BLUFF EROSION HAZARDS AND CONSTRUCTION SETBACKS ON THE GREAT LAKES COASTS OF THE UNITED STATES: A REVIEW

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ABSTRACT
Approximately 34 million people live within the North American Great Lakes Basin: ~32% of the Canadian population and ~8% of the US population. About 12 million of those people live on the Lake Erie coast of New York, Pennsylvania, Ohio, and Ontario. Unconsolidated Quaternary-age bluffs ranging in height from 1.5–55m dominate along 73km of the 123km Pennsylvania coast, and long-term records show that slow-continuous erosion is pervasive, and that rapid (but locally catastrophic) bluff failure is relatively infrequent. As a result, ~90% of the Lake Erie bluff coast in Pennsylvania is designated by the state as a Bluff Recession Hazard Area wherein regulations limit risky bluff-top development. A high degree of variability (space, time) in bluff-retreat rates exists because stratigraphy and geotechnical properties show variation due to materials, depositional geometries, post-depositional processes, hydrology, and anthropogenic influences. This makes it difficult to forecast the magnitude, frequency, and location of larger bluff-failure events and consequently makes pre-emptive mitigation efforts more challenging. Two methods are commonly used to establish coastal construction setbacks on Great Lakes bluff coasts: (i) the "AARRxT" method which uses a simple linear extrapolation of past bluff-change rates to estimate the future bluff position and the setback line for a building being constructed today; and (ii) the "AARRxT+" method which uses a similar approach but incorporates a slope stability factor and/or a relocation buffer. The limitation is that these deterministic methods assume that rates and magnitudes of processes driving change in the past will not change in the future, and they create the impression that bluff change is linear and more predictable than it is in reality. At the property and municipality scales, this makes hazard planning for continuous and catastrophic bluff failure particularly challenging.
Keywords: Great Lakes, bluff erosion, construction setbacks, stable slope angle, buffer.

1 INTRODUCTION

In the United States, about 40% of the population lives in coastal counties that occupy almost 10% of the total US land area. Populations in these coastal counties have been increasing at a rate of about 10% per decade, while population densities are about six times greater than that of inland counties [1], [2]. On Great Lakes coastlines such as Michigan, shoreline property values may exceed $30,000 per linear meter [3]. Land loss through erosion of unconsolidated (cohesive) bluffs, an irreversible geologic process, is thus an issue on many parts of the Great Lakes perimeter that are urbanized, intensively farmed, or preserved for public use. This paper focuses on the Great Lakes coasts of Pennsylvania (principally), New York, Ohio, Michigan, Wisconsin, and Minnesota (Fig. 1) to review a fundamental component of bluff-erosion hazard management, namely the delineation of coastal construction setbacks designed to reduce the impacts of future bluff failure.

Fortuitously, catastrophic coastal land loss is rare on the Pennsylvania and Great Lakes coastlines. The most recent and largest bluff failure event occurred over two decades ago on the Lake Michigan coast when a $1 \times 10^6 m^3$ dune field failure event (500m in length) generated a debris fan that extended ~3 km offshore and covered ~$20 km^2$ of lake floor [4]. Large sudden

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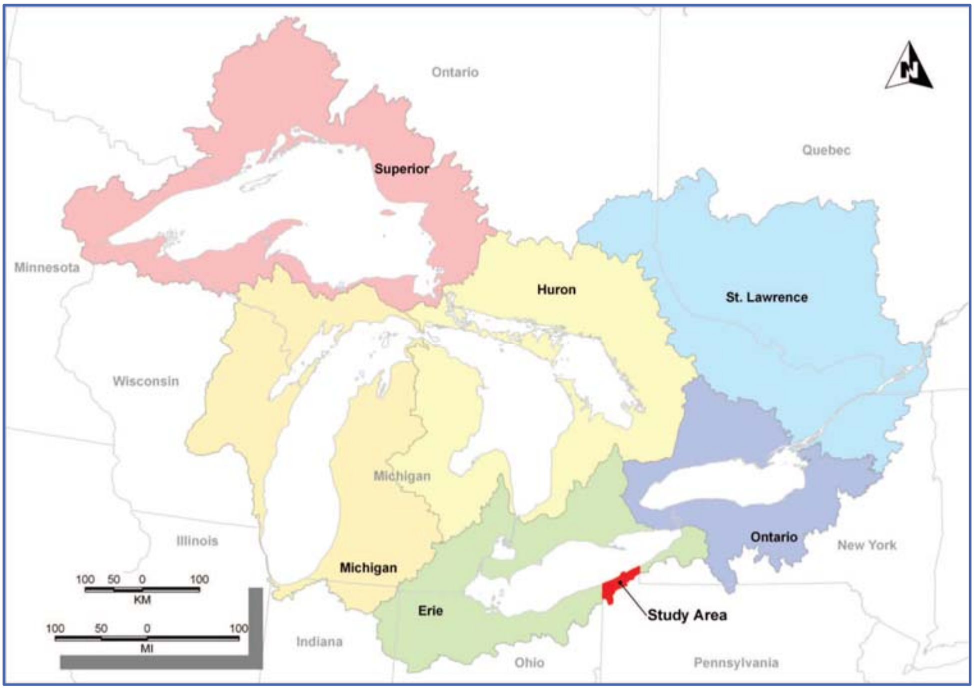

