Evaluating Effectiveness of Length of Closure in Remediating Coliform Contamination in Boracay Island

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Abstract
The international tourist destination of Boracay Island was closed by national authorities last April 2018 due to the persistent high coliform concentrations found in its beach waters. The cause of the contamination is identified as inadequate sanitation systems whose outflow goes to the groundwater. This water in turn leaks out to the sea. The rationale of the temporary closure is to allow natural mechanisms to clean the groundwater—mainly by the shutdown of all coliform contamination sources, coliform die-off and flushing via recharge of rainfall. The period of closure is six months. With a first order die-off rate of 0.03/day for coliform bacteria in karst soils, computer simulations show that the period of closure removes 99.4 percent of the contaminant-marker—adequate to bring the contamination down to levels that are acceptable for recreational waters. A further closure extension of six months would most likely bring the contamination below detection limits.

Keywords: Sanitation, Sustainable tourism, Computer simulations

Introduction

Tourism is one of the industries that the Philippine government has been giving priority to the past years as it has lagged behind its neighbors. The government has capitalized on its popular summer destinations to attract foreign visitors. Nevertheless, many of these locations are not equipped with adequate sanitation facilities to meet the volume of visitors and to make tourism sustainable.

Boracay, off the northern coast of Panay Island in the Visayas region of the Philippines has been ordered closed last 26 April 2018 due to the persistently high coliform concentration in its beach waters. The contamination is caused mainly by unregulated discharge by establishments into the sea and contaminated groundwater migrating seaward.

The freshwater lens of the island resort is contaminated due to the absence of wastewater collection and treatment system that the island needs to meet the volume of visitors. The complete closure to tourists will last for six months. The island resort will reopen in November.

The objective of this study is to evaluate the effect of the closure in the reduction of coliform contamination using computer simulations. The study specifically aims to predict the concentration of fecal indicator bacteria by modeling its transport to an unconfined aquifer from non-point surface sources through the vadose unto the saturated zone. It does not consider the mechanism of coliform migration from the freshwater lens to the shoreline water body. It uses a monthly average recharge and thus, neglects intra-day (tidal) and daily variability (rainfall) in the boundary conditions.

Study Area

Boracay Island belongs to the municipality of Malay in the province of Aklan. It is dumbbell in shape. It is 7 kilometers long and less than a kilometer at its narrowest. The total land area of Boracay is 10.32 square kilometers.

The predominant geology of the island is limestone (Punongbayan, 1990).

Boracay is characterized as having a Type III climate based on the Modified Coronas Classification shown in **Figure 1**. In Type III climates, seasons are not markedly pronounced, although for Boracay, it relatively dry from November to April and wet during the rest of the year.

