

1 **A quantitative risk assessment of waterborne infectious**  
2 **disease in the inundation area of a tropical monsoon region**

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21

22 **Abstract**

23           Flooding and inundation are annual events that occur during the rainy season in  
24 Cambodia, and inundation has a strong relationship with human health. This study  
25 simulated the coliform bacteria distribution using a hydraulic model and estimated the  
26 impact of inundation on public health using a dose-response model. The model  
27 parameters were calibrated using field survey data from Cambodia and obtained good  
28 agreement with the coliform group count (CGC) distribution. The results suggest that  
29 the impact of inundation on human health is most noticeable in residential areas. The  
30 annual average risk of infection during medium-sized flood events is 0.21. The risk due  
31 to groundwater use ranges from 0.12 to 0.17 in inundation areas and reaches as high as  
32 0.23 outside the inundation areas. The risk attributed to groundwater use is therefore  
33 higher than that for surface water use (0.02-0.06), except in densely populated areas at  
34 the city center. There is a high risk for infection with waterborne disease in residential  
35 areas, and the annual average risk during small flood events is 0.94. An assessment of  
36 possible countermeasures to reduce the risk shows that the control of inundation may  
37 bring more risk to public health in Cambodia. Shallower inundation water (< 0.3m)  
38 leads to a higher risk of infection, but if the depth is greater than 2m, the risk is low in  
39 residential areas. The simulated results explain the spatial distributions of infection risk  
40 that is vitally important for determining the highest priority places with relatively high  
41 risk and will be helpful for decision makers when considering the implementation of  
42 countermeasures.

43

44 **Keywords:** The Mekong River, Concentration of coliform bacteria, Dose-response  
45 model, Hydrological model

46

47 **1. Introduction**

48 Most monsoon regions, which are located downstream of continental rivers, face  
49 seasonal flood disasters (e.g., Cambodia and Vietnam from the Mekong River,  
50 Bangladesh from the Brahmaputra River, and Brazil from the Amazon River). Although  
51 these floods bring many benefits to the local people and ecosystem (Kazama et al. 2003;  
52 2007), developing countries often suffer from social and economic damage due to  
53 inundation. Flooding is the leading cause of water-related mortality in most of these  
54 areas. In particular, regions without clean water supplies and proper sewage systems that  
55 must depend on surface and sub-surface water polluted by inundation have serious  
56 problems with waterborne infectious diseases. In addition, flooding can result in  
57 vector-associated problems, including increases in mosquito populations that, under  
58 certain circumstances, increase the risk for mosquito-borne infectious diseases (e.g.,  
59 viral encephalitis). The public health impacts of floods also include damage or  
60 destruction to homes and the displacement of the occupants; these factors may, in turn,  
61 facilitate the spread of infectious diseases because of crowded living conditions and  
62 compromised personal hygiene. The multiple environmental consequences of flooding  
63 can directly affect the public's health. For example, water sources can become  
64 contaminated with fecal material or toxic chemicals, water or sewer systems can be  
65 disrupted, dangerous substances can be released, and solid-waste collection and disposal  
66 can be disrupted.

67 There are four billion cases of diarrhea each year in addition to millions of other cases  
68 of illness associated with the lack of access to clean water (WHO, 2000), and more than  
69 5 million people die worldwide (Hunter et al., 2001). About 75% of the infectious  
70 disease cases are reported in tropical areas, and about 50% of the deaths (4,800

71 thousand people) occur in children under 5 years of age. Waterborne infectious disease  
72 takes hold in inundated areas during the flooding season. It is known that the flooded  
73 water distributes pollutants and contaminated matter from sumps (Smith 2001), and this  
74 commonly occurs in developing countries, increasing waterborne infectious disease.  
75 Epidemics of diarrhea during flooding were reported in Sudan, Mozambique, and India  
76 in 1980, 2000, and 1998, respectively (WHO 2005b). Schwartz et al. (2006) also  
77 reported clinical data for flood-associated diarrhea epidemics in Bangladesh.

78 Numerous attempts have been made by researchers to evaluate the risk of  
79 waterborne infectious disease due to floods. Currieto et al. (2001) conducted a  
80 quantitative analysis of the relationship between waterborne disease and heavy rainfall  
81 in US over a long-term period, and mentioned its obvious association with watersheds.  
82 Kunii et al. (2002) evaluated the health conditions of residents during a flooding episode  
83 in Bangladesh using public questionnaires. Muirhead et al. (2004) studied the  
84 relationship between *E. coli* concentration and water level and turbidity. Lloyd and  
85 Bartram (1991) evaluated the risk by looking at the combination of *E. coli* pollution of  
86 water resources and an environmental index. Information about the dose-response  
87 relationship is useful for evaluating the risk of infection. Lopez-Pila and Szewzyk  
88 (2000) determined this relationship for rotavirus in humans and evaluated the risk of  
89 infection in surface water. Climate change increases rainfall and inundation leading to  
90 waterborne disease outbreaks (Rose et al. 2000; Haines et al. 2006). However, no  
91 studies have tried to assess the risk of waterborne infectious disease due to flood in a  
92 continuous spatial-temporal movement.

93 The Mekong River is one of the largest inundation areas in a tropical monsoon  
94 region, and its basin spreads over six Asian countries. Severe floods have disastrous

95 impacts and cause wide-ranging destruction downstream of the Mekong River basin,  
96 especially in Vietnam and Cambodia. In addition to the damage and destruction to  
97 infrastructure and the displacement of residents, floods mainly affect the public health  
98 by spreading infectious diseases in these regions. Therefore, evaluations and  
99 assessments of the effects of flooding on the spread of waterborne infectious disease and  
100 possible countermeasures are very important in this area. Cambodia has huge inundation  
101 areas which lead to difficulties for field observations. Therefore, an integrated risk  
102 evaluation of waterborne infectious diseases, using numerical simulations coupled with  
103 field observations, has been requested to understand the spatial and temporal  
104 distribution of waterborne infectious diseases.