Figure 1: The geographic setting of the North American Great Lakes and their associated watersheds in the United States and Canada. The Pennsylvania Lake Erie watershed is shown in red [7].

bluff failure events in Pennsylvania are much smaller and typically involve a 10–20m landward movement of the bluff crest at individual rotational slumps that are less than 1km^2 in area. However, slow insidious bluff loss is very common, significantly impacts coastal property owners at the property-parcel scale, and are challenging to forecast and mitigate. Pennsylvania possesses ~123km of Lake Erie shoreline, and the geomorphology of its coastal zone is dominated by unconsolidated Quaternary-age bluffs ranging in height from 1.5–55m above lake level. The central coast includes a large shore-attached strand-plain (Presque Isle State Park) separated from the mainland bluffs by Presque Isle Bay (Fig. 2). Excluding the Presque Isle shoreline, the ~73km mainland coast consists almost entirely of clay-rich glacial till bluffs. Coastal geomorphologic evidence and long-term records of coastal change show that bluff erosion (averaging 0.25–0.33m/year, [5], [6]) is a pervasive problem along the majority of the Pennsylvania bluff coast [6].

In northwest Pennsylvania, ~90% of the bluff coast of Lake Erie is formally designated a Bluff Recession Hazard Area (BRHA) [8] wherein coastal municipalities and the City of Erie impose limitations on potentially risky bluff-adjacent development. The few non-BRHA sectors occur primarily at stream mouths where broad valley re-entrants ensure that the bluff crest is located far (~75m) from the shoreline. Within the BRHA, which includes the active bluff face (a no-build area), new construction and significant renovations to existing structures are subject to minimum setback requirements that are predicated on a Minimum Bluff Setback Distance criterion (MBSD) [8]. This criterion is defined as the product of the expected lifetime of a planned structure (T=50 year for residential; 75 year for commercial;

100 year for industrial), and the average annual bluff-crest retreat rate (AARR) for a municipality that is based on almost four decades of control-point monitoring by Pennsylvania DEP [8]. Generally, the state MBSD line is located 8 to 60m inland from the bluff crest, but in certain municipalities is replaced with a more stringent setback requirement. The economic risks associated with development close to the bluff edge in Pennsylvania are significant. A recent analysis [9] showed that ~$66million of buildings and properties along Pennsylvania's Lake Erie bluff coast are at risk of significant damage or complete destruction from coastal erosion over the next century. Average retreat rates as high as 1m/year at specific control-points, bluff retreat of as much as 11.3m during 4-year monitoring intervals, and significant variability in rates, have been documented [8]. Since the development of the national Coastal Zone Management Act (CZMA) in 1972, the siting of buildings and larger infrastructural elements on bluff coasts nationally has been subject to growing scrutiny in the United States due to increasing concern over flood, erosion, and landslide hazards in the coastal zone. This trend is seen, for example, in the growing incorporation of coastal hazard planning in the hazard mitigation plans of coastal counties on Atlantic, Pacific, and Great Lakes coasts [9].