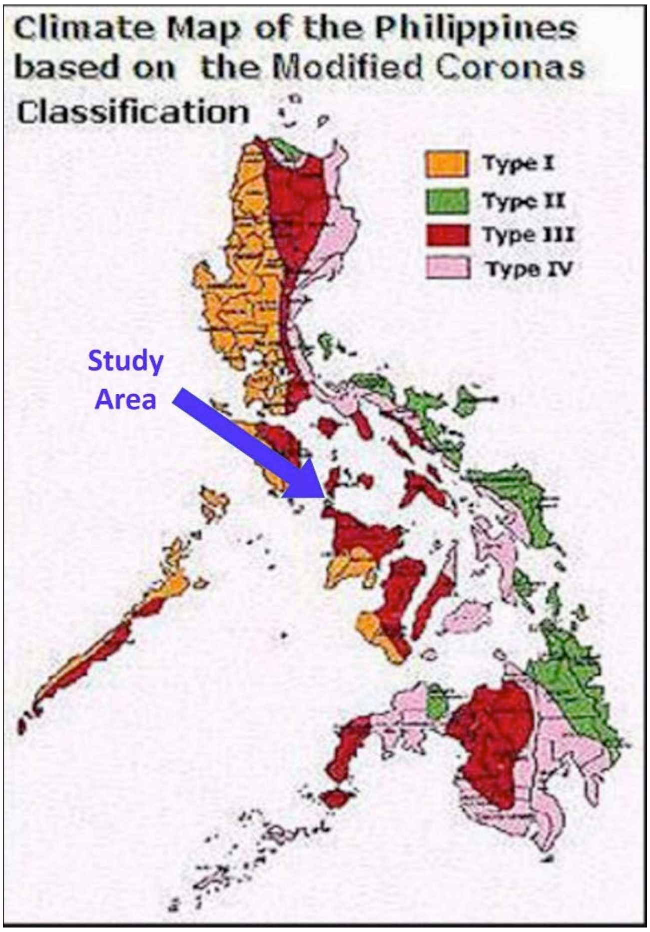

Figure 1. Study Area in the Philippine Climate Map

The annual rainfall in the island is estimated at 1,986 mm. Temperature observations show that the average in the island was 30.75°C. The coldest month is March (27°C) and the warmest, May (35°C).

Review of Related Literature

Total coliforms and fecal coliforms are commonly used as indicators for the presence of feces-derived pathogens in groundwater since their detection protocol is simple and relatively inexpensive. The main bacterial strain in both enumerators is *Escherichia coli* (Foppen, Mporokoso, & Schijven, 2005)

The interest in modeling the transport of *E. coli* arises from its being commonly accepted as a reliable pathogen indicator due to its high concentration, its exclusive presence in feces (Edberg, Rice, Karlin, & Allen, 2000), and its relationship to the presence of pathogenic viruses (Van Cuyk, Siegrist, Lowe, & Harvey, 2004) and protozoans (Personne, Poty, Vaute, & Drogue, 1998). Thus, the effects on the water table of percolating septic wastewater from septic tanks are monitored through the differentiation of enteric *E. coli*.

Escherichia coli is a gram-negative, rod-shaped bacterium and is considered one of the smaller bacteria with an average length of 1.95 micrometer or μm and an average diameter of 0.67 μm (Foppen & Schijven, 2005).

Like any bacteria foreign to the subsurface, the persistence of fecal coliforms is associated primarily with high water content (Poucher, et al., 2007). This is logical since the natural habitat of fecal coliforms is anaerobic and thus, they have to stay submerged so as not to be exposed to air (or oxygen) which is toxic to them.

Methodology

The governing equations for coliform transport through groundwater systems are derived based on the laws of continuity of mass and flux.

As they travel through the porous media in time and distance, bacteria are removed from the transiting water by several processes. Those that are of major importance are adsorption, inactivation or die-off, entrainment in pumped-out water, and biodegradation or more precisely, predation by endemic bacteria.

The transport equation is thus given by

$$\frac{\partial C}{\partial t}+\frac{\rho_b}{\theta}\frac{\partial S}{\partial t}=\nabla\cdot\left(D\cdot\nabla C\right)-V\cdot\nabla C-k_w C-k_s\frac{\rho_b}{\theta}S-qC \tag{3}$$

where
C = concentration
S = adsorbed concentration
ρ_b = bulk density of the medium
D = dispersion coefficient
k_w = first-order biodegradation rate constant in free fluid
k_s = first-order biodegradation rate constant in adsorbed fluid
V = Darcy velocity

Bacterial decay is ordinarily described as a first-order rate (Schijven & Hassanizadeh, 2000).

C and S in equation (3) are physical variables that are related through an adsorption and desorption mechanism. There are three manners, called isotherms, in which attachment could proceed. These are described by:

$$S = k_d C \quad \text{for linear isotherm} \tag{4}$$

$$S = \frac{S_{\max} kC}{1+kC} \quad \text{for Langmuir isotherm} \tag{5}$$

$$S = kC^n \quad \text{for Freundlich isotherm} \tag{6}$$

where
k_d = distribution coefficient
S_{max} = maximum concentration of the medium in Langmuir isotherm
k = Langmuir or Freundlich isotherm
n = Freundlich power index.

The characteristic constants in Langmuir and Feundlich are specific to both bacteria and soil type together. There are still no data available for this. This could only be determined through laboratory experiments.

In an effort to render a simpler mathematical formulation for this field study, the processes of microbial growth and decay have been lumped into one term—a sink term (net death)—in support of the observation that fecal coliforms ultimately do not persist in the subsurface since it is not its natural habitat: its ideal environment is characterized by anaerobic and high nutrient conditions, i.e., in the gut of mammals. Linear isotherm was used by Wall et al. (Wall, Pang, Sinton, & Close, 2008) although they recommended Freundlich isotherm since they argue that it is more accurate for geologically heterogeneous materials such as those found in field conditions.

