

## Impacts of a Changing Earth on Microbial Dynamics and Human Health Risks in the Continuum between Beach Water and Sand

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## Abstract

Humans may be exposed to microbial pathogens at recreational beaches via environmental sources, such as water, sand, and aerosols. Although infectious disease risk from exposure to waterborne pathogens has been an active area of research for decades, sand is a relatively unexplored reservoir of pathogens and fecal indicator bacteria (FIB). Beach sand and water habitats provide unique advantages and challenges to pathogen introduction, growth, and persistence, as well as continuous exchange between habitats. Models of FIB and pathogen fate and transport in sandy beach habitats can help predict the risk of infectious disease from recreational water use, but filling knowledge gaps such as decay rates and potential for microbial growth in beach habitats is necessary for accurate modeling. Climatic variability, whether natural or anthropogenically-induced, adds complexity to predictive modeling, but may increase human exposure to waterborne pathogens via extreme weather events, warming of water bodies and sea level rise in many regions. The popularity of human recreational beach activities, combined with predicted climate change scenarios, could amplify the risk of human exposure to pathogens and related illnesses. Other global change trends such as increased population growth and urbanization are expected to exacerbate contamination events and the predicted impacts of increasing levels of waterborne pathogens on human health. Such changes will alter microbial population dynamics in beach habitats, and will consequently affect the assumptions and relationships used in population models and quantitative microbial risk assessment (QMRA). Here, we discuss the literature on microbial population and transport dynamics in sand-water continuum habitats at beaches, how these dynamics can be modeled, and how climate change and other anthropogenic influences (e.g., land use, urbanization) should be considered when using and developing more holistic, beachshed-based models.

**Keywords:** pathogen, climate change, sand, water quality, modeling

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# 1. Getting Our Feet Wet: Introduction

## 1.1 Overview

Beaches form a physical interface between sea and land, absorbing the energy of waves and providing habitats for diverse microbial communities. Beaches have also assumed an important role in human recreational activities, supporting hundreds of thousands of jobs and billions of dollars in annual revenue (King 1999). Each year, an estimated 140 million plus individuals engage in water-related recreational activities in the US (DeFlorio-Barker et al. 2016). Beachgoers assume that the sand and water they encounter beaches poses no health threat, but this is far from certain in areas where sewage and other sources of fecal waste contaminate beaches with pathogens (Goodwin et al. 2012, Heaney et al. 2009, Korajkic et al. 2011, McQuaig et al. 2012, Sabino et al. 2011, Soge et al. 2009). The epidemiological studies conducted in the US during the National Environmental and Epidemiological Assessment of Recreational Water (USEPA 2009) found that the average risk of acute gastroenteritis attributed to primary contact with water, e.g. swimming and wading, is 15 per 1000 individuals engaging in that activity (DeFlorio-Barker et al. 2018, Wade et al. 2008, Wade et al. 2006, Wade et al. 2010). In the US alone, the annual cost of illnesses related to recreational water exposure is nearly \$3 billion (DeFlorio-Barker et al. 2018) and increased utilization from a growing population may push these numbers even higher.

Human activities have negatively influenced microbial water quality for centuries, leading to disease outbreaks, epidemics and pandemics (Harwood et al. 2016, Hays 2005, IWA 2007, Santo Domingo et al. 2011). Humans exposed to fecal-contaminated water and sand at beaches are at increased risk of infections that cause gastroenteritis, dermatitis, and other illnesses (Bonilla et al. 2007, Heaney et al. 2012). Population growth and urbanization are associated with increased pollution of surface waters from sewage and runoff. Adding to the direct pressures exerted by global inhabitants on water resources, climate change is predicted to influence weather patterns worldwide; altering temperature, precipitation, sea level rise, and storm intensity patterns (IPCC 2014, 2018). For example, mean global sea level rise is predicted to be 0.3 – 0.8 m depending on the emission scenario. The implications of climate-associated changes for microbial water quality in general, and FIB-pathogen relationships in particular, are profound, as these parameters have a dominant influence on the fate of waterborne pathogens and FIB (Patz et al. 2008). Thus, the pressures generated by human population growth and global climate change have strong potential to accelerate issues of microbial pathogens in the beach sand water continuum in the 21<sup>st</sup> century (Islam et al. 2018).

In this paper we review the human health effects and ecology of microbes in the sand, in terms of pathways to the beach, hangouts within the sand-water continuum, how microbes move between sand and water, and challenges to microbe survival and persistence at the sand-water continuum. We present a model of microbial behaviour in sand, and discuss the implications of climate change for human-pathogen interactions in the sand-water continuum using the model as a basis. The article is divided into independent subsections to allow for selective reading. To avoid confusion between the terms sand and sediment, we distinguish the two by their location within the beachshed. The term sand represents the sand area at the beach that is not regularly covered by the water column, while sediment represents that sand area that commonly underlies the water column in a lake or ocean.

## 1.2 The FIB-Pathogen Paradigm

The etiological agents of fecal-associated diseases often originate in the gastrointestinal tracts of human and other animals, and are shed in feces. These pathogens contaminate beach waters and sand by routes such as untreated, improperly treated or accidental spills of sewage, or defecation from humans, wildlife, livestock, and pets (Harwood et al. 2017, Harwood et al. 2014). Fecal-associated pathogens and other waterborne pathogens include bacteria, viruses, protozoa, fungi, and helminths. Some waterborne pathogens are normal inhabitants of aquatic environments, and are not associated with fecal contamination, including the bacteria *Vibrio vulnificus* and *V. parahaemolyticus*, the fungi *Aspergillus* spp. and *Mucor* spp., and the protozoan *Naegleria fowleri* (CDC 2018, Gerba 2009, Hazen et al. 2015, Wright et al. 1996). See Table S1 for some representative pathogens and their respective estimated infective dose.

Regulation and monitoring of recreational water quality worldwide are largely dependent on FIB, such as fecal coliforms, *E. coli*, and enterococci (Parliament 2006, WHO 2003). FIB act as a warning of the increased likelihood of occurrence of fecal-borne pathogens, however, many studies have found poor correlations of FIB with pathogens in water (e.g. (McQuaig et al. 2012, Zhang et al. 2016)). In some cases, FIB overestimate human health risks, while in others, they underestimate them (Byappanahalli et al. 2012, Nguyen et al. 2018, Whitman et al. 2014). Current understanding of the factors that influence relationships among FIB and pathogens is marginal, but studies indicate that temperature, salinity, precipitation, location (water, sediment, vegetation), and contamination sources affect FIB and pathogen levels in water and sand (Lipp et al. 2001, Medema et al. 1997, Whitman et al. 2008). The microbial community also influences pathogen survival by exerting the pressures of predation and competition (Feng et al. 2010). The imperfect relationship between FIB and pathogens hampers our ability to estimate human health risk from FIB levels, and climate change may make these relationships even more tenuous.

The current body of evidence indicates that sole reliance on FIB to predict risk of illness from recreational activities at beaches is inadequate for protecting public health. This disconnect is due, in large part, to the ubiquitous presence of currently utilized FIB in most matrices, which leads to a lack of correlation between FIB and human pathogen concentrations. Exacerbating the difficulty is a disconnect between source and sink relationships, due in part to FIB resuspension and environmental growth of FIB. All of these issues contribute to a lack of understanding of health risks associated with beach sand contact (Harwood et al. 2017, Solo-Gabriele et al. 2016, Whitman et al. 2014).

## 2. Health Risks from Beaches

It is estimated that four billion surface water recreation events occur annually in the US alone (DeFlorio-Barker et al. 2018). Human behaviors at the beach can influence the degree and severity of outcomes associated with exposure, especially among sensitive sub-populations (i.e., immune-compromised patients, elderly people, children) who experience enhanced susceptibility to adverse health-effects (Gerba et al. 1996, Stewart et al. 2008). At the beach, recreational contact occurs not only with the water, but also with the adjacent sand and underlying sediments.

The World Health Organization (WHO) identified beach sands as a possible factor in infectious disease transmission well over a decade ago (WHO 2003), while emphasizing the need for more research to assess health risk. Of the limited studies that exist, one study characterizing the risk of

illness from *Cryptosporidium* spp., enterovirus, and *Staphylococcus aureus* at a marine beach found that pathogen levels in beach sands were lower than that required to reach the U.S. EPA illness risk benchmark of  $1.9 \times 10^{-2}$  (19 illnesses per 1,000) (Shibata and Solo-Gabriele 2012).

Due to a paucity of data, individual nations did not officially recognize sand as a contamination source until relatively recently. In 2012, Canada formally acknowledged sand-based contamination at beaches (Canada 2012). In 2017, Argentina became the first nation to legally recognize the relevance of sand as a source of beach contamination, mandating sand monitoring and contamination mitigation in beach management plans (Ambiental 2017). The five-year review of 2012 recreational water quality criteria in the U.S. (USEPA 2018) includes some discussion of sand as a reservoir and transmission source of nearshore beach contamination, and Portugal has begun discussion regarding similar updates. The upcoming review of the WHO guidelines for safe recreational water environments target for 2020 will integrate updated knowledge regarding sand contaminants at beaches and human health risks associated with exposure (J. Brandão, personal communication).

Human exposure to pathogens can occur as they interact with water and/or sand contaminated with microorganisms from human or other animal sources (Whitman et al. 2010), as graphically represented in Figure 1. For example, hand-to-mouth transfer of *E. coli* and coliphages occurred via exposure to beach sands (Whitman et al. 2009). Epidemiological studies have shown that exposure to beach sand can increase the risk of gastroenteritis (Heaney et al. 2012, Heaney et al. 2009). Sand may also offer a transmission mode for opportunistic pathogens of non-fecal origin such as dermatophytes, which are shed by beach users (Anderson 1979, Havlickova et al. 2008, Solo-Gabriele et al. 2016).



Figure 1: Schematic of the interactions between human beachgoers and the beach environment, potentially leading to exposure to pathogens. Image courtesy of Megan Smith, Jingru Chen, and Michael Winikoff at University of Minnesota.