Developing and implementing setback regulations, policies and guidelines is a complex process both legally and scientifically in the Great Lakes and nationally. This is because of implications regarding the *Takings Clause* (5^{th} Amendment of the US Constitution) on the legal side of the issue and, on the science/engineering side, the necessity of predicting the

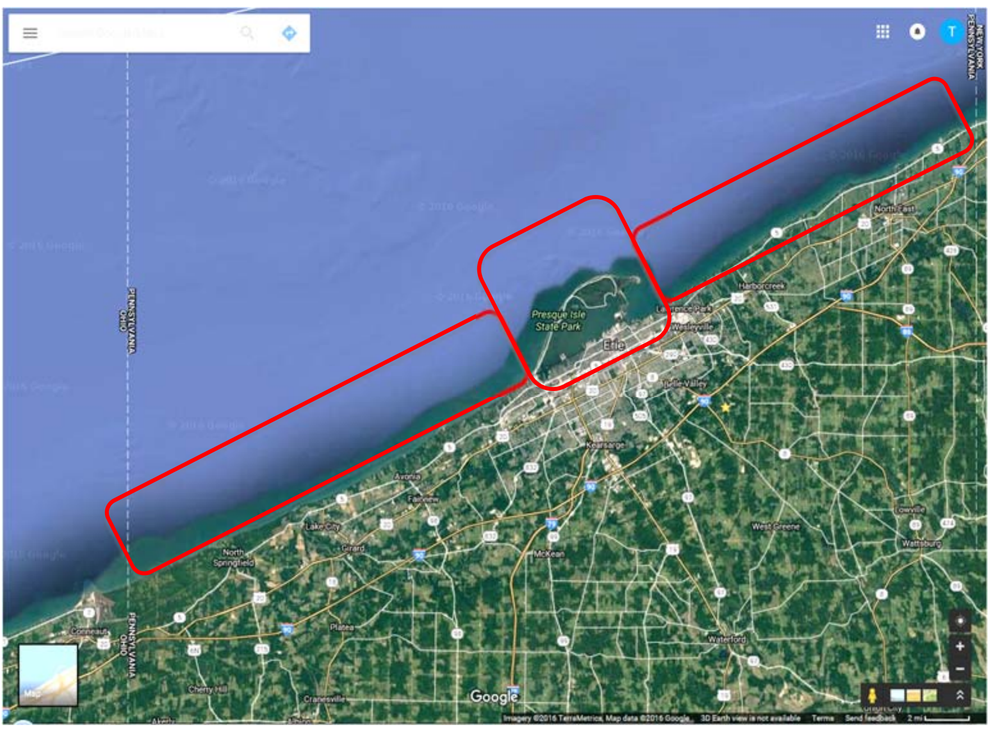

Figure 2: The Pennsylvania coast of Lake Erie. The eastern and western coastal reaches are characterized by cohesive bluffs while the central reach (City of Erie) is dominated by a strand-plain (Presque Isle) and bay coast.

locations of safe development sites on bluff-adjacent property parcels at specific times in the future. Newer trends in defining setbacks with greater science and engineering rigor may have the unintended consequence of limiting construction on smaller lot sizes to the inland parts of the property parcel far from the owner's intended scenic coastal-overlook location. For example, setbacks using methodologies being developed by Wisconsin (on Lakes Michigan and Superior) and California (on the Pacific Ocean) may mean setbacks of over 100m from the bluff edge that can limit development on small lots.

Scientific methods used to accurately estimate the position of a stable or retreating coastal bluff (crest) at selected times in the future are in their relative infancy despite decades of endeavor on the subject. Nationally, estimating future bluff-crest locations relies primarily on deterministic methods because the problem is challenging mathematically and in terms of the geotechnical knowledge required on the ground. A probabilistic approach to resolving this problem (e.g., Bayesian network modeling) is a developing trend in coastal hazard prediction today and, over time, may evolve to a degree of usefulness that matches or exceeds probabilistic approaches used elsewhere in the geosciences. Probabilistic methods are currently used in coastal, earthquake, and flood hazard assessment at the federal level (e.g. sandy-coast erosion hazard and seismic hazard characterizations by the US Geological Survey; and riverine and coastal flood hazard characterizations by the Federal Emergency Management Agency (FEMA)).

US coastal states participating in the NOAA Coastal Zone Management Program [1] follow increasingly similar methods to map bluff crests and determine setback distances, particularly on coasts where bluffs retreat at rates in excess of 0.3m/yr. These coastal sectors are typically referred to using a number of similar terms: erosion hazard areas, coastal erosion areas, bluff recession hazard areas, and high-risk erosion areas. The methods employed to define bluff setback distances have become more rigorous over time and have become more consistent with each other. States that are most proactive in bluff retreat issues now allow government agencies, property developers and owners to view geodata (e.g., hydrology, shorelines and crest lines, retreat rates) and setback lines at the near-property-parcel level of detail within interactive GIS frameworks (e.g. Wisconsin; [10]). However, coastal scientists and engineers still rely heavily on trends in past behavior of the bluff crest to estimate its location at a specific time in the future. Once the estimated future position is established, ideally and most accurately within a GIS framework, a setback from the present location of the bluff crest can be decided upon that will govern the safe placement of proposed structures.