105           In the recent literature regarding flood and inundation analysis in the Mekong  
106 delta, analyses have been carried out using various numerical methods (Inoue et al.  
107 2000; Herath and Dutta 2000; Huu-toi and Gupta 2001). Most of these studies have  
108 focused on the lower part of Mekong river in Vietnam. The lack of available data for the  
109 Cambodian part of the Mekong River has resulted in fewer studies. Even though water  
110 resources and development plans aim to control the annual floods to reduce the  
111 inundation areas and flood damage in the Mekong Delta, no studies have been carried  
112 out to evaluate the effects of such measures and how changes in the inundation areas  
113 would affect the community and public health. The objective of the current study is to  
114 develop a numerical model expressing the coliform bacteria distribution by combining  
115 hydraulic models and models for the concentration of coliform bacteria. The risk is  
116 estimated from the numerical and dose-response models to determine the effects of  
117 floods of different magnitudes on different water sources. As flood-related public health  
118 problems were expected to continue into the recovery phase of the disaster, we

119 performed an initial rapid public health assessment and established surveillance to  
120 monitor ongoing or anticipated flood-related health problems to ensure the detection of  
121 possible waterborne infectious disease outbreaks and flood-related injuries.

122

## 123 **2. Study area**

### 124 **2.1. Lower Mekong River**

125 The Mekong River has a length of approximately 4,900 km making it the world's 10<sup>th</sup>  
126 longest river (Liu et al. 2009). The specific region of the river analyzed in this study is  
127 the Lower Mekong basin located in Cambodia and surrounded by a rectangular region  
128 (140 km by 110 km) with Phnom Penh, the capital city of Cambodia, located at its  
129 center (Fig. 1). The selected area is located in the tropical zone, and the climate is  
130 dominated by two distinct monsoons, the rainy southwest monsoon and the dry  
131 northeast monsoon. Annual precipitation averages approximately 1,680 mm across the  
132 basin, but shows strong seasonal variations in the lower Mekong, with about 85% of the  
133 precipitation occurring during the rainy southwest monsoon season. The southwest  
134 monsoon from the Indian Ocean lasts from May to October, while the northeast  
135 monsoon from China is active from October to April and brings a dry spell to the basin  
136 (Kite 2001; Zhou et al. 2006). During the southwest monsoon period, the basin  
137 experiences frequent rainfall. Therefore, the Mekong flood season lasts from July  
138 through December with an average discharge of 25,000 m<sup>3</sup>/s. The low flow season lasts  
139 from January to June with an average discharge of 6,000 m<sup>3</sup>/s.

140 There are two large tributaries in the lower part of the Mekong: the Bassac and  
141 Tonle Sap. These rivers join at Phnom Penh, the capital city of Cambodia. The Bassac  
142 River flows towards the China Sea, whereas the Tonle Sap River flows from the

143 Mekong River to the Great Lake (Tonle Sap Lake), which lies in the northern part of the  
144 study region and acts as a retention pond for the Mekong. Tonle Sap Lake flows  
145 downstream in the dry season, but the flow reverses direction in the rainy season. The  
146 lake area is about 3,000 km<sup>2</sup> in the dry season, and it expands to 10,000 km<sup>2</sup> in the rainy  
147 season. This is a unique hydrological phenomenon in this region. This area has huge  
148 inundation areas that have been expanded by a Colmatage system. Colmatage is a  
149 natural irrigation and drainage system that operates through intakes in the dikes along  
150 the rivers, according to the flood water level. Farmers use the Colmatage system during  
151 the flood season by cutting the levees in flooded areas for irrigation purposes. Flood  
152 water flows to the inundation areas through the gaps made in the levee.

153

## 154 **2.2. Public health in Cambodia**

155 The population in Cambodia is concentrated in Phnom Penh city, and sanitation and  
156 infrastructure development greatly differ between urban and rural areas. This difference  
157 is wider than in other Asian countries (WHO 2004). The water quality of the lower  
158 Mekong River is similar to other rivers in South East Asia, and it can be used for  
159 industrial water after rapid filtration. In Cambodia, diarrheal disease is the second most  
160 prevalent disease, affecting 2% of the entire population and 19% of children under 5  
161 years of age (McFeters 1990). In addition, the mortality of children under 5 years,  
162 which strongly correlates with sanitation conditions, is the worst among all Southeast  
163 Asian countries, with 14% child mortality in Cambodia compared with the mean  
164 mortality for Southeast Asia of 4.6% (WHO 2005a).

165

166

167 **3. Materials and methods**

168 **3.1. Data set**

169 GTOPO30 global elevation model data from the United State Geological Survey  
170 (USGS) was used for the numerical simulation. Water level and suspended solid (SS)  
171 data were provided by the Mekong River Commission (MRC) (MRC 1995-2002).  
172 Cambodian population distribution data and state border data were produced from  
173 analog map data made by the Japan International Cooperation Agency (JICA). The  
174 coverage of sanitary facilities (water supply and sewage system, pit and digestion tank)  
175 and the health index were reported by the Japan Bank of International Cooperation  
176 (JBIC 2000). These data are available in digital map format. Daily groundwater level  
177 data from the Department of Hydrology, Ministry of Water Resources and Meteorology  
178 of Cambodia was also used as input for the numerical model.

