

Possible Impacts of Sea Level Rise on Disease Transmission and Potential Adaptation Strategies, A Review

Ana C. Dvorak ^a, Helena M. Solo-Gabriele ^{a,*,+}, Andrea Galletti ^{a,1}, Bernardo Benzecri ^a,
Hannah Malone ^a, Vicki Boguszewski ^b, Jason Bird ^{c,+}

^a Dept. of Civil, Architectural and Environmental Engineering. University of Miami. Coral Gables, FL. USA.

^b Vice Chair of the Monroe County Climate Change Advisory Committee, and Yoga In Ya Consulting, Key West, FL. USA.

^c ch2m, Tampa, FL, USA.

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* Corresponding Author. Tel. +1-305-284-2908; fax: +1-305-284-3492, Email address:

hmsolo@miami.edu

⁺ Participants in “Florida Resilient Redesign II” organized by the Florida Climate Institute.

¹ Currently with Department of Civil, Environmental and Mechanical Engineering (DICAM), University of Trento, Trento, Italy.

1 **ABSTRACT**

2 Sea levels are projected to rise in response to climate change, causing the intrusion of sea water
3 into land. In flat coastal regions, this would generate an increase in shallow water covered areas
4 with limited circulation. This scenario raises a concern about the consequences it could have on
5 human health, specifically the possible impacts on disease transmission. In this review paper we
6 identified three categories of diseases which are associated with water and whose transmission
7 can be affected by sea level rise. These categories include: mosquitoborne diseases, naturalized
8 organisms (*Vibrio* spp. and toxic algae), and fecal-oral diseases. For each disease category, we
9 propose comprehensive adaptation strategies that would help minimize possible health risks.
10 Finally, the City of Key West, Florida is analyzed as a case study, due to its inherent
11 vulnerability to sea level rise. Current and projected adaptation techniques are discussed as well
12 as the integration of additional recommendations, focused on disease transmission control. Given
13 that sea level rise will likely continue into the future, the promotion and implementation of
14 positive adaptation strategies is necessary to ensure community resilience.

15

16 **Keywords:** disease transmission, sea level rise, mosquitoborne disease, climate change,
17 naturalized microbes, fecal-oral microbes, community resilience

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38

39 **1 Introduction**

40 Sea level rise is a consequence of climate change and rising global temperatures. Climate change
41 has been positively related to human influences; therefore, its effects over sea level are unlikely
42 to disappear in the future (IPCC 2014, U.S. EPA 2016, Shindell et al. 2017). In fact, sea level
43 trends show that the mean rate of global averaged sea level rise was in the range of 1.5 to 1.9
44 mm/yr between 1901 and 2010 and in the range of 2.8 to 3.6 mm/yr between 1993 and 2010
45 (IPCC 2014), demonstrating a rapid increase over the last decade. It is expected that sea level
46 rise by 2100 could be even higher than predicted (between 0.26 to 0.82 m), and will continue
47 rising after 2100 (FOCC 2010).

48

49 Since its recognition, several studies have been executed to evaluate the impacts of sea level rise
50 and climate change on coastal communities and to establish adaptation strategies, mainly from
51 the point of view of future planning and infrastructure, resources and socio-economic impact
52 (Bates et al. 2008, Bloetscher et al. 2014, FOCC 2010, Hanson et al. 2011, SFRCC 2015, Tebaldi
53 et al. 2012). However, until recently the implications over public health were not fully
54 considered (Ebi et al. 2009, Crimmins et al. 2016, Swaminathan et al. 2017, Veenema et al.
55 2017), and few practical adaptation strategies focused on health risk prevention have been
56 developed (Bloetscher et al. 2016, Boguszewski 2015, Craig 2010, FIHI 2016, FPHI 2014,
57 Ramasamy and Surendran 2011, Ramasamy and Surendran 2012, SFRCC 2015). Therefore, the
58 objectives of this manuscript are to describe possible changes in the transmission of water-
59 related diseases in response to sea level rise in coastal communities, as well as to describe
60 potential engineering solutions to mitigate the transmission of these diseases. Diseases
61 considered are those associated with water: those associated with standing water and subsequent
62 mosquito breeding, and those transmitted through water contact, inhalation, or ingestion of water
63 or consumption of contaminated fish/shellfish. As a critical case of the need to prepare for
64 potential changes in disease transmission, the City of Key West, Florida, a case study site, is
65 used to exemplify some of the adaptation strategies.

66

67 To address these objectives this study includes a literature review on sea level rise and water-
68 related diseases. The literature is also reviewed for general strategies to reduce disease
69 transmission with an emphasis on evaluating the influence of salinity, given that the focus is on
70 coastal communities. Sea level rise data were collected from sources such as: the Florida Oceans
71 and Coastal Council (FOCC), the Intergovernmental Panel on Climate Change (IPCC), the

72 National Oceanic and Atmospheric Administration (NOAA) and the U.S. Army Corps of
73 Engineers (USACE). This data was compared and analyzed to evaluate past, current and future
74 trends of sea level in South Florida. Technical reports and papers published by the Centers for
75 Disease Control and Prevention (CDC), the World Health Organization (WHO), the Florida
76 Institute of Health and Innovation (FIHI), the Florida Department of Health (FDOH), the U.S.
77 Environmental Protection Agency (U.S. EPA), and the Pan American Health Organization
78 (PAHO) were reviewed and analyzed to obtain data regarding the selected water related diseases,
79 including: transmission route, infection cases statistics and vulnerability to changes in water
80 salinity patterns.

81

82 Some of the descriptive examples that focus on the case study site of Key West were inspired
83 through a workshop entitled, “Review of the Florida Resilient Redesign II Proposal for the case
84 of study (City of Key West),” which was organized by the Florida Climate Institute to address
85 the needs of the Southeast Florida Regional Climate Change Compact (SFRCC). The goal of the
86 workshop was to “identify the physical and planning adaptations necessary to reduce the risk and
87 potential for disruptions, damage and economic losses associated with climate change and to
88 develop transferable models relevant to development and redevelopment opportunities
89 throughout the region”. The purpose of the SFRCC is to “coordinate mitigation and adaptation
90 activities across county lines.” The compact was signed on behalf of four southeastern counties
91 in Florida, USA which from north to south include Palm Beach, Broward, Miami-Dade and
92 Monroe. Key West is the southernmost city located in the southernmost county, Monroe County.
93 This city is considered by many to already experience some impacts from sea level rise. The Key
94 West working group for this meeting consisted of experts who spent two days visiting field sites

95 and designing potential adaptation strategies for Key West, with the objective to design an
96 urban-coastal community that is resilient and able to adapt to: sea level rise of a minimum of 60
97 cm by 2060, tidal flooding, extreme rainfall and storms, increased storm surge, water supply
98 constraints, increase in temperature, heat waves, among others. The list of participants in the
99 working group is included in the supplemental text. This manuscript includes a summary of the
100 Key West working group findings along with additional recommendations.

101

102 **2 Sea Level Rise Review**

103 Sea level rise has become a matter of increasing global concern in the last three decades. In fact,
104 sea levels have been rising constantly over the past century with a global mean rate on the order
105 of 1 mm/year (Gregory 2013). It is expected that over the next 15 to 30 years, the effects of sea
106 level rise would become even more noticeable, with continually increasing rates of rise,
107 especially along the United States East and Gulf Coasts (Spanger-Siegfried et al. 2014, U.S. EPA
108 2016), as well as in Southeast Asia, Oceania and Eastern South American coasts (IPCC 2014).

109

110 In the last decades, the trend has increased dramatically, at a rate more than 50% higher than the
111 historic global mean value of 1 mm/year during the 20th century. In particular, over the last 20
112 years the rate of increase is 300% over the prior rate, at around 3.2 mm/y for global mean sea
113 level rise (IPCC 2014). Much of the available data supports evidence that the rate of sea level
114 rise is likely to increase in the upcoming decades, while no evidence currently proves that it
115 could possibly have a steady or even decreasing future trend (Bloetscher et al. 2016, FOCC
116 2010, Gregory 2013, IPCC 2014).

117

118 Sea level rise is related to climate change, which has been caused by global warming (IPCC
119 2014). Global warming has its roots in industrial development, with the massive release of CO₂
120 during the industrial revolution and beyond, ultimately allowing the greenhouse effect to take
121 place. This is directly related to industrial development, making it unlikely for the rate of sea
122 level rise to decrease in the near future (Gregory 2013). The IPCC has developed a sequence of
123 scenarios for global warming depending upon the amount of CO₂ emitted to the atmosphere as a
124 result of stringent mitigation efforts versus a high emission scenario. Given this range of
125 scenarios the IPCC predicts increases in mean global temperature to vary between 1.0 to 3.7 °C
126 by the end of the century. Consequently, sea level is anticipated to rise due to three main causes:
127 warming of the ocean (thermal expansion), loss of glaciers (increased water volume in the sea),
128 and reduction of liquid water storage capacity on land (IPCC 2014). On a global average, the sea
129 level is anticipated to increase between 0.40 to 0.63 meters within (state a timeframe or a
130 location).

131

132 In South Florida, an analysis of measured sea level data indicates clear trends of sea level rise.
133 For example, the analysis shows an average rate of increase of 4.62 mm/yr at the Virginia Key
134 (Miami) tide station located along the Atlantic shore of south Miami-Dade County, 3.96 mm/yr
135 at the Lake Worth Pier tide station (north end of Palm Beach County), and 2.40 mm/yr at the
136 City of Key West tide station. In particular, the City of Key West, has recorded sea level data
137 since 1922. From this data it is possible to observe the obvious upward trend in sea level over the
138 recorded period (Figure 1a). In addition, comparing the data for the last 15 years (Figure 1b), it
139 can be noted that in this period the rate of increase has become more pronounced (6.6 mm/yr),
140 approaching the high level predictions from the National Oceanographic and Atmospheric

141 Administration (NOAA) and U.S. Army Corps of Engineers (USACE). Furthermore, the
142 recorded data show that the rates of increase for Virginia Key and Lake Worth Pier have
143 experienced similar outcomes over the last 15 years, resulting in rates of 7.2 mm/yr and 15.7
144 mm/yr, respectively.

145 Insert Figure 1.

146 South Florida is of special interest when considering the possible impacts of continuing sea level
147 rise, since it is considered one of the world's most vulnerable areas (Bloetscher et al. 2016). It is
148 believed that in this region sea level rise will probably become higher than the global average,
149 due to predicted changes in ocean currents such as the Gulf Stream which, runs along the
150 Atlantic coastline of eastern Florida (SFRCC 2015). In addition, saltwater intrusion into the
151 Biscayne Aquifer, the main source of freshwater for Miami-Dade County residents, would
152 impair the water supply and surface soils (FIHI 2016). For example, studies have shown that a
153 net 18 square kilometers of freshwater resources were lost from the Biscayne Aquifer since 1995
154 (Prinos et al. 2014), presumably associated with changes in climate, particularly increased sea
155 levels and saltwater intrusion. In addition, it has been demonstrated that climate driven seawater
156 intrusion and salinization of coastal environments can affect their biochemistry and promote the
157 release of contaminants retained in the soil (Le Monte et al. 2017). Moreover, both Miami-Dade
158 County and the City of Key West have experienced an increase in the frequency of flooding and
159 stress to the storm water management systems (Spanger-Siegfried et al. 2014). Buildings in
160 these communities were previously built at least 1 meter above the actual sea level, as a
161 preventive measure from flooding problems. However, using 5 year moving averages current sea
162 level rise in the area is already over one-tenth of a meter as observed from the Key West station
163 period of record (1922-2016). Furthermore, current predictions indicate an increase in sea levels

164 of around another half a meter by the end of 2060 (Rahmstorf 2006, U.S. EPA 2015, Gregory
165 2013), further decreasing the safety margin of most buildings to just 40 cm.

166

167 **3 Identified Diseases**

168 Although there are many diseases associated with water, the focus of this study includes three
169 categories of disease (mosquitoborne diseases, naturalized organisms and fecal oral diseases) and
170 those with the largest prevalence rates between the latitudes of 26°58' N to 20°59' N. These
171 latitudes were chosen to represent the latitudes for the counties in the SFRCC, which range from
172 26°58' N in northern Palm Beach County to 24°33' N at Key West. The study range was further
173 extended, assuming a temperature increase of 3°C; which is consistent with forecasts for global
174 temperature warming by the turn of the century (IPCC 2014), assuming a scenario with low-end
175 anthropogenic reductions in CO₂ emissions. The decrease in temperature associated with latitude
176 in the northern hemisphere is 0.86°C per latitude degree (Gates et al. 1999), resulting in an
177 equivalent latitude reduction by 3 degrees and 29 seconds to set the southern extent to 20° 59' N.

178

179 3.1 Mosquitoborne diseases

180

181 Vector borne diseases are caused by pathogens transmitted to humans through a vector
182 (mosquitoes, ticks, flies, among others). The seasonal and geographic distributions of vector
183 borne diseases will likely be altered as a result of climate change (Beard et al. 2016).
184 Mosquitoborne diseases are of particular interest, since the expansion of shallow stagnant water
185 sets an ideal scenario for mosquito reproduction and propagation (Craig 2010). The majority of
186 mosquitoborne diseases are arboviruses, which are caused by viruses. A notable exception is

187 malaria, with a parasitic protozoan as the primary infectious agent (WHO 2016). This paper
188 includes a discussion of the most notable arboviruses and also malaria.

189
190 The most common arboviruses detected in the United States cause encephalitis, an inflammation
191 of the brain tissues. In most cases arboviral encephalitis infections in humans are mostly
192 asymptomatic or generate flu like symptoms, with fever, headaches, muscular pain and
193 weakness. Only a small proportion of human infections progress to develop encephalitis. As
194 these infections are caused by viruses, antibiotics are not an effective treatment for humans.
195 Currently, vaccines for the encephalitis illnesses mentioned are very limited and in the
196 experimental stages (FDOH 2014). The first approved arbovirus vaccine specifically for dengue
197 fever was permitted for use in six countries during 2017. It consists of a live attenuated virus that
198 promotes host immunity to the virus. However, its effectiveness depends on the age of the
199 vaccinated group and local transmission intensity (Ferguson et al. 2016).

200
201 Among arboviruses that cause encephalitis, St. Louis Encephalitis virus (SLEV), Eastern Equine
202 Encephalitis virus (EEEV), La Crosse Encephalitis Virus (LACV) and West Nile virus (WNV)
203 are most frequently detected (CDC 2015a). In particular, WNV represents the most recurrent
204 arboviral illness in the United States, with 2469 reported cases nationwide as of the year 2013
205 (Lindsey et al. 2014).

206
207 Other important arboviruses to be considered are dengue fever, Chikungunya, Zika and yellow
208 fever viruses, which are transmitted by *Aedes aegypti*. Although at the moment dengue does not
209 pose a major public health threat in the US, it represents a major concern worldwide within the

210 target latitudes, with 390 million cases reported as of 2010 (CDC 2017a). In 2013 a dengue
211 outbreak affected the Americas and the Caribbean, including Puerto Rico and the Virgin Islands,
212 resulting in 837 cases reported in US territories (CDC 2015a). In 2009-2010 Key West suffered
213 its worst outbreak, with 22 cases reported (Radke et al., 2009). In contrast to viruses like SLEV,
214 EEEV and WNV, for which humans do not serve as a reservoir of infection for mosquitos,
215 dengue virus has humans as its main reservoir from which mosquitos can become infected
216 (FDOH 2014). Therefore, tourist destinations could be more susceptible to dengue. At tourist
217 destinations visitors from endemic countries can carry the virus to these areas and serve as the
218 reservoir for additional disease transmission via mosquitos. As a result uninfected tourists and
219 local residents at these locations can become infected thereby propagating local transmission and
220 transmission within the home countries of the tourists upon their return.

221

222 Similarly, Chikungunya virus is not considered a major public concern through local
223 transmission in the continental US. In 2016, 248 travel-associated cases (where the virus
224 transmission occurred in endemic countries and the infected person traveled back to the US)
225 were documented in 38 states, most of them in California and New York (CDC 2017c). Locally
226 acquired infections (where virus transmission occurs through the bite of infected mosquitos
227 within that location) are reported within the US territories (Puerto Rico and the Virgin Islands),
228 with a total of 180 cases, 99% of them in Puerto Rico (CDC 2017c). An outbreak began in 2013
229 within central and south America; since then more than 1.7 million suspected cases have been
230 reported. In 2017 only, over 122 thousand confirmed cases within 17 countries were reported by
231 the Pan American Health Organization (PAHO 2017a).

232

233 Yellow fever, on the other hand, is rarely detected in the US. Nevertheless, some countries in the
234 Caribbean and South America within the target latitudes are considered endemic areas or have
235 high risk of transmission. The disease has been well controlled through mass vaccination
236 campaigns, especially in Africa, where no outbreaks were detected during 2015, within the target
237 latitudes identified through this paper. Outside the latitudes, however, yellow fever transmission
238 continues with three countries in South America reporting circulating yellow fever virus in 2017
239 (PAHO 2017b) and an on-going 2016 outbreak in Southern Africa which ended February 2017
240 (WHO 2017a).