In the US and Great Lakes Basin today, there are two favored general means by which construction setback lines are established on bluff coasts. While there are variations between states, there is a high degree of general consistency on Atlantic, Pacific, and Great Lakes coasts. The two methods used are: (i) the frequently used "AARRxT" method which uses a future estimated bluff position as the setback line for a building being considered for construction today; and (ii) the less used "(AARRxT)+" method [11] which uses a similar approach but moves the setback line further landward by typically incorporating a slope stability (SSS) factor and/or a relocation safety buffer (SB). Of the two approaches, the "(AARRxT)+" method, in various forms, is the more conservative method of the two. Pending development and adoption of newer probabilistic approaches, it is a standard to emulate for states not already using it. The most common variations in the use of the "(AARRxT)+" method concern the value chosen for "SB" which varies by state, the incorporation of a setback multiplier for tall bluffs steeper than 20% or 11.25degrees (e.g., in Michigan), and factoring in seismicity in the "SSS" term (e.g., in California) [1].

2 BLUFF RETREAT, FUTURE LOCATIONS, AND SETBACKS

2.1 The AARRxT method

The simplest method of calculating a construction setback distance is to calculate the product of a long-term average annual bluff retreat rate (AARR) and the expected lifetime or planning horizon (T) for a planned structure near the bluff. While Pennsylvania and New York, for example, use this method on Lakes Erie and Ontario, Pennsylvania allows coastal municipalities to impose more rigorous setback standards if considered prudent. Pennsylvania utilizes three structure-lifetime categories for the T term, namely 50 years for residential buildings, 75 years for commercial buildings, and 100 years for infrastructural elements (e.g. pumping stations and utility facilities). Other states, such as New York, Minnesota, and Wisconsin use 40 to 50 year structure lifetimes, but the trend nationally, particularly where bluff retreat proceeds at significant rates (> 0.3m/year), is to move towards longer structure lifetimes such as a 100-year benchmark. This trend is being driven by (i) improvements in construction codes nationally over the past several decades, particularly in coastal zones; and (ii) by the transition in quality and monetary value of ocean- and lake-front residential structures since World War II from small summer cabins to large year-round first and second homes.

Identifying the AARR in the method above relies on the use of historical data with varying degrees of positional error [12], duration of coverage over time, and frequency of data collection. Longer datasets with shorter sampling frequencies allow the statistically best erosion-rate averages to be extracted from historical data. At least 50 years of annually collected data is ideal [13]. The further the dataset departs from this ideal, the greater the uncertainties can become [14]. The ideal requirement for long data-coverage duration and short data-collection frequencies is an ongoing limitation in determining accurate AARRs and consequently bluff setbacks. However, this problem will be resolved over time as data collection continues and sampling frequencies become shorter as technology allows more rapid and economic data collection [15].

The more pressing problem is that this deterministic method assumes that rates and magnitudes of processes driving change in the past will not change in the future, and it assumes that bluff change is linear for mathematical expediency. While producing useful results, these assumptions may not be valid over time and location and are consequently subject to uncertainty. However, this is the current state of the science of predicting where a future coastal bluff crest will be located in most US states.

The most prevalent AARR reference feature used on all US bluff coasts today is the bluff crest (edge). This is typically picked using one or more of the following methods: (i) visually in the field by topographic survey; (ii) from variable-scale historical aerial photographs; (iii) from photogrammetry using aerial photo stereo pairs; (iv) from orthorectified large-scale aerial photos; or (v) from visual analysis of LiDAR DEM (digital elevation models) contour-spacing changes. LiDAR DEMs allow the crest to be picked from first derivative (slope) or second derivative (rate of change of slope) maps using an *a-priori* threshold value to identify the crest where bluffs have curved topography. Typically, AARRs are calculated using mathematical routines such as the end-point rate (when there are two data years), and the regression-analysis rate (when there are multiple data years) [16]. Determining the actual development setback is then, at its simplest, a process of plotting a line landward of the bluff edge by taking the product of AARR and T or, in some cases, a T value related to a specified planning horizon. On California's Pacific coast, municipalities use a safety-factor multiplier (values of 1.0 to 4.0, [13]) or an *a priori* buffer (an SB term; ~3m) to allow for uncertainties in future retreat rates due to expected increases in sea-level change rates. Because increases in lake level are known to increase rates of bluff retreat [6], Great Lakes states would benefit from knowing future lake-level trends for the most probable global climate change scenarios over the next century.

