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Wave-Driven Coastal Flooding on Coral Reef-Lined Coasts: Processes, Models, and Knowledge Gaps

Introduction

Low-lying tropical coasts fringed by coral reefs face acute flooding hazards from wave-driven water level extremes. Coral reefs are natural breakwaters that dissipate a large fraction (often >90%) of incoming deep-water wave energy [1] [2]. However, rising sea levels and changing wave climates are diminishing this protective effect, exposing reef-lined shores to more frequent flooding [3] [4]. A key question is: *what drives coastal flooding on reef-fringed coasts – is it the offshore wave energy or the water level over the reef?* In other words, do extreme wave events or elevated water levels (tides, surges, sea-level rise) play the dominant role in flooding? The answer, as emerging research shows, is that both factors are critical and interdependent. This literature review synthesizes the physical processes of wave transformation on reefs, the latest modeling techniques and data collection methods, and current understanding of the relative roles of wave energy and water level in driving flooding. It also highlights knowledge gaps to guide future research. Throughout, foundational concepts like wave setup (from radiation stress theory) and empirical runup formulations are connected to recent findings to build physical intuition. The goal is to provide a budding coastal scientist with a thematic overview of wave-driven flooding on coral reef-lined coasts – from fundamental hydrodynamics to cutting-edge tools – and to identify where further investigation is needed.

Wave Transformation on Fringing Reefs

Wave Breaking and Energy Dissipation: As ocean waves propagate over a shallow fringing reef, they undergo rapid transformation. The reef crest (often at the seaward edge of the reef flat) forces deep-water waves to break, dissipating a majority of their energy through turbulent bores and bottom friction. In fact, healthy coral reefs with complex roughness can dissipate **~97%** of incident wave energy under typical to storm conditions [5]. This dissipation is far greater than on gentle sandy beaches, due to the abrupt depth change and rough reef surface [6]. The primary consequence of this strong dissipation is a drastic reduction in **sea-swell (SS) wave heights** across the reef flat. Field studies have shown that breaking on the outer reef (plus friction across the reef flat) removes most of the high-frequency wave energy before it reaches the shoreline [7]. In essence, the reef acts as a low-pass filter for waves [8] [9] – short-period wind waves and swell are mostly expended at the reef edge, while lower-frequency motions can still penetrate.

Wave Setup: A direct outcome of wave breaking on reefs is **wave setup**, a quasi-steady rise in mean water level landward of the break point due to the imbalance of momentum flux (a classic radiation stress concept). On fringing reefs, wave setup can be a dominant component of the total water level at the shoreline [10] [11]. As waves break and dissipate their energy, they push water onto the reef flat, elevating the water level until the pressure gradient and gravity balance the momentum of breaking waves. Notably, wave setup on steep reef profiles can be substantial – lab experiments and field observations confirm that **wave setup contributes significantly to coastal flooding** in these environments [11]. Longuet-Higgins and Stewart's (1964) theory of radiation stresses provides the physical intuition: bigger incoming waves (and more abrupt depth-limited breaking) generate larger setup. In reef environments, wave setup often varies with the tide and water depth, as discussed later.

Infragravity Waves and Resonance: When waves break in groups, the time-varying breakpoint generates **infragravity (IG) waves** – long oscillations typically in the 25–200 s period band – that can propagate across the reef. On wide reef flats, these IG waves and even longer **very low-frequency** (VLF) motions can become significant at the shoreline [12]. In fact, low-frequency motions often dominate the variability of water level on the reef flat after the short-period waves have dissipated. Field observations at sites like Ipan reef in Guam have demonstrated that at certain water levels the reef flat can support **resonant modes** for IG waves [13]. The reef flat and lagoon system may behave like a natural basin where specific long-wave standing modes are excited by incoming wave groups. When the water depth is suitable, the IG wave energy can amplify at the shoreline (anti-nodes of the standing wave) and cause large shoreline water-level oscillations [13]. This resonant amplification means that even if individual swell waves are mostly broken, the cumulative effect of grouped waves can still induce coastal flooding through oscillatory surges or bores. Conversely, if the combination of reef geometry and water depth does **not** coincide with these mode frequencies, the reef effectively suppresses low-frequency motion, greatly reducing IG wave heights and thus limiting runup at the coast [14]. This was shown in flume experiments: a reef with roughness can dampen long waves, whereas a smooth reef flat lets them reflect and stand. In short, **IG waves and wave setup are often the dominant drivers of runup on reef-lined coasts**, with IG waves particularly important during energetic wave-group events [11].

