

Pearl: A New Model for Evaluating Bay Sanitation Conditions and Managing Shellfish Growing Water Closures

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ABSTRACT

The objective of this paper is to introduce a new model, Pearl, designed to evaluate bay sanitation conditions and manage shellfish growing area closures. The Pearl model can be used in one of two modes. In the stand-alone mode, Pearl can perform a multi-year analysis using observed fecal coliform data collected from within shellfish growing areas to determine if shellfish harvested from those areas may pose a human health risk for shellfish consumers. Shellfish growing areas that are identified through a stand-alone Pearl analysis are candidates for closure rule adjustments. Run in tandem mode with a previously released model, Aquarius, Pearl can be used to adjust closure rules and maximize the number of days a shellfish growing area can remain open to harvest with no increased risk of illness to shellfish consumers. Pearl increases the sensitivity of the existing National Shellfish Sanitation Program's closure assessment method. The use of Pearl could open harvesting areas that might otherwise be closed, thereby increasing the profits of shellfish growers with no increased risk of illness to shellfish consumers.

Keywords: Modeling, Shellfish sanitation, Water quality, Rainfall closure rules.

1. INTRODUCTION

The molluscan shellfish industry in the United States grows and markets oysters, clams and mussels, which are filter-feeders that concentrate potentially harmful constituents (e.g., metals, pathogens) as they filter water to feed. To protect public health, the Federal Food and Drug Administration (FDA) established the minimum requirements necessary to regulate the interstate commerce of molluscan shellfish to safeguard public health, but individual states may adopt more stringent regulatory standards (NSSP, 2009).

Pathogens that are associated with fecal material frequently contaminate coastal watersheds and shellfish growing areas. The presence of fecal coliform bacteria in ambient water samples taken from shellfish growing areas indicate that potential fecal contamination has occurred. The NSSP mandates that state shellfish authorities shut down shellfish harvesting if water quality in the growing area drops below established food safety levels (NSSP, 2009). The rationale behind closure rules is that a closure period allows tidal cycles to flush the harvesting area and reduce the fecal coliform concentration and any associated pathogens. For example, the California Department of Public Health (CDPH) may close a shellfish growing area for 4 days when the 24-hour cumulative rainfall exceeds 30 mm (1.20 in) (CDPH, 2006).

At present, regulatory agencies use regression models (multiple regression or logistical regression) to calculate closure rule thresholds and durations. Using a regression analysis establishes a relationship between the response variable (observed fecal coliform concentration) and several predictor variables, such as observed rainfall, river flow, river stage, water temperature, salinity, and tidal stage (Kuntz, 1998 and DNREC, 1997). We have developed an alternative, non-regression model, "Pearl", that can be used in two modes. In the stand-alone mode, Pearl performs a multi-year analysis using fecal coliform concentration data from shellfish growing areas to determine which growing areas may potentially cause health problems for shellfish consumers. These areas are candidates for closure rule adjustments. In the tandem mode with another model, Aquarius (Conte and Ahmadi, 2011), Pearl can be used to optimize the closure threshold and duration and also its supplementary equations increase the sensitivity of the NSSP statistical methods. The objective of this paper is to introduce a new model, Pearl, designed to evaluate bay sanitation conditions and manage shellfish growing area closures.

2. THE PEARL MODEL

The Pearl model consists of input, calculation, and output components.

2.1. Inputs

There are two kinds of data required for input to the Pearl model: closure journals and fecal coliform data.

2.1.1 Closure Journals

A closure journal is a list of closure periods for a specific growing area with closure starting dates and closure durations. Closure journals are based on closure rules that govern conditionally approved areas under which a harvest area is closed for a pre-determined period when the concentration of fecal coliform bacteria exceeds a certain threshold.

For example, a closure journal for a specific growing area may have a starting date of 15 December 2011 at 0800 h and closure duration of four days. This means that the shellfish area was closed for harvest from 15 December 2011 at 08:00 h to 19 December 2011 at 0759 h. A record in the closure journal includes six fields, location, growing area, closure starting date, closure starting time, duration in days, and comments. The comments field shows the reason for the closure triggering the closure.