179 Field observations were carried out to collect coliform group counts (CGC) as a  
180 measure of the concentration of coliform bacteria and to interview the local people  
181 during four different seasons to understand the effects of flood magnitude. We  
182 conducted four field observation sessions on October 23, 2004; September 19, 2005;  
183 and September 27 and 28, 2006. Coliform bacteria concentration shows significant  
184 variations in measurements over the time and spatial extent. Therefore, observations  
185 were made in two consecutive days in same places to understand the variation of  
186 coliform bacteria concentration over short period of time. However, no significant  
187 difference was found between two data sets. We used coliform test papers made by  
188 Shibata scientific technology LTD to measure CGCs at 14 points in the inundation area  
189 (Fig.1). At each point, three measurements were taken and the data were averaged. The  
190 most probable number (MPN) method was also used at four observations time periods

191 to compare the concentration of coliform bacteria with CGC (Fig. 2). There was a good  
192 correlation between the two measures. We assumed that the coliform bacteria  
193 concentration data in rivers was uniformly 5.0 CFU/ml (APFED 2003). We also  
194 measured the concentration of coliform bacteria in Prey Veng city at 17 groundwater  
195 well points during the rainy season and 24 points during the dry season. The  
196 concentrations in the dry and rainy seasons were almost equal, with a mean value of 367  
197 MPN/100 ml.

198 The public health center of Kampong Cham province collects daily data on patient  
199 outcomes for all diseases. We used patient numbers for diarrhea and dysentery as a  
200 measure of waterborne infectious disease. We mainly focused on children under 5 years  
201 of age due to their high susceptibility to poor sanitation conditions (WHO 2005a). It is  
202 worth noting that this data does not represent actual patient numbers because not all  
203 patients visit a health center or hospital when they are sick. However, in this analysis,  
204 we assumed that the health center counts did represent all patients.

205

### 206 **3.2. Flood modeling**

207 The hydraulic models, which consisted of a dynamic wave model in channels and a  
208 non-uniform flow model in inundation areas, were connected by a surge model at  
209 Colmatages. Groundwater movement by Darcy's law and other hydrological processes  
210 were also considered. For the simulation of river flooding, the boundary conditions were  
211 represented by water level data from Kampong Cham, upstream of the Mekong at Prek  
212 Kdam on the Tonle Sap River, and Tan Chau, downstream of the Mekong at Chau Doc  
213 on the Bassak River. The integrated model developed by Kazama et al. (2007) showed  
214 good agreement between remote sensing data and water level variation after calibration

215 of the model parameters. We used this model to express the advective movements of  
216 coliform bacteria.

217 Suspended solids (SS) were estimated by satisfying the continuity equation such that  
218 SS moves with the same concentration at rivers, consistent with the uniform data  
219 observed by MRCS. Only deposition is considered, using Rubey's empirical equation:  
220

$$w_f = \sqrt{sgd} \left\{ \sqrt{\frac{2}{3} + \frac{36\nu^2}{sgd^3}} - \sqrt{\frac{36\nu^2}{sgd^3}} \right\} \quad (1)$$

221  
222 where  $w_f$  is the sedimentation rate ( $\text{ms}^{-1}$ ),  $\nu$  is the kinetic viscosity ( $\text{m}^2/\text{s}$ ),  $s$  ( $= 1.6687$ ) is  
223 the specific gravity of sedimentation in water, and  $d$  is the diameter (m). The diameter  
224 was obtained by field observations at the Mekong River bank at Phnom Penh by  
225 considering the particle size distribution with a passing probability of 80%. From these  
226 data, we estimated  $4.5 \times 10^{-5}$  m/s as the sedimentation rate.

227

### 228 **3.3. Coliform movement model**

229 During flooding, coliform bacteria from contaminated sources spread into inundation  
230 areas via water and sedimentation (Muirhead et al. 2004). The coliform concentration  
231 movement was expressed using the discharge calculated from the non-uniform flow  
232 model, coliform group load, and survival rate by radiation. Residential areas are the  
233 main source of coliform load, as detected by the digital map, and the load amount is  
234 estimated from the population and the coverage ratio of sanitary facilities using the  
235 following equation.

$$236 \quad C = n \times c \times (1 - s/100) \quad (2)$$

237 where  $C$  is the coliform group load amount (CFU/day),  $n$  is the population (persons),  $c$

238 is the individual coliform group load amount ( $= 2.0 \times 10^{10}$  CFU/person/day) (Kaneko  
239 1997), and  $s$  is the coverage ratio of sanitary facilities in each province.

240 The survival rate per hour is determined mainly by the water temperature, solar  
241 radiation, and other bacteria (MacFeters 1990; Gameson and Saxon 1967). Downstream  
242 of the Mekong, the temperature is almost constant throughout the year and does not  
243 greatly affect the survival rate. On the other hand, solar radiation in tropical regions  
244 does strongly affect the survival rate. Therefore, we estimate the survival rate of  
245 coliforms from solar radiation using the relationship between the net cumulative  
246 radiation and water depth (Gameson and Saxon 1967). We developed a formula to  
247 estimate the survival rate from Gameson and Saxon's results, as shown in Figure 3. In  
248 addition, the net cumulative radiation was evaluated by considering the reflection of  
249 downward radiation on the water surface due to the SS concentration using the  
250 following equation:

$$251 \quad S = (1 - R/100)S_{\max} \quad (3)$$

252 where  $S$  is the net cumulative solar radiation ( $\text{J}/\text{cm}^2/\text{day}$ ),  $S_{\max}$  is the downward solar  
253 radiation ( $\text{J}/\text{cm}^2/\text{day}$ ), and  $R$  is the reflection (%).

254 Oki et al. (2001) used the following function to explain the relationship between SS  
255 concentration and reflection:

$$256 \quad R = 0.0809 + 0.0146U \quad (4)$$

257 where  $U$  is the SS concentration ( $\text{mg}/\text{l}$ ), as calculated by the hydraulic simulation  
258 considering sediment movement. We can evaluate the temporal and spatial distribution  
259 of coliform group counts using the hydraulic model-like SS estimation for the advection  
260 and the coliform movement model, consisting of the above equations, for the survival  
261 rate.