241

242 At the beginning of 2016, Zika virus was declared by the World Health Organization a Public
243 Health Emergency of International Concern, as a result of Brazil's outbreak that began during
244 May 2015. Although a mosquitoborne disease, the virus is also transmitted through sexual
245 routes, and has been known to cause birth defects (microcephaly) when pregnant women are
246 infected. At the moment, 2654 cases of microcephaly have been reported worldwide (WHO
247 2017b). In the United States, 935 cases of Zika virus infection have been reported, all of them
248 travel-associated (CDC 2017b). However, local mosquitoborne transmission of the virus in the
249 U.S. was first confirmed by the CDC at the beginning of August 2016, with 216 cases in Florida
250 as of April 2017 and one additional locally transmission case in Florida as of November 2017.
251 More intense spread has been documented in the US territories, with almost 37,000 locally
252 acquired mosquitoborne infections (CDC 2017b).

253

254 Malaria is of concern in a worldwide scenario, and is currently transmitted within the latitudes
255 selected for this paper. In 2015, the WHO estimated a total of 212 million cases, of which the

256 majority occurred in the African region (90%), followed by the South East of Asia (7%). The
257 infections in the Americas represented 0.3%. A total of 429 thousand deaths were also reported
258 for this disease for the same year (WHO 2016). However, efforts to control the disease
259 transmission have been able to reduce the number of cases present in comparison with the year
260 2000; with a global reduction of 14% in the total number of infections and 52% in the number of
261 deaths (WHO 2016). Treatment methods reported by the WHO have included medically based
262 methods, such as artemisinin based combination therapy, plus environmental based methods,
263 such as use of insecticide-treated mosquito nets and indoor residual spraying.

264

265 3.2 Naturalized Organisms

266

267 Naturalized organisms are those that thrive in seawater and in contaminated fresh waters. These
268 organisms include the *Vibrio* bacteria and toxic algae. Of the *Vibrio* species, the most common
269 to cause infection are: *Vibrio vulnificus*, *Vibrio parahaemolyticus* and *Vibrio cholerae* (CDC
270 2015b). *V. vulnificus* and *V. parahaemolyticus* cause an infection called vibriosis, which can
271 manifest mild to severe gastroenteritis, primary sepsis, or skin and soft tissue infection,
272 depending on the transmission route (Newton et al. 2012). The infection is mainly contracted by
273 the ingestion of raw shellfish (especially oysters) or by exposing open wounds to brackish or sea
274 water. In contrast, *V. cholerae* causes an infection known as cholera, which is characterized by a
275 life threatening acute watery diarrhea. However, the infection is easily treated. Most of the cases
276 are caused by ingestion of water or food contaminated with human fecal matter (Newton et al.
277 2012). Similar to *V. vulnificus* and *V. parahaemolyticus*, *V. cholerae* can also be transmitted by
278 eating raw shellfish harvested from contaminated waters.

279

280 The expansion of areas covered with shallow waters could also implicate a geographical
281 extension of the incidence area of toxic algae blooms and exposure of new populations (Craig
282 2010, Trtanj et al. 2016, Buratti et al. 2017). Toxic algae blooms are characterized by a rapid
283 increase of the toxin producing algae, caused by changes in water quality such as: temperature,
284 nutrients and light. Common toxic algae blooms in the United States are caused by cyanobacteria
285 and Florida red tide blooms (*Karenia brevis*) (FDOH 2017).

286

287 Toxins produced by some algae can be harmful for humans and animals that drink or are in
288 contact with contaminated waters. In the case of cyanobacteria, the toxins are believed to
289 accumulate in fish and shellfish, high concentrations of the toxins can affect the gastrointestinal
290 tract, nervous system and skin. In the case of Florida red tide, the algae produce a suite of natural
291 toxins called brevetoxins (Fleming et al. 2011). The most common human health manifestation
292 is gastrointestinal illness due to the consumption of contaminated seafood (Kirkpatrick et al.
293 2010) and respiratory irritation caused by inhalation of toxins mixed with sea spray produced
294 when waves break at the shore (Kirkpatrick et al. 2011). During times of red tides, it is advised
295 not to ingest shellfish like clams, shrimps, lobster and oysters harvested from waters with red
296 tides, since shellfish (as filter feeders) can concentrate toxins (FDOH 2017). People with
297 underlying respiratory susceptibilities (e.g., uncontrolled asthma) should avoid the beaches
298 during times of active nearshore blooms (Bean et al. 2011).

299

300 3.3 Fecal-oral diseases

301

302 In a sea level rise scenario, the intrusion of seawater could cause disturbances to sewer systems
303 (by flooding the collection lines). Therefore, it is also important to consider the diseases that are

304 typically transmitted by exposure to contaminated waters, especially those pathogens that follow
305 a fecal-oral route. According to the Centers for Disease Control and Prevention (CDC), the most
306 frequent fecal-oral pathogens associated with outbreaks in the United States are: *Campylobacter*
307 *jejuni* (bacteria), *Giardia intestinalis* (protozoa) *Cryptosporidium* sp. (protozoa), *Shigella*
308 (bacteria), *Escherichia coli* O157:H7 and O111 (bacteria) and enteric viruses (CDC 2015b). Of
309 particular significance is the transmission of protozoal illnesses for which common disinfection
310 systems, via chlorination, are not effective; failing to inactivate the protozoal microbes.
311 Furthermore, *Legionella* sp. is the waterborne pathogen with the highest incidence in the United
312 States (CDC 2015b). However, *Legionella* is not transmitted via fecal-oral routes. It is
313 transmitted by the inhalation of contaminated aerosols. Its natural reservoir consists of warm
314 fresh water (WHO 2007) with outbreaks typically associated with improperly treated municipal
315 water in residential settings, and the inhalation of aerosols from cooling towers. Although
316 *Legionella* is typically found in freshwaters, several studies have demonstrated that the bacteria
317 can survive in marine environments (Heller et al. 1997, Gast et al. 2011). The ability to tolerate
318 salty water thereby raises concerns over disease transmission of *Legionella* species in coastal
319 environments, especially in situations that promote the formation of aerosols from contaminated
320 waters.

321

322 4 Disease Mitigation

323

324 4.1 Mitigation of mosquitoborne diseases

325

326 The life cycle of a mosquito includes a larval stage that requires stagnant water, and an adult-
327 female blood feeding stage required for the development of eggs in the female after mating. The

328 time it takes for a blood feeding female to develop from an egg is variable depending upon the
329 mosquito species. For *Aedes aegypti* development occurs over a period of about 10 days but can
330 be shorter in areas of high humidity and warmer temperatures (da Cruz Ferreira et al. 2017).
331 Mitigation of mosquitoborne diseases will require interruption of the circular life cycle (Figure
332 2). These mitigation strategies can be separated into mechanical, biological, and chemical
333 controls. However, for the cycle to continue, suitable ambient temperatures and salinities are
334 necessary.

335

336 With respect to temperature, for the United States, most cases of mosquitoborne diseases occur
337 during the warmer months (June-September), when the vector is more active. However, in some
338 states like Florida, the incidence can be observed even during winter months, due to warmer
339 temperatures in the region. In fact, climate change not only contributes to a higher exposure of
340 mosquitoborne diseases by spreading the areas of mosquito reproduction, it also causes the
341 expansion of the mosquito active season by the increasing the number of warm temperature
342 months (Craig 2010). To further increase mosquito reproduction, some mosquito species, which
343 are traditionally considered to be fresh water mosquitos, have adapted to reproduce within
344 brackish water environments after events of sea water intrusion (Ramasamy and Surendran 2011,
345 2012). The case of *Aedes aegypti* is of particular concern since it is the vector responsible of
346 transmitting dengue, Chicungunya, Yellow Fever and Zika viruses. Table 1 summarizes the most
347 relevant mosquito species for the latitudes selected, along with their related diseases and the
348 optimal salinity and temperature ranges for their reproduction and survival. Overall, the species
349 considered in this paper are capable of thriving in brackish water (salinity between 5 and 30 ppt.)
350 with *Culex* and *Aedes* spp. associated with fresh and brackish waters and *Anopholes* spp. capable

351 of reproducing under high (39 ppt) salinity conditions. *Aedes* spp. has the widest temperature
352 range (17 to 34 °C) with optimal temperatures for the latitudes selected. Therefore, sea level rise
353 and the intrusion of warm sea water will likely contribute to the establishment of ideal conditions
354 for mosquito reproduction and the propagation of mosquitoborne diseases.

355

356 There are three categories of mitigation for mosquitoborne diseases. The first type of mitigation
357 strategy involves mechanical control methods. Mechanical methods are focused on preventing
358 water stagnation to minimize the availability of mosquito reproduction sites. It is anticipated that
359 water stagnation will increase with sea level rise. This is because waters along coastlines tend to
360 be shallow due to relatively flat bottom slopes associated with the flat terrestrial topography. Sea
361 level rise will result in a horizontal extension of shallow waters inland due to the flat topography
362 of the area, thereby increasing the spatial extent of flat shallow waters towards more populated
363 areas. One critically important method to reduce mosquito reproduction is to prevent the
364 accumulation of water, at both large and small scales. On the large scale standing water can be
365 avoided by draining and/or pumping of shallow surface water ponds, surface grading, subsoil
366 drainage, deepening of shallow areas, and hydraulic filling, among others (Salvato 1992). At the
367 smaller individual property owner scale, measures include: elimination of standing water from
368 barrels, empty cans, tires, gutters, boats, garbage containers, unused swimming pools, proper
369 disposal of used containers and tires to avoid undesired water collection, keeping swimming
370 pools and hot tubs in proper functioning conditions, continuously changing water in flower pots,
371 pet bowls and bird baths (every three to four days), cleaning roof gutters and draining flat roofs,
372 covering with a screen or lid any rainwater collection barrel or cisterns, repairing broken
373 windows or door screens, and the installation of mosquito traps, among others (Connelly et al.

374 2014). Also, new South Florida building codes are proposed that would allow the use of water
375 cisterns to collect rainwater; which could help minimize the quantity of storm water drainage.
376 However, these cisterns should be kept properly covered, to avoid becoming new breeding sites.

377

378 The second category of mitigation strategies, biological methods, focuses on using biological or
379 ecological means of controlling mosquito proliferation, which are one of the most effective
380 methods to reduce mosquito populations and mitigate arboviral disease transmission. Biological
381 methods are based on non-chemical (larvicides) alternatives that interrupt the life cycle of the
382 mosquito, with minimum environmental impact. These can be achieved by the introduction of
383 organisms that prey on or compete with target species. In the case of mosquito control, predatory
384 fish and copepods have been shown to be successful (WHO 2017c) in reducing the mosquito
385 population. When introducing predatory fish to the mosquito source site, it is important to select
386 native species which would prevent threats to the indigenous fauna (WHO 2017c). Many fish
387 species native to Florida can be potentially used for larvae control (Connelly et al. 2014). Each
388 of the fish requires optimal temperature and salinities for their survival (Table 1). Predatory
389 copepods, small crustaceans naturally found in fresh and brackish waters, can also feed on early
390 stage larvae. These crustaceans can be used in stagnant water that is not intended to be drained.
391 As well as in the case of fish, it is important to introduce native copepods. Therefore, these
392 should be collected from local source waters and then introduced into the mosquito reservoir
393 (Connelly et al. 2014). In some cases, reintroduction of copepods is necessary until their
394 populations are sustainable (WHO 2017c).

395

396 Another form of biological and ecological mitigation is the application of *Bacillus thuringiensis*
397 *israelensis* (Bti), a naturally occurring soil bacteria that is believed to generally have minimal
398 impacts on non-target organisms (Salvato 1992). Bti, which is effective in controlling several
399 mosquito species (*Aedes* and *Culex*), produces toxic proteins that are ingested by the larvae,
400 causing disruption of cell membranes and subsequently death of the organism (Boyce et al.
401 2013). Although most of the toxins produced by Bti are non-toxic to humans, studies have shown
402 some strains may release beta-exotoxins shown to be toxic to mammalian cells (Gonzalez Rizo et
403 al. 2016); caution is needed in selecting Bti strains that minimize unintended impacts.

404

405 Additionally, the application of novel techniques has been gaining interest amongst the
406 authorities responsible for mosquito control. These techniques include the introduction of
407 genetically modified (GM) mosquitos to control their population. The method is based on
408 modifying the genome of the organisms to control a specific trait, which is then passed down to
409 its descendants. In mosquitoborne disease mitigation, genetic engineering can be used to prevent
410 disease transmission, by either altering mosquito philology (so the disease-causing virus or
411 protozoa cannot survive) or by reducing the population through sterility (making the male sterile
412 or causing the death of the descendants). Genetically modified (GM) mosquitos have been used
413 to reduce populations with success in several countries, achieving a high rate of reduction of
414 *Aedes aegypti* population (Connelly et al. 2014). For example, a field trial (23-week period)
415 executed in the Cayman Islands in 2010 successfully introduced genetically modified males that
416 were able to reproduce with wild females, resulting in an 80% population reduction (Harris et al.
417 2012). The same types of genetically modified males were evaluated in Brazil, with a 95%
418 reduction of the mosquito adult population in a year (Carvalho et al. 2015). However, over time

419 there has been opposition regarding the effectiveness of these trials in Brazil since the population
420 of *Aedes aegypti* has been shown to drop and then rise after the release of GM mosquitos (FKEC
421 2017). An alternative to this approach is the use of *Wolbachia* strains (a naturally occurring
422 parasitic bacteria that can self-sustain in mosquito populations) as a biocontrol. This technique
423 reduces adult lifespan and interferes with fertility and pathogen replication (Iturbe-Ormaetxe et
424 al. 2011, Suh et al. 2017)

425

426 Chemical methods (larvicides and insecticides), the third method of mitigation, are applied to
427 control larvae and adult mosquito populations. There are several U.S. EPA approved chemicals
428 that can be used as larvicides, and can be applied in liquid form (spraying) or as pellets or tablets.
429 Larvicides can be classified as insect growth inhibitors, organophosphates, or oil films. Insect
430 growth inhibitors (S-Hydroprene, S-Kinoprene, Methoprene and S-Methoprene) prevent larvae
431 from developing into adult mosquitoes, by interfering with growth hormones (U.S. EPA 2001).
432 Organophosphates affect the nervous system of the larvae, inhibiting growth. Oil films control
433 mosquitos through a physical process. They are applied as thin layers over the water surface and
434 restrict oxygen access, causing larvae to drown (U.S. EPA 2017). Adult mosquito control with
435 insecticides is achieved by spraying affected areas with U.S. EPA approved chemicals, such as:
436 malathion, naled (organophosphates), prallethrin, etofenprox, pyrethrins, permethrin, resmethrin
437 and sumithrin (synthetic pyrethroid) (U.S. EPA, 2017).

438

439 Chemical controls should only be considered when mechanical and biological control methods
440 have not been effective or are not possible to use. The use of chemical methods should be
441 limited as this mitigation strategy is known to result in the development of resistant mosquitos

442 (Salvato 1992). Resistance is believed to be caused by mutations that lead to higher metabolic
443 detoxification and lower sensitivity of the target proteins (Liu et al. 2015). Repeated applications
444 of pesticides result in the survival of mosquitos with such mutations thereby creating a new
445 population with the mutations suitable for survival. In practice, the development of insecticide
446 resistance has been linked to recent arboviral disease outbreaks, as in the case of Chicungunya
447 fever in the Republic of Congo (Kelvin 2011). Moreover, the WHO has identified a threat on the
448 effectiveness of malaria control methods due to the development of chemical resistance to
449 insecticides, particularly to pyrethroid. Sixty of 78 countries surveyed had reported resistance to
450 at least one type of insecticide (WHO 2016).

451

452 To successfully achieve proper domestic prevention, it is important that the community is
453 continuously informed about available mitigation techniques, including eliminating standing
454 water from their property and utilization of long sleeve clothing and insect repellants to minimize
455 the probability of a mosquito bite. Therefore, comprehensive information campaigns should be
456 included as part of an integrated strategy to minimize mosquitoborne disease propagation.

457 Insert Figure 2.

458

459 4.2 Mitigation of naturalized microorganisms

460 As in the case of vector borne diseases, sea level rise can increase the geographical expansion of
461 the incidence area, exposing new populations to harmful microorganisms naturally found in
462 water, the *Vibrios* and harmful algae. Warmer water bodies, due to climate change and changing
463 levels of coastal nutrients (nitrogen and phosphorous), will likely play an important role in the
464 persistence of naturalized microbes. In addition, *Vibrio* proliferation is sensitive to salinity,

465 whereas growth of toxic algae is dependent upon solar radiation (Figure 3). Therefore, designing
466 a proper monitoring system to detect or predict the presence of harmful microbes found naturally
467 in water (based on critical environmental factors), should be considered as part of the plans to
468 adapt to sea level rise, especially when temperatures, salinity (Table 2) and nutrients are at the
469 optimal range.