Bottom Friction and Reef Roughness: Coral reefs are characterized by rough, complex bathymetry – coral heads, spur-and-groove formations, boulders, etc. High bottom friction is a critical mechanism by which reefs dissipate wave energy across the reef flat [6]. Recent studies have quantified the influence of roughness by comparing smooth vs. rough reef conditions. For example, **laboratory flume experiments** by Buckley *et al.* (2018) introduced large roughness elements to mimic coral and found that the roughness reduced low-frequency wave motions on the reef flat and **cut wave runup by ~30%** on average, compared to a smooth reef case [15] [16]. Physically, the roughness causes additional frictional energy losses, attenuating the IG waves and even the setup to some degree. This has crucial implications: **if coral reefs lose their roughness (due to coral degradation or sand infill), more wave energy, especially at low frequencies, will reach the shore and runup elevations will increase** [16]. Healthy, rugose coral canopies have been observed to enhance friction and wave damping [17] [18]. Thus, living reefs not only reduce wave heights through breaking, but also through frictional damping – a natural coastal protection that hinges on reef health.

Drivers of Coastal Flooding: Wave Energy vs Water Level

Water Level Modulation of Wave Impacts: A fringing reef's effectiveness as a wave buffer depends strongly on the **water depth over the reef flat**. At low water levels (e.g. low tide), the shallow reef forces waves to break at the reef crest, causing **greater attenuation and larger setup** gradients on the reef [19]. At high water levels (e.g. during high tide or storm surge), waves can penetrate further landward with less breaking, meaning *more* wave energy reaches the shoreline but the fractional setup may be reduced. **Field measurements on Funafuti Atoll (Tuvalu)** illustrate this tidal modulation: at low tide, breaking-induced energy dissipation and wave setup were significantly higher, whereas at high tide the reef transmitted more of the sea-swell energy to the shore [19]. In other words, lower water levels produced *higher* wave breaking and setup (an antiphase relationship between tides and setup), while higher water levels allowed larger shoreward wave heights [20]. This seems counter-intuitive – how can a lower sea level lead to higher runup?

The resolution lies in the reference frame: at low tide the baseline waterline is lower, but the *additional* elevation due to wave setup and swash can be greater than at high tide, potentially leading to similar or even greater runup heights relative to the instantaneous sea level. However, from a flooding perspective, the *absolute* water level might still be highest when a large wave event coincides with a high tide or elevated mean sea level. Many observed flooding events on reef islands occur when **both** drivers align – for instance, an energetic swell arriving during a king tide (higher water level) often causes the worst flooding [21] [3].

Offshore Wave Forcing: Offshore wave energy (characterized by significant wave height and period) is obviously a fundamental driver of coastal flooding potential. Large wave events (swell from distant storms or locally generated storm waves) provide the raw energy that can run up and inundate coastlines. On open beaches, empirical models like **Stockdon et al. (2006)** show runup heights scaling with offshore wave height and length, without an explicit dependence on water level. On reef-lined coasts, however, the situation is more nuanced. **Becker et al. (2014)** analyzed observations from three Pacific fringing reefs and found that the **water level over the reef flat essentially controls how much of the offshore wave energy reaches the shoreline** [2]. At these sites, during higher water levels, more wave energy crossed the reef (leading to higher shoreline wave heights), whereas at lower water levels waves were effectively cut off at the reef crest [7]. The sensitivity of shoreline wave heights to water level can vary from site to site, depending on the reef's width and roughness in addition to depth [7]. For example, a wide reef flat might still dissipate most waves even at high tide, whereas a narrow reef will transmit proportionally more wave energy for the same depth. **Storlazzi et al. (2011)** noted that just a modest increase in water depth over a reef can dramatically increase the fraction of deep-water wave energy that propagates to the beach, thereby raising erosion and flooding risk [3]. In essence, *offshore wave energy sets the potential, but reef water depth modulates the realization of that potential*.