262

### 263 **3.4. Risk evaluation**

264 To evaluate the attributed risk, we used the dose-response model, which indicates the  
265 probability of infection for a given exposure amount according to the single-hit  
266 hypothesis. The dose-infection model is based on the following function:

$$267 \quad R_Y = 1 - (1 - P(D))^{365} \quad (5)$$

268 where  $R_Y$  is the probability of infection of a host that is infected once for one year and  
269  $P(D)$  is the probability of infection for one exposure, depending on exposure amount  $D$ ,  
270 which is expressed by equation (6) based on the Beta-Poisson formula:

$$271 \quad P(D) = 1 - \left[ 1 + \frac{D}{\beta} \right]^{-\alpha} \quad (6)$$

272 where  $\alpha$  and  $\beta$  are empirical parameters that depend on the pathogen. Here we used  $\alpha =$   
273  $0.1778$  and  $\beta = 1.78 \times 10^6$  for *E. coli* (Rose et al. 1999). We assumed that daily water  
274 drinking water volume was 2 liters, and the exposure level in the inundation area and  
275 groundwater were estimated by the coliform movement model to be 367 MPN/100 ml,  
276 the mean value of the field survey. The conversion rate of CGC in MPN experiments  
277 with *E. Coli* was determined by the relationship observed in field surveys (Fig. 2)  
278 (Gronwold and Wolpert 2008).

279         Considering seasonal changes in water resources, we assume that residents use  
280 surface water if the flood model shows inundation, and groundwater otherwise. We used  
281 a constant value for the *E. coli* in groundwater which was recorded from field  
282 observations (367MPN/100ml). Here, we assumed that *E. coli* can be expressed by the  
283 concentration of coliform bacteria.

284

## 285 **4. Results and Discussion**

### 286 **4.1. Spatial distribution of coliform concentration**

287 Figure 4 shows the simulated and observed concentrations of coliform bacteria  
288 measured by test papers at the sampling points during the rainy season. Each data point  
289 represents the average of the measured values from four observations (average of the  
290 measured concentrations of coliform bacteria from October 23, 2004; September 19,  
291 2005; and September 27 and 28, 2006). The simulated data was from the end of  
292 September 2000. Although the observed and simulated results were not from the same  
293 date, the process and phenomena were similar across different years, which will be  
294 important for helping us to understand the relative risk distribution attributed to  
295 different sources in the study area. Figure 4 shows that the observed values at sampling  
296 points 4 and 10 were much higher than the simulated results. The reason for these  
297 differences is that point 4 has a higher population than that used to produce the digital  
298 data, and point 10 is close to an irrigation pond and is full of water during the entire  
299 season. With the exception of these two cases, the observations were in good agreement  
300 with the simulated results.

301

### 302 **4.2. Provincial risk assessment**

303 When we consider using CGC for risk assessment, the contact opportunity should be  
304 evaluated as well as the concentration. The contact opportunity can be substituted with  
305 the inundation period, but the coliform concentration is not correlated with the  
306 inundation period. Here, the annual integrated concentration is used for the risk  
307 assessment according to the following equation:

308 
$$\bar{E} = \int_{t=1year} E dt \tag{7}$$

309 where  $E$  is the simulated CGC and  $\bar{E}$  is the annual integrated CGC. The annual  
310 integrated CGC represents the sum of the concentrations of coliform bacteria with  
311 which the residents in a calculation area come into contact over the course of a year. We  
312 assumed that a larger concentration means a higher risk.

313 Figure 5 shows the correlation between the annual integrated CGC simulated  
314 for a year and the mortality rate for children under 5 years of age in 3 provinces within  
315 inundation areas. It clearly shows that mortality increases with coliform concentration.  
316 Using this result, we can conclude that the concentration of coliform bacteria can be  
317 used as a risk index for waterborne infectious diseases.

318

### 319 **4.3. Distribution of risk assessment**

320 The dose-response model coupled with the hydraulic model can estimate the spatial and  
321 temporal distribution of the probability  $R_Y$  of infection of a host as the risk of  
322 waterborne infectious disease. Figure 6 shows the distribution of the annual risk in the  
323 case of a small flood (in 1998), a medium-sized flood, (in 1993), and a large flood (in  
324 2000).

325 Figure 7 depicts the distribution of the risk of surface water use in inundation  
326 areas. Rural communities experience low risk (0.02-0.06), where as high-risk areas exist  
327 in urban and residential areas with a mean risk of 0.70. This is much higher risk, but  
328 most urban residences use bottled mineral water for drinking. The high-risk area pattern  
329 differs by flood magnitude. Figure 7 clearly shows that there are no areas of  
330 concentrated high risk during a large flood. Large floods spread the concentration of

331 coliform bacteria further from the source point and dilute the concentration.

332 Nevertheless, residential areas still have a high risk of infection.

333 Figure 8 shows the distribution of the risk of groundwater use in the dry areas,

334 using the hydraulic simulation results. Rural communities living in hilly regions

335 surrounded by inundation areas use groundwater for their daily needs. Field

336 observations recorded the risk of infectious diseases for one year in the whole area as

337 0.23. This is significantly greater than the infection risk due to the surface water

338 (0.02-0.06) in the region outside the inundation area. People in inundation areas use

339 groundwater after the inundation retreats. After the inundation, groundwater may

340 accumulate a lot of pollutants and may be contaminated with infectious pathogens.

341 According to Figures 7 and 8, the infection risk attributed to groundwater (0.12-0.17) in

342 inundation areas is still higher than the risk due to surface water use (0.02-0.06), except

343 in largely populated areas.

344

#### 345 **4.4. Infection risk and water sources**

346 The simulations explain the diffusion processes that cause large discharges to bring the

347 risk of infectious disease to places further away, in terms of annual average risk and the

348 risk due to surface water use. The locations that are high risk due to surface water use

349 are closer to densely populated areas and near the border of inundation areas; these

350 areas exposed to risk independent of the flood magnitude. Remote areas where people

351 use groundwater throughout the year have a constant risk of 0.23. According to Figure 6,

352 a medium-sized flood produces new and wider risk areas in the southeast region. This

353 means that some record-breaking floods produce new risk areas where people have not

354 had experience dealing with waterborne infectious diseases. These kinds of places are

355 vulnerable for spreading diseases.

