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OPMS - A web-based ocean pollution monitoring system

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ABSTRACT

Marine pollution poses significant risks to both marine ecosystems and human health, requiring effective monitoring and control measures. This study presents the Ocean Pollution Monitoring System (OPMS), a web application designed to visualize the seasonal and annual fluctuations of marine pollutants along coastal regions in Canada. The pollutants include fecal coliform and biotoxins such as paralytic shellfish poisoning (PSP), and amnesic shellfish poisoning (ASP). The OPMS utilizes 20 years of data from nearly 15,000 shellfish harvesting sites across six provinces of Canada, allowing users to explore trends and the impact of these pollutants in user-selected geographical regions. The seasonal fluctuation patterns of fecal coliform and biotoxin levels were extracted by Functional Principal Component Analysis (FPCA) previously. OPMS visualizes these results in finer granularity to provide environmental managers and policymakers with a decision-support tool in shellfish safety and water quality management. The tool is accessible at http://opms.uvic.ca.

1. Introduction

Marine pollution encompasses a broad range of pollutants that can degrade ocean environments and harm both marine organisms and human life. They include chemical substances like heavy metals and pesticides, and biological hazards such as fecal coliform and biotoxins. These pollutants pose significant risks, impacting not only aquatic life but also human populations that depend on these ecosystems for food, recreation, and livelihood (Davis, 2021). Ensuring the health of marine biodiversity and the safety of shellfish consumption requires diligent oversight and control of these pollutants.

Fecal materials are waste from the digestive system of warm-blooded animals, including humans. They consist of 75 % water; the majority of the remaining solid fraction is 84–93 % organic solids including nutrients and bacterial biomass (Osuka et al., 2012). These bacteria include genera originating from feces (e.g. *Escherichia*) and genera of non-fecal origin (e.g. *Enterobacter*, *Klebsiella*, *Citrobacter*) (Sanitation Health in Transition, n.d.). The presence of fecal coliforms in high concentrations in the marine environment is indicative of a source of pollution such as sewage. Sewage produces unpleasant odors and visible debris. Water bodies polluted by fecal coliforms have caused nearly 120 million cases of gastrointestinal infection (Pandey et al., 2014). Many countries use Fecal Indicator Bacteria (FIB) as a water quality measure (Noble et al., 2003). Elevated levels of fecal coliforms indicate the presence of fecal pollution in the seawater (Polo et al., 1998) and lead to regulatory closure of shellfish harvesting due to concerns about potential public health risks (Zimmer-Faust et al., 2018). Bivalve shellfish, such as oysters, clams, and mussels, filter large amounts of water, potentially accumulating fecal coliforms and other pollutants (Leung et al., 2022). Consumption of polluted shellfish can cause foodborne illness in humans

Abbreviations: OPMS, Ocean Pollution Monitoring System; PSP, Paralytic shellfish poisoning; ASP, Amnesic shellfish poisoning; DA, domoic acid; CSSP, Canadian Shellfish Sanitation Program; FPCA, Functional Principal Component Analysis; FPC, Functional Principal Component; BC, British Columbia; QC, Quebec; NB, New Brunswick; PE, Prince Edward Island; NS, Nova Scotia; NL, Newfoundland and Labrador.

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(Zaghloul et al., 2020). In addition, the introduction of excess nutrients would favor the growth of certain microorganisms, leading to an imbalance in the microbial community (Sliva and Williams, 2001). Furthermore, excess organic matter from fecal pollution and decaying algae can deplete oxygen and create "dead zones" harmful to marine life (Kirchman, 2021). Waters polluted with fecal bacteria are also more likely to suffer from enrichment of nutrients such as nitrogen and phosphorus (Fuhrmeister et al., 2015). When these nutrients enter marine ecosystems in excess, it results in eutrophication, a process characterized by rapid growth of algae and the formation of algal blooms (El Semary, 2020).

Blooms of harmful microalgae are another source of health concern for human beings and marine life. The toxin-laden algae are filter-fed by shellfish; the subsequent consumption of such shellfish products can then lead to various types of shellfish poisoning, such as Amnesic Shellfish Poisoning (ASP) and Paralytic Shellfish Poisoning (PSP). Each type of shellfish poisoning is characterized by specific symptoms in humans. Outbreaks of ASP and PSP have been reported worldwide, with significant public health impacts. For example, in the United States, the Centers for Disease Control and Prevention (CDC) reported that an average of 900 cases of shellfish-related illnesses are recorded annually. Globally, outbreaks of PSP have been particularly concerning in coastal regions where harmful algal blooms are frequent, leading to hundreds of cases of severe illness each year. Additionally, a notable ASP outbreak in Canada in 1987 caused 107 illnesses and several fatalities due to polluted shellfish (Todd, 1993). These trends highlight the importance of monitoring and regulating shellfish harvesting areas to prevent widespread health issues (James et al., 2010).