At some reef-lined islands, offshore wave height is indeed the dominant predictor of runup and total water level variance. For instance, a recent study on La Réunion found that **offshore significant wave height explained ~98% of the variance in wave setup and ~79% of the variance in runup**, with tides accounting for the remainder [22]. This suggests that wave forcing is the primary driver, but importantly, even a small fractional influence of water level can make the difference between overtopping or not in marginal events. Moreover, the contribution of water level rises with extreme conditions – e.g. an El Niño-driven regional sea-level increase or a storm surge on top of tide can elevate the baseline such that waves that normally wouldn't flood the land are suddenly able to do so.

Combined Effect and Extremes: Major flood events on reef-lined coasts typically require a **concurrence of high water levels and energetic waves**. Historical flooding incidents in the Pacific bear this out. For example, in December 2008 a series of large swells (generated by distant storms) arrived in the western Pacific and caused severe flooding on atolls – but significantly, these events coincided with seasonally higher sea levels [21]. In July 2022, the **worst coastal flooding in American Samoa since 2009** occurred when an extrinsic swell combined with a king tide; this event was declared a disaster by FEMA [21] [3]. These cases underscore that asking *"wave energy or water level?"* is somewhat misleading – it is the **product of both** that often delivers the knockout punch. **Low-frequency oscillations** further complicate matters: if a high tide and swell also excite a resonant IG oscillation on the reef flat, the resulting *IG setup* (sometimes termed **"dynamic setup"** [23]) can intermittently raise water levels even higher than the quasi-steady setup. Cheriton *et al.* (2016) observed that island overwash was strongly driven by the combination of **elevated offshore water level and IG wave heights on the reef flat**, with peak flooding occurring when high tide aligned with maximum IG wave energy on the reef [24]. In summary, **offshore wave height and reef water level are both essential drivers**: wave height provides the energy for runup, and water level (tides, surge, or sea-level rise) controls the efficiency of wave transmission and the baseline elevation from which runup begins.

Contrast with Sandy Beach Runup: It is worth noting how reef-lined coasts differ from typical open beaches. On a sandy beach, runup empirical formulas (e.g. the **Stockdon et al., 2006** parameterization) indicate that runup increases with larger waves and steeper beach slope, but they **do not include tide or water level as an explicit parameter** [25]. This is because on a gently sloping beach, a higher tide simply shifts the wave breaking location upward without necessarily changing runup statistics (assuming similar breaking conditions). In reef environments, by contrast, the **reef flat acts as a hard threshold**: if the water is too low, waves will break at the outer edge and little energy reaches the shore; if the water level is high enough, even moderate waves can suddenly propagate inland. As Barnes *et al.* (2024) put it, the **wave-suppressing ability of a reef is *water-level dependent*** [26]. Therefore, **climate change impacts on reef coasts are twofold: rising sea level not only raises the still-water level but also allows higher wave energy to reach the shoreline** [27]. This dual effect means traditional beach-based runup predictions may seriously underestimate future flooding on reef-fringed coasts if they don't account for the reef depth changes. Reef-lined shores thus demand specialized models that integrate wave dynamics with water level variations, as discussed next.

Advances in Modeling Techniques

Predicting wave-driven flooding on coral reef-lined coasts is challenging due to the nonlinear, multi-scale processes (wave breaking, IG wave generation, resonance, setup) and the complex geometry of reefs. A range of modeling approaches has been developed, from highly detailed physics-based models to fast statistical tools, often used in hybrid combinations for efficiency.