470

471 For *Vibrio*, the optimum temperature for growth is between 15 and 30°C (Craig 2010). In fact,
472 changes in *V. vulnificus* abundance and a consequent increasing trend in the number of infection
473 cases around the world, have been mostly attributed to climate change (Deeb 2013, Newton et
474 al., 2012, Randa et al. 2004, Vezzulli et al. 2012, Semenza et al., 2017). This increase has been
475 specifically accredited to increasing water temperatures which has expanded the active season
476 and geographical range of *Vibrios*. In the case of toxic algae, optimum temperature for algal
477 growth is in the 20 to 35°C range for cyanobacteria (Konopka and Brock 1978) and 15 to 30°C
478 for *Karenia brevis* (Magaña and Villareal 2006) (Table 2), and changes in surface temperature
479 could also be linked with more frequent and intense harmful algae blooms (Moore et al., 2008).
480 For example, the average mean temperature in Key West (25.5°C, 1948 to 2015 period of record,
481 Key West International Airport, National Climatic Data Center) is within the optimum range for
482 growth of *Vibrios* and harmful algae. A 3°C increase in ambient temperature would push the
483 mean temperature in Key West more towards the center of the optimum range for algae growth
484 and towards the higher end for cyanobacterial growth. Increases in atmospheric temperature due
485 to global warming will likely increase the period and intensity of naturalized-microbe growth
486 and persistence in tropical and subtropical climates with changing dynamics between types and
487 species of naturalized organisms that dominate the microbial ecosystems.

488

489 Along with climate change, certain types of liquid discharges to coastal environments could
490 contribute to localized rise of seawater temperature and changes in salinity patterns. Examples
491 of high temperature discharges that can be exacerbated with global warming are: industrial
492 effluents (especially warm purge coming from cooling towers), irregular septic and wastewater
493 pipes leakage, power plants cooling system outfalls, and storm water runoff. Of these, discharges
494 of power plant cooling blowdown are highly relevant for their major environmental impacts,
495 related to the high volumes disposed and warm temperatures (up to 48 °C, which must be cooled
496 down to at least 30 °C during the warmer months prior to discharge) (Delgado and Herzog 2012,
497 Fleischli and Hayat 2014). Therefore, efforts should be made to decrease the volume of water
498 discharged; for example, using reclaimed water in closed loops as part of the power plant cooling
499 systems (Veil 2007), and to reduce thermal pollution to water bodies, by implementing less water
500 dependant technologies, such as dry or hybrid cooling systems (Fleischli and Hayat 2014). In this
501 sense, mitigation of naturalized organisms would include avoiding optimum temperature
502 discharges as much as possible (Figure 3).

503

504 The salinity over which *Vibrio* bloom is relatively wide, between 5 and 25 ppt, with lower levels
505 in purely fresh or purely ocean water. On the other hand, the optimum salinity range for
506 cyanobacteria is towards the fresh and brackish water range (0 to 10 ppt) whereas for *Karenia*
507 *brevis* is in the more saline range (25 to 45 ppt), suggesting that the distribution of these algal
508 types will vary depending upon the distribution of freshwater inputs and dilution available along
509 the coasts. Climate change may increase the variation of salinity gradients along the coast (Deeb,
510 2013, Havens 2015). During the periods of heavy rain and high river flows the salinity of

511 estuarine and coastal environments could drop, expanding the area of low to moderate salinity
512 towards the coast (Havens 2015). During drought periods, with the combination of sea level rise
513 (salt water intrusion), the salinity of estuarine environments could rise, expanding the area of
514 high to moderate salinity towards the land (Deeb 2013). Both scenarios could promote the
515 development of new optimal environments for *Vibrio* and harmful algae, increasing public health
516 risk by expanding the geographical range. One potential means of controlling salinity is through
517 the use of gates and other surface water control structures which can shorten salinity gradients in
518 areas where populations are more likely to be exposed.

519

520 In addition to temperature and salinity, nutrient levels are also linked to *Vibrio* concentrations
521 and have a major impact on algae blooms. Primary sources of nutrient inputs include agricultural
522 runoff, urban storm water, and wastewater (Figure 3). These sources are frequently
523 contaminated with animal fecal waste and fertilizers both of which have high levels of nitrogen
524 and phosphorus which are then washed to receiving waters after rain events or from leaking
525 sewers. Therefore, the aim should be multifaceted, reducing the volume of storm water
526 (Livingston and McCarron 1992) and sewage that is disposed in water bodies, and also reducing
527 its nutrient load by minimizing fertilizer use (Kirkpatrick et al. 2014) and cleaning up of animal
528 waste. In the case of *Vibrio*, they are commonly found in association with plankton (Turner et al.
529 2009, Lipp et al. 2003), in particular copepods (Lizárraga-Partida et al. 2009). In fact, the *V.*
530 *cholera* pandemic of the early 1990's was attributed to an upwelling event that brought nutrient
531 rich deep ocean waters to the surface, resulting in plankton blooms and subsequent cholera
532 outbreaks that crossed the continent of South America (Gil et al. 2004). Thus, controlling
533 anthropogenic sources of nutrients which are commonly found along coastal areas, should be

534 considered as part of the strategic approach to minimizing the potential for *Vibrio* infections and
535 the incidence of algae blooms. Furthermore, some of the methods described previously to avoid
536 standing water could be beneficial to efforts to minimize the propagation of algae blooms, since
537 they generally flourish in nutrient rich calm waters, especially cyanobacteria (FDOH 2017)
538 (Figure 3). Similarly, blooms of *K. brevis* have been associated with water circulation features
539 along the West Florida Shelf (Maze et al. 2015) and with nutrients (Olascoaga et al. 2008). The
540 impacts of nutrients, however, are complex. For example, Weisberg et al. (2014) emphasizes
541 ecological dynamics which may result in other algae species outcompeting *K. brevis*, depending
542 upon the level of nutrients. Algae are also susceptible to other environmental factors which
543 might be more difficult to control and could encourage algal blooms, such as solar irradiance.
544 Higher irradiance is associated with higher growth rates (Magaña and Villareal, 2006) and it is
545 unclear how climate change will influence the radiant energy reaching different regions of the
546 Earth.

547

548 Along with monitoring and controlling environmental factors that affect the growth of
549 naturalized organisms, attention should be paid to additional routes of exposure, which include
550 consumption of contaminated shellfish. This would apply for waters with high concentration of
551 *Vibrio* or other pathogens. Thus, it is also necessary to improve the shellfish decontamination
552 technologies. In fact, most of the positive cases of *Vibrio* spp infections in the United States are
553 caused by consumption of contaminated raw shellfish (Horseman and Surani 2011). Traditional
554 post-harvest procedures (PHP), such as: thermal treatment, gamma irradiation, freezing, and
555 high-hydrostatic-pressure treatments, are effective in eliminating the bacteria. However, they
556 often result in oyster death and reduction of its quality (changes in odor, color and texture) (Fang

557 et al. 2015). Novel procedures including chitosan microparticles (Fang et al. 2015), UV
558 disinfection (Ramos et al. 2012) and high salinity shock treatment (Larsen et al. 2013), represent
559 promising alternatives to decontaminate live oysters without affecting their quality.

560

561 Considering the increasing trend of *Vibrio* infection cases and harmful algae blooms, and the
562 difficulty to control their populations in their natural environment, it is important to educate the
563 general population about the risk of infection, to prevent unnecessary contact with *Vibrio* and
564 toxic algae, and to interrupt the transmission route (Figure 3). This becomes more relevant if
565 areas flooded by sea level rise would be used for recreational purposes. Educational campaigns
566 should include the following information/enforcements: avoid eating raw shellfish from high risk
567 areas (e.g., with ideal temperature and salinity for *Vibrio* bacteria and/or with active toxic algae
568 blooms), avoid entering recreational waters with open wounds (lacerations, puncture wounds and
569 scratches) to avoid exposure to skin pathogens such as *Vibrio vulnificus*, maintain good hygiene
570 and rinse with treated freshwater after seawater or brackish immersion, use protective gloves
571 while manipulating raw shellfish, use protective shoes to avoid cuts at the beach, signage to
572 avoid recreational activities in waters with active algae blooms, avoid use of water with active
573 algae blooms for irrigation without treatment, and avoidance of the coast during active blooms to
574 prevent skin, eye and respiratory irritation from contact and inhalation of aerosolized seawater.

575 Insert Figure 3

576

577 4.3 Mitigation of fecal-oral diseases

578

579 As in the case of mosquitoborne disease and diseases from naturalized microbes, sea level rise
580 could have a direct impact on the transmission of fecal-oral diseases, particularly by modifying
581 the environmental conditions that favor pathogen proliferation and increasing the exposure to
582 these pathogens. In addition to *Vibrio* there are other pathogens that can be transmitted through
583 seawater. These additional pathogens usually come from humans or animals and can be
584 transmitted to water through bather shedding (Elmir et al. 2009), direct fecal sources on the
585 beach (Wright et al. 2011), from poorly treated storm water (Sinigalliano et al. 2007), and from
586 leaks in the sanitary sewer system (Solo-Gabriele et al. 2011, Trtanj et al. 2016). Once in the
587 water they can impact coastal sediments which tend to retain pathogens (Mueller-Spitz et al.
588 2010) and release them through tidal and wave action (Feng et al. 2013, Phillips et al. 2014)
589 (Figure 4).

590

591 A vast majority of these additional pathogens are transmitted through the ingestion of
592 contaminated water, but a few can be transmitted through inhalation (*Legionella*) and skin
593 contact in particular through open wounds (*S. aureus*) (Plano et al. 2013). Moreover, changes in
594 temperature could also be related to higher risks of infection, pathogens such as *Legionella* sp
595 and *Campylobacter jejuni* thrive in particularly warm waters (up to 42 and 45 °C) making them
596 of concern as temperatures rise. Other pathogens such as *Cryptosporidium*, *Shigella*, and *E. coli*
597 O157:H7 also thrive under high temperature conditions (up to 37 °C) (Table 2).

598

599 Most of these pathogens have traditionally not been considered to be part of the natural
600 background of coastal ocean conditions; however, an overwhelming number of research studies
601 have shown that even fecal-oral pathogens can become naturalized and persist for long periods of

602 time in beach sands found in the intertidal zone (Whitman et al. 2014, Solo-Gabriele et al. 2016).
603 These beach sands tend to accumulate microbes with the highest levels found just above the high
604 tide line (Shah et al. 2011) thereby serving as a reservoir of potentially infectious pathogens
605 (lower part of Figure 4). With the increase in sea level, the extent of the intertidal zone will
606 increase as Florida tends to be very flat along its coast resulting in a larger coastal area impacted
607 by tidal fluctuations. This anticipated increase in the intertidal fluctuations can serve to promote
608 greater proliferation of microbes.

609

610 To control pathogens along the coast, the sources of fecal contaminants would need to be
611 minimized. This would require hardening and sealing of older sewer systems which often have
612 significant amounts of infiltration and exfiltration. It would also require the redesign of domestic
613 sewer collection systems which in many parts of Florida rely on gravity flow. With increasing
614 groundwater levels, there will be less elevation through which water can flow by gravity and
615 many of the sewer systems along the coast may need to be converted to force mains. Sewage
616 treatment plants, with processes running by gravity, may also need to be redesigned to account
617 for the higher water levels. Sewage effluents from treatment plants (usually secondary effluents)
618 should be directed away from coastal areas. Even if treated to secondary standards (treated
619 through at least sedimentation and aerobic biological processes), sewage effluent still harbors
620 pathogens (Johnson et al. 1997, McLellan et al. 2015) and nutrients; the pathogens posing a
621 direct infectious risk whereas the nutrients are indirect through their impacts on *Vibrio* and
622 harmful algae. Alternatives to coastal outfalls include deep well injection and reuse of effluent.
623 In addition, the use of advanced treatment such as to a tertiary level (targets nutrient removal),
624 reduces the potential for the spread of pathogens and nutrients. Septic tank systems which rely on

625 gravity should be replaced with sewer networks once water levels impact their corresponding
626 drain fields (Cooper et al. 2016).

627

628 Storm water is a known source of fecal bacteria (Hernandez et al. 2014, Patz et al. 2008) and
629 efforts will be needed to treat storm water prior to discharge to coastal waters to prevent human
630 exposures to fecal-oral pathogens. Storm water treatment systems include initial retention of the
631 first flush, infiltration systems, vortex separation systems, and water quality baffle boxes (CH₂M
632 Hill Inc. 2012) along with extended detention and controlled discharge of higher level runoff.
633 With increases in water levels, storage volumes of storm water will decrease within underground
634 and above ground reservoirs. As such storm water systems will need to be redesigned such that
635 the storage volume which treats the first flush is maintained prior to discharge.

636

637 Human and animal densities in various areas would also need to be considered to assess the
638 ability of the water to dilute microbes from bather shedding (Elmir et al. 2009) and fecal inputs
639 (Wright et al. 2009). For fecal inputs from domesticated animals, policies can be put in place
640 requiring that owners properly dispose of fecal waste. For wild animals, coastal management
641 systems can be put in place that would minimize the excessive congregation of certain types of
642 animals (e.g., vegetated dune structures tend to deter the congregation of birds). Additional
643 transmission routes also include consumption of shellfish harvested from contaminated waters.
644 In this case, post-harvest decontamination procedures also play an important role in efforts to
645 minimize cases of infection.

646 Insert Figure 4.

647

648 5 Case of Study: City of Key West

649

650 The City of Key West is a 14.5 square kilometer island, with an estimated population of 26,990
651 people (US Census Bureau, 2017). The Florida Keys, located off the southern coast of Florida,
652 are an archipelago with Key West at its southernmost point (Figure 5). The island receives over
653 three million tourists annually. The United States Navy established a naval base on Key West in
654 1822. The Naval Air Station, located within 1.6 km of Key West on Boca Chica Key, was
655 established in 1940. The island of Key West boasts a population density of 1703 persons per
656 square kilometer (whereas the rest of the state of Florida has an average of 135 persons per
657 square kilometer) and receives more than 100 times the number of tourists than it has residents.

658 Insert Figure 5.

659 Key West is a limestone island which allows water to not only flood by overland flow, but also
660 to well up from the ground (Spanger-Siegfried et al. 2014). Seawalls, an effective flood-
661 prevention method in many areas of the world, are inadequate by themselves in preventing tidal
662 inundation due to the island's porous geology (Spanger-Siegfried et al. 2014). While flooding on
663 Key West was previously limited to storm surge events, storm drains are now known to back up
664 and overflow onto the streets during the full and new moon; the City could be seeing 200 tidal
665 floods annually by the year 2045 (Spanger-Siegfried et al. 2014). Today, even very small
666 amounts of precipitation (on the order of 25 mm), along with extreme tidal events, can cause the
667 island to flood (Spanger-Siegfried et al. 2014). Even though the flooding tends to be shallow, for
668 the time being, this can affect roads and other infrastructure, and cause damage to residences and
669 businesses.

670

671 Key West has taken several measures to minimize coastal contamination and prevent flood
672 damage. The city has also eliminated 99.9 % of septic tanks and cesspits, reducing the risk of
673 waterborne pathogen spreading in a flooding scenario (CDM 2001, Monroe County 2007). Since
674 1989 the city installed a centralized collection sewer system that conveys (via pumping)
675 wastewater to a treatment facility. Efforts during this upgrade included the detection and
676 elimination of leaks from public and private sewer pipes, and the reduction of seawater intrusion
677 to the system and the reduction of exfiltration which would contribute towards the contamination
678 of groundwater. Since the year 2000, the treated wastewater is disposed by a deep well injection
679 system.

680

681 To address flooding, Key West has developed strict building standards and improved its storm
682 water infrastructure. One of the first integrated floodplain management plans was prepared by
683 the city of Key West in 1971, in cooperation with the National Flood Insurance Program (NFIP),
684 administered by the Federal Emergency Management Agency (FEMA) (Monroe County 2007).
685 This plan established construction standards for the island and mapped special flood hazard
686 areas. The plan, in conjunction with enhanced building codes, established specific building
687 requirements for these areas. Most important of these requirements being the minimum elevation
688 of new construction. The City of Key West established a minimum finish floor elevation of 30
689 cm for the whole city and an addition of 0.5 m freeboard elevation within type A flood zones,
690 which are zones where a static rise in water levels can be expected during flood events. The City
691 also passed legislation that allows building heights to exceed the zoning requirements by an
692 amount equal to the provided freeboard of a structure up to 1.22 m, which acts as an incentive to

693 promote building resilience and lowers the potential for those structures to be damaged while
694 reducing flood insurance premiums (Reed et al. 2013).

695

696 The latest storm water management plan for Key West included the development of a hydrologic
697 and hydraulic computer simulation model of the City to identify flood prone areas and facilitate
698 the implementation of future adaptation strategies to manage storm water and mitigate flooding.
699 The plan proposes 37 specific projects, with the aim of reducing flooding, decreasing the amount
700 of storm water that is discharged to coastal waters and improving water quality (CH₂M Hill
701 2012). The projects include: installation of new gravity recharge wells (especially in the higher
702 elevation areas), installation of new piping to improve collection in some areas, installation of
703 pump-assisted storm water recharge wells in low lying critical areas, retrofitting existing outfalls
704 with baffle boxes to reduce sediments and sediment-associated nutrients, and new infiltration
705 control facilities where possible (exfiltration trenches), among other plans. Given the City's
706 policy of improving water quality and reducing contaminant load to coastal waters, the
707 construction of new outfalls is discouraged. However, in some cases, were the elevation is too
708 low the construction of outfalls may be the only feasible option to remove standing water. It was
709 estimated that the implementation of these recommended projects will divert more water into the
710 ground (which is an acceptable practice since there is no potable groundwater source on the
711 island); 51% in comparison with 45% that is currently diverted with the existing storm water
712 infrastructure (CH₂M Hill 2012). The City of Key West is also implementing a low impact
713 development or green infrastructure approach to improve storm water quality, including the
714 removal of nutrients.