A statistically significant relationship between waterborne diarrheal diseases and severe weather-related events has been observed in several studies (Auld et al. 2004, Cann et al. 2013, Herrador et al. 2015, Levy et al. 2016, Thomas et al. 2006). If climate variability increases microbial burdens in the beach environment (via enhanced transport mechanisms such as increased surface runoff, intense wave action, etc.), it is likely to result in increased human exposure and resultant disease through recreational contact with water via swimming, water-sports, activities at the sand-water continuum (Mannocci et al. 2016) and direct contact with beach sand (Solo-Gabriele et al. 2016). Beach sand frequently harbors higher levels of FIB than the water it borders, and contact with this sand can elevate human health risk (Heaney et al. 2012, Heaney et al. 2009, Sabino et al. 2014, Whitman and Nevers 2003, Yamahara et al. 2007, Zampieri et al.). Strong winds and many water activities also generate aerosolized particles, creating an additional exposure route for beachgoers.

Due to its ability to estimate risk from activities that may lead to exposure to pathogens, the use of quantitative microbial risk assessment (QMRA) to estimate adverse human health outcomes from waterborne and other beach-associated pathogens has increased in recent years (Ashbolt et al. 2010, Brandão et al. 2015, Haas et al. 1999, Jang and Liang 2018, Schoen and Ashbolt 2010, Shibata and Solo-Gabriele 2012). Data generated through the QMRA process can also be used in the development of predictive models. The QMRA framework can help assess the impacts of changing environmental conditions at beaches and may enable more accurate management actions to prevent climate change-driven health impacts (Hofstra 2011, Schijven et al. 2011, Sterk et al. 2013).

Development of useful predictive models for human health risk will require concerted efforts to better understand the beach sand-water continuum from a microbiological perspective, and the environmental changes that may influence the accuracy of these models. Key questions can only be answered by taking a toolbox approach, using classical and molecular microbiological methods, along with an understanding of coastal processes, chemistry and physics, to better understand the factors that lead to growth and persistence of potential pathogens in sand/water interfacial areas. Here, biological, chemical, and physical forces interact to control microbial community level processes as well as the survival of pathogens. These factors must be understood to correctly parameterize predictive models that may rapidly and accurately forecast health risks associated with beach sand exposure.

### **3. Pollution Pathways: Sources of Fecal Microorganisms**

Pathogens and FIB enter beach habitats via direct deposition from humans and animals, contaminated surface waters, stormwater runoff and contaminated groundwater (Hellberg and Chu 2016, Hofstra 2011). Both human and non-human contamination sources can cause health risks. FIB can also reach the beach sand-water continuum from extra-intestinal reservoirs, such as deposition and growth on algae or macrophytes, or via soil and sediment erosion from stormwater runoff (e.g., soil (Abreu et al. 2016, O'Mullan et al. 2017)). Beaches with denser amounts of seaweed and filamentous green algae, can have higher levels of FIB (Anderson et al. 1997, Quilliam et al. 2014). The mechanical manipulation of beach sands can also affect the density and spatial distribution of FIB (Kinzelman et al. 2004, Kinzelman et al. 2003, Russell et al. 2014). Regional differences in the generation and disposal of fecal waste (e.g., wastewater reuse in

agriculture, sanitation infrastructure and livestock management practices) can also influence the dominant source(s) and quantities of FIB impacting a given water body (Hellberg and Chu 2016, Kroeze et al. 2016). Climate changes may exacerbate fecal loading of beaches from these sources due to increases in storm intensity, rises in water levels and increased tides.

### 3.1 Direct Inputs/Deposition

FIB and pathogens associated with humans and other animals can be deposited directly onto beach sands or into recreational waters. A recent analysis of historical FIB data from Florida beaches determined that the frequency of exceedance of water quality standards was lowest at beaches with low densities of humans, dogs, and birds. Thus, these sources need to be considered in beach management actions (Kelly et al. 2018).

#### 3.1.1 Direct Human Inputs

Human fecal contamination can be directly deposited to the beach environment via faulty infrastructure, such as wastewater collection systems, accumulation of solid waste such as diapers, or by bathers. For example, in Manhattan Beach, California, U.S., an untreated sewage spill in 2006 resulted in a \$1 million loss in economic revenue. It also raised questions about standards for post-event remediation of FIB and pathogens in beach sands, and the proper procedures to safely re-open a contaminated beach (Bishop and Cain 2006). Direct beach contamination via soiled diapers can be alleviated by use of waste receptacles, but if not present, beach-goers may resort to disposal directly on the beach, potentially contaminating the sand (Edge et al. 2018).

A number of studies have linked bather shedding to pathogen levels (Elmir et al. 2007, Graczyk et al. 2010, Graczyk et al. 2007, Plano et al. 2011, Sunderland et al. 2007). Gerba (2000) estimated that the average person in contact with recreational water sheds about 0.14 g fecal matter per bathing event. Previous work has also found correlations between bather density and *Cryptosporidium parvum*, *Giardia duodenalis*, *Enterocytozoon bieneusi* (Graczyk et al. 2010), *Staphylococcus aureus* (including methicillin-resistant strains, (Elmir et al. 2007, Enns et al. 2012, Plano et al. 2011), and fungal (Brandão et al. 2002, Stevens et al. 2012) abundance at beaches. These findings suggest that beach sand can serve as a reservoir for a variety of microbial and opportunistic fungal pathogens sourced from humans.

Changes in climate, demographics, or cultural practices leading to increased bather density may increase risk for beach goers (Schoen and Ashbolt 2010). High air temperatures may move crowds to beaches for relief, especially if exceptional, extreme heat events occur (Moreno et al. 2009, Smith 1993). Expansion of recreational use at beaches may be particularly prominent near urban centers, due to urban heat islands, leading to increased pathogen loading in beach environments (Perkins et al. 2014, Shuval 2003).

#### 3.1.2 Direct Animal Inputs

Deposition of animal feces onto beaches or in near shore water can also result in water quality advisories and/or beach closures (Edge and Hill 2007, Wang et al. 2010, Wright et al. 2009). Specific beaches may experience fecal contamination from a variety of animal sources depending upon location, e.g. horses, wildlife, dogs and cats. Some animals can be sources of both bacteria and fungi that cause skin infections such as ringworm (Brandão et al. 2002). A study conducted at



a dog-friendly Miami-Dade County beach indicated that dog droppings were the largest source of FIB (Wang et al. 2010, Wright et al. 2009), but without an associated health risk. While exposure to animal feces is often thought to present less risk than exposure to an equal amount of human feces, exposure to feces from cattle and poultry is known to increase health risks of recreational water use (Brown et al. 2017, Soller et al. 2010).

Bird droppings deposited onto beach sands can serve as a reservoir for subsequent transfer to nearshore waters as well (Russell et al. 2013). Gull feces are known to contain relatively high concentrations of FIB such as *E. coli* ( $10^5 - 10^9$  CFU/g) and enterococci ( $10^4 - 10^8$  CFU/g) (Fogarty et al. 2003), as well as human pathogens such as *Campylobacter jejuni* and *Salmonella* spp. (Kinzelman et al. 2008, Levesque et al. 1993, Lu et al. 2011). Several studies have documented significant improvements to beach water quality after removal of birds and their fecal deposits at beaches (Converse et al. 2012, Edge et al. 2018, Goodwin et al. 2016, Kinzelman and McLellan 2009). However, populations of gulls and Canada geese have been growing in many urban settings around the world and particularly around the Laurentian Great Lakes (Marzluff 2001, Shochat et al. 2010). Climate changes can affect the regional bird abundance, as observed in northern Europe, potentially leading to new bird associated problems at beaches (Virkkala and Lehtikoinen 2017).

### 3.2 Surface and Storm Water Inputs

In addition to direct deposition, fecal contamination of beach sand or adjacent surface water often occurs via inputs from rivers, creeks, streams or estuaries (Molina et al. 2014, Nevers and Whitman 2005, Staley and Edge 2016). The 1999 Annapolis Protocol (WHO and USEPA 1999), identified riverine inputs as potential sources of contamination for coastal waters. Globally, 80% of untreated wastewater flows into surface waters (United Nations 2015), though the amount of contamination delivered via surface waters is site-specific (WHO and USEPA 1999). See Section 5.2.3 Precipitation for further discussion of precipitation effects at the beach.

Stormwater runoff in urban settings, contaminated by leaking sewer lines, lift station failures, sanitary sewer-cross connections, combined sewer overflow (CSO) events, and impervious surface runoff, can also transport FIB and pathogens to the beach environment (Brownell et al. 2007, Marsalek and Rochfort 2004, Nevers and Whitman 2005). Agricultural runoff can also contribute high loads of ruminant fecal contamination to adjacent water bodies via runoff from concentrated animal feeding operations (CAFOs), grazing fields, or following manure application (Harmel et al. 2010, Jamieson et al. 2002, Staley et al. 2013). Surface waters polluted by agricultural runoff can contain high concentrations of zoonotic pathogens (Islam et al. 2004, Jones et al. 2013, Quilliam et al. 2011).

#### 3.2.1 Climatic Changes and Anthropogenic Factors

Storm intensification, extreme precipitation, and other severe weather events (IPCC 2014, 2018) may introduce pathogens to coastal waters and beaches (Ackerman and Weisberg 2003, Curriero et al. 2001, Fowler and Hennessy 1995, Hellberg and Chu 2016, Hofstra 2011, Mearns et al. 1995, Mimura 2013, Patz et al. 2008, Trenberth 1999). Heavy precipitation events are predicted to increase in both frequency and intensity at some locations, and can result in greater resuspension of FIB from beach sand into the water column and increases in the dissolved organic matter that can influence microbial growth or inactivation. Subsequent effects on water quality can last up to

5-7 days after the event (Ackerman and Weisberg 2003, Curriero et al. 2001, Williamson et al. 2017). Direct fecal deposition, from birds or dogs, or runoff directly onto sand may also be distributed over a greater area of beach as a result of extreme weather events which facilitate increased wave activity (Bonilla et al. 2007, Halliday and Gast 2011, Heaney et al. 2014).

Furthermore, Yamahara (2009) found that periodic wetting, which may change in frequency due to climate changes, may stimulate growth of FIB populations in beach sand. Periodic tidal rewetting enables FIB deposited in dry sands to persist for longer periods (Halliday and Gast 2011, Yamahara et al. 2012). With a shift toward urbanization and a tendency for cities to develop along coastlines, changes in the coastline may substantially impact human exposure levels, likely fostering a continued increase in risk of exposure (Shuval 2003).