The Canadian Shellfish Sanitation Program (CSSP) was established in 1948 and collectively managed by the Canadian Food Inspection Agency (CFIA), Environmental and Climate Change Canada (ECCC), and the Department of Fisheries and Oceans Canada (DFO). These governmental departments have performed multidecade monitoring on fecal coliform bacteria and biotoxins at shellfish harvesting sites along Canada's coast. According to the thresholds defined by Health Canada, closure and reopening schedules for individual sites are carried out accordingly based on the monitoring data.

Lately, macro-scale analyses of these multi-decade historical data of fecal coliform bacteria, ASP, and PSP have been conducted (You et al., 2024a; You et al., 2024b; You et al., 2023). Functional Principal Component Analysis (FPCA) was applied to extract variation patterns of the bacteria and biotoxin levels at the harvesting sites in each of the coastal provinces (British Columbia, Quebec, New Brunswick, Prince Edward Island, Nova Scotia, Newfoundland and Labrador). The magnitudes of overall amplitudes and seasonal changes were quantified as functional principal component (FPC) scores, which can be utilized as indicators to reflect the characteristics of the pollution at each site. These findings provide an understanding of the temporal and spatial dynamics of these pollutants. In order to provide public, informative, and practical support for specific site-wise management, an open, interactive, and user-friendly tool is required.

This paper introduces a tool called the Ocean Pollution Monitoring System (OPMS), an R Shiny-based web application. This tool allows user to visualize the seasonality and annual fluctuations of fecal coliform and biotoxins of each site by providing an interactive platform for exploring the level and trend of these pollutants and their correlation with environmental factors, such as precipitation. OPMS aims to enhance the decision-making process for users in marine pollution control and public health protection.

2. Method

2.1. Data and preprocessing

The OPMS integrated three datasets from CSSP, fecal coliform bacteria concentrations, domoic acid, and paralytic shellfish toxins, across six coastal provinces: British Columbia (BC), Quebec (QC), New Brunswick (NB), Prince Edward Island (PE), Nova Scotia (NS), and Newfoundland and Labrador (NL). The number of fecal coliform bacteria (bacteria count per 100 mL sea water) was determined according to the standard method (American Public Health Association, 1926). The data presented in the OPMS are the integration of 23 years (2000–2023) instead of 2000–2020 described in You et al. (You et al., 2023).

Biotoxin data were integrated from 20 years of measurements (2000−2020) of toxin contents in the whole flesh of blue mussels (*Mytilus edulis*) and soft-shell clams (*Mya arenaria*). DA measurements were determined against Certified Reference Material (CRM-DA-h) using high-performance liquid chromatography (HPLC) at a detection limit of 0.01 μg/g (You et al., 2024a). PST measurements were determined based on two methods: the bioassay method was applied before 2010 at the detection limit of 40 μg/100 g, and progressively transitioned to the HPLC method with detection at 1 μg/100 g after 2012 (You et al., 2024b). Additional precipitation data were the records (in millimeters; cumulative amount over the five days before sampling) from the Meteorological Service of Canada (MSC) at the closest weather stations.

Since the original raw data were collected based on the mandate for public health monitoring, the data were more frequent in the periods and at sites of high risk. This resulted in high sparsity and skewness in the datasets; rigorous data preprocessing was conducted, which finally derived 52 weekly means in the year at each site for subsequent analyses as described in You et al. (You et al., 2022). Logarithmic transformation of these weekly means was used in the subsequent analysis by FPCA in the three previously published articles (You et al., 2024a; You et al., 2024b; You et al., 2023).

The derived patterns, correlations, environmental factors, and the weekly means of FC and biotoxins were collected in the database accessible to OPMS. This provides a foundation for identifying relationships between pollutants and environmental factors such as precipitation, temperature, and salinity.