2.2 The (AARRxT)+ method

A significant improvement to the “AARRxT” method to determine a bluff setback line is to treat the coastal bluff as a landform in dynamic equilibrium with numerous subaerial, subsurface, and hydrodynamic (lake) processes that shape it. This general approach to setback delineation is being considered for use (or is already in use in some form) in ocean states such as California and Oregon; and in the Great Lakes states of Michigan, Minnesota, Wisconsin and New York [11], [17], [18]. The method locates a more conservative setback line landward of one calculated using the “AARRxT” method.

The AARRxT term is retained in this method (“recession setback” term in Fig. 3) as the means to estimate how far the bluff crest may retreat in the future based solely on its historical behavior. AARRxT will obviously approach a value of zero on long-term stable bluffs that are no longer subject to erosive hydrodynamic, subaerial, and subsurface processes. On the Great Lakes, such stable bluffs are likely to occur where strand-plain development has isolated formerly active bluffs from wave energy for up to several centuries. This type of natural bluff stabilization occurs, for example, along the Pennsylvania (at Erie) and Ontario (at Toronto) coasts where wave power is locally reduced by growth of late Holocene coastal strand-plains (Fig. 2), and/or by urban development on infilled land that now isolates the bluffs from lake waters.

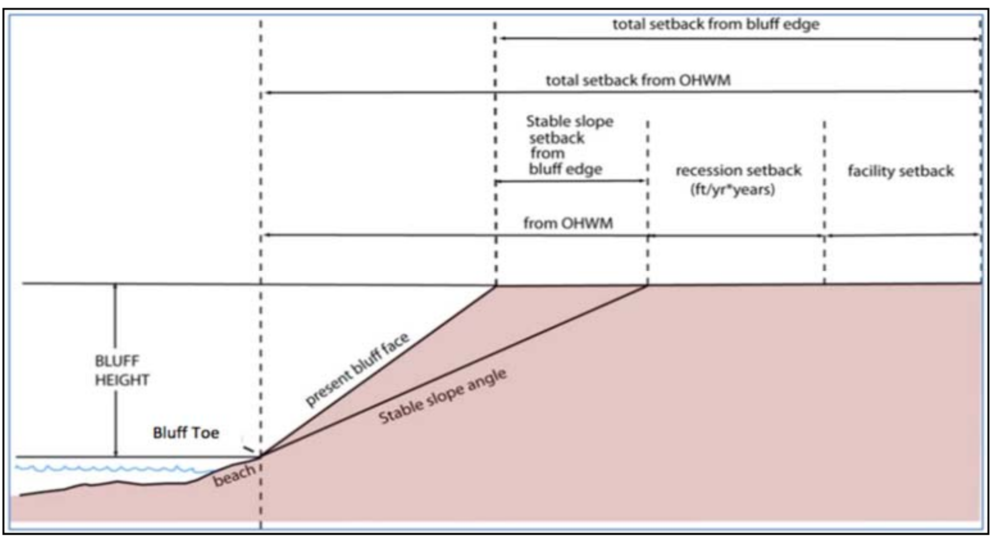

Figure 3: Schematic diagram showing elements and reference features used to determine construction setback lines as used for Wisconsin coastal bluffs and similar to federal FEMA guidelines. The image shows the components of the (AARRxT)+ method: the Stable Slope Setback (SSS); the Recession Setback (AARRxT); and the Minimum Facility Setback (SB) [11].

The "(AARRxT)+" method adds an SSS term (Fig. 3) which is a stable slope setback, also referred to as a slope-stability setback line or a factor-of-safety line. It recognizes that topographic slopes in general exist in a dynamic state and will weather and erode over long time periods to develop a stable slope that will cause landward movement of the crest line. The timescales involved in this process are not well understood: for coastal bluffs, the relevant timescale is likely on the order of decades to centuries depending on geotechnical properties and climate. This factor is recognized by the International Building Code (IBC) in guidelines for building on sloped terrain [19].