Areas experiencing increased drought may also observe increases in microbial exposure resulting from a higher concentration and diversity of microbial communities, including pathogens in depleted water supplies (O'Dwyer et al. 2016, RIVM 2010). Drought conditions may also improve habitat for certain pathogens, including the opportunistic fungal group *Candida*, which can survive in dry sands (Sabino et al. 2011, Shah et al. 2011). Climate change may alter the timing of snowmelt events, shifting them to earlier in the season, as well as reduce snowfall amounts, ultimately decreasing snowmelt in the spring and perpetuating drought conditions in some areas (Adam et al. 2009).

### 3.3 Groundwater Inputs

Leaking sewers and defective septic systems can be responsible for inputs of a variety of contaminants via groundwater to the beach environment (Bishop et al. 1998, Foster and Chilton 2004, Kracht et al. 2007, Rutsch et al. 2008). It has been demonstrated that subsurface transport of microorganisms for considerable distances is possible under certain conditions (Ahmed et al. 2005, Arnaud et al. 2015), and with a combination of urbanization and aging infrastructure, the effects of this contamination source are likely to increase. See Section 5 for details on mechanisms of transport.

In sum, fecal microorganisms enter beaches and waterways by both direct and indirect routes and via point or non-point sources. Direct routes include deposition from animals and humans. While human input sources are thought to create the most health risks, inputs from gulls and birds can also be problematic. Indirect beach contamination can occur via surface and storm water run-off from urban and agricultural environments or via growth of fecal bacteria on extra-intestinal matrices, including algae, plants and sediment. Climate changes may exacerbate fecal loading of beaches due to increases in storm intensity, rises in water levels and increased tides.

## 4. Hangouts: Biofilms and Other Reservoirs of Fecal Microorganisms

Microorganisms in most environments tend to reside in multispecies communities attached to surfaces known as biofilms, rather than living a planktonic existence, and sand is no exception (Figure 2) (Tan et al. 2017). Bacteria form and/or incorporate themselves into biofilms for the benefits of communal living as well as for protection. Bacteria secrete extracellular polymeric substances (EPS) that are critical for attaching to a surface as well as encapsulating the community to protect against predation, creating microenvironments (e.g., oxygen and nutrient gradients) and promoting “microbial talk” (quorum sensing) (Jayatilake et al. 2017). The close proximity

between biofilm members contributes to potentially sharing genetic traits, even across microbial kingdoms. Biofilm structure and EPS composition are related to both the bacterial species and the energy of the surrounding environment. Biofilms can behave as both viscoelastic solids and liquids (Figure 2) (Fabbri et al. 2017, Peterson et al. 2015), allowing them to structurally deform under various shear stresses.

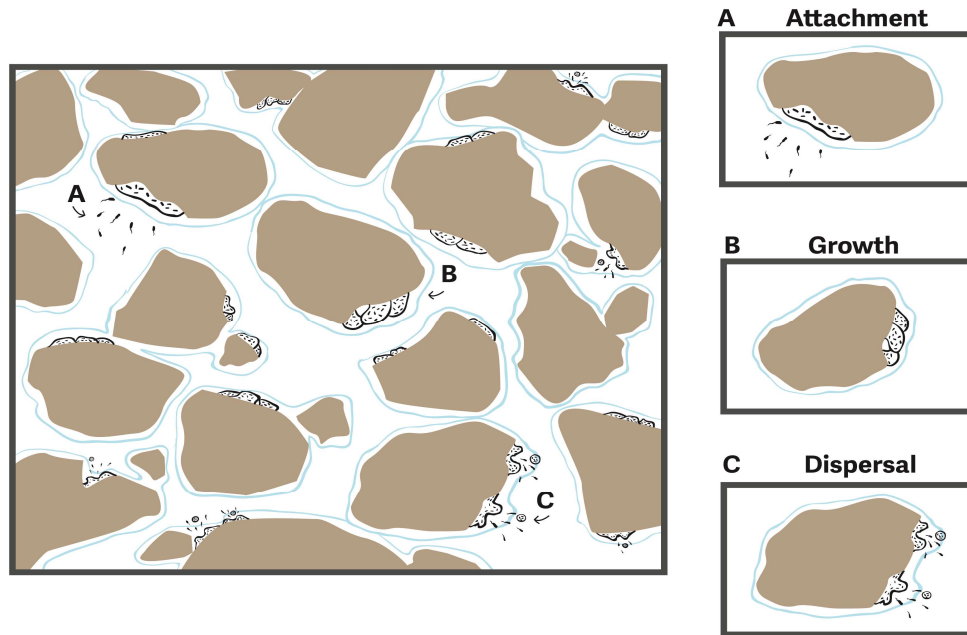


Figure 2: Biofilm stages and dynamics within the context of sand at the sand-water interface. Image courtesy of Jingru Chen at University of Minnesota.

If forces overcome the viscoelastic biofilm, portions will detach and ultimately be released into the water column (Figure 2). Such disruptions to the biofilm structure can be caused by waves and tides. Boehm and Weisberg (2005) and Phillips et al. (2014) found that enterococci concentrations in nearshore water were associated with spring tides, and 60% of sand-associated enterococci can be released to water during high waves (wave height 1.9-10.5 cm), respectively.

One conceptual model for beach sand proposes that biofilms build up and concentrate FIB under low energy conditions. The onset of higher-energy conditions, such as a tidal surge or high wave activity, may release the FIB from the sand biofilms and into the adjacent surface waters, resulting in exceedances of FIB water quality standards (Feng et al. 2016). Similarly, FIB settling and accumulation would be prevented at high energy beaches by constant removal or dilution through hydrodynamic mixing and sediment transport (Figure 3). Feng et al. (2016) demonstrated that percent exceedances of local beach FIB water quality standards were negatively correlated with long-term mean wave energy at Florida beaches. Donahue et al. (2017) found associations between different beach geomorphologies and FIB, e.g. Florida beaches in bays and marsh areas, which are generally characterized by low wave energies, had significantly more exceedances above regulatory thresholds compared to open coast beaches. Similarly, Yamahara et al. (2007) found that sheltered beaches in California had higher FIB than open ocean beaches with higher wave

energy. Abreu et al. (2016) observed higher microbial loading at beaches with artificial infrastructure designed to embay and protect them in the Madeira Archipelago.

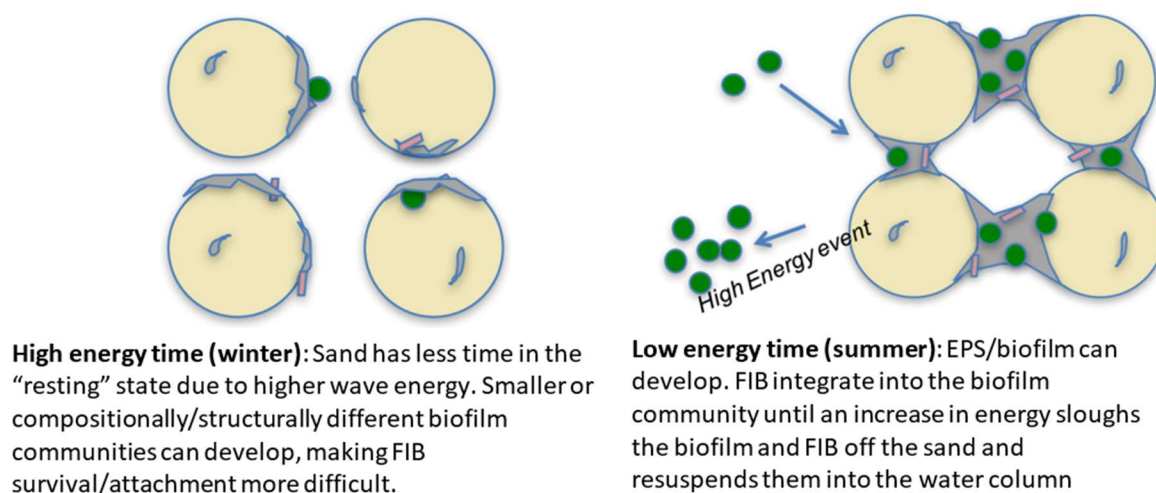


Figure 3: Conceptual model of biofilm development and FIB attachment/release as it relates to wave energy. Images depict model sand grains with biofilm and FIB (green circles) incorporated into the community.

The amount of biofilm on sand particles, as measured by EPS levels, appears to be related to wave energy (Piggot et al. 2012). This wave energy gradient seems to follow the reverse gradient of EPS, with higher EPS levels at the lower wave energy beaches (Piggot et al. 2012). The seasonal nature of wave energy, which is higher in the winter than during the summer, promotes a greater accumulation of EPS during September (summer) versus February (winter) (Figure 3 and S1).

At fluvial beaches, seasonal flow fluctuations are mostly/solely observed, and biofilms are very complex communities formed by algae, cyanobacteria, fungi, bacteria, and protozoa embedded in a dense EPS matrix (Corcoll et al. 2012). During the summer of 2016, several water, biofilm, and sediment samples were collected from a dam in *Alentejo*, Portugal. Images of bacterial biofilms assembled on the sediments (see Figure S2) show dense EPS and a close association between phytoplankton and bacteria. Although FIB were not found in the *Alentejo* dam, human pathogens linked to healthcare-associated infections were found, including *Enterobacter cloacae* (Mezzatesta et al. 2012), *Klebsiella pneumoniae* (Percival et al. 2015) and *Acinetobacter baumannii* (Antunes et al. 2014). *Aeromonas* species, responsible for human gastroenteritis and more severe extra-enteric conditions, including wound infections and septicaemia, were also detected (Skwor et al. 2014).

Given the dynamics between biofilms and wave energy, a conceptual model that describes the FIB release from biofilm in sand,  $X_{fib,sand}$ , (in units of numbers of microbes per time) may resemble the following:

$$X_{fib,sand} = f(T, M, r_{eps}) \quad (1)$$

Where  $T$  is the time since the last energetic event was greater than 1 standard deviation of the mean wave height,  $M$  is the magnitude of the event above the mean wave height, and  $r_{eps}$  is the rate of EPS development in the sand (in units of mass per time).  $T$  may vary between beaches as well as seasonally, e.g.  $T$  may be smaller during the wetter heavy storm season and larger during prolonged dryer periods, resulting in seasonal variation in biofilm-associated FIB.