2.2. Application process design

As shown in Fig. 1, the application process design starts with the main interface where users can choose to explore the fecal coliform or biotoxin data branches as the two major groups of pollutants. Considering the differences in data collection scheduling in different provinces and users' research concerns, the pollution levels in different provinces are analyzed and displayed separately in the design so that users can more intuitively obtain the regional differences and relationships with influencing factors. Since the pollution results were obtained from the FPCA processing of the high-dimensional raw data, the first two FPCs were applied to explain the main variation patterns in the data. The FPC scores were divided into different color ranges based on their percentiles to help users select sites of interest at the provincial level. By zooming in and out of the map for a selected site, users can view detailed statistics including FPC scores, trends of pollutant concentration, and their correlations with precipitation.

2.3. Construction and operation of this application

The open-source R Shiny web application framework and packages (shiny, leaflet, DT, tidyverse, ggmap, Hmisc, cowplot) (Chang et al., 2021; Cheng, 2021; Xie et al., 2021; Wickham et al., 2019; Kahle and Wickham, 2013; Harrell and Dupont, 2020; Wilke, 2015) were used to build this interactive web application. In the user interface, the built-in function in R Shiny was used to establish the general application interface. In the main panel, users can get basic information about the website. In addition, they can scroll down to easily view information about web page operations and data introduction and why it's important to pay attention to shellfish safety. Also, users can access the "Tutorial". Clicking the "Home" button at the top of the interface would return users to the main interface. Finally, by clicking the "Fecal Coliform" or