Phase-Resolving Hydrodynamic Models: To capture the fine-scale processes like wave breaking and IG wave generation, **phase-resolving models** are used. These models (usually variants of Boussinesq-type or nonlinear shallow water equations with dispersion) can simulate the **wave shape and evolution** across the reef. For example, Yao *et al.* (2020) applied a 1D Boussinesq model to field reef environments and successfully reproduced key processes: **breaking-wave induced IG waves** and the existence of reef flat normal modes [28]. The model showed that IG waves are generated by the oscillation of the breakpoint (driven by wave groups) and that the reef flat can support standing wave patterns when the IG wavelength matches the reef geometry [11] [29]. Similarly, **SWASH (Simulating WAves till SHore)**, a nonhydrostatic wave-flow model, has been used (e.g. in Barnes *et al.*, 2024) to simulate waves over fringing reefs with high fidelity [30] [31]. These models resolve individual waves and thus capture the intermittent bores, the time-varying setup, and transient flooding of the shoreline. They require detailed bathymetry and are computationally intensive, but they provide tremendous insight – for instance, identifying exactly at what reef depth a given site shifts from wave-limited to depth-limited transmission [32] [4]. Process-based models like **XBeach (Non-hydrostatic)** have also been widely used; Quataert *et al.* (2015) calibrated XBeach on a Marshall Islands atoll and explored reef changes, finding that steeper and smoother reefs lead to higher runup, and that wave runup will increase with **sea-level rise, larger waves, and coral degradation (lower friction)** [33]. Such models can even simulate overwash and inundation when coupled with wetting-drying algorithms, making them powerful for scenario testing (e.g. how a 0.5 m sea-level rise increases flood extent).

Hybrid Statistical-Dynamical Approaches: While phase-resolving models are accurate, running them for every possible storm, tide, and sea-level scenario is impractical. Thus, researchers have developed **hybrid**

approaches that combine dynamical modeling with statistical or machine-learning techniques to expand the parameter space efficiently. One example is the **hybrid model by Anderson *et al.* (2021)**, which couples process-based models with statistical emulation [34] [35]. In their Earth's Future study, they used a suite of coastal models (Delft3D + XBeach from the CoSMoS modeling system) to simulate numerous combinations of waves, water levels, and winds for a coastal site. They then trained a **Gaussian Process regression surrogate** on these simulations [34]. The result is a fast-running model that can predict nearshore water levels and flooding for *any* combination of offshore conditions, including long time-series or Monte Carlo projections of future climate scenarios [36]. This hybrid approach was able to incorporate **large-scale climate variability** by feeding in climate-conditioned offshore forcing (for example, including the effects of El Niño on regional sea level and wave spectra) [37] [38]. Such frameworks can output not just static flood maps but the *chronology* of flood events, allowing analysis of changing frequency of both extreme floods and minor "nuisance" flooding under climate change [39] [37]. Essentially, the hybrid method preserves physics where needed (wave transformation on the reef) but sidesteps brute-force simulation of millions of scenarios by statistical interpolation.

Bayesian Network and Meta-Models: Another sophisticated tool is the use of **Bayesian networks** to predict wave-driven flooding on data-sparse reef coasts. Pearson *et al.* (2017) developed the **BEWARE** (Bayesian Estimator of Wave Attack in Reef Environments) system [40] [41]. In this approach, a **database of synthetic reef responses** was first created by running a physics-based model (XBeach) for thousands of combinations of wave conditions, water levels, and reef configurations [42]. This yielded an open-access dataset of how waves transform and what runup or overtopping occurs for varied scenarios. Then, a Bayesian network (essentially a probabilistic model) was constructed to rapidly estimate flooding probabilities and runup heights given new input conditions [43]. The power of BEWARE is that it can make near-instant predictions and can be integrated into **early warning systems** for atoll communities [43]. It's particularly useful for regions with limited direct observations, as it leverages physical modeling to inform the statistics [44] [45]. Importantly, this system allows **"what-if" analysis**: one can query how flood risk would change *if* the coral reef degraded (lower roughness), or *if* sea level rises by a certain amount [46]. By capturing the conditional relationships (e.g. "if reef depth increases, then transmitted wave height increases"), the Bayesian model helps identify key drivers of flooding for different sites. Such tools highlight that while every reef-lined coast is unique, generalizable predictors (reef slope, depth, width, roughness, offshore wave climate) can be quantitatively related to flooding outcomes in a probabilistic sense.