356 Table 1 show the summary of the estimated risk, depending on the flood magnitude  
357 and water use. Small floods lead to a subsequent dry period in remote areas and the risk  
358 from groundwater wells increases in those areas because of the increase in groundwater  
359 use. The infection risk due to surface water use increases as the flood magnitude  
360 increases and become stable once the flood magnitude reaches middle-size. Due to the  
361 significantly higher risk of surface water use in highly populated areas (0.610-0.937),  
362 mean annual risk in the whole area attributed to surface water use show slightly higher  
363 values than the risk attributed to groundwater use (Table 1). However, the resultant risks  
364 in suburban and rural areas due to groundwater use are comparatively higher than the  
365 risks of surface water use. The mean annual risk in residential areas becomes very high  
366 (0.94) during small flood events. On the other hand, the annual average risk in and  
367 around residential areas decreases as the flood magnitude increases because shallow  
368 water has high concentrations of coliform due to storing and enrichment. During the dry  
369 season, we can see many isolated ponds in the inundation areas and a lot of people  
370 enjoy swimming and bathing in these ponds. The infection risk exists not only in  
371 drinking water, but also due to contact with contaminated water (Geldreich 1998).

372

#### 373 **4.5. Reduce the risk using countermeasures**

374 The reason for the high risk of infection in residential areas is that the surface water is  
375 polluted with high concentrations of coliforms when the water level is lower. Figure 9  
376 depicts the relationship between the annual average risk in the residential areas and the  
377 surface water level (the safe water level). Each flood scale has a rapid decrease in risk  
378 until the water level reaches 0.3 m and then the rate of reduction is less as the water

379 level continues to increase. In the case of a small flood, the risk does not go below 0.5,  
380 even when the water level for safe surface water use is 2.0 m. Although the local people  
381 prefer to use groundwater during the dry season, the Cambodian groundwater is  
382 contaminated with arsenic in many places, and the risk is too high (Feldman et al. 2007).  
383 Therefore, one countermeasure to prevent infection is to restrict the people to using  
384 surface water during the low water level season, once the water falls below a certain  
385 level (e.g. 0.3 m in Figure 9). This countermeasure can reduce 50% of the risk and is a  
386 very effective method. In practice, people particularly in high risk areas (but not  
387 restricted to) must be advised to use household water treatment methods like boiling to  
388 treat the infected water before drinking. Moreover, a simple and cost-effective method  
389 like solar disinfection can be promoted by public campaigns.

390         One of the other problems causing the high risk of infection in residential areas  
391 is that the water sources are located closer to garbage dumping sites. Therefore,  
392 separation of the water sources from infection sources, such as garbage disposal sites  
393 and septic tanks, is another potential countermeasure for reducing the risk of waterborne  
394 infectious diseases. Moreover, changing the structure of drainage and irrigation channels  
395 to remove stagnant water from storage ponds also reduces the risk. It is not only  
396 measures affecting the infrastructure, but also “software” measures, such as health  
397 programs, that are effective for reducing the infection risk (Courtney 2007). The  
398 simulated results in our study explain the spatial distributions of infection risk attributed  
399 to different sources (e.g., surface water and groundwater) in different geographical  
400 settings (e.g., urban, suburban and rural areas). Such distribution maps for risk are  
401 vitally important for determining the highest priority places with relatively high risk and  
402 will be helpful for decision makers when considering the implementation of

403 countermeasures.

404

## 405 **5. Conclusions**

406 This study developed models to evaluate the risk of waterborne infectious disease in  
407 inundation areas in a developing country, Cambodia. The model combined hydraulic,  
408 hydrologic, and dose-response models. The model parameters were calibrated using  
409 field survey data in Cambodia and obtained good agreement with the CGC distribution.  
410 The annual average risk in the study area is 0.21, in the case of a medium-scale flood.  
411 The risk of groundwater use is 0.12-0.17 in inundation areas and as high as 0.23 outside  
412 the inundation areas. The risk attributed to groundwater use is therefore higher than that  
413 due to surface water use (0.02-0.06), except in densely populated areas at the city center.  
414 There is a high risk of infection with waterborne disease in residential areas, and the  
415 annual average risk during small flood events is as high as 0.94. The annual average risk  
416 around residential areas decreases as the flood magnitude increases because shallow  
417 water has a higher concentration of coliform due to storing and enrichment.  
418 Qualitatively, the reduction of flood scale increases the infection risk. An assessment of  
419 possible countermeasures to reduce the risk shows that restricting surface water use in  
420 residential areas, except in low water level seasons ( $< 0.3\text{m}$ ), may increase public health  
421 risks in Cambodia. This macro-scale analysis will be useful for making decisions  
422 regarding countermeasures for reducing the risk of infection. In practice, linkage  
423 between macro- and micro- scale countermeasures will be needed to protect the public  
424 health in inundation areas.

425

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434

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516 **Figure captions**

517 Figure 1 – (a) The study area in Cambodia and (b) the sampling locations for the  
518 coliform group counts.

519 Figure 2 – The correlation of the concentration of coliform bacteria (*E. coli*) with CGC.

520 Figure 3 – The relationship between the mortality ratio of coliforms and net cumulative  
521 solar radiation (an Improvement on the results by Gameson and Saxon 1967).

522 Figure 4 – A comparison between the observed and simulated concentrations of  
523 coliform bacteria.

524 Figure 5 – The relationship between the annual integrated CGC and the annual infant  
525 mortality rate in each province.

526 Figure 6 – The annual infection risk, depending on flood magnitude.

527 Figure 7 – The infection risk due to surface water use, depending on flood magnitude.

528 Figure 8 – The infection risk due to groundwater use, depending on flood magnitude.

529 Figure 9 – The average annual infection risk in residential areas and the water level of  
530 surface water use restrictions.