The magnitude of the wave heights,  $M$ , may also influence  $X_{fib,sand}$ . A high-energy beach creates an environment with more frequent reworking and re-mobilization of sand and sediments compared to a low-energy beach. The higher the  $M$ , the more reworking of the sand, more turbulence and more sand shear, minimizing the degree to which biofilms can accumulate. A study conducted by Phillips et al. (2014) found that  $M$  influenced the degree to which FIB can be removed from beach sand. Under controlled experimental conditions within a wave flume, only 60% of FIB were removed by waves with  $M$  values of up to 10 cm, suggesting that very large waves would be necessary to completely clear out the FIB reservoir from sand. Vogel et al. (2016) also suggests that FIB are transferred to surface waters during high intensity wave events. In addition, FIB are also more rapidly mixed offshore, leading to lower concentrations in adjacent surface water and less potential for them to re-associate with beach sand; as discussed in section 5 (Cruising: Transport). The accumulation of EPS,  $r_{eps}$ , is influenced by the type of pollution (point vs. nonpoint source), sand grain size, and sand grain mineralogy. Vogel et al. (2017), Haack et al. (2003), and Skalbeck et al. (2010) all observed that coarse sands have lower FIB densities, compared to fine sands.

There also appear to be relationships between sand mineralogy and the attachment of EPS, and subsequently, FIB to sand grains. For example, a comparison of the release of FIB into pore waters from a quartz dominated sand beach in California and a carbonate dominated sand beach in south Florida are in conflict. Only 3% of the total sand FIB were released through pore water volume flushing in the south Florida sand (Phillips et al. 2011b) as compared to nearly 100% at the California study site (Yamahara et al. 2007). Similarly, at a beach that underwent renovation, replacing calcium carbonate dominated sand with quartz sand (Hernandez et al. 2014), substantial decreases were observed in FIB levels in both the sand and adjacent surface water, suggesting that calcium carbonate particles retain EPS and FIB more readily in comparison to quartz. However, other cases have reported that mineralogy may not influence FIB releases from sand, such as is the case reported by Abreu et al. (2016) for beaches in Madeira, Portugal.

The current global trends of increasing sea and lake surface temperatures (O'Reilly et al. 2015, Sharma et al. 2015, Wu et al. 2012), along with increasing wind speeds, wave heights and storm frequency in coastal regions may decrease the diversity of microbial communities and thus make the coastal ecosystems more prone to future disturbances (Byrnes et al. 2011, Tokinaga and Xie 2011, Young et al. 2011). New experimental data are needed to assess the controlling factors in the uptake and release of microbes from beach sands and sediments and subsequent impacts to human beach visitors.

Regulatory practices for monitoring water quality in the beach environment have been guided by the recognition that sewage discharges within coastal waters can serve as a source of microbial pathogens to beach users (USEPA 2012). Compliance and recommendation programs have, therefore, focused on water (Canada 2012, Parliament 2006, USEPA 2012), while disregarding other reservoirs such as sand and sediment, and their associated biofilms (Solo-Gabriele et al. 2016). As sewage treatment processes have been upgraded and sewage discharge pipes extended



and/or eliminated (Solo-Gabriele et al. 2011), the significance of this source is diminishing. Concurrently, recent studies have begun to recognize that on-shore sources of FIB, as reflected by the accumulation of FIB in beach sands, may dominate contaminant levels observed in nearshore water (Alm et al. 2003, Phillips et al. 2011a, Sabino et al. 2014, Solo-Gabriele et al. 2016, Whitman et al. 2014), including bird fecal droppings whose *E. coli* successfully establish themselves in sand, as Edge and Hill (2007) found. Biofilms play a vital role in the “hangouts” of microorganisms in sand by shielding whole multi-species communities from external factors and protecting propagules that will withstand erosion associated with high energy waves.

## 5. Cruising: Mechanisms of Transport

FIB may be transported through the beach sand matrix and across the sand-water continuum via two general pathways: through-beach or over-beach. Through-beach transport of FIB, including their distribution in the subsurface and potential transport to surface waters via groundwater discharge is governed by infiltration and exfiltration (water flowing into, through and out of the unsaturated and saturated portions of the beach face); interstitial flows; and FIB-sediment interactions (which include attachment, detachment and straining) (Bradford et al. 2014, Brown and Boehm 2016, Molnar et al. 2015, Solo-Gabriele et al. 2016). Air-water interfaces can also affect FIB transport in the vadose zone, as FIB movement may be limited by thin water films and their associated physical restrictions to flow (Flury and Qiu 2008, Wan and Tokunaga 1997). The over-beach transport pathway is mainly associated with erosion of beach sand, with FIB detachment from eroded sand grains delivering FIB to adjacent surface waters (Vogel et al. 2016). Erosion of beach sand occurs in response to waves, tides, rainfall, and human actions (e.g. sand pumping schemes, beach grooming).

### 5.1 Physicochemistry and Soil Type

Soil type plays a key role in determining both groundwater flow and the dominant mechanisms that control microbial transport because of its relationships to pore size, hydraulic conductivity, and soil structure. The shrink-swell nature of clay soils can result in the formation of macropores that facilitate preferential flow and more rapid microbial transport than predictions based upon the bulk soil properties alone (Arnaud et al. 2015, Mohanty et al. 2015, Zopp et al. 2016). In contrast, the sandy soils common to beach ecosystems are relatively unstructured and less conducive to macropore formation. However, even in these soils, transport can still be short circuited by preferential flow when sands of varying particle size result in paths of higher hydraulic conductivity through the same matrix (Wang et al. 2013). In the absence of significant preferential flow, pore-scale mechanisms driven by interaction energies between the charged surfaces of organisms and soil particles become increasingly important, and can dominate in beach systems.

### 5.2 Waves and Tides

#### 5.2.1 Waves

Waves are a dominant force along most freshwater and marine shorelines and play a key role in the transport of FIB within the beach environment. Waves lead to the infiltration of large quantities of surface water and associated constituents (e.g., FIB and nutrients) across the beach face, particularly in the swash zone (area of wave run-up) (Malott et al. 2017, Robinson et al. 2018, Xin et al. 2010). They drive rapid infiltration-exfiltration across the unsaturated and saturated portions of the beach face in the swash zone at a frequency of seconds (Heiss et al. 2015), as well as driving



deeper interstitial flow circulations through saturated beach sediments (Longuet-Higgins 1983, Malott et al. 2016).

### 5.2.2 Tides

Tides, like waves, drive large amounts of water infiltration-exfiltration across the beach face with potential to transport FIB across the sand-water continuum. Tide-induced surface water infiltration generally dominates in the upper intertidal region and exfiltration dominates towards the low tide mark (Robinson et al. 2007). Gast et al. (2015) observed that microspheres, which were used as surrogates for bacteria, were transported from their initial location (0.05 m below the sand surface, just below the predicted high tide line) vertically to the groundwater table by tide-induced infiltration.

Interestingly, however, some studies have shown higher concentrations of FIB in supratidal sands, above the high tide mark, compared to sands in the intertidal zone where greater infiltration and vertical transport of FIB into the beach matrix is expected to occur (Abdelzaher et al. 2010, Enns et al. 2012, Phillips et al. 2011a, Whiley et al. 2018). In addition, using shotgun sequencing, Mohiuddin et al. (2017) showed a greater taxonomic diversity in the supratidal sand than in adjacent surface water and Staley and Sadowsky (2016) showed that backshore sands had microbial communities distinct from those in nearshore sands. These findings may be because of lower moisture content in the supratidal sand compared to intertidal sands, which limit the survival of protozoan predators (Whitman et al. 2014), along with various endogenous sources such as bird fecal droppings (Brown and Boehm 2016).

Tide-induced exfiltration has been linked to the transfer of FIB across the sand-water continuum (Boehm et al. 2004, Enns et al. 2012), while elevated nutrients and dissolved organic matter in the discharging groundwater may increase the persistence of FIB in surface water (Boehm et al. 2004). Enns et al. (2012) also found significantly higher enterococci levels in knee-depth surface water samples during the ebbing tide compared to the incoming tide, suggesting that enterococci may be washing out of the sand near the shoreline into the surface water. Findings regarding the impact of tide-induced flows on FIB may also vary depending on the targets and detection techniques.

### 5.2.3 Precipitation

Rainfall events may facilitate the movement of FIB within the beach environment. Direct runoff across the beach surface may lead to over-beach transport of FIB toward the shoreline, and in some cases to the surface water (Silva et al. 2014). For example, Beversdorf et al. (2007) showed that FIB were washed out from the sand to the surface water by rainfall at a Laurentian Great Lakes urban beach, with *E. coli* levels in surface water increasing nearly 100-fold within 30 minutes after inception of a rainfall event. Alternatively, infiltration of rain through unsaturated sand surfaces may deliver FIB to the subsurface, and to the water table, where they may be transported via through-beach mechanisms (Russell et al. 2012). Silva et al. (2014) suggested that over-beach rather than through-beach transport was the most plausible mechanism during rainfall events at a freshwater beach. Heaney et al. (2014) presented data showing that rainfall within the previous 24 hours was negatively associated with enterococci CFU/g in sand, suggesting that rainfall may wash culturable enterococci from the sand. They did not, however, examine the transport mechanism by which this wash-out may occur.

Snowmelt events can also increase the amount of contamination in surface waters, ultimately increasing the discharge of pollutants at coastal waters and beaches (Jamieson et al. 2002, Kistemann et al. 2002, Whitman et al. 2008). Many microbes, including pathogens, tend to survive better at colder temperatures (Boehm et al. 2018, Dorner et al. 2007, Jamieson et al. 2002, Staley et al. 2017). Melt periods would thereby increase microbial contamination, including delivery of pathogens, which have been stored in snow or ice during colder periods (Kistemann et al. 2002, Rogers et al. 2004, Zhang et al. 2006).