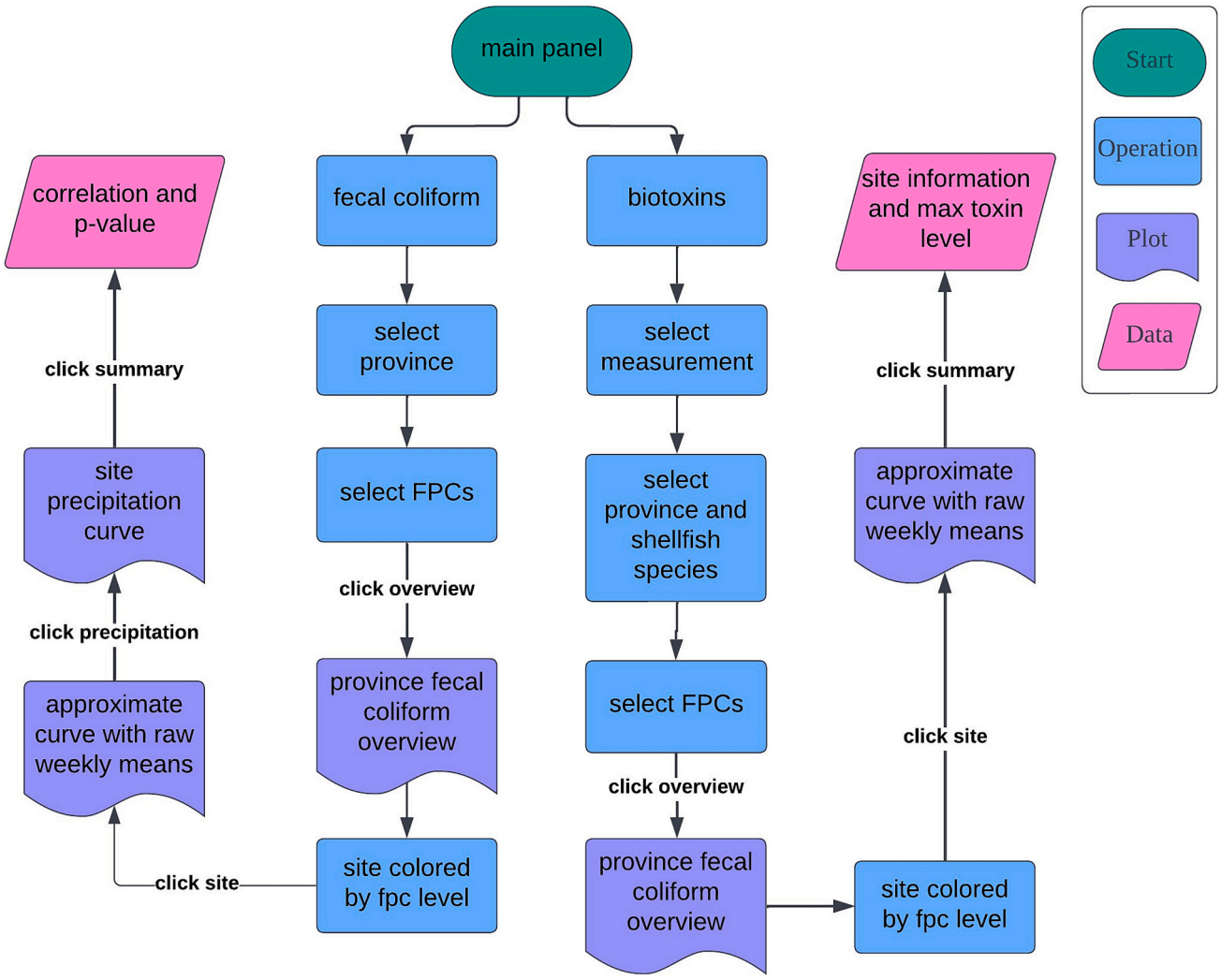


Fig. 1. Application operation flowchart. After entering the main interface, users can sequentially select the fecal coliform or biotoxins panel (if biotoxins then select specific toxin measurement), a province, and an FPC. Click "Overview" to show the pollutants curve of the province. The color of each site point on the map informs users of approximate FPC scores, which reflect the strengths of specific variation patterns in pollutant levels. The map is zoomable to facilitate the selection of a specific site by a mouse clicking (Fig. 2); the statistical information of fecal coliform or biotoxins at the corresponding site will be displayed on the right, which includes raw weekly means, approximated curve by FPC, as well as the correlation with precipitation or site-wise max biotoxin observations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

"Biotoxins" button above the main interface, users can enter the relevant interface showing the fecal coliform or biotoxins data analysis results. For example, let's take the case of fecal coliform as illustrated in Fig. 2; the map on the left side of the main interface displays sampling sites' FPC scores in a province. On the right side, the analytical results and the annual change curves of pollutants and precipitation are displayed. Various option buttons have been created in the application to allow users to select a specific province, measurement of a specific biotoxin, and FPC scores according to their needs.

In the establishment of this web application, when users selected an FPC and the fecal coliform or biotoxins in the interface, such inputs are used by the Innerjoin R function to filter and match the fecal coliform and precipitation data corresponding to the site, as well as the geographic location information, longitude, and latitude. The colorFactor R function was used to grade the FPC scores and represent pollutant concentration through the depth of different colors; each color represents the 1/10 (1/5 for biotoxins) percentile of an FPC. The Leaflet (Cheng, 2021) R package was used to draw the map, displaying water quality monitoring sites in the province. Also, the values of selected FPC scores of these sites are presented in different colors. The renderPlot R function was used to create a graphic template, and the ggplot2 to draw the curves on the right (Fig. 3). Each point on the curve represents the weekly mean level of coliform or biotoxins corresponding to the abscissa. The weekly pollutant value over several decades is represented by the red dot. The renderDataTable R function displays the correlation and P-value between pollutants and precipitation at the selected site.

According to available data, precipitation is an important factor influencing fecal coliform levels. The precipitation curve can be revealed by clicking on the "Precipitation" button at the top of the fecal coliform approximation curve (Fig. 4). The detailed correlation and statistical confidence result between fecal coliforms and precipitation can be found by clicking on the "Summary" button (Fig. 5). For the Biotoxin panel, clicking on the "Summary" button will show site information and max biotoxin level (Fig. 5). The practical demonstration of each step is described in the user manual accessible by clicking on the "Tutorial" button on the left side of the main panel.

3. Results and discussion

The OPMS platform provides an accessible and user-friendly tool for both the general public and government agencies to monitor the dynamics of fecal coliforms and biotoxins along coastal Canada. This