Emerging Techniques: Recent efforts also include **"metamodels"** or reduced-order models like the **Hybrid Coral Reef Wave and Water Level Metamodel (HyCReWW)** [47], which similarly aim to simplify the complex physics into a manageable predictive formula. Other studies are exploring **global forecasting** for reef flooding by leveraging large datasets and maybe even neural network models [48]. There is also an increasing emphasis on **ensemble approaches** that combine multiple models (to account for uncertainty in, say, bathymetry or wave climate). Regardless of approach, modern modeling acknowledges that *neither waves nor water level alone suffice* – the interplay must be captured. For instance, a model might output total water level as: *TWL = tide + surge + wave setup + runup (swash)*, where wave setup itself is a function of wave breaking which in turn depends on water depth. Capturing these feedbacks is crucial. The latest models also seek to include **reef flexing or overtopping** explicitly – simulating when waves actually spill over the island and how that water flows inland (important for estimating damages and freshwater lens impacts on atolls).

Innovations in Data Collection

Accurate field data are vital for understanding reef hydrodynamics and validating models. Traditional measurements on reef-lined coasts have included in situ **pressure sensors** and wave gauges deployed across the reef (from the fore-reef slope to the reef flat and shoreline) [49] [50]. These yield time-series of wave heights, setup, and currents at specific locations. However, reefs pose logistical challenges – they are often remote, shallow, and hazardous during wave events, making instrument deployment and maintenance difficult. Recent advances are enhancing our ability to observe wave processes on reefs:

- **Drone-Based LiDAR Scanning:** A breakthrough technique demonstrated by Fiedler *et al.* (2021) is the use of **hovering drone-mounted LiDAR** to measure waves and runup in the surf zone [51]. In this approach, a laser scanner is mounted on a quadcopter UAV that hovers ~20 m above the breaking waves, scanning a cross-shore transect up to ~150 m wide [51]. This provides an unprecedented view: the LiDAR captures the **instantaneous water surface and wave swash on the beach** with high spatial and temporal resolution, without risking equipment in the crashing waves. The drone LiDAR can measure wave crest shapes, runup excursions, and even do bathymetry inversion (by analyzing wave celerity) from a safe vantage point [52]. Validation tests showed that the hovering LiDAR's accuracy in measuring runup and wave heights is nearly equivalent to that of a fixed terrestrial LiDAR scanner [53]. The mobility of drones allows surveying **remote reef sites** where setting up instruments is infeasible. This technique has enabled capturing whole wave transformation sequences (wave breaking, bores propagating, runup and backwash) in ways that single-point pressure sensors might miss. Such rich datasets are invaluable for validating numerical models' detailed predictions of wave profiles and swash dynamics on reef-lined coasts [52]. As drone and LiDAR technology advances, we can expect more routine 3D mapping of wave overwash events and erosion in reef environments.

- **Video and Image-based Monitoring:** In some studies, fixed cameras or **video monitoring systems** have been used on islands to estimate wave runup and overwash occurrence. By tracking the swash excursion on beaches (through pixel intensity or edge detection), researchers can derive runup statistics similar to how it's done on mainland coasts. This has been applied on atolls to document wave overtopping frequency under different conditions. Likewise, **satellite imagery and aerial photos** taken during or after extreme events have helped identify how far inundation reached (useful for hindcasting the event with models by providing a "high water mark").