The use of the linear isotherm follows the reasoning that the sorption is reversible and instantaneous at equilibrium (Harvey & Garabedian, 1991) for low pore-water velocities as in the case of this study. The same assumption was made by Bekhit et al. (Bekhit, El-Kordy, & Hassan, 2009) in their colloid and bacteria combined transport finite difference model. Thus,

$$\frac{\partial S}{\partial t} = k_d \frac{\partial C}{\partial t} \qquad R = 1 + \frac{k_d \rho_b}{\theta} \tag{7}$$

where R is the retardation factor, which is the ratio of mean pore-water velocity to the mean contaminant transport velocity. Equation (3) can then be rewritten as:

$$R\frac{\partial C}{\partial t} = \nabla \cdot (D \cdot \nabla C) - V \cdot \nabla C - [k_w + k_s(R-1)]C - qC \tag{8}$$

Equation (8) can be further simplified to:

$$R\frac{\partial C}{\partial t} = \nabla \cdot (D \cdot \nabla C) - V \cdot \nabla C - \lambda C - qC \tag{9}$$

where λ is the first-order total *die-off* rate defined as:

$$\lambda = k_w + k_s(R-1) \tag{10}$$

An analytical solution is not possible for the initial-boundary value problem described by the governing equations for transport. Numerical methods are used for this task. The most common methods are the Finite Difference and Finite Elements.

As yet, there are no numerical models designed for bacteria transport in the subsurface. An accommodation is to use models designed for solutes as demonstrated by Caloza in his dissertation (Caloza, 2012).

Visual MODFLOW Flex®, the software employed in this study, uses the Finite Difference method. The theoretical background as well as the numerical procedures of this method, including the setup and techniques of the banded matrix solver, can be found in any good groundwater modeling book such as that of Wang and Anderson (Wang & Anderson, 1982) and therefore will not be described here.

For this study, the die-off rate is assumed to be 0.03/day based on a similar study on a karstic geological island formation (Caloza, 2012). The island is assumed to be monolithic and isotropic.

The boundary condition of recharge is determined via a monthly accounting procedure based on the method originally presented by Thornthwaite and Holzman

(Thornthwaite & Holzman, 1939) was used to make a water balance analysis. The required data for the model are: mean monthly temperature (degrees Celsius), monthly total precipitation in millimeters (mm) and the latitude (decimal degrees) of the study area. The latter is used for the computation of the day length, which is needed for the computation of potential evapotranspiration.

The computed monthly effective recharge is presented in Table 1.

Table 1. Computed Monthly Recharge in Boracay Island

Month	Recharge, mm
January	30.8
February	54.5
March	41.3
April	31.3
May	20.0
June	65.7
July	60.3
August	52.3
September	31.3
October	64.4
November	92.1
December	47.9
Annual	591.9

The model uses May as the start month.

A constant head boundary condition is also set for the shoreline or surrounding waters (sea) and is held at 0 meters, which is the mean sea level. The bottom of the model volume (**Figure 2**) has a no flow boundary condition. There are no rivers or lakes in the island.

For transport, the concentration of contaminant in the recharge is assumed zero since all anthropogenic activities in the surface have been minimized due to the government shutdown. Since Visual MODFLOW Flex® does not yet handle flux boundary conditions, the contaminant concentration in the seawater that surrounds the island is held zero. This is supported by the fact that the contaminant is outbound due to the higher concentration of the coliform in the groundwater.

The government mandated closure is assumed to effect zero or near-zero effluents due to absence of tourists and the consequent reduction of the workforce and resident populations.

Results and Discussion

The coliform concentration distribution (contours) in MPN/100 ml by November are shown side by side in **Figure 3**.