715

716 All of the aforementioned measures have already managed to improve water quality (reduced
717 amount of nutrients and reduced contamination with urban sewage bacteria). In fact, the Monroe
718 County Canal Management Master Plan Phase I reported that in 3 years of operation of the wells,
719 tests found a 77.8% decrease in fecal coliforms in the city's canal. The current system of water
720 management at Key West mitigates some of the health risks associated with heavy storms and
721 floods. However, additional mitigation is needed to address areas that suffer from more frequent
722 flooding.

723

724 The areas within the City of Key West that are believed to be most vulnerable to sea level rise
725 are: Key West International Airport, Rest Beach, Smathers Beach, and the Indigenous Park
726 Neighborhood (Figure 5). These sites are the most low-lying within the island and represent key
727 economic drivers for the city due to the provision of housing to local residents and their role in
728 attracting and transporting tourists to the island. For the purpose of this paper, engineering
729 solutions for these areas that are already being developed are reviewed, with a particular focus on
730 solutions identified through the Florida Resilient Redesign II (FRRII) Workshop. This was a
731 design collaboration of the Florida Climate Institute, with the specific engagement of local
732 governments, Universities (Florida Atlantic University, Florida International University and
733 the University of Miami), and additional stakeholders.

734

735 Key West International Airport (EYW) serves 362,000 passengers annually. Fifty percent of its
736 runway will be flooded with only one-third meter of sea level rise. Due to the lack of available
737 space in this and other nearby islands, the FRRII proposes a mixed use of the Boca Chica Naval
738 Air Station, for civilian and military airline access. An alternative solution would be to elevate

739 the EYW airport. Similar projects have been executed elsewhere in Florida, for example the city
740 of Miami Beach is undertaking a major project where entire roads are being raised by 60 to 90
741 cm (DK&P 2016).

742

743 Rest Beach and Smathers Beach continuously suffer beach erosion from wave energy during
744 storms and from runoff resulting from heavy rain and require continuous sand replenishment.
745 Unfortunately, this practice will eventually become unviable in the future with the sea level rise
746 scenario. Therefore, the suggestion is to allow water to inundate the coastline, where applicable,
747 and reconnect the Atlantic Ocean to the salt ponds behind the beaches facilitating the flow of
748 water to and from the ponds (Figure 5). This will result in the permanent wash-down of some
749 beaches and potentially their eventual disappearance.

750

751 There are several advantages to this approach. It will create a natural buffer zone to the island
752 against storms, it could also allow the increase of biodiversity in the area and it could also create
753 new recreational areas. However, it would also implicate the relocation of highway A1A,
754 increasing the traffic inside the city and the possible accumulation of standing water in these
755 ponds. A practical solution to the later problem would be to increase the depth in areas that are
756 constantly flooding, allowing a greater flow of water from the ocean preventing stagnation. In
757 addition, the removed soil could be used to elevate residences and streets. The addition of pumps
758 to promote water movement is also a possibility; this will serve to aerate the water and maintain
759 a constant flow.

760

761 The Indigenous Park neighborhood holds the City's heaviest concentration of flood damaged
762 (repetitive loss) properties and is a critical residential neighborhood in Key West, as it houses
763 much of the City's workforce. As a solution for this region the FRRII proposes to reduce the
764 width of the streets and create a bio swale along them for storm water conveyance and treatment
765 (Figure 6). The soil removed to create this bio swale could then be used to elevate streets and
766 other infrastructure in the City. In some cases, underutilized roadways, not required for
767 residential access, could be converted to greenways or linear parks that serve many functions and
768 provide multiple benefits including recreational, aesthetic, storm water drainage, and wildlife
769 habitat. This design would provide storm water conveyance and treatment (including nutrient
770 uptake), which improves the performance of the storm water management system. In addition,
771 houses could be raised and integrate rooftop rainwater cistern collection systems. The cisterns
772 could contribute not only to storm water management, by capturing water, but they could also
773 reduce the City's carbon footprint and resource consumption, with the reuse of captured rain
774 water, reducing the potable water demand and associated pumping from the Florida mainland.

775 Insert Figure 6.

776 Coastal areas of the City intended to be protected in place may require further shoreline
777 enhancements including the use of wave energy dissipaters. While sea walls are one of the most
778 common methods to prevent coastal erosion, the use of conventional fixed walls creates a static
779 structure that does not respond well to undermining and is not easily adapted to future
780 conditions. The use of living sea walls and adaptable structures offers an improved solution over
781 conventional walls by incorporating living systems and rip rap which are both more adaptive
782 than a fixed structure, providing enhanced levels of protection in changing conditions.
783 Innovative wall design also offers an added benefit such as the concaved/curved design which

784 dissipates wave energy rather than reflecting it like vertical walls. The use of living shorelines,
785 reefs and breakwaters also significantly reduce wave energy offering additional shoreline
786 protection from erosion. The various strategies would be studied to ensure appropriate design
787 and placement to mitigate the adverse effects of wave energy along coastlines. Through these
788 strategies, the impacts to natural ecology, water resources and potential for increased vectors can
789 be managed to acceptable levels.

790

791 One of the biggest concerns when facing sea level rise, as discussed previously, is the possible
792 health impact and propagation of diseases that could be related to the expansion of shallow water
793 covered areas; therefore, adaptation and resilience are crucial (Ebi and Semenza, 2008, Ebi et al.
794 2013). On this matter, Key West has already made progress, as the city is currently applying
795 some of the techniques proposed to control disease transmission.

796

797 In the case of arboviral diseases, the city executes an integrated approach to control mosquito
798 populations. The Florida Keys Mosquito Control District employs Bti as biological larvicide, the
799 application is executed by air or ground, depending on the size of the mosquito reproduction sites
800 (FKMCD 2017). In addition, the Florida Keys Mosquito Control District is also responsible for
801 the execution of the adult mosquito control program in the area, which is focused on targeting
802 females (blood feeders). Spraying is executed from the ground with trucks or by air with
803 helicopters, depending on the extension of the affected area (FKMCD 2017). Furthermore, the
804 Florida Keys Mosquito Control District in association with Oxitec are currently evaluating the
805 application of genetic engineering to reduce the *Aedes aegypti* vector. In this case, genetically
806 modified male mosquitos would be introduced that would pass genes that would cause the death

807 of their offspring (Oxitec 2016). However, there is strong opposition among residents who are
808 questioning the success of the trials in Brazil (FKEC 2017).

809
810 For naturalized and fecal-oral microbes the enhancements made by Key West to the sewer
811 collection system, the new wastewater treatment plant, the elimination of point sources of
812 contamination (septic tanks) and the deep-well injection system, have already proven to improve
813 water quality in the area. This represents an important factor in controlling the transmission of
814 fecal-oral and waterborne diseases as well as the incidence of toxic algal blooms, since it reduces
815 the occurrence of ideal conditions for their propagation (specifically nutrient and sediment load).
816 However, due to the increase of sea water volume that needs to be managed, it is important to
817 maintain optimal conditions of the collection systems and to upgrade the infrastructure as
818 required in a timely manner. In addition, to control *Vibrio* infections the city should consider the
819 development of a surveillance system that could predict the behavior and incidence of the
820 bacteria as a function of environmental conditions (temperature, salinity, sediments and
821 nutrients) (Mott et al. 2008). In this respect, the state already notifies the public about the
822 occurrence of positive infection cases and deaths related to *Vibrio vulnificus* by county, with data
823 ranging back to 2008. This information is available in the Florida Department of Health (FDOH)
824 website, along with basic information about the bacteria and prevention recommendations.

825
826 Aside from sewer disposal, other important nutrient inputs that should be considered are storm
827 water runoff. In fact, storm water runoff is considered one of the major sources of pollution in
828 the state of Florida, given its high water volumes and the amount of pollutants it can carry.
829 Therefore, the aim should be to reduce the amount of storm water that is disposed in water

830 bodies, as well as improve its quality (Livingston and McCarron 1992). Reduction of the
831 quantity can be achieved through reuse projects which store storm water on site for later uses.
832 Improvement in water quality can be achieved through upstream water management to minimize
833 contaminant sources, retention of the first flush of water captured such as through rain gardens
834 and green roofs, and additional treatment technologies such as vortex flow sediment capture
835 systems and UV disinfection.

836

837 The FRRII has already considered measures that would reduce the impact of storm water runoff.
838 One of the objectives of the plan entails balanced water use and reuse, including rainwater
839 catchment (collecting cisterns) and storm water management through low impact design that
840 promotes treatment and reuse. In addition, the city could implement a policy that encourages the
841 population to reduce the use of fertilizers, minimizing the content of nutrients in storm water
842 runoff. As part of the resilient redesign, not only reuse of water should be considered, recovery
843 and reuse of nutrients from wastewater and storm water runoff should be added as part of the
844 objectives, to minimize environmental impact and improve sustainability. Several technologies
845 are being studied to improve the rate of nutrient recovery from wastewater, some of these are:
846 struvite precipitation, adsorption treatments (ion exchange processes), electrochemical
847 precipitation and electrodialysis (Batstone et al. 2015, Puchongkawarin et al. 2015, Franco et al.
848 2017).

849

850 **6 Conclusions**

851

852 Sea level rise is inevitable and with it, associated changes in the extent of disease transmission
853 pathways. The intrusion of seawater and the expansion of shallow water covered areas pose an
854 ideal scenario for the creation of new mosquito breeding sites. Similarly, the geographical
855 expansion of shallow covered areas and the increase in water temperature present ideal
856 conditions for the propagation of waterborne pathogens (specially *Vibrio* spp) and toxic algae
857 blooms, exposing new populations to these health risks. The transmission of fecal oral diseases
858 could also be affected since sewer collection lines will become more vulnerable to flooding and
859 salt water intrusion, increasing potential exposure to these pathogens.

860

861 Given that greenhouse gas emissions are likely to continue, with the consequent increment in
862 average global temperature and sea level, adaptation will be required. Here we propose some
863 adaptation strategies focused on methods to minimize or control disease transmission due to sea
864 level rise. Arboviral diseases can be controlled by the application of an integrated approach that
865 targets mosquito's life cycle at its different stages, with control measures consisting of
866 mechanical, biological and chemical methods. Consideration will be needed to account for
867 changes in salinity patterns, due to salt water intrusion, which at the current time greatly
868 influences mosquito proliferation (mosquito species of interest require < 25 salinity units to
869 reproduce).

870

871 The spread of naturalized microbes, such as *Vibrio* and toxic algae, can be greatly reduced by
872 engineering solutions designed to minimize nutrient (nitrogen and phosphorus) inputs discharged
873 from uncontrolled sewage disposal, storm water, and urban and agricultural runoff. Nutrient
874 recovery technologies should also be considered to improve water quality. Developing a

875 monitoring system based on environmental parameters (salinity, temperature, nutrients, sun
876 light) is also recommended.

877

878 Fecal oral pathogens (and *Vibrio*) can be controlled by minimizing liquid discharges that have
879 direct impact on water temperature and salinity. Power plant cooling blowdown is of particular
880 interest due to its high volume and warm temperatures. The development and application of less
881 water dependent cooling technologies should be considered. Most importantly, proper water and
882 wastewater management is encouraged. This includes the elimination of point sources of
883 contamination (such as sewage effluents), and minimizing non-point sources (such as animals).
884 Efforts are needed to maintain the wastewater infrastructure and its operation should be adapted
885 to withstand higher volumes of salt water. It is also important to reduce the exposure to these
886 pathogens, by the application of novel decontamination processes that allow safe consumption of
887 raw shellfish.

888

889 The engineering solutions described previously acknowledge the inevitable flooding in the future
890 caused by sea level rise. For Key West, innovative solutions will be required. Solutions applied
891 to other cities around the world, such as building a wall at the coast, are not feasible due to Key
892 West's permeable karst coral and limestone subsurface geology. As such, innovative solutions
893 are needed to address sea level rise in Florida. Policy changes that incentivize permitting for new
894 sustainable and resilient strategies will be a first requisite to making the needed infrastructure
895 changes a reality. Municipalities, Counties and States will need to collectively and
896 collaboratively adopt approaches that promote these adaptation strategies, as permitting
897 responsibilities fall within these multiple jurisdictions. This will require cross agency integration

898 of policies which can be facilitated by groups such as the Southeast Florida Regional Climate
899 Change Compact.

900

901

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906

907

908 **REFERENCES**

- 909 Bates B.C., Kundzewicz Z.W., Wu S. and Palutikof J.P., Eds. Climate Change and Water.
910 Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat,
911 Geneva, 210 pp, 2008.
- 912 Batstone D., Hülsen T., Mehta C. and Keller J. “Platforms for energy and nutrient recovery from
913 domestic wastewater: A review,” *Chemosphere*, vol. 140, pp. 2–11, 2015.
- 914 Bean J.A., Fleming L.E., Kirkpatrick B., Backer L.C., Nierenberg K., Reich A., Cheng Y.S.,
915 Wanner A., Benson J., Naar J., Pierce R., Abraham W.M., Kirkpatrick G., Hollenbeck J.,
916 Zaia J., Mendes E. and Baden, D.G. “Florida red tide toxins (brevetoxins) and
917 longitudinal respiratory effects in asthmatics”, *Harmful Algae*, vol. 10(6), pp. 744–748,
918 2011.
- 919 Beard, C.B., Eisen, R.J., Barker, C.M., Garofalo, J.F., Hahn, M., Hayden, M., Monaghan, A.J.,
920 Ogden, N.H., and Schramm, P.J., “Chapter 5: Vectorborne Diseases.” In, *The Impacts of
921 Climate Change on Human Health in the United States: A Scientific Assessment*. U.S.
922 Global Change Program, Washington, DC, pp. 129–156, 2016.
923 <https://health2016.globalchange.gov>.
- 924 Beck-Johnson L., Nelson W., Paaijmans K., Read A., Thomas M. and Bjørnstad O. “The Effect
925 of Temperature on *Anopheles* Mosquito Population Dynamics and the Potential for
926 Malaria Transmission.” *PLoS ONE*, 8(11), e79276, 2013.
- 927 Beitinger T. and Bennett W. “Quantification of the role of acclimation temperature in
928 temperature tolerance of fishes,” *Environmental Biology of Fishes*, vol. 58, pp. 277–288,
929 2000.

- 930 Bloetscher F., Berry L., Rodriguez-Seda J., Hammer N., Romah T., Jolovic D., Heimlich B. and
931 Cahill M. "Identifying FDOT's Physical Transportation Infrastructure Vulnerable to Sea
932 Level Rise," *J. Infrastruct. Syst.*, vol.20 (2), 2014.
- 933 Bloetscher F., Polsky C., Bolter K., Mitsova D., Palbiche K., King R., Cosio I. and Hamilton K.
934 "Assessing Potential Impacts of Sea Level Rise on Public Health and Vulnerable
935 Populations in Southeast Florida and Providing a Framework to Improve Outcomes".
936 *Sustainability*, vol. 8, 315, 2016.
- 937 Boguszewski V. "Monroe County Adaptation Guide 2015 for the Health Care Community".
938 2015.
- 939 Boyce R., Lenhart A., Kroeger A., Velayudhan R., Roberts B., Horstick O. "Bacillus
940 thuringiensis israelensis (Bti) for the control of dengue vectors: systematic literature
941 review," *Tropical Medicine and International Health*, vol. 18 (5), pp. 564–577, 2013.
- 942 Buratti F.M., Manganelli M., Vichi S., Stefanelli M., Scardala S., Testai E., Funari E.,
943 "Cyanotoxins: producing organisms, occurrence, toxicity, mechanism of action and
944 human health toxicological risk evaluation." *Archives of Toxicology*, vol. 91(3), pp.
945 1049-1130, 2017.
- 946 Camp Dresser & McKee (CDM), Inc. "Monroe County Stormwater Management Master Plan",
947 2001 [Online]. Available: <http://fl-monroecounty.civicplus.com/DocumentCenter>
948 /View/5309
- 949 Carvalho D.O., McKemey A.R., Garziera L., Lacroix R., Donnelly C.A., Alphey L., et al.
950 "Suppression of a Field Population of *Aedes aegypti* in Brazil by Sustained Release of
951 Transgenic Male Mosquitoes," *PLoS Negl. Trop. Dis.* 2015
952 doi:10.1371/journal.pntd.0003864

- 953 Centers for Disease Control and Prevention (CDC). Summary of Notifiable Infectious Diseases
954 and Conditions — United States, 2013. Atlanta: CDC-Morbidity and Mortality Weekly
955 Report, 2015a.
- 956 Centers for Disease Control and Prevention (CDC). Surveillance for Waterborne Disease
957 Outbreaks Associated with Drinking Water — United States, 2011–2012. Atlanta: CDC-
958 Morbidity and Mortality Weekly Report, 2015b.
- 959 Centers for Disease Control and Prevention (CDC). Dengue Epidemiology. 2017a. [Online].
960 Available: [<https://www.cdc.gov/dengue/epidemiology/index.html>]
- 961 Centers for Disease Control and Prevention (CDC). Zika virus disease in the United States,
962 2015–2017, 2017b. [Online]. Available: [<http://www.cdc.gov/zika/geo/united-states.html>]
- 963 Centers for Disease Control and Prevention (CDC). Laboratory-confirmed chikungunya virus
964 disease cases reported to ArboNET by state or territory - United States, 2016 Final Data.
965 2017c. [Online]. Available: [<https://www.cdc.gov/chikungunya/geo/united-states-2016.html>, accessed November 25, 2017]
- 966 CH₂M Hill Inc. City of Key West 2012 Stormwater Master Plan. CH2M Hill, Englewood,
967 Colorado, 2012
- 969 Clark T., Benjamin J. and Remold S. “Differences in the effects of salinity on larval growth and
970 developmental programs of a freshwater and a euryhaline mosquito species (Insecta:
971 Diptera, Culicidae),” The Journal of Experimental Biology, vol. 207, pp. 2289-2295,
972 2004.
- 973 Connelly C.R., Bolles E., Culbert D., DeValerio J., Donahoe M., Gabel K., Jordi R., McLaughlin
974 J., Neal A., Scalera S., Toro E. and Walter J. “Integrated Pest Management for Mosquito
975 Reduction,” University of Florida-IFAS Extension, 2014.