The SSS term ("stable slope setback" in Fig. 3) may be derived in at least four ways, using site-specific to regional-scale data. Although not yet widely used, the most geotechnically rigorous method is to use site-specific slope stability analysis modeling [20] which uses site-collected data to identify a horizontal distance landward of the bluff crest beyond which the risk of a future slump failure is minimal. By convention, this "safety line" occurs when a modeled Factor of Safety term exceeds a value of 1.1 (for a pseudo-static case in earthquake-prone areas such as the Pacific coast) to 1.5 (for the static case where there is no seismic risk). The SSS term can alternatively be derived by in-field slope measurements of nearby stable bluff areas such as has been conducted in Wisconsin (18.4–21.8 degrees; [17]). Depending on climate and bluff geotechnical properties, bluff slopes inferred as stable have a significant range in values: from 11.25 degrees (till bluffs on Lake Michigan), to as high as 35 degrees (marine bluffs on Chesapeake Bay, Maryland). Stable slopes of 60 degrees may be reasonable for bedrock cliffs in Wisconsin, and for bedrock bluff ledges at the bluff toe in Pennsylvania. On the Canadian coast of Lakes Erie and Ontario, a universal stable slope of 18.5 degrees is used for planning purposes [21]: a plane is simply projected upward from the base of the bluff (or Ordinary High-Water Mark; OHWM) to intersect the bluff top landward of the existing bluff crest. This defines a reference line from which the AARRxT and SB distances are then referenced. A similar approach is used in Wisconsin (Fig. 3).

Thirdly, the SSS term may be derived by adopting IBC guidelines for building near moderate-to-steep-gradient static slopes (>33 % or >18.5 degrees). In municipalities such as Ventura and Liberty Lake in California, and Spokane and Clark Counties in Washington, IBC guidelines have been adapted so that the minimum criterion for inland slopes is that a building foundation be located no closer to a slope crest than a distance equal to at least the smaller of (i) 12m or (ii) one third of the total slope height above the toe. In cases where the slope is steeper than an *a priori* 45 degrees (100 %) benchmark, the suggested setback (12m or slope height/3) is measured from where an imaginary 45-degree plane, projected upward from the toe of the slope, intersects the terrain behind the slope crest. This slope consideration by the IBC recognizes that steep natural slopes, even in the absence of hydrodynamic (e.g., lake) processes, evolve over long timeframes into less-steep slopes. The IBC stable slope criterion is thus a good starting point when considering alternative ways to reduce the impacts of slumps on buildings and infrastructure. Lastly, the SSS term may be derived by assigning it a horizontal distance value landward of the bluff crest based on the maximum landward headwall retreat observed from the historical record of large (catastrophic) slumps in the area. On parts of the Pennsylvania coast, large but infrequent rotational slumps may yield an SSS value of as much as 20 m.

Regardless of how the SSS term is derived, geometric considerations mean that taller bluffs will necessarily have larger SSS values, for any given stable slope angle, than lower bluffs (Fig. 3). On tall bluffs, therefore, an "unbuildable land" issue becomes important for property owners, but it can be addressed. In Wisconsin, for example, the stable slope (SSS) component of setback at a site can be reduced if a property owner adopts mitigation methods to improve slope stability (e.g. by removing groundwater from the substrate, by slope regrading, by plantings, etc.). In cases where either a rock cliff, or a bedrock toe at the base of an unconsolidated bluff, has a significant wave-cut notch present, municipalities in Wisconsin recommend adding the maximum horizontal depth of the notch to the SSS distance. Fortuitously, wave-cut notches are not well developed on the Pennsylvania Lake Erie coast due to the comparatively mild wave climate and lower bedrock and glacial-till strengths.

The SB term is a minimum facility setback distance, safety buffer, or building relocation buffer ("facility setback" in Fig. 3) that is used to increase the setback of a proposed building from the future bluff edge determined using the AARRxT and SSS terms. The rationale is that a setback based on the design life of a building, the average annual retreat rate, and the stable slope angle, will theoretically result in the building sitting exactly at the future-bluff edge once the building design life is reached. This would limit any last-minute mitigation actions or limit attempts to move the structure because access would not be possible on the lakeward side of the building. Nationally, the SB term addresses this dilemma by adding a 3–10m buffer.

3 THE CASE FOR THE (AARRXT)+ METHOD

Of the two approaches reviewed above, the "(AARRxT)+" method, and its variants, are the most rigorous methods currently used to identify safer, more conservative, bluff setbacks on ocean and Great Lakes coasts in the US. The "(AARRxT)+" approach is a methodology to emulate until better science-supported probability-based methods are developed and adopted. It is superior to the "AARRxT" method because it fundamentally recognizes that slopes are by nature unstable and tend to reduce grade (and therefore exhibit crest retreat) over time via weathering and erosion. This grade reduction due to natural subaerial and subsurface processes takes place even in the absence of hydrodynamic processes affecting the foot of the slope. The grade reduction and crest-retreat concepts are fundamental factors incorporated in IBC recommendations [19] for construction setbacks on static slopes where wave-induced erosion of the lower slope is absent.