Note that several closures may be triggered sequentially on a single day at six-hour intervals. In this case, the effective closure duration starts at the earliest trigger, and lasts through the longest duration. For example, in Table 1, on 24 April 2003 at 4:00 h, the 24-hour cumulative rainfall exceeded 30 mm (1.20 in.), and the closure rule was triggered. Subsequently, on the same day at 10:00 h and 16:00 h, the 24-hour cumulative rainfall also exceeded 30 mm (1.20 in.), and the closure rule was triggered again. The effective closure starts on 24 April 2003 at 4:00 h and ends on 28 April 2003 at 15:59 h, for a duration of 4 days and 12 hours. The closure journal can be directly input into the Pearl model as a comma delimited text file.

2.1.2. Fecal Coliform Data

Regulatory agencies collect and archive observed fecal coliform data. Each observation has six essential fields: location, growing area, sampling station, date, time, and concentration. If the sampling date and time of a fecal coliform observation for a growing area falls within a closure period for that area, that observation is classified as a sample taken during the “closed” period; otherwise, it is classified as a sample taken during the “open” period. The fecal coliform observed data is input into Pearl via a comma delimited file.

Table 1. A portion of a typical closure journal showing the closure duration and the reason for triggering the closure rules in the comments field.

Location	Growing Area	Closure Starting Date	Closure Starting Time	Closure Duration Days	Comments
Humboldt Bay	A	4 Apr. 2003	16:00	5	24-hour cumulative rainfall exceeded 30 mm and 7-day cumulative rainfall exceeded 76 mm
Humboldt Bay	A	24 Apr. 2003	4:00	4	24-hour cumulative rainfall exceeded 30 mm
Humboldt Bay	A	24 Apr. 2003	10:00	4	24-hour cumulative rainfall exceeded 30 mm
Humboldt Bay	A	24 Apr. 2003	16:00	4	24-hour cumulative rainfall exceeded 30 mm
Humboldt Bay	A	6 Dec. 2003	4:00	5	24-hour cumulative rainfall exceeded 30 mm and 7-day cumulative rainfall exceeded 76 mm
Humboldt Bay	A	6 Dec. 2003	10:00	5	24-hour cumulative rainfall exceeded 30 mm and 7-day cumulative rainfall exceeded 76 mm
Humboldt Bay	A	6 Dec. 2003	16:00	4	24-hour cumulative rainfall exceeded 30 mm
Humboldt Bay	A	6 Dec. 2003	22:00	4	24-hour cumulative rainfall exceeded 30 mm

2.2. Calculations

The Pearl model uses the actual closure journal maintained by the state regulatory agency to divide the observed fecal coliform data set into three subsets. The “open” subset includes samples collected when the shellfish growing area was open for harvest, the “closed” subset includes samples collected when the shellfish growing area was closed to harvest, and the “combined” set consists of both the open and closed subsets.

2.2.1. Equations

All calculations performed in Pearl are based on NSSP recommended methods, and all calculations are performed on each fecal coliform subset (open, closed, combined) separately. For each subset, Pearl organizes the fecal coliform samples from each observation location into sequential, groups, each consisting of 30 samples, as required by the NSSP. The first group includes the first thirty samples. The second group begins with the second sample and adds the following 29 samples (samples 2 through 31). This data grouping procedure is repeated for all observations in each subset. Pearl then calculates four statistics (geometric mean, estimated 90th

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percentile, upper limit of geometric mean, and upper limit of estimated 90th percentile) for each data group in each of the subsets. The following equations are used to calculate the statistics:

Calculate arithmetic mean of the logarithms (base 10) of the fecal coliform concentrations:

$$\bar{x} = \sum_{i=1}^n x_i / n \quad (\text{Equation 1})$$

Calculate standard deviation of the logarithms (base 10) of the fecal coliform concentrations:

$$sd = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n - 1}} \quad (\text{Equation 2})$$