- 976 Cooper J.A., Loomis G.W., Amador J.A. "Hell and High Water: Diminished Septic System
977 Performance in Coastal Regions Due to Climate Change," PLoS ONE, vol. 11(9), 2016.
- 978 Craig R.K. "A Public Health Perspective on Sea-Level Rise: Starting Points for Climate Change
979 Adaptation," Widener Law Review, vol. 15, pp. 521-540, 2010.
- 980 Crimmins, A., Balbus, J., Gamble, J.L., Boeard, C.B., Bell, J.E., Dodgen, D., Eisen, R.J., Fann,
981 N., Hawkins, M.D., Herring, S.C., Jantarasami, L., Mills, D.M., Saha, S., Sarofim, M.C.,
982 Trtanj, J., and Ziska, L., (eds.), "The Impacts of Climate Change on Human Health in the
983 United States: A Scientific Assessment." U.S. Global Change Research Program, 2016.
984 <https://health2016.globalchange.gov>.
- 985 da Cruz Ferreira, D.A., Degener, C.M., de Almeida Marques-Toledo, C., Bendati, M.M., Fetzer,
986 L.O., Teixeira, C.P., Eiras, A.E. "Meteorological variables and mosquito monitoring are
987 good predictors for infestation trends of *Aedes aegypti*, the vector of dengue,
988 chikungunya and Zika," Parasites and Vectors, vol. 10, 78, 2017. Deeb, R., "Climate
989 Change Effects on Vibrio Bacteria in the Winyah Bay Estuary and the Projected Spread
990 of Vibrio under Future Climatic Scenarios," 2013.
- 991 Delgado A. and Herzog H. "Simple Model to Help Understand Water Use at Power Plants,"
992 Massachusetts Institute of Technology, 2012.
- 993 deRegnier D., Cole L., Schupp D. and Erlandsen S. "Viability of Giardia Cysts Suspended in
994 Lake, River, and Tap Water," Applied and Environmental Microbiology, vol. 55(5), pp.
995 1223-1229, 1989.
- 996 Dover, Khol & Partners (DK&P) "North Beach Master Plan." Miami Beach, 2016.

- 997 Dohm D., O'guinn M. and Turell M. "Effect of Environmental Temperature on the Ability of
998 Culex pipiens (Diptera: Culicidae) to Transmit West Nile Virus," *J. Med. Entomol.* vol.
999 39, pp. 221-225, 2002.
- 1000 Ebi K.L. and Semenza J.C. "Community-based adaptation to the health impacts of climate
1001 change," *Am. J. Prev. Med.* vol. 35(5), pp. 501-507, 2008.
- 1002 Ebi K.L., Balbus J., Kinney P., Lipp E., Mills D., O'Neill M. and Wilson M. "U.S. Funding is
1003 Insufficient toAddress the Human Health Impacts of and Public Health Responses to
1004 Climate Variability and Change," *Environmental Health Perspectives*, vol. 117(6), pp.
1005 857-862, 2009.
- 1006 Ebi K.L., Lindgren E., Suk J.E. and Semenza J.C. "Adaptation to the infectious disease impacts
1007 of climate change," *Climatic Change*, vol. 118(2), pp. 355-365, 2013.
- 1008 Elmir S.M., Shibata T., Solo-Gabriele H.M., Sinigalliano C.D., Gidley M.L., Miller G., Plano L.,
1009 Kish J., Withum K. and Fleming L. "Quantitative evaluation of enterococci and
1010 Bacteroidales released by adults and toddlers in marine water," *Water Research*, vol.
1011 43(18), pp. 4610-4616, 2009.
- 1012 Fang L., Wolmarans B., Kang M., Jeong K. C. and Wright A. C. "Application of Chitosan
1013 Microparticles for Reduction of Vibrio Species in Seawater and Live Oysters
1014 (*Crassostrea virginica*)," *Appl. Environ. Microbiol.*, vol. 81(2), pp. 640–647, 2015.
- 1015 Feng Z., Reniers A., Haus B.K., and Solo-Gabriele H.M., "Modeling sediment-related
1016 enterococci loading, transport, and inactivation at an embayed nonpoint source beach,"
1017 *Water Resources Research*, vol. 49(2), pp. 693-712, 2013.

1018 Ferguson N., Rodríguez-Barraquer I., Dorigatti I., Mier-y-Teran L., Laydon D. and Cummings
1019 D. “Benefits and risks of the Sanofi-Pasteur dengue vaccine: Modeling optimal
1020 deployment,” *Science*, vol. 353(6303), pp. 1033-1306, 2016.

1021 Fleischli S. and Hayat B. “Power Plant Cooling and Associated Impacts”. NRDC Issue Brief,
1022 (April), 2014.

1023 Fleming L.E., Kirkpatrick B., Backer L.C., Walsh C.J., Nierenberg K., Clark J., Reich A.,
1024 Hollenbeck J., Benson J., Cheng Y.S., Naar J., Pierce R., Bourdelais A.J., Abraham
1025 W.M., Kirkpatrick G., Zaias J., Wanner A., Mendes E., Shalat S., Hoagland P., Stephan
1026 W., Bean J., Watkins S., Clarke T., Byrne M., Baden D.G. “Review of Florida red tide
1027 and human health effects,” *Harmful Algae*, vol.10 (2), pp. 224-233, 2011.

1028 Florida Department of Health (FDOH), “Surveillance and Control of Selected Mosquito-borne
1029 Diseases in Florida”. Tallahassee: Florida Department of Health, 2014.

1030 Florida Department of Health (FDOH) “Aquatic Toxins” 2017. [Online]. Available:
1031 [<http://www.floridahealth.gov/environmental-health/aquatic-toxins/index.html>].

1032 Florida Institute of Health and Innovation (FIHI). “Health and Sea Level Rise: Impacts on South
1033 Florida”. 2016

1034 Florida Public Health Institute (FPHI). “Regional Climate Action Plan. Health Impact
1035 Assessment (HIA): Minimizing the Health Effects of Climate Change in the South
1036 Florida Region”. 2014.

1037 Florida Keys Environmental Commission (FKEC), “Say No to Genetically Modified Mosquitoes
1038 Release in the Florida Keys,” 2017. [Online]. Available: [<http://fkec.org/index.php/gmo-mosquitos>] (accessed November 25, 2017).

- 1040 Florida Keys Mosquito Control District (FKMCD), "Florida Keys Mosquito Control District-
1041 Mosquito Control Methods." 2017. [Online]. Available:
1042 [<http://keysmosquito.org/mosquito-control-methods/>] (accessed November 24, 2017).
- 1043 Florida Oceans and Coastal Council (FOCC) Climate Change and Sea-Level Rise in Florida: An
1044 Update of "The Effects of Climate Change on Florida's Ocean and Coastal Resources."
1045 [2009 Report], Tallahassee, Florida. 2010.
- 1046 Fong T. and Lipp E. "Enteric Viruses of Humans and Animals in Aquatic Environments: Health
1047 Risks, Detection, and Potential Water Quality Assessment Tools," Microbiology and
1048 Molecular Biology Reviews, vol. 69(2), pp.357–371, 2005.
- 1049 Franco D., Lee J., Arbelaez S., Cohen N., Kim J.-Y., "Removal of phosphate from surface and
1050 wastewater via electrocoagulation." Ecological Engineering, 108, 589-596, 2017.
- 1051 Gall G., Cech J., Garcia R., Resh V. and Washino R. "Mosquito fish – an established predator."
1052 California Agriculture, 1980.
- 1053 Garénaux A., Jugiau F., Rama F., de Jonge R., Denis M., Federighi M. and Ritz M. "Survival of
1054 *Campylobacter jejuni* Strains from Different Origins Under Oxidative Stress Conditions:
1055 Effect of Temperature," Curr Microbiol, vol. 56, pp. 293–297, 2008.
- 1056 Gast R., Moran D., Dennett M., Wurtsbaugh W. and Amaral- Zettler L., "Amoebae and
1057 Legionella pneumophila in saline environments". Water Health, vol. 9(1), pp. 37–52,
1058 2011, doi:10.2166/wh.2010.103.
- 1059 Gates W.L., Boyle J.S., Covey C., Dease C.G., Doutriaux C.M., Drach R.S., Fiorino M.,
1060 Gleckler P.J., Hnilo J.J., Marlais S.M., Phillips T.J., Potter G.L., Santer B.D., Sperber
1061 K.R., Taylor K.E., and Williams D.N. "An overview of the results of the Atmospheric

- 1062 Model Intercomparison Project (AMIP 1)," Bull. Amer. Meteor. Soc., vol. 80, pp. 29-55,
1063 1999.
- 1064 Gil A.I., Louis V.R., Rivera I.N.G., Lipp E., Huq A., Lanata C.F., Taylor D.N., Russek-Cohen
1065 E., Choopun N., Sack R.B. and Colwell, R.R., "Occurrence and distribution of *Vibrio*
1066 *cholerae* in the coastal environment of Peru," Environmental Microbiology, vol. 6, pp.
1067 699-706, 2004.
- 1068 González Rizo A., Menéndez Díaz Z., García García I., Anaya Martínez J., González Broche R.,
1069 Calderón Camacho I.R., Baró Robaina Y., Companioni Ibañez A., Gato Armas R.
1070 "Detection of beta-exotoxins in isolates of *Bacillus thuringiensis* native to Cuba
1071 [Detección de beta exotoxinas en aislamientos de *Bacillus thuringiensis* nativos de
1072 Cuba]," Revista Cubana de Medicina Tropical, vol. 68(1), pp. 105-110, 2016.
- 1073 Gregory J., "Projections of sea level rise, Climate Change 2013: The Physical Science Basis",
1074 2013.
- 1075 Griffin D., Donaldson K., Paul J. and Rose J. "Pathogenic Human Viruses in Coastal Waters,"
1076 Clinical Microbiology Reviews, vol.16(1), pp. 129-143, 2003.
- 1077 Hanson S., Nicholls R., Ranger N., Hallegatte S., Corfee-Morlot J., Herweijer C., Chateau J. "A
1078 global ranking of port cities with high exposure to climate extremes." Climatic Change,
1079 vol. 104, pp. 89-111, 2011.
- 1080 Harris A.F., McKemey A.R., Nimmo D., Curtis. Z., Black I., Morgan S.A., Oviedo M.N.,
1081 Lacroix R., Naish N., Morrison N.I., Collado A., Stevenson J., Scaife S., Dafa'alla T., Fu
1082 G., Phillips C., Miles A., Raduan N., Kelly N., Beech C., Donnelly C.A., Petrie W.D. and
1083 Alphey L. "Successful suppression of a field mosquito population by sustained release of

- 1084 engineered male mosquitoes.” Nat Biotechnol., vol. 30, pp, 828-30, 2012. doi:
1085 10.1038/nbt.2350.
- 1086 Havens K. “Climate Change: Effects on Salinity in Florida’s Estuaries and Responses of Oysters,
1087 Seagrass, and Other Animal and Plant Life,” 2015.
- 1088 Heller R., Höller C., Süßmuth R., Gundermann K.O. “Effect of salt concentration and
1089 temperature on survival of *Legionella pneumophila*,” Letters in Applied Microbiology,
1090 vol. 26, pp. 64-68, 1997.
- 1091 Hernandez R.J., Y. Hernandez N.H., Jimenez A.M. Piggot J.S. Klaus, Z. Feng A. Reniers, and
1092 Solo-Gabriele H.M. “Effect of full-scale beach renovation on fecal indicator levels in
1093 shoreline sand and water,” Water Research, vol. 48, pp. 579-591, 2014.
- 1094 Hill J. and Cichra C. “Biological Synopsis of Five Selected Florida Centrarchid Fishes with an
1095 Emphasis on the Effects of Water Level Fluctuations,” Water Supply Management
1096 Division St. Johns River Water Management District Palatka, Florida, 2005. Special
1097 Publication SJ2005-SP3.
- 1098 Horseman M. and Surani S. “A comprehensive review of *Vibrio vulnificus*: An important cause
1099 of severe sepsis and skin and soft-tissue infection,” Int. J. Infect. Dis., vol. 15(3), pp.
1100 e157–e166, 2011.
- 1101 Intergovernmental Panel on Climate Change (IPCC), “Climate Change 2014: Synthesis Report.
1102 Contribution of Working Groups I, II and III to the Fifth Assessment Report of the
1103 Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and
1104 L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp., 2014.

- 1105 Islam M., Rezwan F. and Khan S. "Survival of *Shigella flexneri* in Artificial Aquatic
1106 Environment: Effects of Different Physicochemical Stress Factors," Journal of Diarrhoeal
1107 Diseases Research, vol. 14(1), pp. 37-40, 1996.
- 1108 Iturbe-Ormaetxe I., Walker T. and O'Neill S. "Wolbachia and the biological control of
1109 mosquito-borne disease." EMBO reports, 12, pp. 508-518, 2011.
- 1110 Johnson D.C., Enriquez C.E., Pepper I.L., Davis T.L., Gerba C.P., Rose J.B. "Survival of
1111 Giardia, Cryptosporidium, poliovirus and Salmonella in marine waters," Water Science
1112 and Technology, vol. 35 (11-12), pp. 261-268, 1997.
- 1113 Jude P., Tharmasegaram T., Sivasubramaniyam G., Senthilnanthan M., Kannathasan S.,
1114 Raveendran S., Ramasamy R. and Surendran S. "Salinity-tolerant larvae of mosquito
1115 vectors in the tropical coast of Jaffna, Sri Lanka and the effect of salinity on the toxicity
1116 of *Bacillus thuringiensis* to *Aedes aegypti* larvae." Parasites & Vectors, vol. 5, pp. 269,
1117 2012.
- 1118 Kelvin A. "Outbreak of Chikungunya in the Republic of Congo and the global picture." J Infect
1119 Dev Ctries, vol. 5, pp. 441-444, 2011.
- 1120 Kern W.H. "Some Small Native Freshwater Fish Recommended for Mosquito and Midge
1121 Control in Ornamental Ponds." Entomology and Nematology Department, UF/IFAS
1122 Extension ENY-670, 2002.
- 1123 Kirkpatrick B., Pierce R., Cheng Y.S., Henry M.S., Blum P., Osborn S., Nierenberg K., Pederson
1124 B.A., Fleming L.E., Reich A., Naar J., Kirkpatrick G., Backer L.C. and Baden D. "Inland
1125 transport of aerosolized Florida red tide toxins," Harmful Algae, vol. 9(2), pp. 186-189,
1126 2010.

- 1127 Kirkpatrick B., Fleming L.E., Bean J.A., Nierenberg K., Backer L.C., Cheng Y.S., Pierce R.,
1128 Reich A., Naar J., Wanner A., Abraham W.M., Zhou Y., Hollenbeck J. and Baden D.G.
1129 “Aerosolized red tide toxins (brevetoxins) and asthma: Continued health effects after 1h
1130 beach exposure,” *Harmful Algae*, vol.10(2), pp. 138-143, 2011.
- 1131 Kirkpatrick B., Kohler K., Byrne M., Fleming L.E., Scheller K., Reich A., Hitchcock G.,
1132 Kirkpatrick G., Ullmann S. and Hoagland P. “Human responses to Florida red tides:
1133 Policy awareness and adherence to local fertilizer ordinances,” *Science of the Total
1134 Environment*, vol. 493, pp. 898-909, 2014.
- 1135 Konopka A., and Brock T.D., “Effect of Temperature on Blue-Green Algae (Cyanobacteria) in
1136 Lake Mendota,” *Applied and Environmental Microbiology*, vol. 36(4): 572-576, 1978.
- 1137 Kumar T., Majid M., Onichandran S., Jaturas N., Andiappan H., Salibay C., Tabo H., Tabo N.,
1138 Dungca J., Tangpong J., Phiriyasamith S., Yuttayong B., Polseela R., Nhu B.,
1139 Sawangjaroen D., Tan T., Lim Y. and Nissapatorn V. “Presence of *Cryptosporidium*
1140 *parvum* and *Giardia lamblia* in water samples from Southeast Asia: towards an integrated
1141 water detection system,” *Infectious Diseases of Poverty*, vol. 5(3), 2016.
- 1142 Larsen A., Scott Rikard F., Walton W. and Arias C. “Effective reduction of *Vibrio vulnificus* in
1143 the Eastern oyster (*Crassostrea virginica*) using high salinity depuration,” *Food
1144 Microbiol.*, vol. 34(1), pp. 118–122, 2013.
- 1145 LeMonte J.J., Stuckey J., Sachez J., Tappero R., Rinklebe J. and Sparks D. “Sea Level Rise
1146 Induced Arsenic Release from Historically Contaminated Coastal Soils,” *Environ. Sci.
1147 Technol.*, vol. 51, pp. 5913–5922, 2017.