In summary, microbial transport in the beach environment may proceed via over- or through-beach routes, and is influenced by matrix composition and type, precipitation, wave and tidal action. Interactions between microorganisms and particles are particularly important in through-beach transport. Waves and tides drive infiltration and exfiltration of water into the beach subsurface, and erosion of sand mediates detachment of microorganisms from particles, allowing transport of microorganisms to surface waters. Precipitation in the form of rainfall or snowmelt mediates over-beach transport of microorganisms to surface waters.

## **6. Bimmers: Environmental Stressors**

The diverse microbial community in beach sand must survive a wide range of biotic and abiotic factors affecting its growth and survival. Significant fluctuations of nutrients, competitors, moisture, and temperature influence the survival and composition of the microbial community, creating a complex structure both spatially and temporally (Winfield and Groisman 2003).

### **6.1 Competition and Starvation**

Nutrient availability in sand can be extremely limited, creating potential starvation conditions for microorganisms. Delivery of nutrients to pore water via infiltration and exfiltration across the beach-water interface can lead to enriched microbial populations, including the potential increase of pathogenic organisms such as *Campylobacter*, *Salmonella*, and *E. coli* O157:H7 (Williams et al. 2007). Other mechanisms of nutrient introduction, such as beach wrack (stranded macroalgae) (Imamura et al. 2011) and interaction with attached algae, aquatic vegetation, and phytoplankton (Byappanahalli et al. 2006) can also enhance microbial growth (Lim and Flint 1989). Without continuous nutrient sources, microbial abundance and community composition can shift dramatically in sands (Hood and Ness 1982).

The nutrient content in sand and sediment can also vary between climatic regions, leading to differential survival of FIB in tropical versus subtropical and temperate environments. Despite this, survival of fecal microbiota in tropical environments is less studied than in other systems (Anderson et al. 2005, Ishii et al. 2007, Kim et al. 2014, Lee et al. 2006, Sanger et al. 1999).

Competition among members of the microbial community can also impact survival of FIB. Feng et al. (2010) identified resident bacterial communities as the predominant biological stressor responsible for the die-off of *E. coli* in beach sands, while protozoan predation and phage infection were negligible.

## 6.2 Predation

Microbial communities in beach sand also face the threat of predation by microfauna, including protozoans and nematodes. While these microscopic animals have the potential to impact bacterial growth (Alm et al. 2006, Hartz et al. 2008), the composition of potential predators is not well-understood. While some studies identified protozoans as contributing significantly to bacterial decline in sand filters (Bomo et al. 2004), predation has been shown to play a minor role in regulating the population size of *E. coli* and *Enterococcus faecalis* in sand (Feng et al. 2010, Mika et al. 2009). Similarly, the impacts of protozoa on FIB decay rates were negligible in tropical sediments from Singapore, and protozoa presence was not correlated with FIB presence or concentration (Nshimiyimana 2017).

## 6.3 Desiccation and Solar Radiation

The absence of moisture transforms the sand environment dramatically, resulting in some of the harshest conditions for microbial survival (Evans and Wallenstein 2012, Jang et al. 2017). Nutrients and moisture are continuously refreshed along the beach face due to seiche, tidal, or wave action. Accordingly, microbial community structure is much different in foreshore and backshore locations (Cloutier et al. 2015). In a Laurentian Great Lakes study, the difference between the zones was greater than that between study sites miles apart (Cloutier et al. 2015), as well as those experiencing extended dry conditions with only periodic wetting.

Moisture levels across beaches vary in response to changes in tides, lake levels, seiches, and hydrometeorological conditions, and the wetted beach zone can shift even hourly. While fecal microbiota are abundant in the wetted foreshore (Whitman and Nevers 2003, Wright et al. 2011), they are less abundant but still recoverable above the high tide mark (Abdelzaher et al. 2010) or backshore sand of freshwater beaches (Byappanahalli et al. 2006, Staley et al. 2015). Variable moisture also impacts microbial populations and communities by influencing microbial predation, nutrient availability, and inactivation (Mika et al. 2009). Moreover, decreased moisture and increased sunlight negatively impact microbial viability (Caro et al. 1999). Exposure to sunlight is thought to be the single biggest factor controlling the viability of *E. coli* in the environment (Jang et al. 2017). This impact, however, is limited to sand surface areas and water depths where sunlight reaches (Whitman et al. 2004). Increases in humic substances may provide an effective shield for microbes against UV-irradiation from the sun and in sand serve as a moisture retention metric (Monteith et al. 2007, Weyhenmeyer et al. 2016, Williamson et al. 2017).

It should be noted, however, that excessive moisture can also be detrimental to microbial survival, and most bacteria require a water activity value within narrow ranges. Shah et al. (2011) found an inverse relationship between moisture content and survival of FIB, yeasts, and nematodes. Eichmiller et al. (2014) found that moisture significantly impacted decay rates of microbial markers and pathogens, with slower decay occurring at 14 versus 28% moisture.

## 6.4 Temperature

Temperature conditions in the beach sand can similarly threaten microbial survival. While higher temperatures promote the growth of bacteria in sand (Ishii et al. 2007), those >50°C hindered survival of *E. coli* and enterococci (Mika et al. 2009). In many instances temperature and sunlight are inextricably interrelated. Similarly, some fecal microorganisms survive under cold, frozen

conditions (Francy et al. 2003, Ishii et al. 2006). In laboratory studies, FIB increased over a wide range of temperatures (4 to 44.5°C), but the optimal growth conditions occur at 23-32°C (Beverdors et al. 2007). However, the decay rate of FIB in soils was minimized at cooler temperatures (<25°C) (Ishii et al. 2006). Similarly, Staley et al. (2016) determined that *E. coli* survived longer in fine sand at an even cooler temperature (15°C) in laboratory mesocosm experiments. As with sunlight, temperature is closely tied to sand moisture (they are inextricably linked), as the equilibrating force of moisture minimizes temperature fluctuations and the associated changes in microbial density.

A rise in global temperature is predicted to result in increases to water surface temperatures (IPCC 2014, 2018), which can directly affect growth and survival of microbes in waterways (Liu et al. 2006). The persistence of fecal microbes in the environment is predicted to decrease according to many climate change models, since fecal microbes generally degrade faster when temperature increases (i.e., bacterial die-off processes are enhanced) (Boehm et al. 2018, Bussi et al. 2017, Noble et al. 2004, Sokolova et al. 2012). For example, there is a reported negative association between *Campylobacter* and temperature (Hokajarvi et al. 2013, Viau et al. 2011). Alternatively, others predict that rising temperatures may increase the occurrence of pathogenic microbes. Similarly, the presence of *Salmonella* spp. in Hawaiian coastal streams was positively correlated with water temperature (Viau et al. 2011). Likewise, the presence and persistence of *Vibrio* spp., which are capable of multiplying in water environments, are closely and positively correlated with water temperatures (Baker-Austin et al. 2016, Baker-Austin et al. 2013, Huehn et al. 2014, Sterk et al. 2015).

An additional concern associated with climate change-related elevated surface water temperature is the increased prevalence of algal blooms, both filamentous varieties (which may serve as a point of attachment/harbor both FIB and pathogens) and blue-green bacteria (capable of producing toxic compounds) (Moore et al. 2008, Vanden Heuvel et al. 2010). Harmful algal blooms (HABs) are also predicted to increase with the rise of sea surface temperatures and global average lake surface temperature over the next century (Brookes and Carey 2011, Rigosi et al. 2015). These HABs, along with microbes that they may be carrying, may be deposited at the sand-water continuum during tides and due to waves (Maghsoudi et al. 2015).

Surface water temperature changes can also affect contaminant plume buoyancy and dynamics and negatively impact FIB that are susceptible to solar inactivation. Conversely, changes to relative densities may lead to increases in sinking plumes that are more resistant to solar inactivation, yielding potentially higher survival and persistence of contaminants in the environment.

Numerous abiotic and biotic factors affect the growth and survival of fecal microbiota in waterways and in sands. The main factors affecting these microorganisms are temperature, desiccation, nutrient availability and sunlight. However, soil microbial community structure in sands and beach water are also strongly influenced by microbe-microbe and microbe-host interactions. Global climate change will have a major impact on sand microbiota by increasing temperature and likely water availability.

## 7. Putting It All Together: Modeling

A conceptual model summarizing the various FIB sources, and fate and transport processes in coastal waters described in previous sections is shown in Figure 4. Mechanistic models of FIB are

useful tools for understanding the relative importance of the various sources, fate processes, and transport pathways, and for making predictions. Development of improved models to better account for more of the complex processes controlling subsurface microbial transport has been highlighted as a critical knowledge gap (Bradford et al. 2013). Debate continues regarding the merit of different approaches, resulting in a continuing need for studies that bridge this gap by specifically relating process-oriented understanding to field-scale observations (Harvey et al. 2007, Tufenkji 2007). These problems become more challenging when climatic change begins to play a role.

