and infrastructure that need to remain functional immediately following a disruptive event. These are typically addressed implicitly through the use of Risk Categories or importance classifications in the design process. None of the reviewed codes and standards specifically identify recovery objectives or goals. Performance levels for buildings and bridges are predominantly life safety focused and do not include recovery. Performance-based seismic design procedures for buildings and bridges are beginning to emerge that address recovery in performance, but more research and guidance is needed to apply recovery considerations across all systems of the built environment for improved community resilience.

A design hazards summary table (Table 6-1) illustrates, by comparison, resilience principles of hazard design levels (Section 6.1), and recovery consideration (this section) in current codes and standards. It highlights the needed adjustments to achieve a common performance for design within and across sectors. While the view is high level, the comparison is useful for understanding the sector differences that require further evaluation of site-specific consequences and costs to determine desired recovery goals and the broader design performance levels, which also differ between hazards for the same sector. A holistic design solution would emerge from this this iterative process. As noted in Section 6.2, adaptation practices are as of yet largely distinct from the core design codes and standards for new construction and are not included in this comparison table.

Table 6-1: Key Resilience Provision Comparison of Codes and Standards by Sector and Hazard

	Commonality of Design Hazards (Baseline Event MRI, yr)*			Recovery Performance Provisions (Risk Category IV or Highest)		
Sector	**Flood**	**Wind****	**Seismic**	**Function Loss**	**Recovery Time**	**Damage Cost*****
Buildings (ASCE 7)	100/500	100/1700	500/2475	Continued operation	Days to weeks	<10%
Water	500	ASCE 7	ASCE 7	Continue operation	Days to weeks (per AWWA J100)	No criteria
Electric Power	100/500	ASCE 7	ASCE 7	Emergency backup	No criteria, relies upon operational guidance docs	No criteria
Transportation**	<100/100	ASCE 7	1000/2500	Continued operation, no collapse	Days to weeks	No criteria

*Routine / Design event levels. ASCE 7 alignment is shaded green
**Additional MRI used are based on design categories, code versions, and between modes
*** Percent of facility/system replacement cost

6.4 Interdependencies

Review of the current codes and standards for the built environment highlighted the fact that codes and standards are currently “stove-piped” and developed independently of each other. This tends to limit the effectiveness of codes and standards to address interdependencies within the built environment. Designs of specific components of the built environment are highly focused on the individual component (building, bridge, road, water conveyance, etc.), which is appropriate given the difference; however, the designs do not consider the role of the component holistically in a network, system, or community. A resilience perspective would add consideration of how the component fits within a system, its role/importance, and how its function is affected by other systems.

The unavoidable interdependencies of the built environment play an important role in recovery and community resilience. Individual buildings are often dependent on other buildings due to geographic proximity, or commonality of functional purpose (e.g., a university campus, or buildings within a community that support healthcare delivery). Additionally, buildings are connected to dispersed and overlapping infrastructure networks. Water and wastewater systems rely on the electric power system, communication systems need water and electricity, all rely on goods and services delivered over transportation networks and, increasingly, on wireless communications, and each infrastructure system includes building structures among its physical components. Damage of the built environment from hazards or slow recovery of one system is likely to affect the others. In effect, the modern built environment is a system of systems.

There are several challenges with incorporating the complex interdependencies of the built environment into codes, standards, or guidelines, as these interdependencies are complex and highly specific to individual communities.

6.5 Gaps and Areas for Improvement

This assessment of the codes, standards, and best practices that govern the design and construction of the built environment identified several technical gaps and areas for improvement to support community resilience. Specific assessments pertaining to each of the systems of the built environment are provided in Chapters 2 through 5.

Overall, the literature review and assessment revealed that the minimum requirements of current codes and standards are not sufficient to achieve a resilient community. The following general areas of focus have been identified to support future research and development of codes, standards, and best practices to improve community resilience:

- Codes, standards, and best practices that govern the design and construction of water, electric power, and transportation systems are largely focused on component-level design only and do not consider system-level performance. Water, electric power, and transportation have subsystems (e.g., potable, wastewater, and stormwater) that are supported by individual components (e.g., plants, piping, tanks, pumping stations, reservoirs). The components and subsystems must work together to provide functionality that supports community resilience. ***Future development of codes, standards, and best practices should ensure that component-based design criteria are informed by system-level performance objectives.***
- Buildings and infrastructure systems that comprise social institutions (e.g., healthcare or community education facilities) need guidance to provide resilient performance through performance objectives and design criteria that address damage, repairs (temporary and permanent), and functional recovery within a specified timeframe. For example, transit facilities, stations, maintenance facilities, terminals, parking structures, hangars, warehouses, etc. are designed based on model building codes. ***To improve the resilience of social institutions in communities, guidance is needed to inform the selection of***

Risk Categories in codes and standards and additional performance objectives and design criteria needed to support their resilience.