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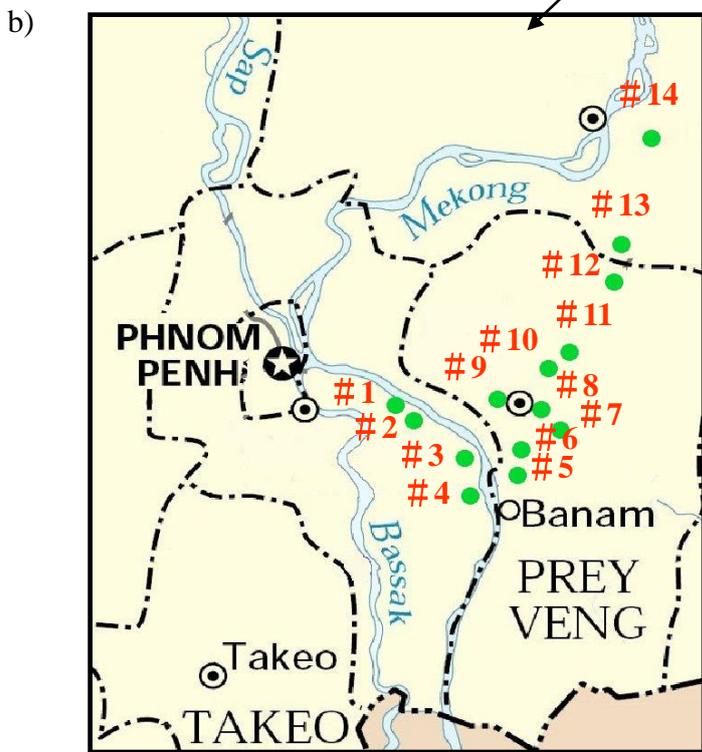
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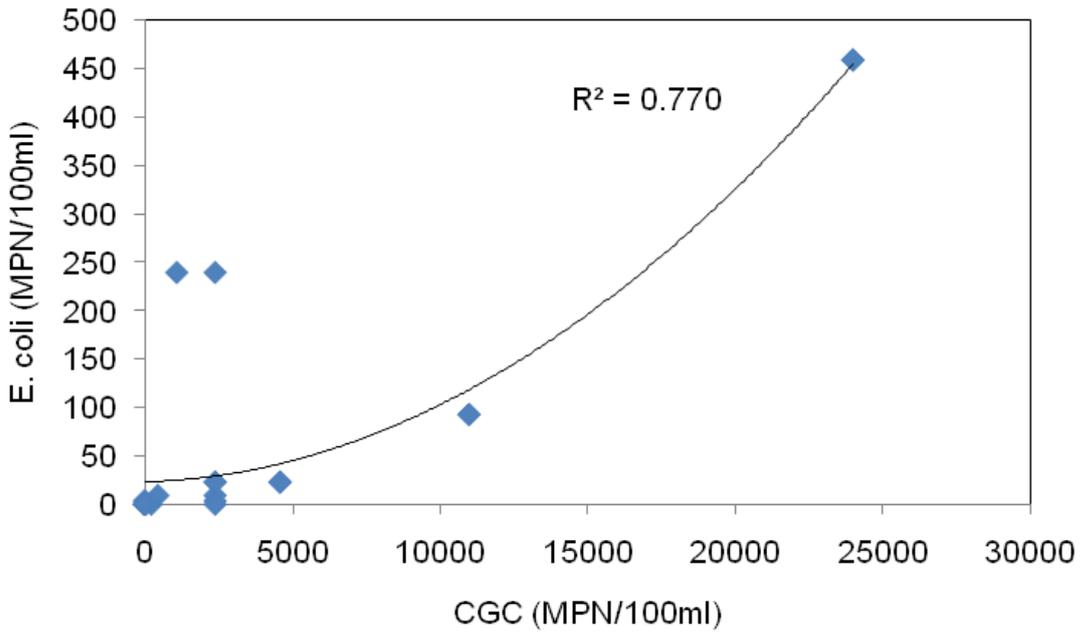
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**Fig. 1** (a) The study area in Cambodia and (b) the sampling locations for the coliform group counts



588  
589 **Fig. 2** The correlation of the concentration of coliform bacteria (*E. coli*) with CGC