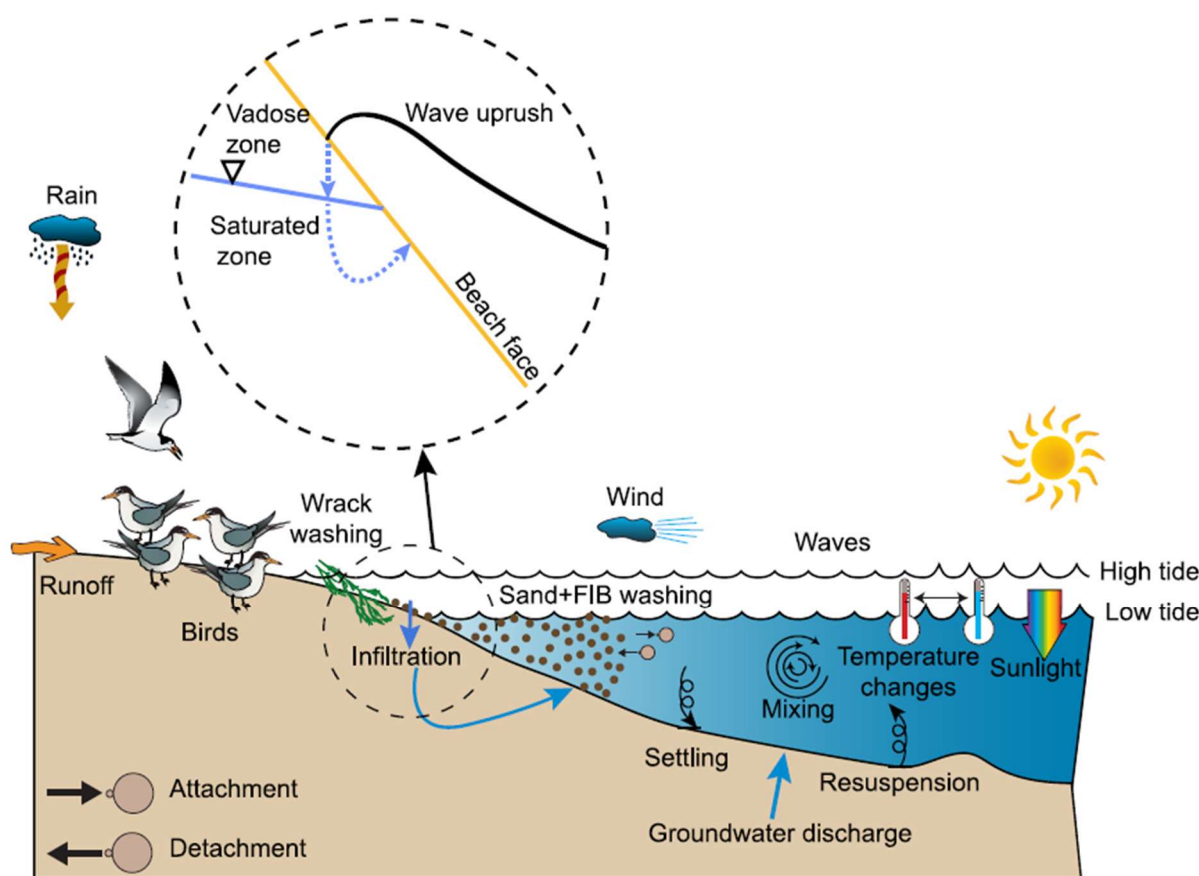


Figure 4: Conceptual diagram showing key processes that influence FIB levels in the nearshore area. Not shown are potential changes in salinity, pH, dissolved oxygen (DO), or Dissolved Organic Carbon (DOC) in the water column, which could modulate many of the processes illustrated.

In turbulent environments, such as the surf zone and close to the shoreline where FIB sampling typically takes place, additional processes such as waves and wave-current interactions may become important. Waves are important not only due to their direct impact on currents but also due to their role in changing bottom shear stress (Chao et al. 2008, Thupaki et al. 2013) and the resuspension of sand- and sediment-bound FIB (Gao et al. 2015, Thupaki et al. 2013). Since temperature is tightly coupled to nearshore hydrodynamics (via stratification, thermal bars and



density-driven currents), temperature affects FIB levels in the nearshore through both biotic and abiotic processes. Temperature changes in coastal areas are also associated with tributary inputs (Liu et al. 2006) and groundwater discharge (Safaie et al. 2017), two recognized sources of FIB (Boehm et al. 2004).

Process-based FIB models use some form of the advection-dispersion-reaction equation (shown below in its unsteady, 3D form):

$$\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} + w \frac{\partial C}{\partial z} = \frac{\partial}{\partial x} \left( K_H \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_H \frac{\partial C}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_V \frac{\partial C}{\partial z} \right) - S \quad (2)$$

where  $(u, v, w)$  are the unsteady, 3D velocity components in the coordinate directions  $(x, y, z)$  respectively ( $z$  denotes the vertical coordinate and  $t$  is time),  $C$  denotes the FIB concentration,  $K_H, K_V$  are the horizontal and vertical mixing coefficients and  $S$  is a general loss term ( $= k C$  if a first order removal rate constant  $k$  is used). Hipsey et al. (2008) provided a general formulation for the net loss term that accounts for growth, water temperature, salinity, dissolved organic carbon, base mortality, light-mediated inactivation, pH, dissolved oxygen, settling losses, suspended sediment concentration, and predation and grazing losses. A variety of simpler forms for the net loss term have been used successfully in marine and freshwater environments (Gao et al. 2015, Safaie et al. 2016). A detailed review of the FIB fate and transport processes and their mathematical representation is available in Nevers et al. (2011).

## 7.1 Modeling FIB in the Sand-Water Continuum

Improving model descriptions of interactions between FIB and sand/sediment reservoirs may be key to further improving the performance of the current generation of models. Recent work aiming to model the transport of FIB within sand at marine and freshwater beaches includes considering sediment transport and sediment-bound FIB transport (Brown and Boehm 2016, Feng et al. 2015, Gao et al. 2011, Thupaki et al. 2013) within the beach and in nearshore waters. Accurate simulation of processes, such as wave run-up on the beach face, cyclical wetting and drying associated with tides and waves, infiltration of water and lateral movement of water and FIB close to the sand-water continuum, all require small spatial steps (cm to meter scale). An awareness of how temporal changes associated with climate change or anthropogenic effects impact these processes is also key to modeling them.

One way to model dynamic FIB-particle interactions is to quantify sediment (and associated FIB) transport with multiple size class formulations – for example, a “fine” particle class with which *E. coli* are known to readily associate and a “coarse” size class – to simulate changes in bed morphology and the release of FIB from the sand reservoir. Rules for if and how exchange takes place between different pools of FIB must be defined. To quantify sediment-related enterococci at Hobie Beach in Florida, Feng et al. (2015) modeled “clean” and “contaminated” sand classes and their evolution in time. The distribution of the contaminated sand fraction in this approach describes the availability of FIB for resuspension. In contrast, the models described in Gao et al. (2011) and Thupaki et al. (2013) used a single size class.

Different approaches have been used to model interactions between FIB and sediment in the past, including: (a) models of attachment-detachment kinetics based on the mobile-immobile



framework used in subsurface transport modeling (Brown and Boehm 2016, Vangenuchten and Wagenet 1989) and (b) sorption isotherm-based approaches typically used to describe partitioning of chemicals in the environment (Gao et al. 2011, 2015, Thupaki et al. 2013). Gao et al. (2011) used a linear coefficient  $K_D = (C_s / C_D)$  for sediment-water partitioning of enterococci based on the assumption that attachment–detachment dynamics are “fast” relative to the time scales associated with advection and dispersion. Here  $C_s, C_D$  denote the mass-specific (e.g., CFU/g) concentration of attached FIB and volume-specific (e.g., CFU/mL) concentration of unattached FIB, respectively. While the use of a partition coefficient may approximate the distribution of FIB empirically in some locations, there is limited proof that suspended and sorbed FIB are in equilibrium or that a single partition coefficient is valid for all environments (Nevers et al. 2011).

If FIB models considering sediment-bacteria interactions are extended to include multiple size classes (e.g., fine and coarse sediment), then model complexity increases significantly, introducing a large number of parameters and assumptions that are difficult to constrain and justify. Therefore, questions of model parsimony, complexity and equifinality (Beven 2006) should be addressed based on a careful comparison of different approaches. In addition, novel field experiments and data that elucidate fundamental mechanisms of sediment transport with a focus on FIB transport and biofilms are needed. Erosion of biofilm-bound fluvial sediments and associated FIB is a complex topic. The model of biofilm dynamics presented in section 4 and in Vignaga et al. (2013) questions the validity of current sediment transport formulations that assume that grains of sand roll over one another at some critical shear stress. This conceptual model may serve as a first step in developing a physically-based model that considers biofilm mechanics.

It is not clear how representative available data are for different environments and for extreme events, which may become more common in a changing climate (Alexander et al. 2006, Brown et al. 2008, Sneed 2017). For example, the “fast” FIB attachment–detachment kinetics assumption that justifies the use of a linear partition coefficient has some basis in previous groundwater studies as discussed in Bai and Lung (2005). Other data from streams and agricultural soils seem to favor the opposite assumption, i.e. “slow” kinetics relative to advection and dispersion based on evidence that bacteria, once attached, will remain in that state under the action of EPS (Jamieson et al. 2005). Field data from marine and freshwater sites collected under different conditions (e.g., for calm conditions as well as storm events; for bottom sediment and for the water column; close to river mouths and far from any riverine source), with an eye on sediment–water partitioning of FIB, will help test and validate superior model formulations for current and future predictions of nearshore FIB fate and transport.

Mechanistic models are important tools to assess processes and impacts affecting FIB dynamics in the nearshore. But subsurface microbial transport and interactions at the sand-water continuum remain critical knowledge gaps, especially in turbulent and wave-impacted environments. Existing models are based on the advection-dispersion-reaction equation, but can vary greatly in relevant parameters and model complexity.

Modeling sediment- and sand-bound FIB transport is a complex, but important step in understanding beach microbial dynamics. There are several ways to do this, but effective models must account for tradeoffs between inclusion of interaction parameters and parsimony. Existing models are at odds in terms of how to predict dynamics at the sand-water continuum, especially in

light of climate change effects. This opens the door for further field data validation and model development revolving around sand- and sediment- FIB transport and their effects at beaches.

## 8. Emerging Concerns and Challenges

### 8.1 Contaminants of Emerging Concern

In recent years, contaminants beyond FIB have captured the attention of beach managers and researchers alike. These contaminants of emerging concern can include chemical, biological and physical threats to the health of both human users and aquatic ecosystems.

A wide range of pharmaceuticals are released into recreational water bodies from sources such as treated and untreated municipal wastewater. In particular, increasing attention is focused on antimicrobial chemicals and antimicrobial resistant microorganisms. As a result of misuse in humans, including over-prescription by medical professionals and over-use in agricultural settings, many environmental bacteria and fungi have developed clinically-relevant resistance to antimicrobial substances (Huijbers et al. 2015, Landers et al. 2012, Llor and Bjerrum 2014). Infections caused by antimicrobial-resistant microorganisms such as *Staphylococcus aureus* and *Enterobacteriaceae* (O'Gara 2017, Price et al. 2017) increase hospitalization and mortality rates, as well as health care costs (Cosgrove and Carmeli 2003, de Kraker et al. 2011). Pathogens carrying resistance genes to antibiotics of clinical relevance have been isolated from recreational and other surface waters worldwide (Arvanitidou et al. 2001, Huijbers et al. 2015, Leonard et al. 2015, Sukumaran and Hatha 2015, Young et al. 2016), though the significance of beaches as reservoirs for, and transmitters of, antibiotic resistance genes is not well understood (Allen et al. 2010). These microorganisms, unlike FIB, can be directly associated with adverse human health outcomes, and have shown increases in resistance coinciding with temperature increases (MacFadden et al. 2018). In addition, several fungal strains in drinking water are relatively resistant to disinfection techniques like chlorination and ultraviolet (UV) disinfection, as well as anti-fungal chemical compounds (Babic et al. 2017).