- **Offshore Wave Buoys and Tide Gauges:** To feed models and understand the offshore forcing, instrumentation such as wave buoys, wave-rider gauges, or acoustic Doppler profilers are moored outside the reef to measure incoming wave spectra. On the reef flat or lagoon, pressure sensors capture the low-frequency oscillations and mean water level (setup). Additionally, tide gauges (and even bottom pressure recorders) at these islands give the baseline sea level changes (including tides, seasonal anomalies, etc.). For example, the NOAA gauge at Pago Pago, American Samoa recorded a notable upward jump in mean sea level after the 2009 earthquake-induced subsidence [54], which has been correlated with increased flooding frequency. Without such long-term water level records, distinguishing climate-driven sea-level rise from other processes would be difficult.

- **Integrated Field Experiments:** Large multi-instrument deployments have been carried out at specific sites (often as part of international experiments). These might include cross-shore arrays of pressure sensors, current meters, and sometimes even **wave-foil sensors or ADVs** to get turbulence data. A notable example is the field study at Roi-Namur on Kwajalein Atoll, where instruments captured a holistic picture of wave breaking, setup, infiltration and overwash on the atoll's shore [55]. Such datasets have been critical to develop and calibrate models like XBeach for reef environments [55].

Looking ahead, emerging technologies could further fill data gaps. For instance, **autonomous surface vehicles** (wave gliders) could map wave transformation over reefs without endangering crew. **Seafloor pressure loggers** that can be left in place for years can record long-term IG wave climate on reefs to detect trends. Even **crowdsourced data** (e.g. islander photographs of flood events or drone footage from local communities) are being explored to augment scientific observations. All these efforts in data collection serve to improve understanding of the physical processes and to validate that our models are capturing reality – especially for extreme, infrequent events where empirical experience is limited.

Climate Change Impacts and Reef Health Considerations

Coral reef-lined coasts are on the frontline of climate change impacts. **Sea-level rise (SLR)** is perhaps the most direct concern: as mean sea level increases, the protective relative shallowness of reef flats diminishes. A higher water level means waves that previously broke on the outer reef can now propagate farther in, delivering more energy to the shoreline [2] [27]. Model projections for reef sites consistently show a nonlinear response: beyond a certain reef depth, the **shoreline wave heights and runup begin to increase rapidly with further sea-level rise** [56] [57]. Essentially, reefs have a finite capacity to dissipate wave energy; once the water gets deep enough, that capacity is overwhelmed. **Barnes et al. (2024)** used the SWASH model for a reef in American Samoa and found that rising sea levels will **escalate nearshore extreme water levels primarily by allowing larger sea-swell waves across the reef**, compounding the flood hazard [32] [58]. Intriguingly, they identified thresholds of reef submergence at which the increase in transmitted wave energy is especially pronounced [59] [4]. Planners of atoll nations are keenly aware of this: today's 2 m swell at high tide might cause minor splash, but the same swell with 0.5 m of SLR could cause destructive overwash.

Another aspect is **changes in wave climate**. Climate change can alter the patterns of storminess and swell generation in the ocean basins. Studies (e.g. Storlazzi et al. 2015) suggest that some regions may experience **increases in extreme wave heights or shifts in wave direction** under future climate scenarios [60]. If a reef coast that historically was sheltered from the largest swells starts receiving them due to a direction change, that could drastically raise flood risk. Combined with SLR, even a moderate uptick in wave heights can lead to a disproportionate increase in overwash frequency [57] [61]. Many future predictions for atoll islands show that by mid-to-late 21st century, annual flooding events may become routine, effectively rendering some islands uninhabitable [62]. For example, a modelling study on atoll island habitability (Storlazzi et al., 2018 in *Sci. Adv.*) found that by the 2050s–2060s, the return period of significant overwash could drop to **yearly** for atolls in the Marshall Islands, primarily due to SLR pushing even average wave events into flooding territory.