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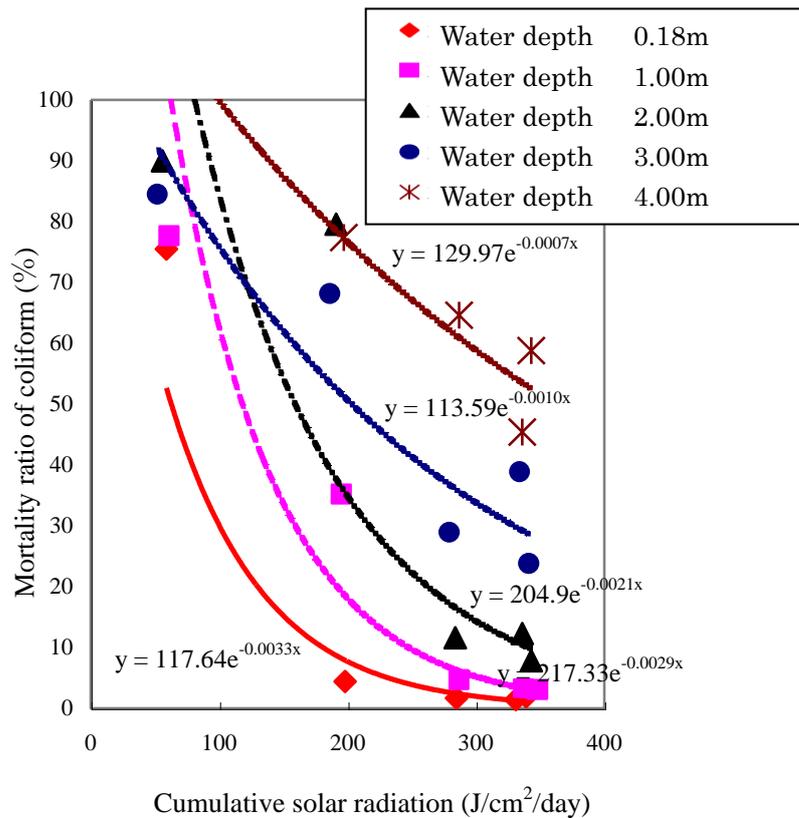
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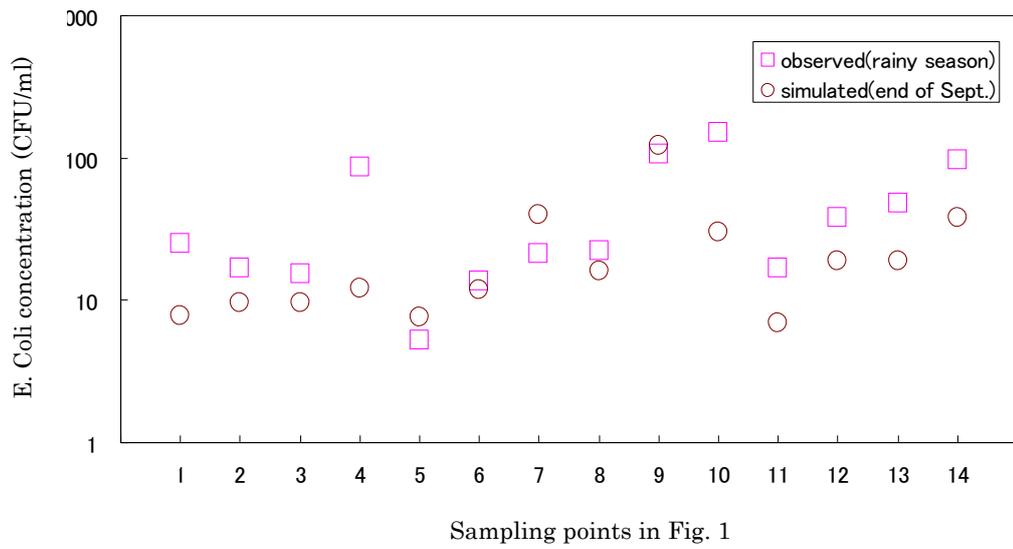
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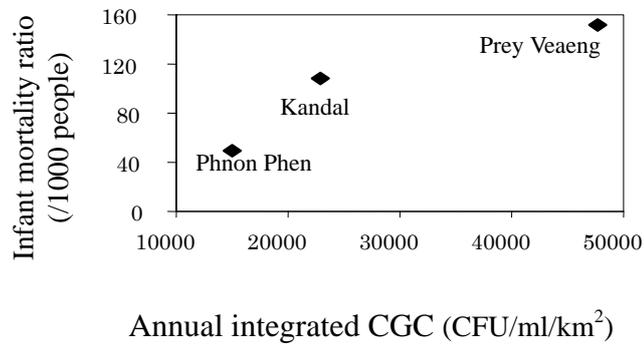


614 **Fig. 3** The relationship between the mortality ratio of coliforms and net cumulative solar  
615 radiation (an Improvement on the results by Gameson and Saxon 1967)

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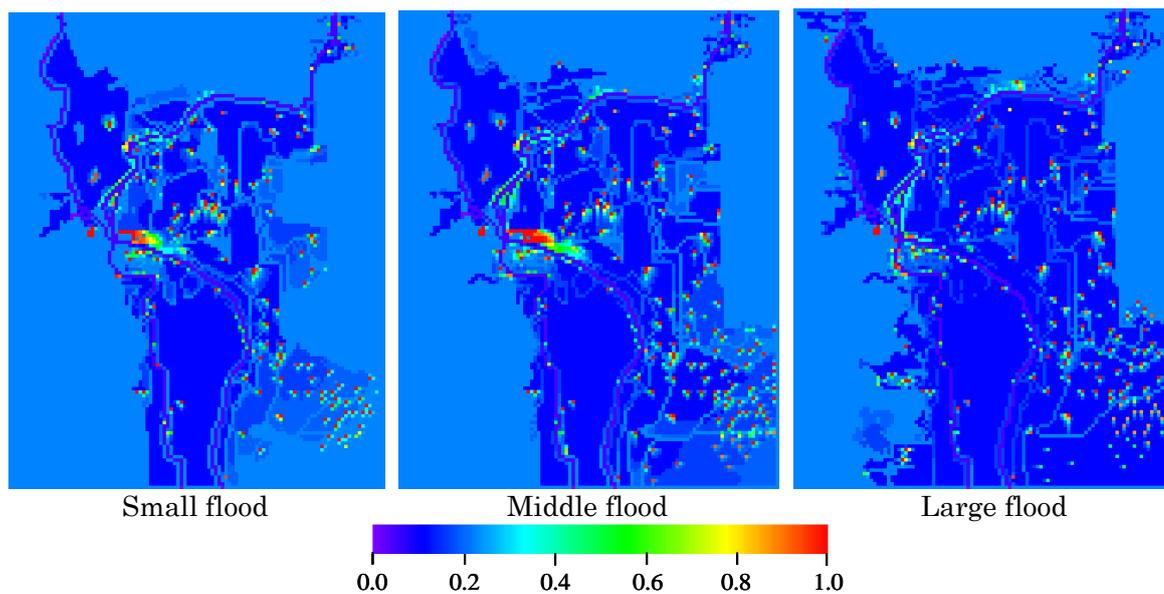