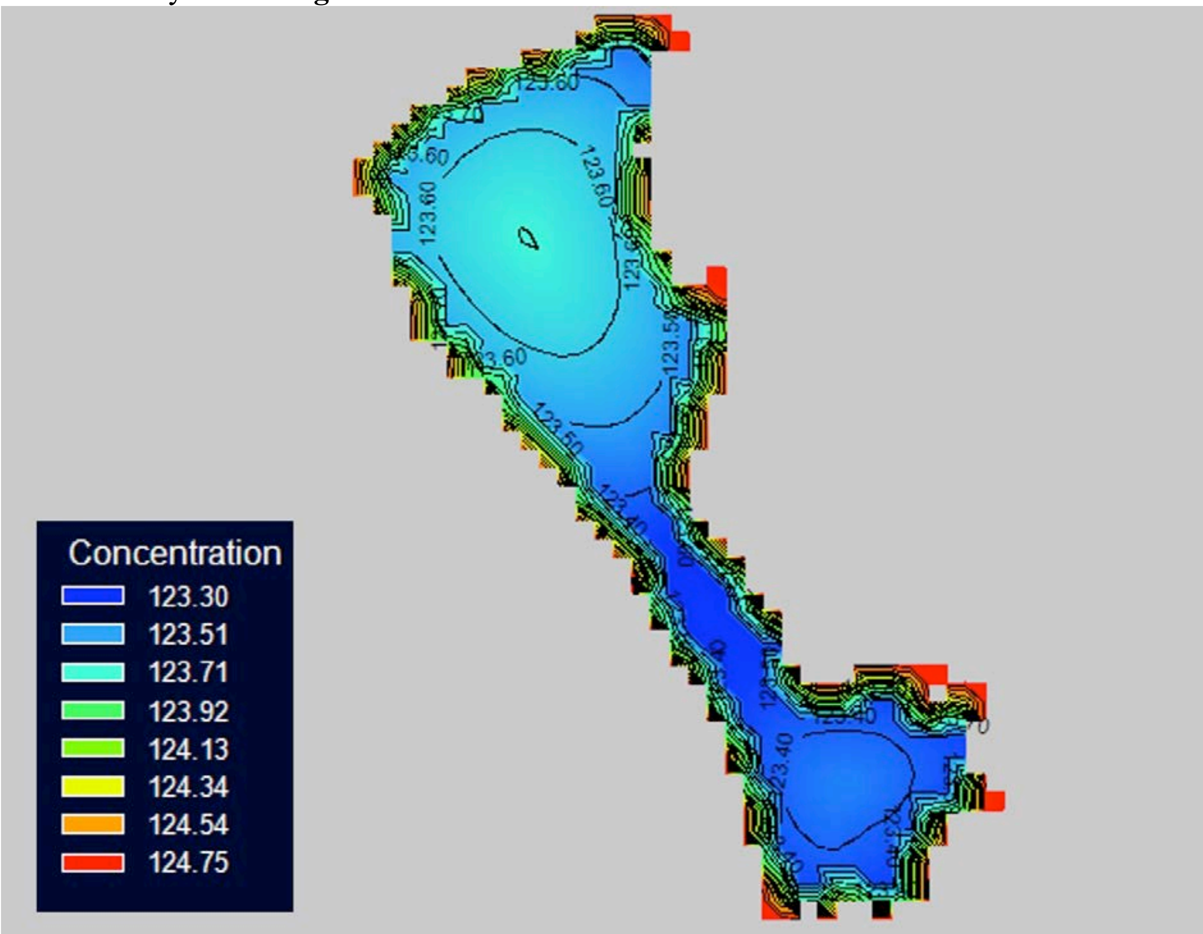

Figure 3. Groundwater Coliform Concentration After 6 Months

The concentration was reduced to a 124 MPN/100 ml from an initial 22,000 MPN/100 ml or about 99.4. This is near the level of acceptable coliforms concentration for recreational waters, which is 100 MPN/100 ml (Department of Environment and Natural Resources, 2016).

Extending the model run to one year shows further reduction of coliforms to almost zero level. **Figure 4** shows results of the ninth and 12th month along with the results of the first and third months.