An additional concern regarding antimicrobial resistance genes is the potential for horizontal gene transfer in both sand and aquatic environments (Droge et al. 1999). Horizontal gene transfer “hot spots” in the environment are characterized by elevated microbial and nutrient levels, including the pore water of soil/sand particles and biofilms (Gaze et al. 2013). Among studies performed on horizontal gene transfer in bacteria isolated from water, Yin et al. (2013) observed transfer of antibiotic resistance genes from several host genera, including *Pseudomonas* and *Acinetobacter* to *E. coli*, but more information on horizontal gene transfer in sand and other beach environments will be required to determine the importance of these environmental reservoirs to human health.

Plastic particles are also often classified as contaminants of emerging concern, due to their potential impact on microbial communities in both sand and nearshore water. Evidence exists that the presence of microplastics in sediments, sand, and water can alter microbial community dynamics (Kleinteich et al. 2018). Microplastics can foster the growth of microplastic-specific bacteria assemblages in marine environments (Oberbeckmann et al. 2018), potentially leading to the emergence of altered microbial communities in contaminated environments.

## 8.2 Localized Impacts on Contamination at the Beach

Microbial dynamics at beaches are highly dependent on a range of conditions, which vary spatiotemporally (Korajkic et al. 2013). Factors such as beach morphology, orientation, sand granulometry and chemistry, land use, and infrastructure can have substantial impacts on both the amount of contamination in the water that can be exchanged at the sand-water continuum and beach microbial community structure. Microbial dynamics at beaches are also affected by hydrometeorological trends (Gronewold et al. 2016), changes to the trophic state and turbidity of water (Binding et al. 2015, Weiskerger and Whitman 2018), and by short- and long-term climate changes (Abreu et al. 2016, Whitehead et al. 2009, Whitman and Nevers 2008).

Each beach system is subject to different contamination sources, depending upon nearby land use, usage by humans, presence of infrastructure, domesticated animals and wildlife, and proximity to rivers and streams. Due to this large variation, effective models of contaminant dynamics in water, sand, and at the sand-water continuum should be site-specific. By combining further *in situ* data collection and modeling, the influence of sand/water dynamics can be used as the basis for nearshore policy changes and minimizing the risk of infection in beachgoers.

## 8.3 Land Use Planning: A Beachshed Approach

Anthropogenic land use changes near beaches change the magnitude and type of contaminant inputs to the nearshore environment. Urbanization, for instance, removes land surfaces capable of infiltration and fosters precipitation-mediated runoff (and associated upstream contaminants) to beaches or tributaries, potentially increasing contaminant inputs (He and He 2008, Molina et al. 2014, Reeves et al. 2004). This is concerning for developing areas, where urbanization and a lack of wastewater infrastructure increases the risk of beach contamination (Hofstra and Vermeulen 2016, Kiulia et al. 2016). Wastewater and agriculture-related land use upstream of beaches may also release antimicrobial resistance genes to surface water systems (Finkl and Charlier 2003, Packett et al. 2009, Roberts and Prince 2010, Roberts et al. 2009, Rodriguez-Mozaz et al. 2015, Sapkota et al. 2007, Sayah et al. 2005).

The multitude of factors influencing contamination at the sand-water continuum at beaches underscore the need for a “beachshed” approach to beach health. Limiting monitoring and research to contaminants in surface water alone neglects other potential sources of contamination. Therefore, it is important that future nearshore water quality management actions focus on the beach system as a whole, rather than only the water column. Likewise, an understanding of sand contamination dynamics and associated models can be used as a basis for policy changes to maximize the effectiveness of beach management for human and environmental health.

As we move into the future of beach management, researchers and managers alike will increasingly contend with contamination from new threats like antimicrobial-resistant bacteria, opportunistic pathogens, and microplastics. However, due to many different contamination sources, usage patterns and ecosystem conditions at individual beaches, a standard “one size fits all” approach to beach management will not likely be effective. Instead, an individualized, “beachshed” management approach, that accounts for the entire beach system and differences among beaches, will maximize the effectiveness of management.

Table 1: Examples of climatic conditions and predicted effects on selected microbes by geographic location and study site.

Environmental Condition	Microbe	Predicted Effects	Study Site		Geographic Location	References
			Beach Sand	Recreational Water		
Increased Water Temperature	<i>Vibrio</i> spp.	Increased environmental presence		●	Baltic Sea region, Germany, The Netherlands	(Baker-Austin et al. 2013, Huehn et al. 2014, Sterk et al. 2015)
	<i>Staphylococcus aureus</i> and MRSA	Increased persistence	●	●	California, USA	(Goodwin et al. 2012)
	<i>Leptospira</i> spp.	Increased range and extended seasonality		●	Indian Ocean, China, The Philippines	(Desvars et al. 2011, Sumi et al. 2017, Zhao et al. 2016)
Altered Precipitation	<i>Cryptosporidium</i> spp. and <i>Giardia</i> spp.	Increased environmental presence with increased precipitation		●	New Zealand Systematic Review	(Britton et al. 2010, Young et al. 2015)
	<i>Candida</i> spp.	Increased presence with decreased precipitation (predominantly found in dry sands)	●		Portugal, Florida, USA	(Sabino et al. 2011, Shah et al. 2011)

	Norovirus and Rotavirus	Increased environmental presence and persistence during extreme weather events		•	Brazil, USA	(McBride et al. 2013, Victoria et al. 2014)
Increased Wave Activity	<i>E. coli</i>	Elevated numbers in water correlated with increased wave height	•	•	Lake Huron, Canada	(Vogel et al. 2016)
		Associated with wider dispersal of microbes and release into water	•	•	Lake Superior, USA	(Ishii et al. 2007)
	enterococci	Mobilized sand caused a spike in water with increasing wave action	•	•	Florida, USA (experimental, laboratory conditions)	(Feng et al. 2013, Phillips et al. 2014)
		Positive association of microbe density in sand with wave height	•		Rhode Island and Alabama, USA	(Heaney et al. 2014)
		Increased wave activity associated with wider dispersal of microbes	•		North Carolina, USA	(Gast et al. 2011)

## 9. Conclusions

- Beach systems are dynamic mosaics of aquatic, sand, and sediment ecosystems.
- The sand-water continuum plays an important role in the accumulation, transport, and persistence of microbial contamination at beach systems, though it is difficult to model and is often overlooked in nearshore research, management, and policy-making efforts.
- Local hydrogeological, meteorological and infrastructural conditions can influence the spatiotemporally-varying contamination patterns at beaches, so localized monitoring and modeling efforts are needed to effectively manage beach systems in the face of contamination in both the nearshore and at the sand-water continuum.
- Beach management policy is lagging behind much of the research into the role of sand as a contamination source; however, several nations and the WHO have recognized sand as an important reservoir of FIB and route of exposure to pathogens.
- The recognition and ongoing discussion of sand as a contamination source at beaches may signal a paradigm shift toward more holistic, “beachshed” frameworks for guiding beach research and management actions.
- Uncertainty associated with changing weather and climatic patterns may confound efforts to control or interrupt mechanisms of transport responsible for the future exchange of FIB and pathogens at the water-sand continuum, as well as attempts to model processes correlated with the association/disassociation of human health relevant biofilm- and particle-bound constituents associated with beach sands and underlying sediments.

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## 11. Author Contributions

All credited authors participated in the development and organization of the ideas herein, as well as writing and editing of this review. Section leaders included Valerie J. Harwood and Michael J.



Sadowsky (Getting Our Feet Wet), Thomas A. Edge and Erin M. Symonds (Pollution Pathways), João Brandão and Helena M. Solo-Gabriele (Hangouts), Clare Robinson and Laura J. Vogel (Cruising), Gregory T. Kleinheinz (Bummers), Alexandria B. Boehm and Mantha S. Phanikumar (Putting It All Together), Christopher D. Heaney and Tarja Pitkänen (Climate Changes), and Chelsea J. Weiskerger and Julie L. Kinzelman (Conclusions). João Brandão and Chelsea Weiskerger led the effort to develop and build the paper. Beyond section leaders, remaining authors contributed to sections throughout the paper and provided editing assistance. Valerie J. Harwood took the lead on reviewing and editing the final draft assisted by Michael J. Sadowsky, Julie L. Kinzelman and Warish Ahmed.

## Supplemental Information Tables and Figures

*Table S1: Representative waterborne pathogens and respective estimated infective dose (not-specifically waterborne estimations)*

Type	Species	Disease/illness	Infective dose	Reference
Virus	Norovirus	Diarrhea	~20 viral particles	(Hall 2012)
Virus	Adenovirus	Diarrhea and respiratory infection	~150 PFU	(Canada 2002)
Virus	Enterovirus	Diarrhea, vomiting, fever, skin rash, conjunctivitis	<18 PFU	(Canada 2001)
Virus	Rotavirus	Diarrhea, vomiting, fever	1 PFU	(Graham et al. 1987)
Bacterium	<i>Campylobacter jejuni</i>	Diarrhea	800-10 <sup>6</sup> CFU	(Black et al. 1988)
Bacterium	<i>Escherichia coli</i> O157:H7	Diarrhea, kidney failure	1-100 CFU	(Paton and Paton 1998)
Bacterium	<i>Vibrio cholerae</i>	Cholera	10 <sup>3</sup> -10 <sup>8</sup> CFU	(Schmid-Hempel and Frank 2007)
Bacterium	<i>Salmonella enterica</i>	Diarrhea, fever, abdominal pain	>10 <sup>5</sup> CFU	(Kothary and Babu 2001)
Helminth	<i>Ascaris lumbricoides</i> , <i>Trichuris trichiura</i> , <i>Nector americanus</i> and <i>Ancylostoma duodenale</i>	Diarrhea, abdominal pain, malnutrition	~10 larvae	(WHO 2006)
Protozoan	<i>Giardia lamblia</i>	Diarrhea, abdominal pain, nausea	10-100 cysts	(Leggett et al. 2012)

Protozoan	<i>Cryptosporidium parvum</i>	Diarrhea, abdominal pain	1-5 oocysts	(Guerrant 1997)
Fungi	<i>Aspergillus</i> spp.	<i>Aspergiloma</i> , <i>Aspergilosis</i> , <i>Onycomycosis</i> , Allergy	Not available	(Lee et al. 2016, Sabino et al. 2014)
Fungi	<i>Candida albicans</i>	<i>Candidosis (systemic and localized)</i>	Not available	(Loureiro et al. 2005, Vogel et al. 2007, WHO 2003)

CFU: colony forming unit; PFU: plaque forming unit.