While the "(AARRxT)+" method is being increasingly considered for adoption [13], [17], [18], regional nuances in the calculation and inclusion or exclusion of its component terms are common. Specific examples of variations on the method follow, from which it is clear that there is, in general, much commonality in usage among states and provinces. The province of Ontario, Canada, for example uses the method only when the record of historical bluff positions used to calculate the AARR is at least 35 years in length. In areas where there is no or poor data, a default Erosion Allowance of 30m is used to determine the setback, either by itself or in conjunction with an 18.5 degree (~1:3 slope) SSS term if that can be estimated [1]. An SB term (Fig. 3) is not used on the Ontario coast. Ontario's planning horizon for its Great Lakes bluffs uses a single T value of 100 years. Along with a similar T-value used by the municipality of Point Arena, California, on the Pacific Ocean, these are among the most conservative planning horizon terms used in North America.

Several Wisconsin coastal counties have adopted the "(AARRxT)+" method, in whole or in part, and the Wisconsin Coastal Management Program has developed a model ordinance for construction setback distances [11]. Web-based building-setback and stable-slope angle calculators are available for parts of the Lake Michigan and Lake Superior coasts of Wisconsin to promote wise bluff-top development with a significant reduction in hazards [22]. By inputting data on the expected structure lifetime (T); bluff height; present slope angle and estimated stable slope angle (SSS); and AARR; the building setback calculator estimates a safe property setback that includes a building relocation (SB) buffer. While the online calculator provides a more scientific approach to setback determination compared to an older 23m minimum state-wide setback requirement (part of the Wisconsin Shoreland Protection Act), the latter can still be used if it indicates a larger setback than the newer setback calculator. Ordinarily, the 23m minimum state-wide setback applies to unincorporated coastal areas and is measured landward from the OHWM [11], [23]. Depending on bluff height and slope, this older standard can, however, result in the 23m setback line intersecting the bluff lakeward of the bluff crest [17], [18].

A disadvantage of the "(AARRxT)+" approach is that it can yield very large setback requirements under certain conditions that may limit the feasibility of widespread adoption on ocean and Great Lakes bluff coasts. Applying the method to the Pennsylvania coast using a maximum bluff height of 55m, an AARR of 0.33m/year, an structure lifespan of 100 years (the MBSD for an industrial structure), an existing bluff slope of 45 degrees, a stable slope angle of 20 degrees, and a 7.5m SB term, yields a setback line that is located ~135m landward of the present bluff crest. This is a distance that significantly exceeds current requirements on the Pennsylvania coast, may approach or exceed the lot depth in certain locations, and would be viewed unfavorably by property owners. This value is almost three times greater than the current 61m setback required by some municipalities for residential, commercial, and industrial properties.

An additional disadvantage to the large setbacks often indicated by the "(AARRxT)+" method is that residential buildings need be located such a large distance back from the bluff edge that the lake view becomes restricted and a legal takings issue may arise. For example, for a common 25m bluff on the Pennsylvania coast, a home occupant's line of sight to the lake would intersect the lake surface ~700m offshore of the beach. This means the home owner does not see the beach, the shoreline, the surf zone and nearshore waters from the ground floor of the building located landward of the bluff top. The magnitude of the lost "water view" increases rapidly with bluff height.

Minnesota does not use an SSS term in their version of the "(AARRxT)+" method and uses a set value of 7.5 m for the SB term to allow for possible structure relocation needs. In areas where historical bluff-change data is absent or of poor quality, the state recommends a default setback value of 38 m. Michigan modifies its "(AARRxT)+" method by adding a "high bluff" multiplier (in the range of 1.0–2.0) to the AARRxT component in incremental steps (5% slope increments) for bluffs that are steeper than 20% (11.25 degrees). The T term also varies, having a value of 30 or 60 years, depending on whether the proposed structure is small and moveable or large and immoveable. The SB term has a set value of 5 m to allow for major storms.

While not yet being considered on US Great Lakes coasts, municipalities in California require that the time-span of data coverage for calculating the AARR term be as long as possible and no less than 50 years in order that meaningful AARR values are derived. Municipalities may also include an allowance for possible increases in bluff-retreat rates due to sea-level rise within the SB term. An increasing number of coastal municipalities in California are also mandating that permitted structures on the bluff top do not require, during construction or at any time during the 100-year planning horizon, any form of shore protection. In Oregon, where a variation of the "(AARRxT)+" method is used, municipalities such as the coastal city of Brookings impose more stringent construction-setback requirements on properties where average slopes exceed 15% (8.5 degrees) or where the property is located along an ocean bluff coast with unconsolidated (often glacial till) sediments. In the state of Washington, the city of Seattle utilizes web-based map products showing steep-slope areas (40% or 22 degrees) and potential slide areas to assist the general public in coastal bluff-hazard and landslide-hazard identification.