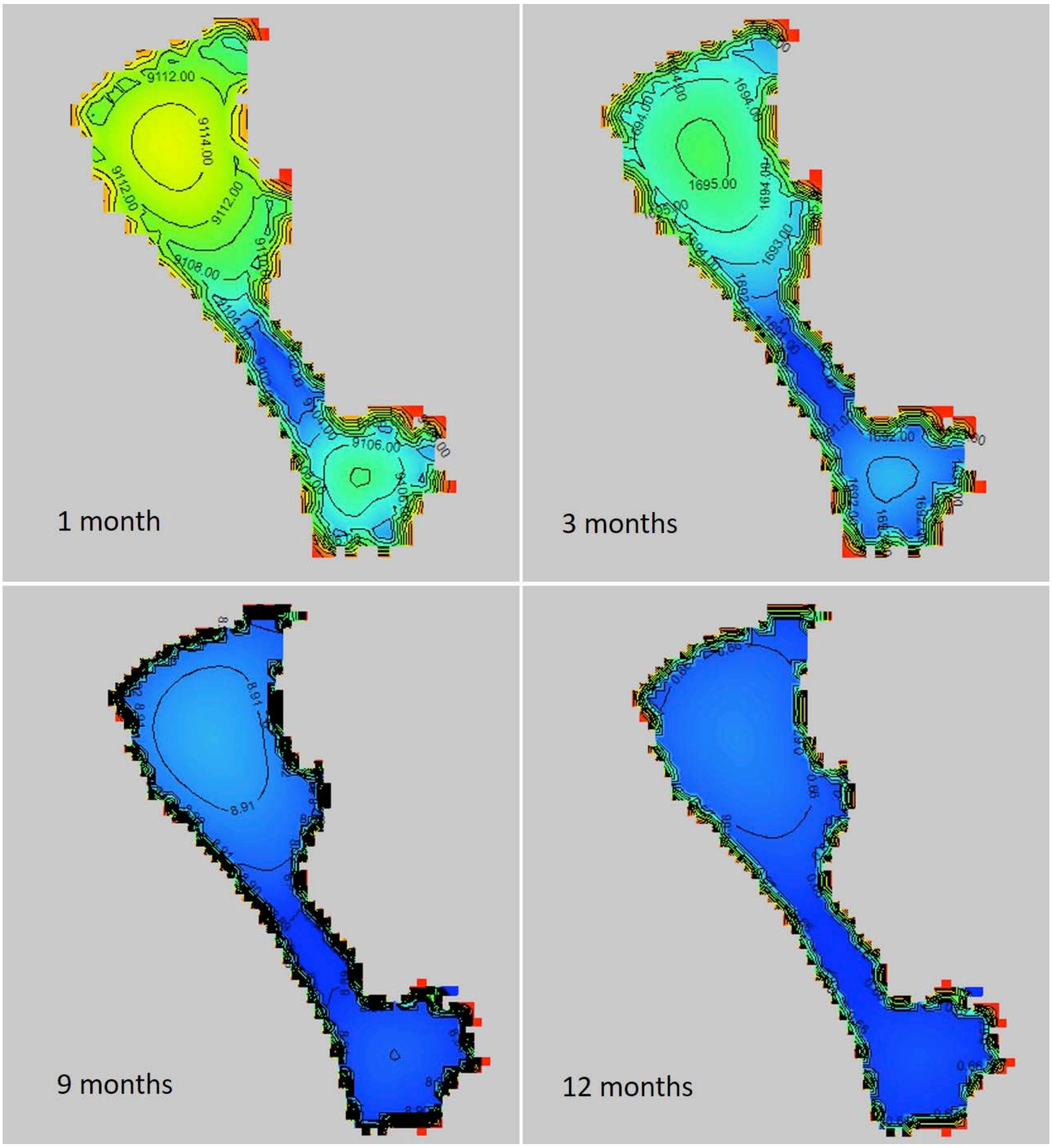

Figure 4. Groundwater Coliform Concentration After 1, 3, 9 and 12 Months

The organic load composed partially of dead bacteria, will not be reduced as rapidly. In the absence of other contaminant data, a parallel model run, this time without the use of retardation, shows that non-degradable solute species will be removed more slowly from the aquifer. **Figure 5** shows the organic load after six months in relative percentages.