Coral Reef Degradation: A critical, but sometimes overlooked, factor is the health of the coral reef itself. **Live corals grow and maintain the reef elevation**, and their complex structures add friction. Unfortunately, climate change (ocean warming and acidification) is leading to **coral bleaching and mortality**, threatening the very existence of reef structures [63] [64]. If reefs cannot keep pace with SLR through vertical growth (accretion), they will effectively become deeper over time relative to sea level. Healthy reef flats in the past have kept up with Holocene sea-level changes by accumulating carbonate material, but current rapid SLR combined with ecological stressors may exceed the growth rate. Barnes et al. note that while some reef flats could *in theory* grow faster with more “accommodation space” (fewer low-tide exposure limits) [65], the **reality of coral decline** means this is unlikely in many areas [66]. Therefore, many researchers take the conservative assumption of a **fixed reef elevation** relative to datum, which is a worst-case for flooding [67]. Coral degradation also means loss of roughness; as mentioned earlier, smoother reefs transmit more wave energy [33]. Quataert et al. (2015) directly examined the effect of reef roughness and found that **eroded or dying reefs (low roughness) could lead to substantially higher wave runup and flooding** – essentially the reef’s protective value is compromised [33]. On a positive note, there is growing interest in **reef restoration or artificial reef structures** as adaptive measures. Studies like Storlazzi et al. (2021) have looked at how strategic placement of reef restoration (e.g. enhancing coral cover in key locations) can **optimize wave energy dissipation and reduce coastal flooding** [48]. The idea is to actively maintain the reef height and roughness so it continues to serve as a natural barrier.

In summary, climate change is expected to **exacerbate wave-driven flooding on reef coasts** through: (1) rising seas that reduce wave breaking efficiency, (2) potentially stronger or more frequent wave events, and (3) degradation of coral reefs reducing friction and elevation. Reef-lined communities thus face a narrowing window of safety. Adaptation strategies may include building seawalls or revetments landward (often not feasible for long perimeters), elevating infrastructure, and ecosystem-based approaches like **reef conservation and rehabilitation** to maintain the natural breakwater. Importantly, projections of future flooding need to consider all these factors – a 1 m sea-level rise could have very different outcomes if the reef remains intact versus if it collapses biologically.

Knowledge Gaps and Future Directions

Despite significant progress in understanding and modeling, there remain several **knowledge gaps and research needs** in the study of wave-driven flooding on reef-lined coasts:

- **Site-Specific Complexity:** Coral reef geometry is highly variable – from wide atoll lagoons to narrow fringing reefs, with or without channels. This variability makes it hard to generalize findings. **Many models use simplified 1D profiles**, which may not capture alongshore variations or the presence of cross-reef channels that can alter flows (e.g. allowing water to drain or concentrate). Field data from only a handful of well-instrumented sites are available, so our empirical basis is narrow. We need more comparative studies across different reef settings to refine how reef width, fore-reef slope, reef flat depth, and morphology quantitatively influence wave runup and flooding. For instance, theory and models predict that **narrow, steep reefs with deep flats are most vulnerable** [33], but more validation across natural reefs would firm up these relationships. **Are there reef configurations that provide unexpected resilience?** Conversely, are there subtle features (like a slight depression on the reef flat or a spur-and-groove pattern) that amplify certain frequencies? These questions warrant further field and numerical investigation.

- **Infragravity Wave Dynamics:** While we know IG waves are important, the precise conditions that lead to **reef resonance vs. damping** are not fully mapped out. Buckley et al. (2018) showed resonance occurs at specific mode frequencies and roughness damps it [11] [16]. But on natural reefs, the spectrum of incoming wave groups and the tide level constantly evolve – how often do resonant peaks actually get excited in real storm conditions? Some observations (e.g. Cheriton et al.) indicate the biggest overwash events coincide with IG peaks at high tide, but we lack continuous long-term records of IG wave statistics on reefs. More deployments of pressure sensors capturing IG frequencies over months to years (especially through storm seasons) would help determine how predictable or stochastic these IG surges are. This links to early warning: can we forecast IG wave setup hours ahead (since they depend on wave grouping)? Research into **real-time IG monitoring and prediction** is a gap, possibly addressable with machine learning on swell spectra.