- 1148 Lindsey N.P, Lehman J.A, Staples J.E and Fischer M. "West Nile Virus and other Arboviral
1149 Diseases-United States 2013". Atlanta: CDC-Morbidity and Mortality Weekly Report,
1150 2014.
- 1151 Lipp E.K., Rivera I.N.G., Gil A.I., Espeland E.M., Choopun N., Louis V.R., Russek-Cohen E.,
1152 Huq A. and Colwell R.R. "Direct Detection of *Vibrio cholerae* and ctxA in Peruvian
1153 Coastal Water and Plankton by PCR," Applied and Environmental Microbiology, vol.
1154 69(6), pp. 3676–3680, 2003.
- 1155 Liu N. "Insecticide Resistance in Mosquitoes: Impact, Mechanisms, and Research Directions,"
1156 Annu. Rev. Entomol. vol. 60, pp. 537–59, 2015.
- 1157 Liu-Helmersson J., Stenlund H., Wilder-Smith A. and Rocklöv J. "Vectorial Capacity of *Aedes*
1158 *aegypti*: Effects of Temperature and Implications for Global Dengue Epidemic
1159 Potential." PLoS ONE, vol. 9(3), e89783, 2014. doi:10.1371/journal.pone.0089783.
- 1160 Liu Y. "Effects of Salinity on the Growth and Toxin Production of a Harmful Algal Species,
1161 *Microcystis aeruginosa*," J. U.S. SJWP, vol. 1, pp. 91-111, 2006.
- 1162 Livingston E. and McCarron E., "Stormwater Management, A Guide for Floridians," 1992
- 1163 Lizárraga-Partida M.L., Mendez-Gómez E., Rivas-Montaño A.M., Vargas-Hernández E.,
1164 Portillo-López A., González-Ramírez A.R., Huq A. and Colwell R.R., "Association of
1165 *Vibrio cholerae* with plankton in coastal areas of Mexico". Environmental Microbiology,
1166 vol. 11, pp. 201–208, 2009.
- 1167 Lürling M., Eshetu F., Faassen E., Kosten S. and Huszar V. "Comparison of cyanobacterial and
1168 green algal growth rates at different temperatures," Freshwater Biology, vol. 58, pp. 552–
1169 559, 2013.

- 1170 Magaña H.A. and Villareal T.A., "The effect of environmental factors on the growth rate of
1171 *Karenia brevis* (Davis) G. Hansen and Moestrup," Harmful Algae, vol. 5, pp. 192-198,
1172 2006.
- 1173 Martin S., Hitch A., Purcell K., Klerks P. and Leberg P. "Life history variation along a salinity
1174 gradient in coastal marshes," Aquat. Biol., vol. 8, pp. 15-28, 2009.
- 1175 Maze G., Olascoaga M.J. and Brand L. "Historical analysis of environmental conditions during
1176 Florida Red Tide", Harmful Algae, vol. 50, pp. 1-7, 2015.
- 1177 McLellan S.L., Fisher J.C. and Newton R.J. "The microbiome of urban waters," International
1178 Microbiology, vol. 18(3), pp. 141-149, 2015.
- 1179 Mettee M.F. "Spring Pygmy Sunfish". Pages 35-46 in R. Wallus and T.P. Simon, editors.
1180 Reproductive Biology and Early Life History of Fishes in the Ohio River Drainage.
1181 Volume 6: Elassomatidae and Centrarchidae. CRC Press, Boca Raton, Florida, USA,
1182 2008.
- 1183 Monroe County. "Keys Wastewater Plan. Key West: Monroe County Engineering Division,"
1184 2007.
- 1185 Moore S., Trainer V., Mantua N., Parker M. Laws E., Backer L.C. and Fleming L. "Impacts of
1186 climate variability and future climate change on harmful algal blooms and human
1187 health," Environmental Health, 7, S4, 2008.
- 1188 Mott, J., Ramirez G., Buck, G., "Vibrio vulnificus Monitoring in Recreational Waters Final
1189 Report," Coastal Bend Bays & Estuaries Program, Corpus Christi, Texas, March, 2008.
- 1190 Mueller-Spitz S., Stewart L., Val Klump J. and McLellan S. "Freshwater Suspended Sediments
1191 and Sewage are Reservoirs for Enterotoxin-Positive *Clostridium perfringens*," Applied
1192 and Environmental Microbiology, vol. 76(16), pp. 5556-5562, 2010.

- 1193 Mullenbach E., Turell D. and Turell M. "Effect of salt concentration in larval rearing water on
1194 mosquito development and survival," Journal of Vector Ecology, vol. 30, pp.165-167,
1195 2005.
- 1196 Murdy E.O. and Musick J.A. "Field guide to fishes of the Chesapeake Bay". JHU Press, 360 p.,
1197 2013.
- 1198 Newton A., Kendall M., Vugia D., Henao O. and Mahon B. "Increasing Rates of Vibriosis in the
1199 United States, 1996–2010: Review of Surveillance Data From 2 Systems." Clinical
1200 Infectious Diseases, vol. 54 (Suppl 5), s391-s395, 2012.
- 1201 Nordlie F., Haney D. and Walsh S. "Comparisons of Salinity Tolerances and Osmotic
1202 Regulatory Capabilities in Populations of Sailfin Molly (*Poecilia latipinna*) from
1203 Brackish and Fresh Waters." Copeia, vol. 3 pp. 741-746, 1992.
- 1204 Olascoaga M.J., Beron-Vera F.J., Brand L. E., and Kocak H., "Tracing the early development of
1205 harmful algalblooms on the West Florida Shelf with the aid of Lagrangian coherent
1206 structures", J. Geophys. Res., vol. 113, C12014, 2008.
- 1207 Oxitec Ltd. Oxitec's vector control solution – A paradigm shift in mosquito control, 2016.
1208 [Online] Available: [<http://www.oxitec.com/oxitecs-vector-control-solution-paradigm-shift-mosquito-control/>]
- 1209
- 1210 Page L.M. and Burr B.M. "Peterson field guide to freshwater fishes of North America north of
1211 Mexico," Houghton Mifflin Harcourt, Boston, Massachusetts, 2011.
- 1212 Page, L.M. and Burr, B.M. "A field guide to freshwater fishes: North America north of Mexico,"
1213 Houghton Mifflin Company, Boston, Massachusetts, 1991.
- 1214 Pan American Health Organization (PAHO). "Number of Reported Cases of Chikungunya Fever
1215 in the Americas, by Country or Territory 2017 (to week noted). Cumulative cases

- 1216 Epidemiological Week / EW 52 (Updated as of 17 November 2017)," 2017a. [Online]
1217 Available: [http://www.paho.org/hq/index.php?option=com_topics&view=rdmore&cid
1218 =8975&Itemid=40931]
- 1219 Pan American Health Organization (PAHO). "Epidemiological Update: Yellow Fever," 2017b
1220 Patrick M. and Bradley T. "The Physiology of Salinity Tolerance in Larvae of Two Species of
1221 Culex Mosquitoes: The Role of Compatible Solutes," The Journal of Experimental
1222 Biology, vol. 203, pp. 821–830, 2000.
- 1223 Patz J., Vavrus S., Uejio C. and McLellan S. "Climate Change and Waterborne Disease Risk in
1224 the Great Lakes Region of the U.S," Am. J. Prev. Med., vol. 35(5), pp. 451-458, 2008.
- 1225 Phillips M.C., Feng Z., Vogel L.J., Reniers A.J.H.M, Haus B.K., Enns A.A., Zhang Y.,
1226 Hernandez D.B. and Solo-Gabriele H.M., "Microbial Release from Seeded Beach
1227 Sediments during Wave Conditions," Marine Pollution Bulletin, vol. 79, pp. 114–122,
1228 2014.
- 1229 Plano L.R.W., Shibata T., Garza A.C., Kish J., Fleisher J., Sinigalliano C.D., Gidley M.L.,
1230 Withum K., Elmira S.M., Hower S., Jackson C.R., Barrett J.B., Cleary T., Davidson M.,
1231 Davis J., Mukherjee S., Fleming L.E. and Solo-Gabriele H.M., "Human-Associated
1232 Methicillin-Resistant *Staphylococcus aureus* from a Subtropical Recreational Marine
1233 Beach," Microb Ecol., vol. 65(4), pp. 1039-51, 2013.
- 1234 Prinos S.T., Wacker M.A., Cunningham K.J. and Fitterman D.V., "Origins and delineation of
1235 saltwater intrusion in the Biscayne aquifer and changes in the distribution of saltwater in
1236 Miami-Dade County", Florida: U.S. Geological Survey Scientific Investigations Report
1237 2014-5025, 101 p., 2014, [Online] Available: <http://dx.doi.org/10.3133/sir20145025>.

- 1238 Puchongkawarin C., Gomez-Mont C., Stuckey D. and Chachuat B. “Optimization-based
1239 methodology for the development of wastewater facilities for energy and nutrient
1240 recovery,” *Chemosphere*, vol. 140, pp. 150–158, 2015.
- 1241 Radke E., Weis K., Stanek D. and Blackmore C. “Florida 2009 Arbovirus Activity by County”.
1242 Tallahassee: Florida Department of Health, 2009.
- 1243 Rahmstorf S. “A Semi-empirical Approach to Projecting Future Sea Level Rise,” *Science*, vol.
1244 315(5810), pp. 368–370, 2006.
- 1245 Ramasamy R. and Surendran S. “Possible impact of rising sea levels on vector-borne infectious
1246 diseases,” *BMC Infectious Diseases*, pp.11-18, 2011.
- 1247 Ramasamy R. and Surendran S. “Global climate change and its potential impact on disease
1248 transmission by salinity-tolerant mosquito vectors in coastal zones”, *Frontiers in
1249 Physiology*, article 198, 2012.
- 1250 Ramos R., Miotto M., Squella F., Cirolini A., Ferreira J. and Vieira C. “Depuration of Oysters
1251 Contaminated with *Vibrio parahaemolyticus* and *Vibrio vulnificus* with UV Light and
1252 Chlorinated Seawater,” *J. Food Prot.*, vol. 75(8), pp. 1501–1506, 2012.
- 1253 Randa M., Polz M., and Lim E. “Effects of Temperature and Salinity on *Vibrio vulnificus*
1254 Population Dynamics as Assessed by Quantitative PCR,” *Appl. Environ. Microbiol.*, vol.
1255 70, (9), pp. 5469–5476, 2004.
- 1256 Reed M.S., Podesta G, Fazey I., Geeson N., Hessel R., Hubacek K., Letson D., Nainggolan D.,
1257 Prell C., Rickenbach M.G., Ritsema C., Schwilch G., Stringer L.C. and Thomas A.D.,
1258 “Combining analytical frameworks to assess livelihood vulnerability to climate change
1259 and analyze adaptation options,” *Ecological Economics*, vol. 94, pp. 66-77, 2013.

- 1260 Ross S.T. and Brenneman W.M. "Distribution of freshwater fishes in Mississippi," Freshwater
1261 Fisheries Report No. 108. D-J Project Completion Report F-69. Mississippi Department
1262 of Wildlife and Freshwater Fisheries and Parks. 1991.
- 1263 Salvato J.A. "Environmental Engineering and Sanitation," 4th Ed., New Jersey: Wiley, 1992.
- 1264 Semenza J., Trinaires J., Lohr W., Sudre B., Löfdahl M., Martinez-Urtaza J., Nichls G. and
1265 Rocklöv J. "Environmental Suitability of *Vibrio* Infections in a Warming Climate: An
1266 Early Warning System," Environmental Health Perspectives, vol. 125(10), pp. 107004.
1267 2017.
- 1268 Shah A.H., Abdelzaher A.M., Phillips M. Hernandez R., Solo-Gabriele H.M., Kish J., Scorzetti
1269 G., Fell J.W., Diaz M.R., Scott T.M., Lukasik J., Harwood V.J., McQuaig S., Sinigalliano
1270 C.D., Gidley M.L., Wanless D., Ager A., Lui J., Stewart J.R., Plano L.R.W. and Fleming
1271 L.E. "Indicator microbes correlate with pathogenic bacteria, yeasts, and helminthes in
1272 sand at a subtropical recreational beach site," Journal of Applied Microbiology, vol.110,
1273 pp. 1571–1583, 2011.
- 1274 Shindell D., Borgford-Parnell N., Brauer M., Haines A., Kuylenstierna J.C.I., Leonard S.A.,
1275 Ramanathan V., Ravishankara A., Amann M., Srivastava L., "A climate policy pathway
1276 for near- and long-term benefits," Science, vol. 356(6337), pp. 493-494, 2017.
- 1277 Sinigalliano C.D., Gidley M.L., Shibata T., Whitman D., Dixon T.H., Laws E., Hou A., Bachoon
1278 D., Brand L., Amaral-Zettler L., Gast R., Steward G.F., Nigro O.D., Fujioka R.,
1279 Betancourt W.Q., Vithanage G., Mathews J., Fleming L.E., and Solo-Gabriele H.M.
1280 "Microbial Landscape Measurements in Water and Sediments of the New Orleans Area
1281 in the Aftermath of Hurricanes Katrina and Rita," Proceedings of the National Academy
1282 of Sciences of the United States of America, vol.104(21), pp. 9029-9034, 2007.

- 1283 Solo-Gabriele H.M., Boehm A.B., Scott T.M. and Sinigalliano C.D. “Beaches and Coastal
1284 Environments”, Chapter 20. In C. Hagedorn, A.R. Blanch, V.J. Harwood (eds.) Microbial
1285 Source Tracking: Methods, Applications, and Case Studies, Springer Science+Business
1286 Media, LLC, New York. pp. 451-483, 2011.
- 1287 Solo-Gabriele H.M., Harwood V.J., Kay D., Fujioka R.S., Sadowsky M.J., Whitman R.L.,
1288 Wither A., Caniça M., Carvalho da Fonseca R., Duarte A., Edge T.A., Gargaté M.J.,
1289 Gunde-Cimerman N., Hagen F., McLellan S.L., Nogueira da Silva A., Novak Babič M.,
1290 Prada S., Rodrigues R., Romão D., Sabino R., Samson R.A., Segal E., Staley C., Taylor
1291 H.D., Veríssimo C., Viegas C., Barroso H. and Brandão J.C. “Beach Sand and the
1292 Potential for Infectious Disease Transmission: Observations and Recommendations,”
1293 Journal of the Marine Biological Association of the United Kingdom, vol. 96(1), pp. 101-
1294 120, 2016.
- 1295 Southeast Florida Regional Climate Change Compact (SFRCC) Sea Level Rise Work Group
1296 (Compact) “Unified Sea Level Rise Projection for Southeast Florida. A document
1297 prepared for the Southeast Florida Regional Climate Change Compact Steering
1298 Committee,” 35 p, October, 2015.
- 1299 Spanger-Siegfried E., Fitzpatrick M.F. and Dahl K. “Encroaching tides: How sea level rise and
1300 tidal flooding threaten U.S. East and Gulf Coast communities over the next 30 years.”
1301 Cambridge, MA: Union of Concerned Scientists, 2014.
- 1302 Suh E., Mercer D. and Dobson S. “Life-shortening Wolbachia infection reduces population
1303 growth of *Aedes aegypti*,” Acta Tropica, vol. 172, pp. 232–239, 2017.
- 1304 Swaminathan A., Viennet E., McMichael A.J. and Harley D. “Climate change and the
1305 geographical distribution of infectious diseases, in Infectious Diseases: A Geographic

1306 Guide” (eds E. Petersen, L. H. Chen and P. Schlagenhauf-Lawlor), John Wiley & Sons,
1307 Ltd, Chichester, UK, 2017.

1308 Tebaldi C., Strauss B. and Zervas C., “Modelling sea level rise impacts on storm surges along
1309 US coasts,” Environmental Research Letters, 11 pp, 2012.

1310 Trtanj, J.M., Jantarasami, L., Brunkard, J., Collier, T., Jacobs, J., Lipp, E.K., McLellan, S.L.,
1311 Moore, S., Pearl, H.W., Ravenscroft, J., Sengco, M., Thurston, J., “Chapter 6: Climate
1312 Impacts on Water-Related Illness. The Impacts of Climate Change on Human Health in
1313 the United States: A Scientific Assessment. U.S. Global Change Research Program,
1314 Washington, DC, 157–188, 2016

1315 Turner J. W., Good B., Cole D. and Lipp E. K., “Plankton composition and environmental
1316 factors contribute to Vibrio seasonality,” ISME Journal, vol. 3(9), pp. 1082-1092, 2009.