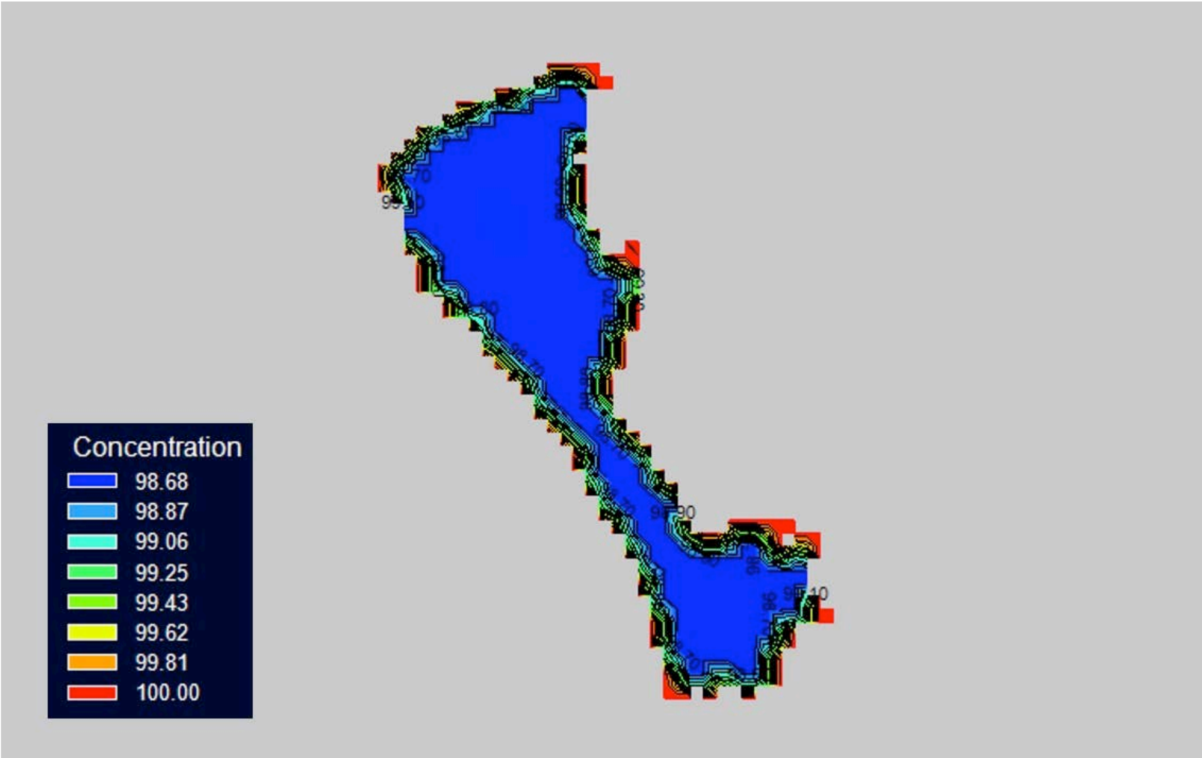

Figure 5. Relative (%) Organic Load Concentration After 6 Months

By estimate, it would probably take more than a decade to reduce the most recalcitrant pollutant—no retardation—to single digit percentages.

Conclusions

The strategy of complete closure, according to the computer model, would reduce the coliform concentration to near acceptable levels. The contamination is reduced by 99.4 percent. The main driver for the disappearance is bacteria die off. The contribution of flushing through recharge is only 1.32%.

Initial field findings as reported in national media outlets support the results of the computer model.

Other contaminants, such as Biological Oxygen Demand (BOD) and nitrates will not be as easily reduced. By estimates from the model, it will take another 10 years to reduce the most recalcitrant pollutant to reach the same magnitude of reduction as the *E. coli*. This assumes the same methodology of simple closure without any other engineering intervention relying on recharge to flush the contaminant.

Recommendations

This modelling effort has not been calibrated although the die-off rate and hydraulic conductivity were derived from an analogous calibrated model. Thus, it is necessary to calibrate the model with actual results from field samples to get an estimate of the die-off rate which should be characteristic of the local conditions of Boracay Island.

Likewise, a time-series of at least seven samplings of the static water level would be adequate to establish the hydraulic conductivity of the subsurface geologic material. Coliform tests give only a partial, if not limited, assessment of the contamination in the aquifer of the island. Tests for other contaminant markers such as BOD, nitrates, phosphates and potassium should also be undertaken to acquire a true picture of the overall contamination of the aquifer.

For a more focused and accurate description for conditions of specific locations within the island further refinements such as delineation of recharge and non-recharge areas, location of septic discharges, and the types of domestic or commercial sewage water treatment facilities in the island are needed. If the modelling effort is to continue with the restoration of anthropogenic activities, a comprehensive inventory of wells—shallow and deep—would also be necessary.

The effects of the closure will only be temporary if no infrastructure intervention—e.g., sewage collection and treatment—was implemented in the intervening months. The coliform concentrations will just return to previous levels in no time.

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