Ohio's Coastal Erosion Area methodology for Lake Erie relies on a unique variation of the deterministic "AARRxT" method [24]. Ortho-rectified aerial photography collected at 10–30-year time intervals is used to determine the AARR at 33m intervals along the bluff. The AARR is then multiplied by T=30 years to define a swath of coast (the Coastal Erosion Area) that extends inland from the most recent bluff crest and extends lakeward to the OHWM line. The CEA thus maps out the area of coast at risk of being lost over a future 30-year time period assuming present erosional trends continue: the landward CEA line is effectively an estimate of where the bluff crest will be in 30 years. Unlike other Great Lakes states, however, new construction or significant renovation is allowed within the CEA but the permit application must demonstrate that adequate shore protection will be in place to protect the new structure for at least the CEA's 30-yr timeframe. Depending on erosion trends, and because the CEA is defined using an AARR, a specific coastal site (e.g. a property parcel or part of a property parcel) may occur within or outside of a CEA during successive CEA updates which are conducted approximately every decade [15].

4 PRESENT STATUS AND FUTURE TRENDS

In the Great Lakes Basin and nationally, deterministic retreat-rate methods (AARRxT; AARRxT+) are the most widely used approaches for estimating future bluff-crest positions, and therefore in locating construction setback lines designed to reduce hazards due to both slow-continuous and large-episodic bluff failure events. Coastal construction setbacks are a sustainable non-engineering solution to bluff-erosion hazards that can work particularly well on undeveloped or low-density developed coastlines. In these settings, impacts associated with restricting where construction can occur on a property tend to be less significant than in urban areas. The current deterministic methods rely on an historical record of past bluff positions to obtain an average retreat rate in order to estimate where the bluff crest may be located at some time in the future. The methods simply rely on the forward projection of historical erosion rates.

The deterministic approach to hazard assessment is very good at identifying historical average retreat rates and prior locations of the bluff crest because it is based on retrospective observations. But the method is very limited in its ability to estimate where a future bluff crest will likely be located, which poses a challenge for coastal hazard management. The limitation exists because the method: (i) ignores the underlying processes and physical properties that drive or resist bluff change and that vary with time and location; (ii) assumes that environmental conditions in the past will remain similar in the future; and (iii) results can be particularly prone to errors due to low sampling frequency and short duration of bluff-position monitoring. The deterministic method also ignores the considerable impacts on bluff retreat that can be induced by changes in the sign or rate of lake-level change over time, bluff geology along a coast, and changes in beach volume at the base of a bluff. Most Great Lakes states still rely on deterministic approaches to coastal erosion planning largely because a more-accurate approach approved by federal agencies such as NOAA and FEMA has not yet been developed.

Current challenges in planning for and mitigating coastal landslides can be addressed by improving upon traditional deterministic methods. Continually-improving predictive modeling methods are now capable of doing a progressively better job across coastal geologic settings and timeframes. For improved outcomes, Bayesian (statistical) network modeling in particular is being increasingly applied to coastal science problems and is ideally suited to providing statistical and probabilistic estimates of coastal-change trends. Recent applications include cliff and landslide analysis [25], [26], and groundwater flow [27], both of which pertain directly to coastal bluff dynamics. Bayesian networks are being successfully used by the US Geological Survey on the Atlantic and Pacific coasts to better predict coastal change given *a priori* knowledge of physical conditions, controlling processes, and historical erosion rates [28], [29]. As inputs, Bayesian network models may use a "prior-behavior" parameter (such as historical bluff retreat); a set of initial-state parameters that define the system (such as bluff height, slope, and stratigraphy; beach geometry; and coastal engineering structures); and the dominant forcing agent causing bluff retreat (such as wave regime or groundwater flux). Bluff retreat on the Great Lakes coasts is well suited to Bayesian modeling because the rates and magnitudes of bluff failure are dependent on interactions between pre-existing conditions, prior failure events and driving processes. Bayesian modeling can accommodate the prior history of a site and can incorporate (by iteration) changes occurring due to feedbacks between the principal controlling processes and the responses of the bluff, to generate better statistics-based estimates of future bluff change.

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