**Fig. 4** A comparison between the observed and simulated concentrations of coliform bacteria

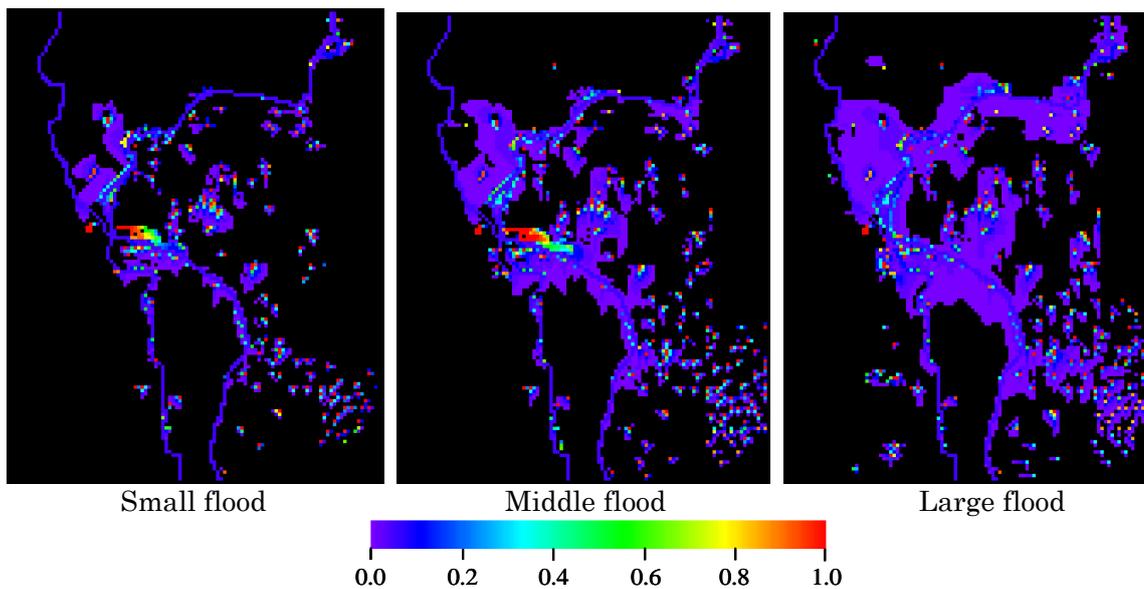


**Fig. 5** The relationship between the annual integrated CGC and the annual infant mortality rate in each province

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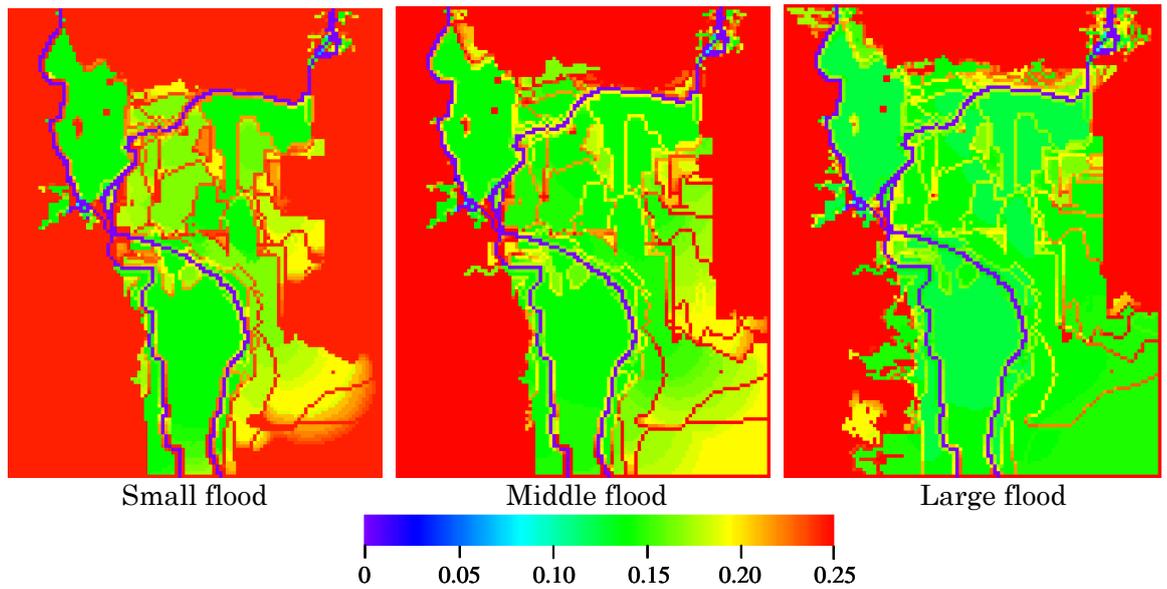


**Fig. 6** The annual infection risk, depending on flood magnitude

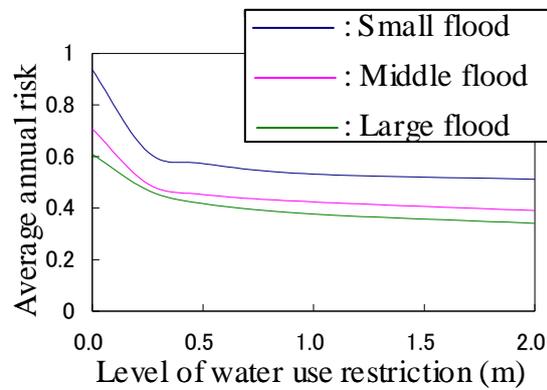


**Fig. 7** The infection risk due to surface water use, depending on flood magnitude

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**Fig. 8** The infection risk due to groundwater use, depending on flood magnitude



**Fig. 9** The average annual infection risk in residential areas and the water level of surface water use restrictions

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Table 1- The estimated risk, depending on the flood magnitude and water use

	Mean annual risk in the whole area	Groundwater use period	Surface water use period	Mean annual risk in residential areas
Small flood	0.215	0.198	0.020	0.937
Middle flood	0.210	0.187	0.026	0.707
Large flood	0.179	0.171	0.026	0.610

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