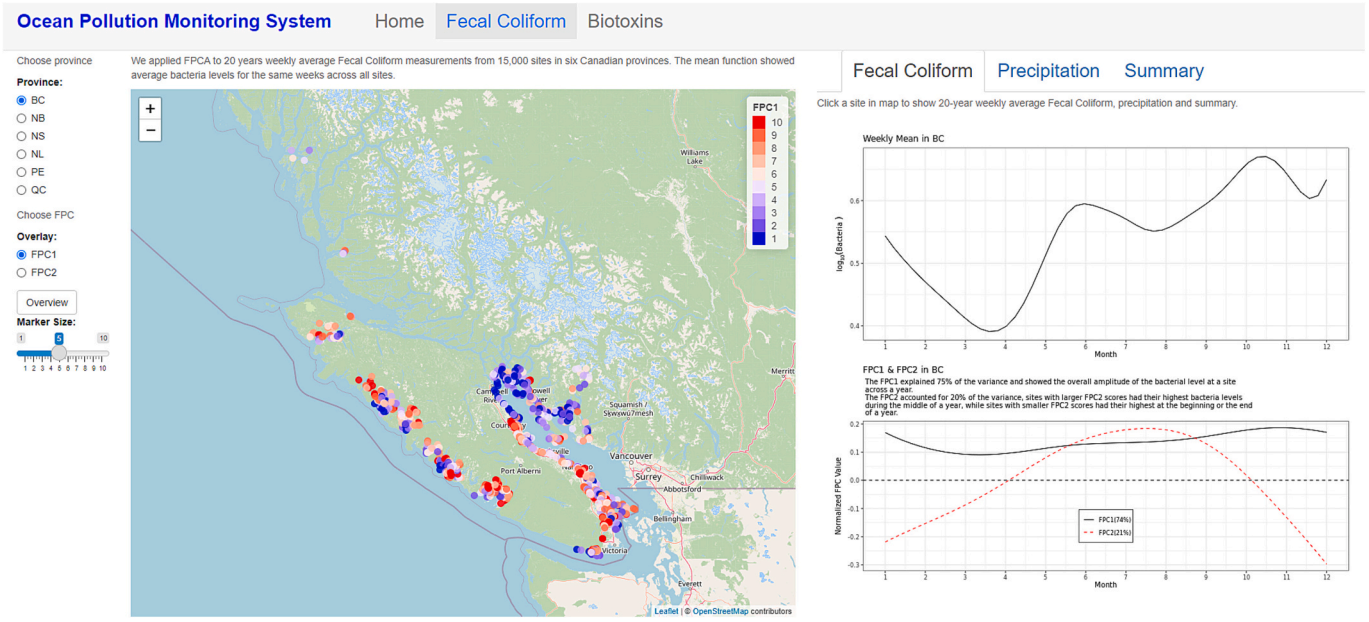


Fig. 2. Fecal coliform panel initial interface, the default selection on the left is to view the fecal coliform-related information in BC. After selecting a province and an FPC, or clicking "overview" on the left, the map shows on the left and the image on the upper right is an overview of the fecal coliform prediction curve, while the bottom right is the FPC score over certain months of the year. After selecting FPCs on the left, the sites on the map were colored by FPC value based on a range (top right of the map), with a higher FPC score at a site indicating a higher bacterial level (You et al., 2023). Click the "Biotoxins" button in the red circle above to enter the Biotoxins panel interface. The operation method is the same as the fecal coliform interface. Similarly, the sites on the map are colored by the FPC value (You et al., 2024a; You et al., 2024b). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