- **Runup and Overtopping Criteria:** On beaches, engineers use formulas (Stockdon, etc.) for runup and overtopping thresholds. For reef-lined coasts, we don't yet have a simple widely-accepted formula for runup that incorporates reef properties. Efforts like **RIOT (Runup-Overtopping Threshold) in Nature Communications (2018)** have proposed simplified predictors for atoll flooding [56] [57], but those are first-cut and may not include all processes. There's a gap in translating the complex physics into **practical engineering tools**. Coastal managers on Pacific islands often ask: *How high should we build a coastal road or seawall?* Answering that requires a reliable estimate of extreme runup. More work is needed to blend physical models and statistics to create reef-specific design guidelines (akin to how the Stockdon formula is used on beaches, perhaps a "reef runup formula" that includes reef depth and width parameters).

- **Data Scarcity and Validation:** Many low-lying reef islands (especially in the developing world) have scant instrumentation. This hampers both research and hazard assessment. The **BEWARE approach** is one solution (creating synthetic data) [42] [43], but it still needs at least some data for calibration and to ensure realism. A big push is needed for international programs to instrument high-risk sites (even if just with basic water level loggers or crowd-sourced data during events). **Citizen science and indigenous knowledge** could be valuable – island communities often know which conditions cause flooding (e.g. "when swell is from the north and the tide is above X"). Documenting and quantifying this local knowledge could fill gaps in formal data and guide model scenarios. Additionally, **satellite remote sensing** might be leveraged to detect flooding extents or wave breaking patterns on reefs (e.g. using Sentinel-2 imagery during big events). Developing techniques to use such remote observations to validate model-predicted flood extents is an open area.

- **Integrating Ecology and Morphodynamics:** Most hydrodynamic models treat the reef as static topography with a roughness parameter. In reality, reefs can **change over time** – coral growth or erosion, sediment deposition, storm-driven morphological alterations. There is a knowledge gap in how these **morphodynamic changes** interact with hydrodynamics. For example, if a severe cyclone throws large coral boulders onto the reef flat, does that increase roughness (damping waves) or create channels (focusing waves)? Likewise, reef **eco-morphology feedback** under rising sea level is uncertain – will increased water depth allow more coral growth (up to a limit) or will it simply drown the reef? Interdisciplinary studies combining coral ecology, sedimentology, and hydrodynamics are needed to project reef state into the future. This also ties into management: **can we assist reefs to keep pace with SLR** (through artificial structures or substrate addition) in a way that preserves their wave-breaking function? These nature-based solutions are promising but require pilot projects to assess efficacy.

- **Future Wave Climate Uncertainty:** Projections of wave climate under climate change (e.g. changes in storm tracks, intensity, or prevailing swell) carry substantial uncertainty. Our flood risk models could be highly sensitive to these changes – for instance, an island might be safe if extreme waves stay below 4 m, but if climate change brings 5 m waves occasionally, the calculus changes. There's a gap in downscaling global wave projections to the island scale and incorporating those in flood models. Collaboration between climatologists and coastal engineers is needed to ensure scenarios used in coral reef flooding studies capture the plausible range of wave futures.

In closing, while we have identified the main drivers (wave energy plus water level) and made great strides in modeling and measurement, **the problem of wave-driven flooding on reef-lined coasts is far from fully solved**. The stakes are high – millions of people live on atolls and reef-fringed islands, and their vulnerability is rising. Continued research should focus on holistic approaches that consider oceanographic, ecological, and social dimensions. By addressing the knowledge gaps above, scientists will be better equipped to predict and ultimately help mitigate the impacts of coastal flooding in these unique and vulnerable environments. As this review demonstrates, a solid physical understanding is the foundation: with that in hand, we can innovate in modeling, gather richer data, and develop strategies to preserve both the protective functions of reefs and the safety of coastal communities.

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