Calculate geometric mean by:

$$= \text{anti log}(\bar{x}) \quad (\text{Equation 3})$$

Estimated 90th percentile:

$$= \text{anti log}(\bar{x} + sd * 1.28) \quad (\text{Equation 4})$$

Upper limit of geometric mean at α significance level:

$$= \text{anti log}\left(\bar{x} + \frac{sd}{\sqrt{n}} * t_{\alpha, (n-1)df}\right) \quad (\text{Equation 5})$$

Calculate the upper limit of estimated 90th percentile at α significance level by:

$$= \text{anti log}\left(\bar{x} + \sqrt{\frac{(n-1)}{\chi_{1-\alpha, (n-1)df}^2}} * sd * t_{0.10, (n-1)df}\right) \quad (\text{Equation 6})$$

Where x_i denotes the logarithms (base 10) of the fecal coliform concentration, \bar{x} denotes the arithmetic mean, sd denotes the standard deviation, n denotes the sample size, α denotes the significance level, t denotes the t-distribution, and df denotes the degree of freedom. The term $t_{\alpha, (n-1)df}$ is calculated using the Excel function $tinv(2 * \alpha, n - 1)$. The term $\chi_{1-\alpha, (n-1)df}^2$ is calculated using the Excel function $chiinv(1 - \alpha, n - 1)$. The value 1.28 in equation 4 is obtained from the standard normal distribution and is equal to $z_{\alpha=0.10}$ for one-sided test.

Equations 3 and 4 correspond to the NSSP guidelines and are used for compliance with shellfish water quality standards by regulatory agencies (CDPH, 2006). Equations 5 (Mann, 1998) and 6 (Sheskin, 2007 and Snedecor and Cochran, 1967) calculate two additional parameters not used by NSSP: the upper limit of the geometric mean and the upper limit of the estimated 90th percentile.

2.2.2. Calculating the "Pearl Limit"

Pearl sorts the upper limit of estimated 90th percentile fecal coliform concentration values from the largest to smallest. It then uses the user-specified NSSP limit (e.g., 43MPN/100 mL for a 5-tube test) to search the sorted list for the first record in which the upper limit of estimated 90th percentile value is less than, or equal to, the user-specified NSSP limit. Once that record is found, Pearl identifies the corresponding estimated 90th percentile value for this record as the "Pearl Limit", which in our example will be 26 MPN/100 mL for a 5-tube test.

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2.3. Outputs

Pearl produces scattergrams that can be used to assess the pattern of fecal coliform concentration in growing areas over time (Figure 1). In the scattergram, fecal coliform concentration is plotted on the y-axis and date on the x-axis. The solid horizontal line represents the NSSP limit of 43 MPN/100 mL. Data above the NSSP limit are in what is termed the “True Positive Zone”. The area below the NSSP limit of 43 MPN/100 mL is divided by a dashed line that represents the Pearl Limit (26 MPN/100 mL in this case). The area below the Pearl Limit is the “True Negative Zone”. The area above the Pearl Limit, but below the NSSP limit, is the “False Negative Zone.” The x's in Figure 1 represent the estimated 90th percentile, and o's represent their upper limits. Each data point in a scattergram (Estimated 90th percent or its upper limit) is based on 30 fecal coliform observations.