- Hazards are not addressed in a consistent manner for buildings and infrastructure systems across codes and standards. Differences exist between the design hazard levels in codes and standards for buildings, water, electric power, and transportation systems. In some circumstances, individual components within the various systems also have varying design hazard levels. These differences result in varying performance for the same hazard event, which could lead to cascading failures within or between systems.
  - Flood loads and design criteria are addressed for the design and construction of buildings that are located within designated NFIP flood zones. However, other elements of transportation, water, and electric power networks (e.g., roadways, substations, pumps) do not address flood loads or design criteria for inundation.
  - Wind loads, seismic load effects, and associated design criteria vary between buildings and infrastructure systems, even though they primarily refer to ASCE 7.
  - Tornado design guidance is provided by ICC 500-2015 for storm shelters, ASCE 7-22 Commentary for buildings, and ASCE 74 (4th edition) for electric power infrastructure. Tornado loads and design criteria are currently being balloted for ASCE 7-22.

  A common baseline for defining hazard levels for all sectors is needed. ***A baseline set of hazard criteria for buildings and infrastructure systems need to be established to support resilient performance at the community level.***
- Minimum design flood hazard criteria are not specified for many components of the transportation (except for bridges), water, and electric power systems. This leaves hazard specifications up to engineering judgment unless state or local regulations provide requirements. Flood design hazard levels in many cases defer to the NFIP FIRMs. The FIRMs are based on insurance risk for buildings, which may not be fully aligned with the overall community resiliency goals. ***Flood hazard design criteria need to be further developed for all infrastructure systems***.
- Adaptation and climate change are not addressed in current codes and standards for the built environment. Several best practices documents are available from ASCE, USACE, and FHWA that provide general guidelines for adaptation planning and using climate change data in design processes. Additionally, several local communities are developing their own climate change and adaptation plans. This includes incorporating concepts into their local building codes through amendments to the model building and floodplain ordinances. ***Best practices and case studies for addressing climate change and adaptation should be evaluated for consideration in codes, standards, and guidance documents, such as uncertainty of future events and additional freeboard requirements for sea level rise.***
- Codes and standards do not address interdependencies to the extent necessary to support community resilience. As a first step, guidance documents for primary

dependencies of essential services could be developed to inform designer practice and community decisions to improve resilience. ***Methods of incorporating interdependencies among and between buildings and infrastructure systems into codes and standards need to be developed.***

- Performance criteria in codes and standards largely focus on life safety and do not explicitly address functionality or recovery. ***A consistent set of performance objectives and design criteria for all segments of the built environment that include life safety, functionality, and recovery are needed.***
- Performance-based design procedures exist for building design but generally are not used for the design of infrastructure systems. Performance based design documents need to address the entire building or infrastructure system, with guidance for structural and nonstructural components. The use of performance-based-design procedures need to be encouraged for infrastructure systems to meet resilient performance objectives. ***Performance-based design methods for resilience should be developed for all sectors of the built environment.***

In conclusion, increased coordination in codes and standards development will help move us toward a more “built-in” building and infrastructure system resilience as a normal design practice because portions of the built environment defer to ASCE 7 hazards criteria as the primary facility design load standard used in the U.S. and ASCE 7 is widely adopted due to its inclusion in the IBC. Also, ASCE 7 is used to design structures for critical control facilities for infrastructure systems. Therefore, it provides a logical frame of reference for further development of other hazard-related codes and standards and for evaluation of systems hazards performance.

More widespread adoption of consistent codes and standards would also benefit by keying off of adoption success of the ICC and collaboratively supporting continuing adoption needs. According to the ICC, 21 states and territories have not adopted either of the two most recent (2015 or 2018) IBC or IRC editions as of 2020. In addition, less than half of all the jurisdictions in the U.S. have adopted ICC codes in general. This disparity in the code adoption status creates additional challenges from a regional resilience level. Neighboring jurisdictions can be designing to adopted codes and standards for their state/locale, but if a recent or comparable version of codes and standards are not adopted, there could be conflicts between design levels by hazard, and performance standards may vary, creating an unbalanced regional resilience design, even within a common building or infrastructure system that spans jurisdictional boundaries. Therefore, adoption of the most recent codes and standards is critical in working toward a regional state of resilience.

Adoption of the most recent codes and standards is not an easy undertaking for many communities, especially for small or impoverished communities, due to lack of technical capabilities or economic resources. State and local governments are witnessing a recent window of opportunity to implement resilient community concepts immediately after a disaster event. It is recommended that disaster recovery periods be utilized as opportunities for the implementation of resilient measures, such as adoption or the upgrading of building codes and standards, due to reduced resistance.

Similar challenges and opportunities continue as well in the suite of other codes and standards presented in this report. Codes and standards for the built environment will continue to be essential in the effective implementation of community resilience. Research and planning efforts to evolve to a more uniform set of performance criteria and consistency among the various methodologies of design within and across systems is needed. In short, planning and research efforts need to resolve the disparities between the various codes and standards for a common event. This may be a generational effort.