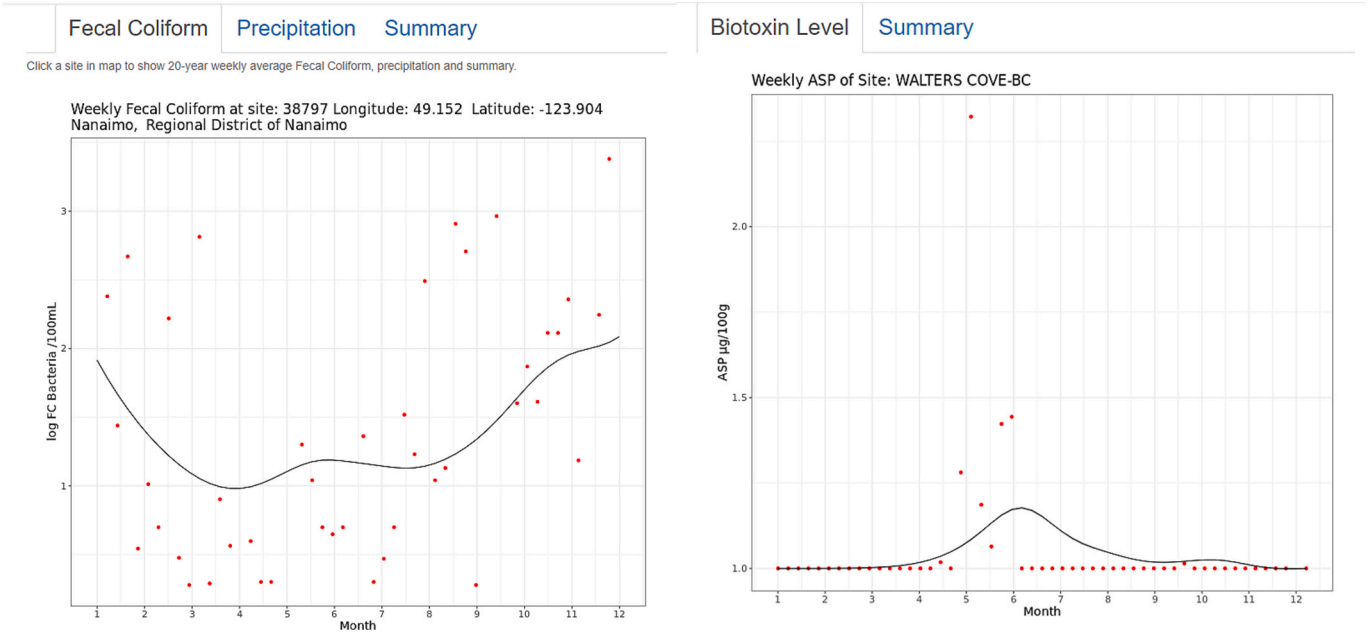


Fig. 3. Log fecal coliform and biotoxins approximate curves when measurement and a province are selected through the buttons on the left of Fig. 2. After clicking on the site, the seasonal variation pattern of a pollutant is displayed on the right. The red points represent the weekly mean generated in (You et al., 2024a; You et al., 2024b; You et al., 2023). Here the image on the left is the Fecal coliform curve at Site 38797 in BC: longitude = 49.152 and latitude = -123.904. The image on the right is the ASP curve at the site of Walters Cove in BC. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

platform displays trends in the data and is not intended as a substitute for existing regulatory criteria implemented by the CSSP. Through the application, users can access a comprehensive dataset that includes nearly all samples of fecal coliform and biotoxins collected between 2000 and 2020 (to 2023 in the case of FC) along both the Pacific and Atlantic coasts. On the website, the weekly pollutant plot feature displays the approximated pollutant curve derived from the analysis method alongside a historic average. This allows users to compare predicted and actual pollutant levels at specific times and locations, aiding to their decision making.

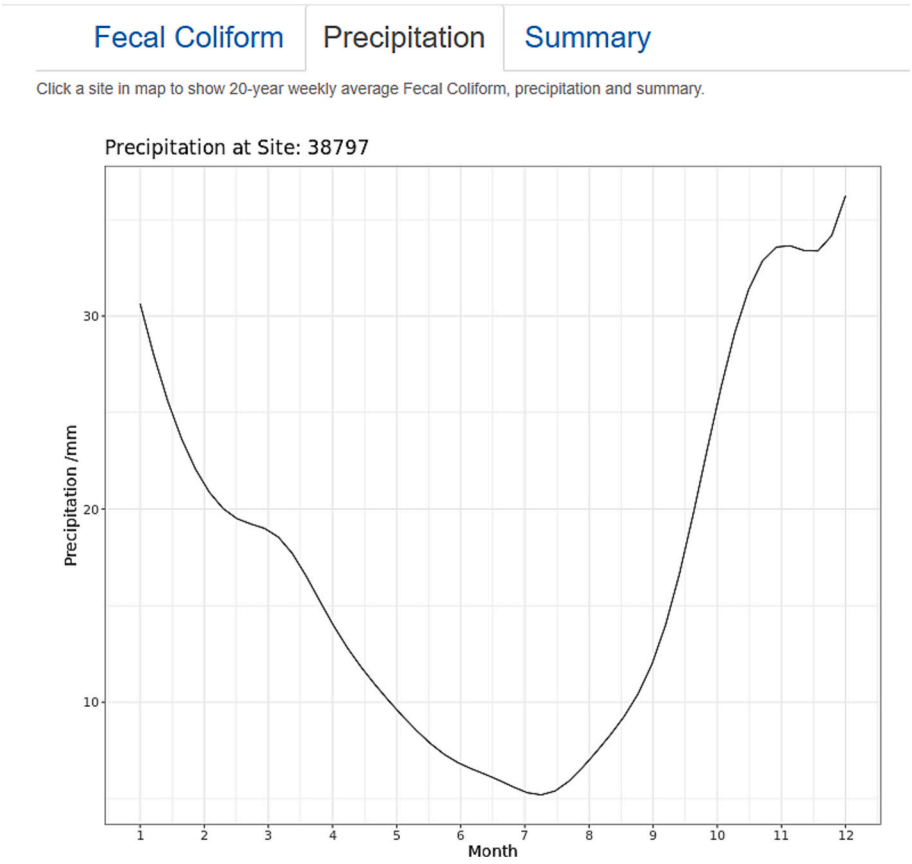


Fig. 4. Site precipitation, after selecting a site on the map, clicking the precipitation button at the top of the right panel in Fig. 2 displays the approximated precipitation pattern at the site over the year. Here is the precipitation curve at Site 38397 in BC.