1317 United States Census Bureau. “State & County QuickFacts. (2017, November 24)” [Online]
1318 Available: <https://www.census.gov/quickfacts/fact/table/US/PST045216>

1319 United States Environmental Protection Agency (U.S. EPA), “Insect Growth Regulators: S-
1320 Hydroprene (128966), S-Kinoprene (107502), Methoprene (105401), S-Methoprene
1321 (105402) Fact Sheet”. United States Environmental Protection Agency, 2001.

1322 United States Environmental Protection Agency (U.S. EPA), “Future Climate Change,” 2015
1323 [Online] Available: <http://www3.epa.gov/climatechange/science/future.html#ref1>

1324 United States Environmental Protection Agency (U.S. EPA), “Climate Change Indicators in the
1325 United States, Fourth Edition.” EPA 430-R-16-004, 2016. www.epa.gov/climate-
1326 indicators.

- 1327 United States Environmental Protection Agency (U.S. EPA), “Controlling Adult Mosquitoes,”
1328 2017. [Online] Available: <http://www2.epa.gov/mosquitocontrol/controlling-adult-mosquitoes>.
- 1330 van Elsas J., Semenov A., Costa R. and Trevors J. “Survival of *Escherichia coli* in the
1331 environment: fundamental and public health aspects.” The ISME Journal, vol. 5, pp.173–
1332 183, 2011.
- 1333 Veenema, Tener G., Thornton C. P., Bender A.K. and Corley A. “Climate Change–Related
1334 Water Disasters’ Impact on Population Health.” Journal of Nursing Scholarship, vol.
1335 49(6), pp. 625-634, 2017.
- 1336 Veil J.A. “Use of Reclaimed Water for Power Plant Cooling”. U.S. Department of Energy, 2007.
- 1337 Verreycken H., Geeraerts C., Duvivier C. and Belpaire C. “Present status of the North American
1338 *Umbra pygmaea* (DeKay, 1842) (eastern mudminnow) in Flanders (Belgium) and in
1339 Europe,” Aquatic Invasions, vol. 5(1), pp. 83-96, 2010.
- 1340 Vezzulli L., Brettar I., Pezzati E., Reid P., Colwell R., Höfle M., and Pruzzo C. “Long-term
1341 effects of ocean warming on the prokaryotic community: evidence from the vibrios,”
1342 ISME J., vol. 6(1), pp. 21–30, 2012.
- 1343 Weisberg R.H., Zheng L., Liu Y., Lembke C., Lenes J.M. and Walsh J.J. “Why no red tide was
1344 observed on the West Florida Continental Shelf in 2010,” Harmful Algae, vol. 38, pp.
1345 119-126, 2014.
- 1346 Whitman R.L., Harwood V.J., Edge T.A., Nevers M.B., Byappanahalli M., Vijayavel K.,
1347 Brandão J., Sadowsky M.J., Wheeler Alm E., Crowe A., Ferguson D., Ge Z., Halliday E.,
1348 Kinzelman J., Kleinheinz G., Przybyla-Kelly K., Staley C., Staley Z. and Solo-Gabriele

- 1349 H.M. "Microbes in beach sands: integrating environment, ecology and public health,"
1350 Rev. Environ. Sci, Biotechnol., vol. 13, pp. 329–368, 2014.
- 1351 Williams A., Avery L., Killham K. and Jones D. "Persistence, dissipation, and activity of
1352 *Escherichia coli* O157:H7 within sand and seawater environments." Federation of
1353 European Microbiological Societies, vol. 60, pp. 24-32, 2007.
- 1354 World Health Organization (WHO). "Legionella and the prevention of legionellosis". Edited by:
1355 Jamie Bartram, Yves Chartier, John V Lee, Kathy Pond and Susanne Surman-Lee, 2007
- 1356 World Health Organization (WHO), "World Malaria Report 2016", 2016. [Online] Available:
1357 [<http://www.who.int/malaria/publications/world-malaria-report-2016/report/en/>].
- 1358 World Health Organization (WHO), "Yellow Fever Situation Report, 28 October 2016", 2017a.
1359 [Online] Available: [<http://www.who.int/emergencies/yellow-fever/situation-reports/28-october-2016/en/>]
- 1360 World Health Organization (WHO), "Situation Report: Zika virus, Microcephaly Guillain-Barré
1361 syndrome. June 2016", 2017b. [Online] Available: [<http://www.who.int/emergencies/zika-virus/situation-report/2-february-2017/en/>]
- 1362 World Health Organization (WHO), "Dengue Control Strategies", 2017c. [Online] Available:
1363 [http://www.who.int/denguecontrol/control_strategies/biological_control/en/]
- 1364 Wright M.E., Solo-Gabriele H.M., Abdelzaher A.M., Elmir S. and Fleming L.E., "The inter-tidal
1365 zone is the geographic location of elevated concentrations of enterococci," Water Science
1366 & Technology, vol. 63(3), pp. 542-549, 2011.
- 1367 Wright M.E., Solo-Gabriele H.M., Elmir S. and Fleming L.E. "Microbial load from animal feces
1368 at a recreational beach," Marine Pollution Bulletin, vol. 58(11), pp. 1649-1656, 2009.
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Table 1. Mosquito and Predatory Fish Species in terms of salinity and temperature ranges.

Vector					
Mosquitos species	Related Diseases	Salinity (ppt)	Temp. (°C)	Notes	References
<i>Culex</i> spp	West Nile Virus Arboviral Encephalitis	<i>Culex tarsalis</i> : 0-25 <i>Culex sitiens</i> : 0-20	18-30	<i>Culex tarsalis</i> is the most common <i>Culex</i> spp mosquito in the US. Responsible for most of the WNV transmissions	(Ramasamy and Surendran, 2011 2012), (Patrick and Bradley 2000), (Dohm et al. 2002)
<i>Aedes Aegypti</i>	Dengue Zika Chicungunya Yellow Fever	0-15 0-9	12-34	Naturally a freshwater mosquito. However, it has been observed to adapt to brackish waters in sea water intrusion scenarios	(Ramasamy and Surendran 2011), (Clark et al. 2004) (Jude et al. 2012) (Mullenbach et al. 2005), (Liu-Helmersson et al. 2014)
<i>Anopheles</i> spp	Malaria	2-39	17-33		(Jude et al. 2012) (Beck-Johnson et al. 2013)
Mitigation					
Predatory Fish Species		Salinity (ppt)	Temp. (°C)	Habitat	References
Eastern Mosquitofish (<i>Gambusia holbrooki</i>)		0.5-35	0-35	Native to US Gulf and Atlantic coasts. Survives in waters with low oxygen concentration. Can be found in fresh, brackish waters and salt marshes	(Gall et al. 1980)
Eastern Mudminnow (<i>Umbra pygmaea</i>)		0-0.5	1-20	Ponds, lakes, ditches and creeks	(Kern 2002), (Verreycken et al. 2010)
Pygmy Killifish (<i>Leptolucania ommata</i>)		0-0.5	18-27	Ponds, lakes, ditches and creeks	(Kern 2002)
Lined Topminnow (<i>Fundulus lineolatus</i>)		0-0.5	18-24	Ponds, lakes, ditches and creeks	(Kern 2002)
Golden Topminnow (<i>Fundulus chrysotus</i>)		0-20	18-25	Coastal Rivers in the Gulf of Mexico. Atlantic coast, from South Caroline to Florida. Requires slow current flows. Primarily freshwater fish	(Ross and Brenneman 1991)
Sailfin Molly (<i>Poecilia latipinna</i>)		0-70	20-28	Native to US Gulf and Atlantic coasts, found in fresh and brackish waters. Absent from turbulent waters	(Nordlie et al. 1992)
Least Killifish (<i>Heterandria formosa</i>)		0-12	20-26	Native to US Gulf and Atlantic coasts, found in fresh and brackish waters	(Martin et al. 2009)
Banded Pygmy Sunfish (<i>Elassoma zonatum</i>)		0-0.5	5-32	Native to US Gulf and Atlantic coastal plain, found in low gradient streams, with marshy environments	(Mettee 2008)
Everglades Pygmy Sunfish (<i>Elassoma evergladei</i>)		0-0.5	5-32	Native to swampy areas of Florida and Georgia, fresh water fish	(Page and Burr 2011)
Bluespotted Sunfish (<i>Enneacanthus gloriosus</i>)		0-0.5	5-32	Native to US Gulf and Atlantic coastal plain, found in low gradient streams, with marshy environments	(Murdy and Musick 2013)

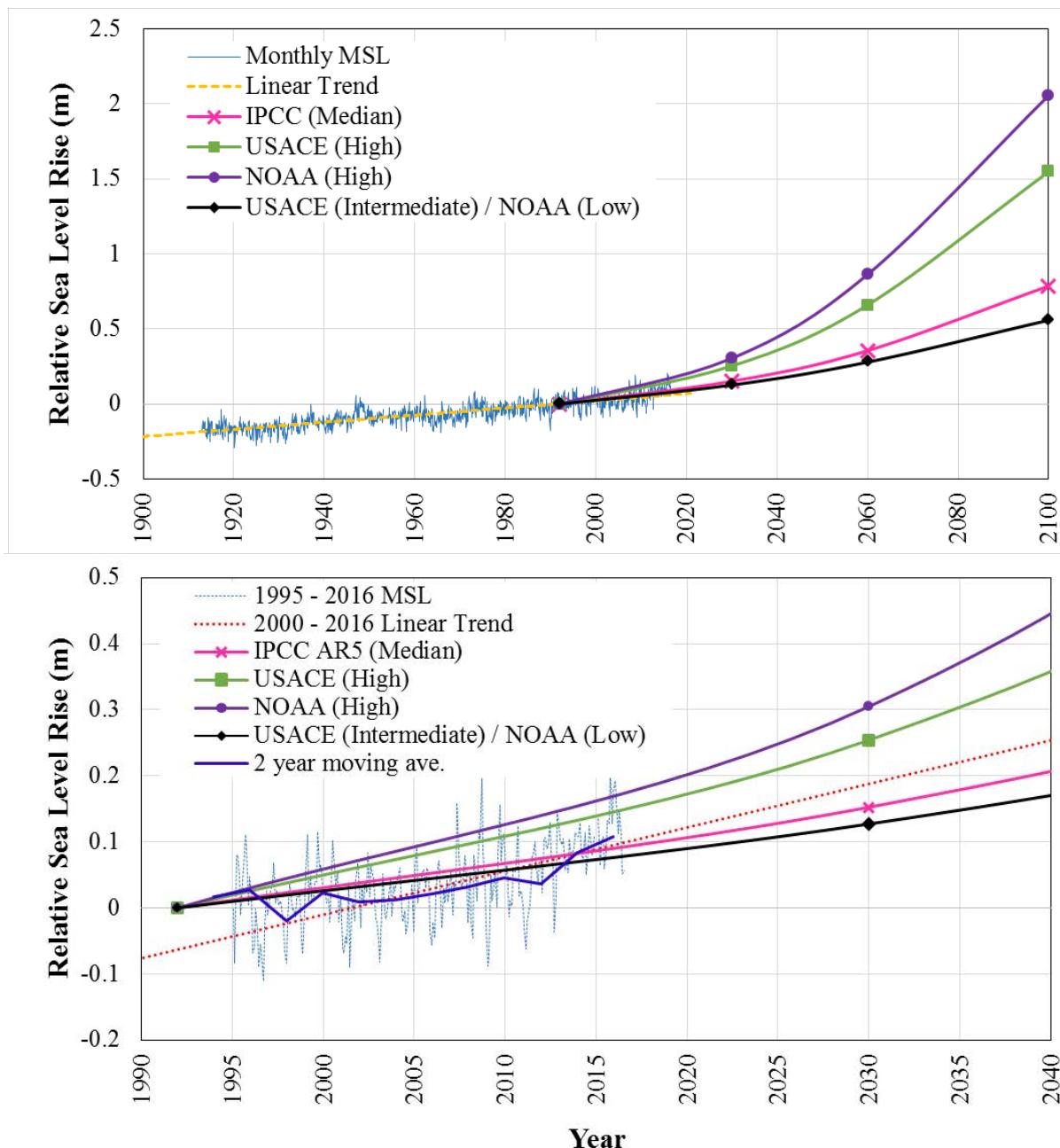
Flier (<i>Centrarchus macropterus</i>)	0-0.5	12-22	Native to US Gulf and Atlantic coastal plain and Mississippi, found in freshwater drainages and swamps	(Page and Burr 1991)
Spotted Sunfish/Stumpknocker (<i>Lepomis punctatus</i>)	0-0.5	20-24	Native to US Gulf and Atlantic coastal plain, found in shallow ponds, creeks and lakes with heavily vegetated environments	(Page and Burr 1991), (Hill and Cichra 2005)
Bluegill or Bream (<i>Lepomis macrochirus</i>)	0-0.5	1-36	Native to the great Lakes and Mississippi river basin, found in lakes and ponds with slow currents	(Page and Burr 1991), (Beitinger and Bennett 2000)
Redear Sunfish or Shellcracker (<i>Lepomis microlophus</i>)	0-0.5	20-31	Native to US Gulf and Atlantic coastal plain, found in low gradient streams and small rivers, found in clear warm waters	(Page and Burr 1991)

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Table 2. Waterborne and fecal-oral pathogens and toxic algae

Pathogen	Related Diseases	Salinity (ppt)	Temp. (°C)	Notes	References
<i>Vibrio</i> sp	Vibriosis Cholera	5-25	15-30	<i>V. spp</i> naturally thrive in warm waters with moderate salinity	(Deeb 2013), (Randa et al. 2004)
<i>Legionella</i> sp	Legionnaire's Disease Pontiac fever	0-0.5	25-42	Natural habitat fresh standing water	(WHO 2007)
<i>Campylobacter jejuni</i>	Campylobacteriosis	0-0.5	30-45	Unable to grow outside host	(Garénaux et al. 2008)
<i>Giardia intestinalis</i>	Giardiasis	0-5	7-28		(deRegnier et al. 1989), (Kumar et al. 2016)
<i>Cryptosporidium</i> sp	Cryptosporidiosis	0-5	1-37	Pathogen related to most of the recreational water infections in the US	(Kumar et al. 2016) (CDC 2015b)
<i>Shigella</i>	Shigellosis	0-20	4-37		(Islam et al. 1996)
E. coli O157:H7	Bloody diarrhea	0-34	4-37		(Williams et al. 2007), (van Elsas et al. 2011)
Enteric viruses	Ocular and respiratory infections Gastroenteritis Hepatitis Myocarditis Aseptic meningitis	0-30 or higher	4-30		(Fong & Lipp 2005), (Griffin et al. 2003)
Cyanobacteria	Affect gastrointestinal track, nervous system and skin	0-10	20-35		(Liu 2006), (Lürling et al. 2013)
<i>Karenia brevis</i>	Respiratory track inflammation	25-45	15-30		(Magaña & Villareal 2006)