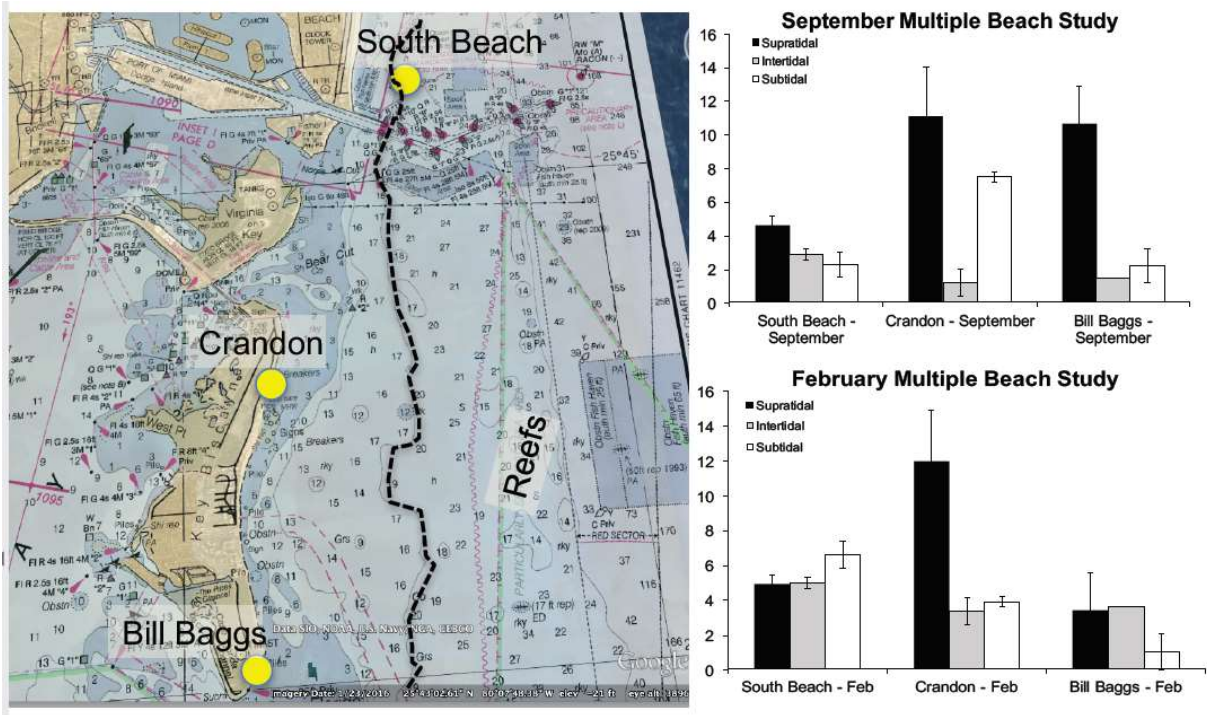
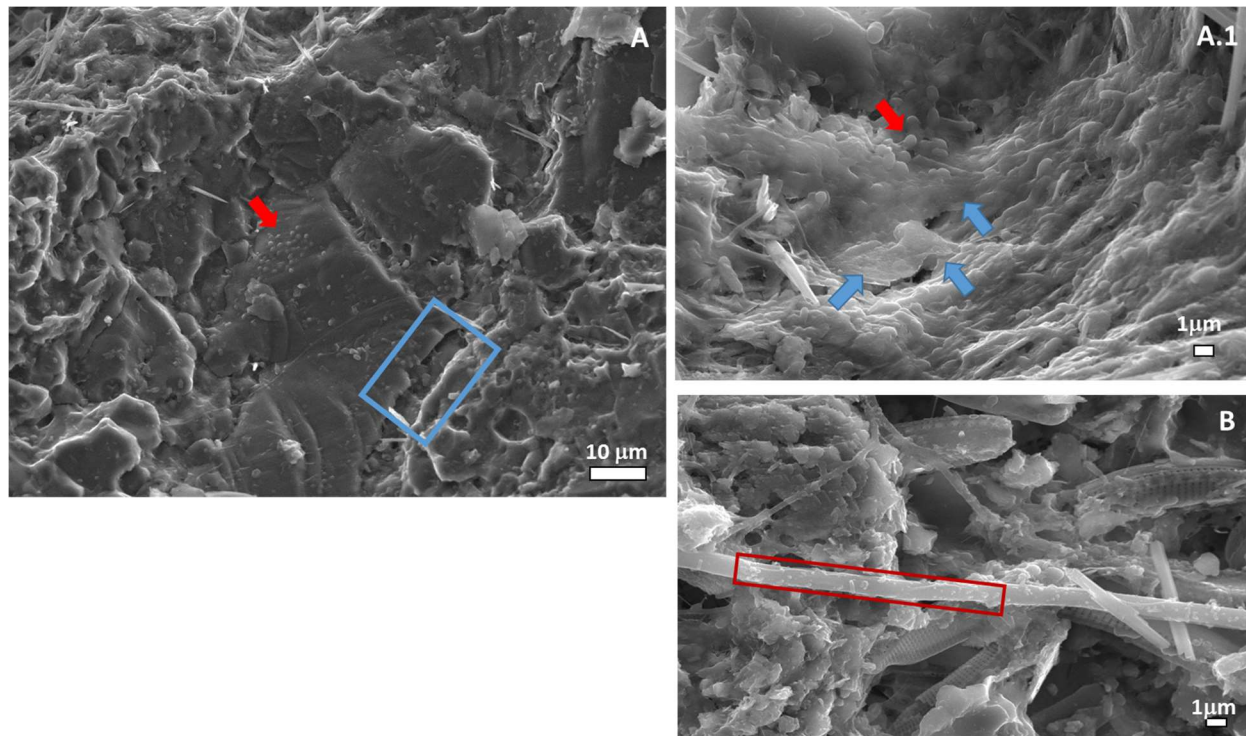


Figure S1: Bathymetry and EPS levels at beaches in south Florida, U.S. Dotted line represents the 6 m contour for water depth. The bathymetry illustrates the gentler bottom slopes at Crandon and Bill Baggs Beaches relative to beaches to the north.



*Figure S2: Biofilms found on sediments of fluvial beaches. In panel A, a lower magnification of the sediment is shown. The red arrow highlights the presence of a bacterial biofilm. The blue rectangle marks the area shown in more detail in panel A.1. The bacteria (cocci and bacilli shaped bacteria shown by red arrows) are surrounded by a thick EPS layer highlighted by blue arrows. Panel B shows the close interaction between phytoplankton organisms and bacterial biofilms, (highlighted inside the red rectangle), where adherent bacteria could be observed on the phytoplankton filament.*

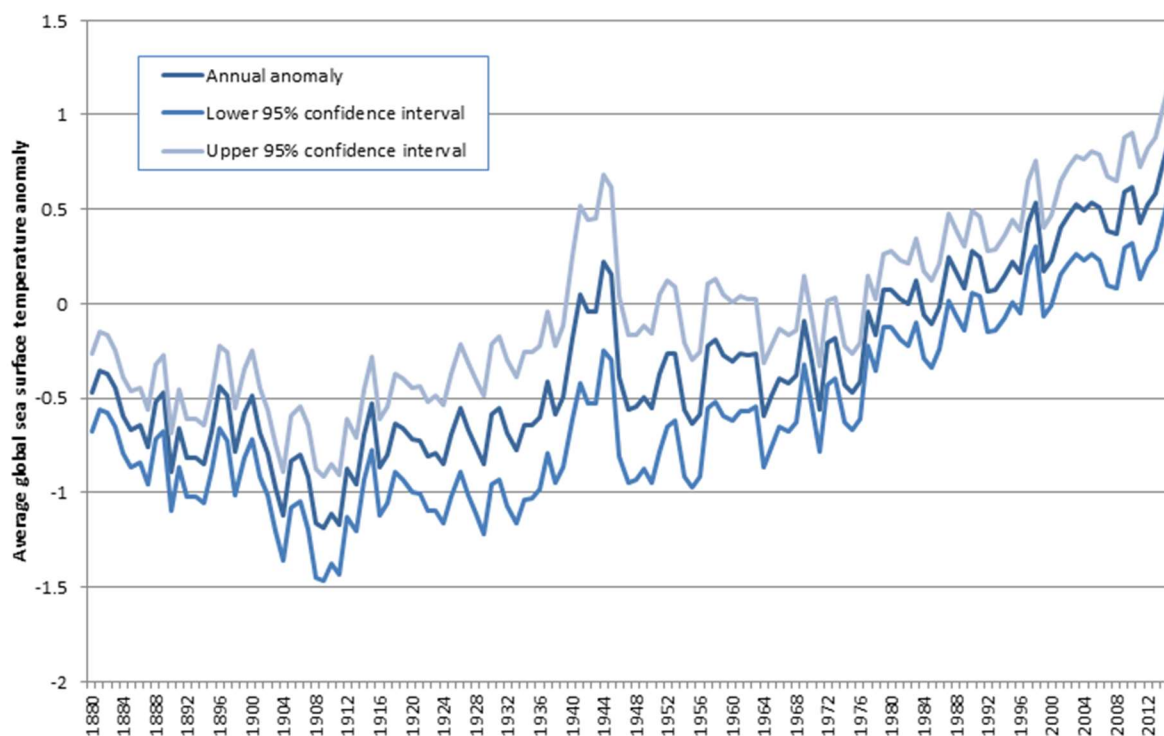


Figure S3: Annual anomaly in average global sea surface temperature in 1880–2015 (NOAA 2016).

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