3.1. Role of functional principal component analysis

FPCA was applied previously to identify large-scale seasonal and spatial trends in fecal coliform and biotoxin levels across Canada's six coastal provinces (You et al., 2024a; You et al., 2024b; You et al., 2023). Since FPCA was a key analytical method used in those studies, we provide here a brief discussion of the method. Principal Component Analysis (PCA) is a conventional method in many data analyses, especially for dimension reduction. PCA assumes complete and regularly spaced data. Whereas the functional version of PCA is more flexible. FPCA accommodates missing values by representing observations as continuous functions (Carroll et al., 2020). This approach preserves temporal and spatial continuity and ensures meaningful trend extraction despite data irregularities. Moreover, FPCA reduces the complexity of large datasets by focusing on a few dominant functional principal components, enabling noise reduction and robust pattern discovery. FPCA effectively addresses challenges posed by sparsity and irregularity in the datasets, such as those from the Canadian Shellfish Sanitation Program (CSSP). It identifies dominant variation patterns, such as seasonal peaks, and quantifies them through functional principal components (FPCs). Our previous studies indicate that FPC1 mainly explains the variance associated with the amplitude of pollutant levels (You et al., 2024b). In OPMS, FPC scores at individual monitoring sites reveal the strength and characteristics of temporal patterns, such as peak seasons of a pollutant.

3.2. Utilization in different regions

To demonstrate the practicality of OPMS, we provide the following use cases to help readers find and understand the distribution of fecal coliforms and biotoxins through the FPC scores. OPMS utilizes FPC scores derived from FPCA to evaluate pollution levels at various sites, which are then geographically mapped using the Leaflet package (Agafonkin, 2010). The gradient of the FPC1 score, ranging from red to blue, intuitively represents pollutant levels. To demonstrate the OPMS data utilization, we selected sites based on their pollutant levels. In British Columbia (Fig. 6), for example, adjusting the main panel to focus on severely polluted areas and selecting sites with dark red FPC1 scores highlights areas with high fecal coliform levels, such as Departure Bay and Comox, or areas with high biotoxins levels, such as Nuchatlitz, Esperanza Inlet, and Port Eliza. Dark blue FPC1 scores for the three pollutants indicate areas of consistently low pollutant levels, such as Sykes Island and Lund. Similarly, in the Atlantic province of New Brunswick (Fig. 7), sites like Baie De Shippagan, which has moderate fecal coliform concentration but low biotoxin concentration, and Hills Island, which has low fecal coliform concentration but high biotoxin concentration.

In British Columbia, the high levels of fecal coliforms in Departure Bay and Comox, are attributable to their location in the Strait of Georgia which is nearby densely populated areas. In addition, there are large river systems with drainage areas such as the Fraser River that include agricultural lands (Hall and Schreier, 1996). The high fecal coliform in Departure Bay is attributable to the nearby Nanaimo's dense population and infrastructure, which significantly contribute to elevated levels of pollutants such as pet waste and human fecal matter carried by stormwater runoff (Sanders et al., 2013) into the bay (Novotny, 2002). The analysis of stormwater runoff on southern Vancouver Island demonstrates that fecal coliform levels are influenced by climatic variables such as precipitation and temperature, with higher levels typically occurring during wetter seasons (Xu et al., 2019). High precipitation events are a key driver of fecal pollution, as stormwater runoff introduces fecal pollutants from urban areas, agricultural lands, and malfunctioning septic systems into coastal waters (Lam et al., 2020).