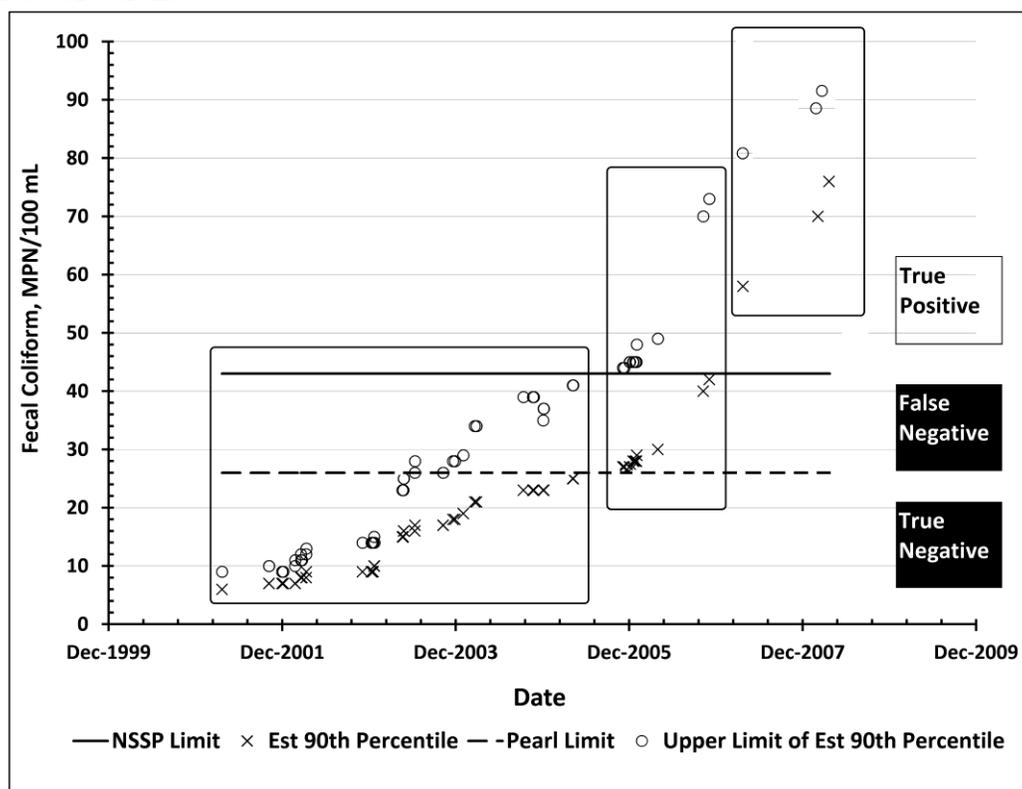


Figure 1. Hypothetical scattergram of the estimated 90th percentile of fecal coliform concentrations and their upper limits, showing three diagnostic zones, True Positive, False Negative, and True Negative.

2.3.1. Interpreting Pearl's Outputs and Comparison with the NSSP Diagnostic Test

A comparison of the outcome of the NSSP diagnostic test with Pearl's scattergram depiction of a growing area in Figure 1 produces the following interpretations of the data. The estimated 90th percentile values of fecal coliform samples that appear below the Pearl Limit (True Negatives Zone) indicate a "clear" growing area. In this zone the upper limit of the estimated 90th percentile values of fecal coliform samples are below the NSSP limit. The estimated 90th percentile values

of fecal coliform samples that appear above the Pearl Limit, and below the NSSP limit of 43 MPN/100 mL (False Negatives Zone) in the scattergram (Figure 1), indicate a "contaminated" growing area. Using Pearl's criteria, the area is "contaminated", but the NSSP diagnostic test incorrectly defines the area as "clear". In this zone the upper limit of the estimated 90th percentile values of fecal coliform samples are above the NSSP limit. The estimated 90th percentile values of fecal coliform samples that appear above the NSSP limit of 43 MPN/100 mL (True Positive Zone) in the scattergram indicate a "contaminated" growing area. In this zone the upper limit of the estimated 90th percentile values of fecal coliform samples are above the NSSP limit.

3. PEARL IN THE TANDEM MODE

Pearl can be used in tandem with another model, Aquarius (Conte and Ahmadi, 2011), to optimize a closure rule's threshold and duration. This process can maximize the number of days a shellfish growing area can safely remain open to harvest with no increased health risk to shellfish consumers. In the closure rule optimization mode, Aquarius uses two inputs: the rainfall data set that corresponds to a given harvesting area and a hypothetical closure rule, which is a modification of an existing closure rule. The user inputs the observed rainfall data set into the Aquarius model as a comma delimited file, and then specifies the hypothetical closure rule using a dialog box.