1397 Figure 1. Sea level data and predictions for the City of Key West, Florida. A. Period: 1913-2016.

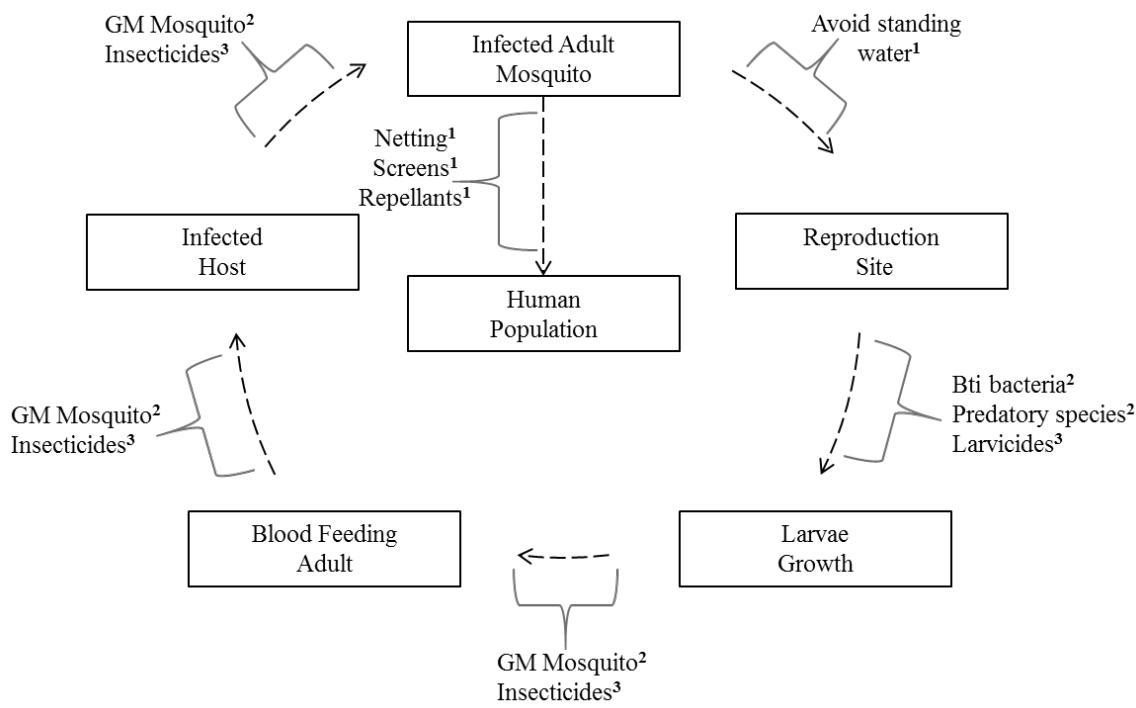
1398 B. Period: 1995-2016

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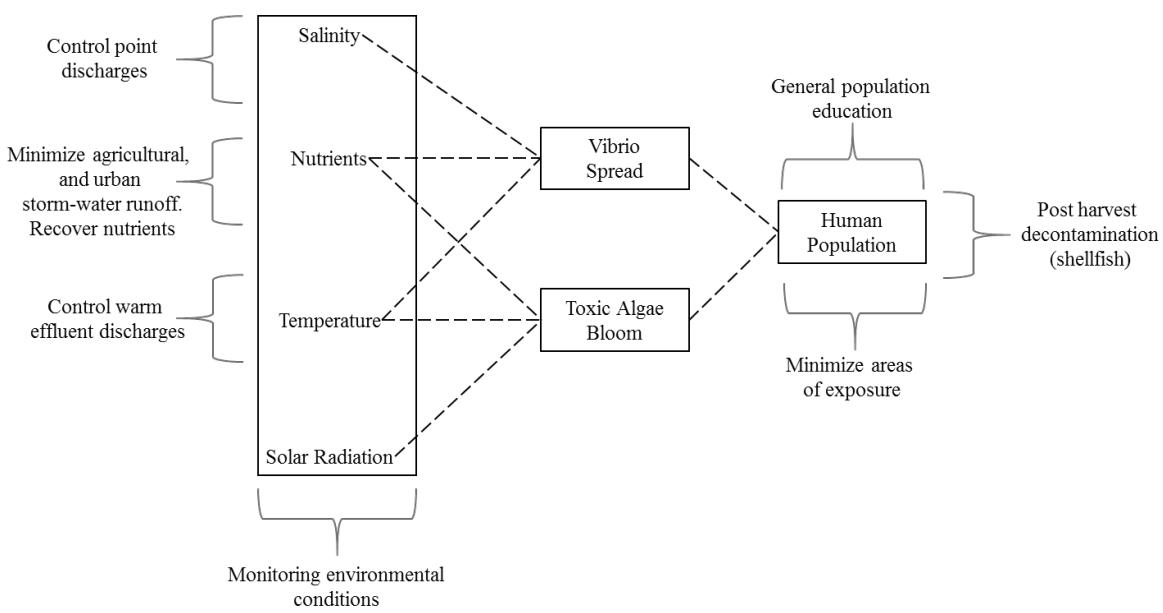
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Figure 2. Mitigation of mosquito-borne diseases. Mitigation can be grouped into three broad categories: 1 - mechanical methods, 2 – biological methods, 3 – chemical methods. Superscripts shown for various mitigation strategies correspond to one of the listed categories.

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Figure 3. Mitigation of *Vibrio* and Toxic Algae Blooms

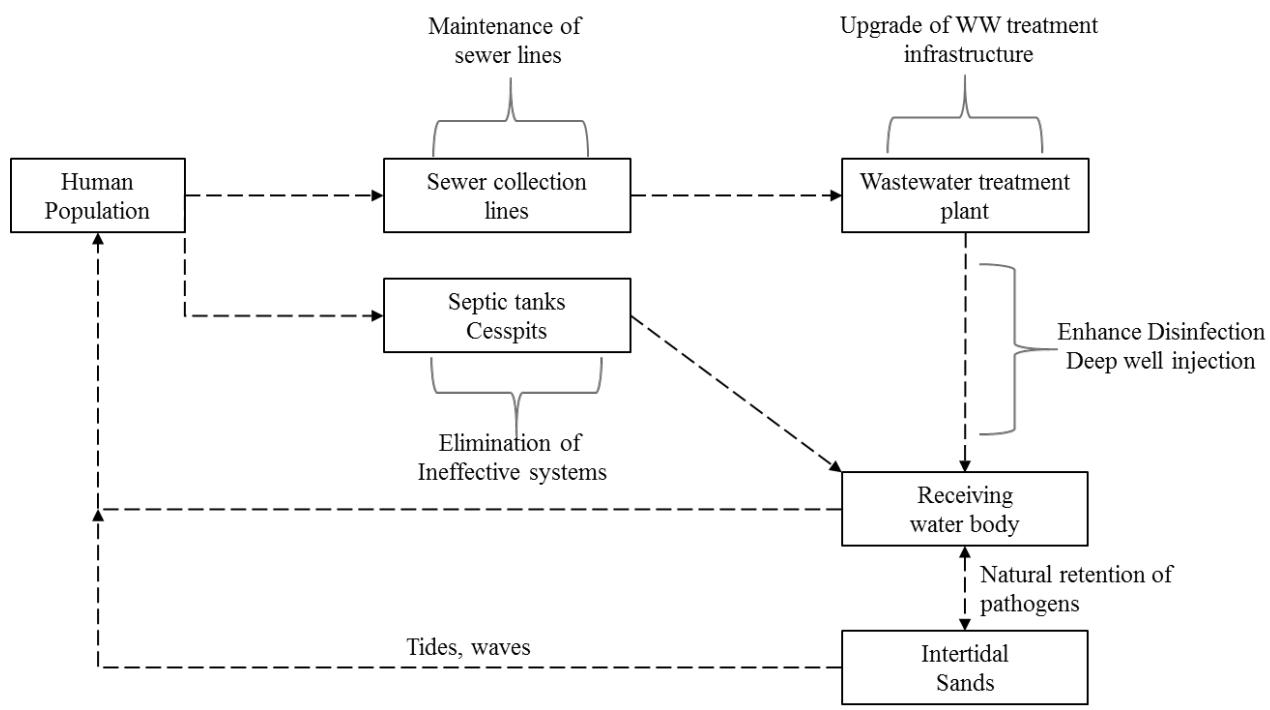
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Figure 4. Mitigation of Fecal-oral Diseases in Coastal Zones

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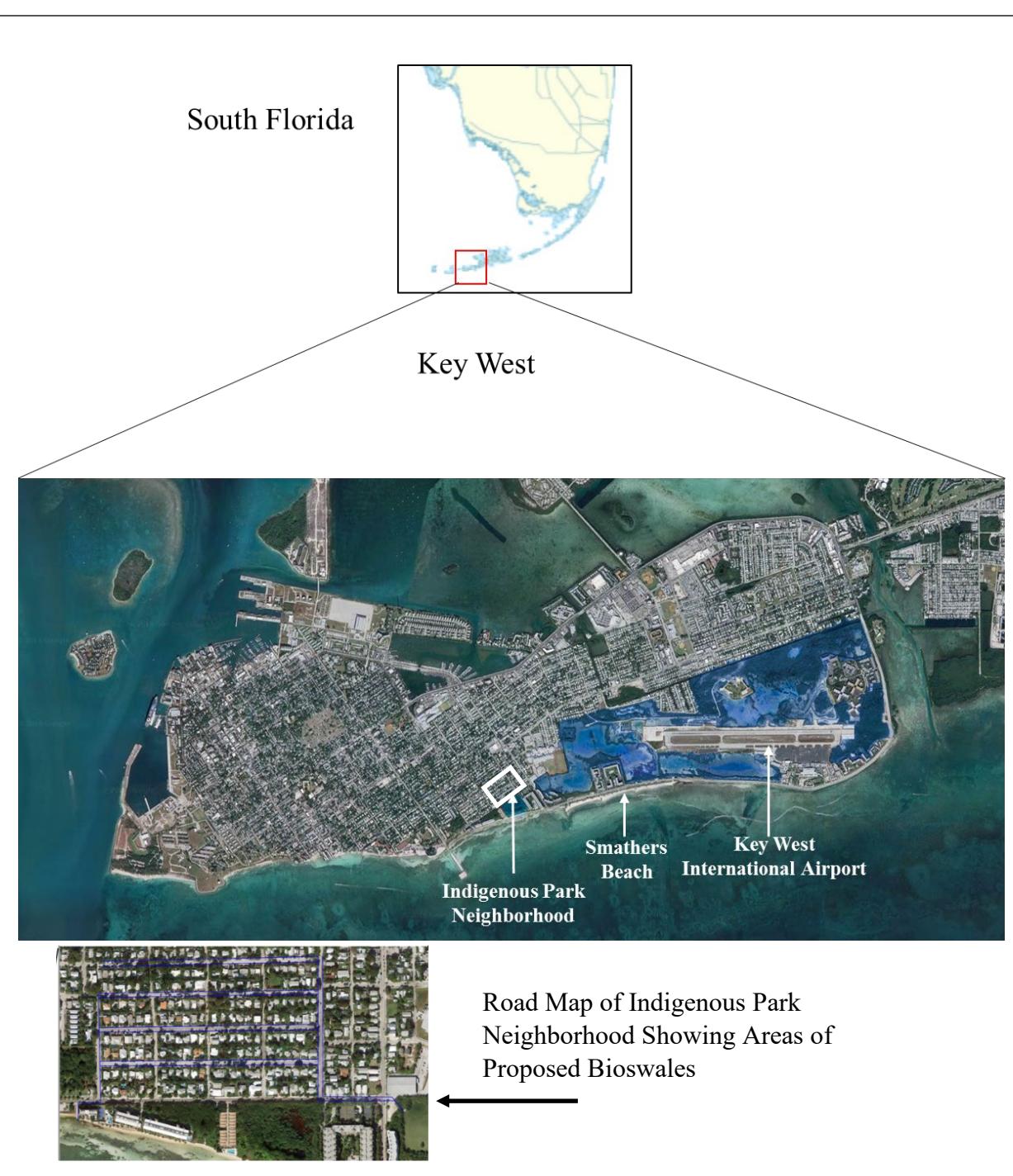


Figure 5. Location of the City of Key West with an Emphasis on the Low Lying Areas of the Key West International Airport, Rest Beach and Smathers Beach, and Indigenous Park Neighborhood

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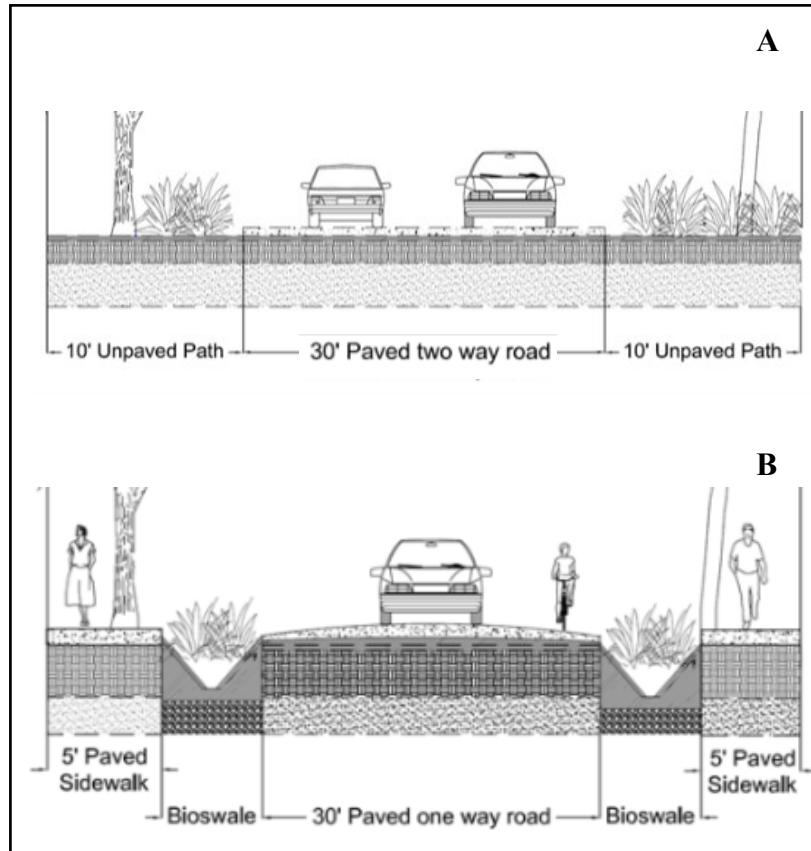
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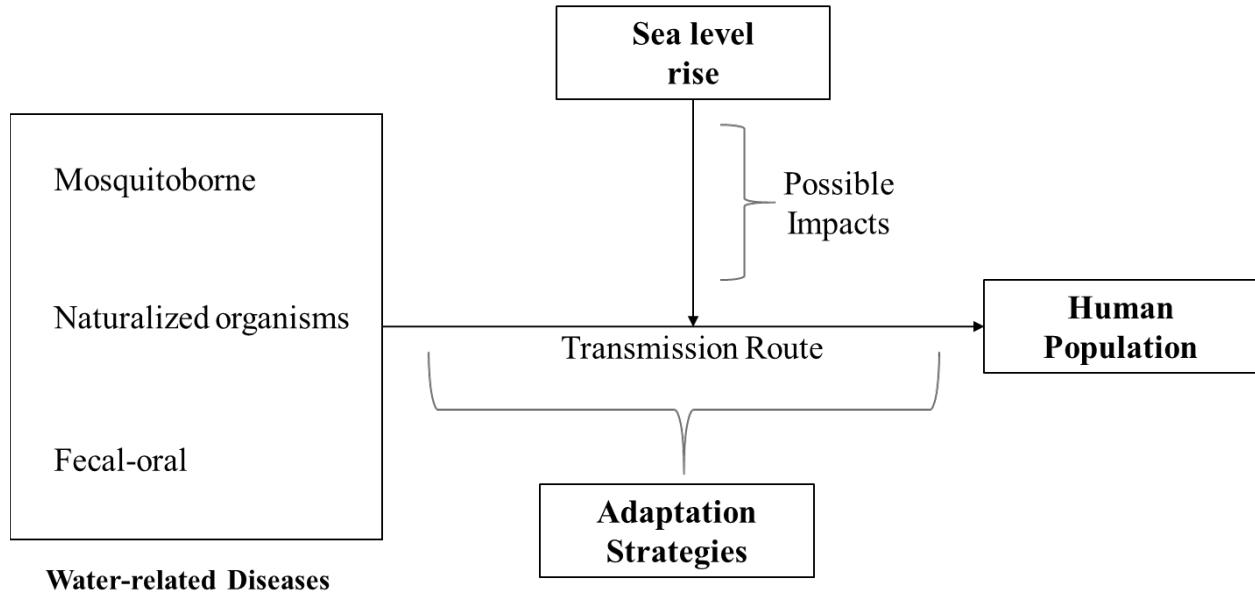


1476 Figure 6. FRRII Solution to Indigenous Park neighborhood streets.

1477 A. Current layout. B. Proposed bioswale

1478

1 Graphical Abstract



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1 **Highlights**

- 2 • Effects of sea level rise will likely impact water-related disease transmission.
- 3 • Three main water-related disease categories were evaluated: mosquitoborne, naturalized
- 4 organisms and fecal-oral.
- 5 • Engineering adaptation strategies were proposed to reduce disease transmission for each
- 6 category.
- 7 • Key West, FL was studied in terms of resilience to sea level rise and mitigation of water-
- 8 related disease transmission.

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SUPPLEMENTAL TEXT FOR:

**Possible Impacts of Sea Level Rise on Disease Transmission
and Potential Adaptation Strategies, A Review**

Ana C. Dvorak ^a, Helena Solo-Gabriele ^{a,*,+}, Andrea Galletti ^{a,1}, Bernardo Benzecri ^a,
Hannah Malone ^a, Vicki Boguszewski ^b, Jason Bird ^{c,+}

^a Dept. of Civil, Architectural and Environmental Engineering. University of Miami. Coral Gables, FL. USA.

^b Vice Chair of the Monroe County Climate Change Advisory Committee, and Yoga In Ya Consulting, Key West, FL. USA.

^c ch2m, Tampa, FL, USA.

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* Corresponding Author. Tel. +1-305-284-2908; fax: +1-305-284-3492, Email address:

hmsolo@miami.edu

⁺ Participants in “Florida Resilient Redesign II” organized by the Florida Climate Institute.

¹Currently with Department of Civil, Environmental and Mechanical Engineering (DICAM), University of Trento, Trento, Italy.

Resilient Redesign - Key West (Workshop and Local Team Members)

Alison Higgins, Site Captain, Sustainability Coordinator, City of Key West

Andy Hayes, Design Captain, Architect,

Anthony Sarno

Bert Bender, Architect

Colin Polsky, Director, FAU Center for Env. Studies

David Ambos, U.S. Coast Guard

Don Degraw, Dir. Of Airports, Monroe County

Helena Solo-Gabriele, Professor, University of Miami

Jason Bird, Infrastructure Specialist

Jerry Murphy, Assoc. Prof., UF Resilient Communities Initiative

Jim Murley, Exec. Dir., South Florida Regional Planning Council

John Paul Castro

Kelly Clark

Kelly Perkins, HARC, Key West

Michael Roberts, Planner, Monroe County

Nathaniel Danciger

Rod Delostrinos, Director of Community Services, City of Key West

Ripley Rabenaugh, Intern, Key West

Scott Fraser, FEMA Coord. Key West

Steve Russ, FIRM

Terrence Justice, Construction Coordinator, City of Key West

Thaddeus Cohen, Planning Director, City of Key West

Thomas Henderson, Asst. Dir. of Airports