The Aquarius model compares the observed precipitation data against the hypothetical closure rule and determines if the hypothetical closure rule threshold is exceeded. Each time the threshold is exceeded, Aquarius adds a record into the simulated closure journal with a starting date and duration. By applying the hypothetical closure rule to the rainfall data set, Aquarius generates a simulated closure journal that is then automatically input into the Pearl model.

The simulated closure journal, based on hypothetical changes to the closure rule, changes the open and closed status of the growing area. Pearl uses the simulated closure journal to reclassify the open and closed status of the observed fecal coliform data set. For example, a fecal coliform sample that was collected when the area was closed on a given date would be reclassified as "open" under a hypothetical closure rule that opens the harvest area on that date. This reclassification of harvesting area status re-divides the observed fecal coliform data set into three subsets: the "open.", "closed", and "combined". For each subset, Pearl, organizes the fecal coliform samples from each observation location into sequential, groups, each consisting of 30 samples. Pearl then calculates four statistics (geometric mean, estimated 90th percentile, upper limit of geometric mean, and upper limit of estimated 90th percentile) for each data group in each of the subsets. These reclassifications of harvest area status, re-divisions of fecal coliform data sets, and recalculations of four statistics, result in a new set of scattergrams that can be used to evaluate the suitability of the changes in the closure rule.

The user then examines the new scattergrams to determine if all the estimated 90th percentile values are below the Pearl Limit and in the True Negative zone. If so, harvested shellfish would not pose a health risk to shellfish consumers and the modified closure rule can be accepted. If any of the estimated 90th percentile values are above the Pearl Limit, in the False Negative zone, or in the True Positive zone, then the model shows that shellfish harvested from the area being

considered, do pose a possible health risk to shellfish consumers and the hypothetical closure rule should be tightened. To relax or tighten the hypothetical closure rule, the user can employ the model's feedback loop, modify the hypothetical closure rule, and then repeat the steps described to test the applicability of the modified rule. This feedback loop provides a mechanism to fine-tune and optimize closure rules.

4. DISCUSSION

The Pearl model mathematically mimics the procedural actions that regulatory agencies employ to analyze fecal coliform data sets when making decisions regarding the closure of shellfish growing areas. The model uses the same equations and procedures as recommended by the NSSP to calculate the geometric mean and the estimated 90th percentile values of fecal coliform data sets, and adds two additional parameters, the upper limit of the geometric mean and the upper limit of the estimated 90th percentile. The equation to determine the upper limit of the estimated 90th percentile includes sample size in its calculation thereby increasing analytical sensitivity of the Pearl model. The model's output yields plots of the estimated 90th percentile fecal coliform concentration values, and their upper limits of the 90th percentile, in scattergrams that allow the user to visualize fecal coliform sample distribution over time periods. The Pearl model also plots their position on the scattergram relative to the NSSP cutoff of 43 MPN/100 mL and the Pearl Limit based on a 5-tube test.

A major feature of Pearl is its ability to use simulated closure journals generated by the Aquarius model, which allows the user to evaluate tightening or relaxing the rules governing shellfish growing areas closures. Pearl can be used in tandem with Aquarius to perform closure adjustment scenarios for growing areas. Using Pearl's feedback loop and Aquarius' input menu, the shellfish growing area closure rules can be relaxed by increasing the depth of rainfall required prior to closure. The closure rule adjustment illustrates the potential to keep shellfish harvesting area open longer while still protecting the public from consuming contaminated shellfish.

5. CONCLUSION

The Pearl model provides agencies and industry the ability to visualize and analyze fecal coliform observations in ways that permit a qualitative assessment of shellfish closure rule adequacy. Working in tandem with Aquarius, the Pearl model provides a mechanism to make adjustments to shellfish growing area closure rules to maximize days open to harvest and still protect the public from consuming contaminated shellfish.

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