a) Fecal Coliform | Precipitation | Summary

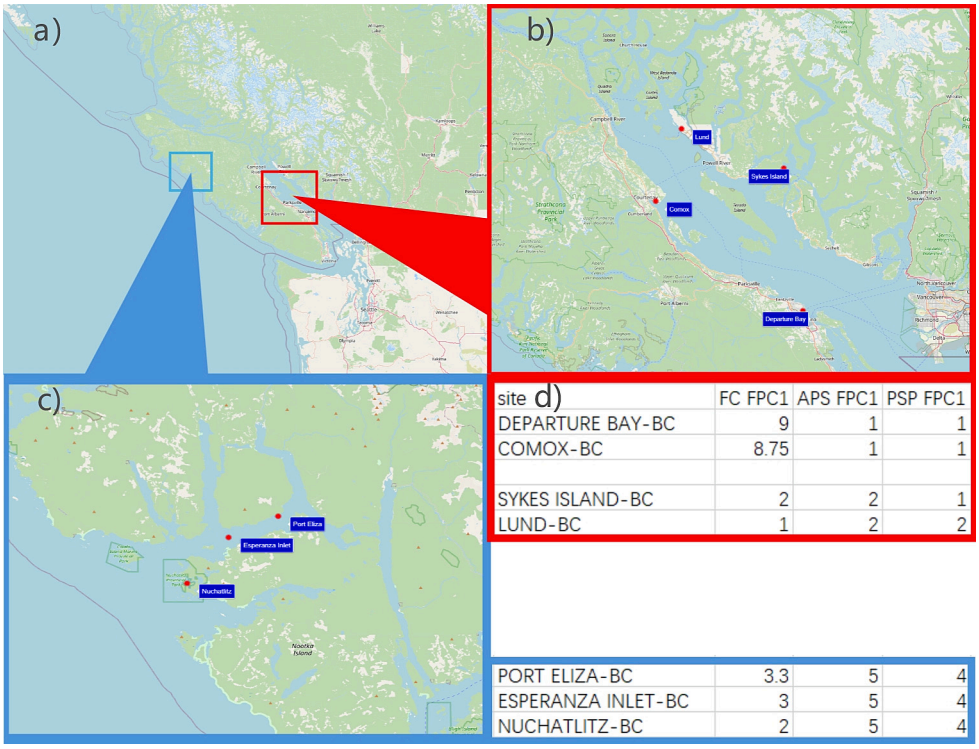
Click a site in map to show 20-year weekly average Fecal Coliform, precipitation and summary.

Name	Value
longitude and latitude	49.1519,-123.904
Site ID	38797
Correlation between approximated FC and Precipitation Levels	0.7
P value of Correlation between approximated FC and Precipitation Levels	2.94e-08

b) Biotoxin Level | Summary

Name	Value
Province	BC
Site Name	WALTERS COVE-BC
Max Biotoxin Level	1.18 µg/g

Fig. 5. Detailed information at a site. a) a summary of fecal coliform at site 38797 in BC. At each site, click "summary" to show sector and site ID and correlation values between approximate levels of fecal coliforms with approximate levels of precipitation considered significant the ($p < 0.05$) (You et al., 2023). b) a summary of biotoxins at the site Walters Cove in BC. At each site click "summary" to show province and location information with max biotoxin level.



site	FC FPC1	APS FPC1	PSP FPC1
DEPARTURE BAY-BC	9	1	1
COMOX-BC	8.75	1	1
SYKES ISLAND-BC	2	2	1
LUND-BC	1	2	2
PORT ELIZA-BC	3.3	5	4
ESPERANZA INLET-BC	3	5	4
NUCHATLITZ-BC	2	5	4

Fig. 6. FPC1 scores for seven sites in BC. The b) shows the location of two sites that have high-level FPC1 scores for fecal coliform, Departure Bay and Comox; two sites that have low-level FPC1 for all three pollutants, Sykes Island and Lund. The c) shows the location of three sites that have high-level FPC1 scores for biotoxins: Nuchatlitz, Esperanza Bay, and Port Elizabeth. The d) shows summary and FPC1 scores for three pollutants across each of these seven sites.

Fig. 7. FPC1 score for two sites in NB. Baie De Shippagan has mid-level fecal coliform with low-level biotoxin (FC:6.3, ASP:1 PSP:1). Hills Island has low-level fecal coliform with high-level biotoxin (FC:3.6, ASP:5 PSP:5).

Impervious surfaces in urban areas exacerbate this by preventing water infiltration and increasing pollutant transport during rainfall (Moazzem et al., 2024). In Comox of BC, high levels of fecal coliform bacteria are also primarily attributable to urban runoff and aging septic systems (Comox Valley Regional District, n.d.). Residential development and outdated septic systems significantly contribute to fecal pollution. The Comox Lake watershed, including the Tsolum and Puntledge Rivers, has a significant impact on the hydrology of the bay, carrying runoff from surrounding mountains into the bay and affecting water quality (Epps and Phippen, 2011). The fecal coliform levels along the east coast of Vancouver Island are notably higher in urbanized areas due to increased human activities and urban runoff (Yang et al., 2021; Zhang et al., 2020). To address high fecal coliform levels in areas like Departure Bay, the wastewater infrastructure and stormwater management systems need to be upgraded to prevent leaks and reduce urban runoff (United States Environmental Protection Agency, n.d.).

Conversely, the Strait of Georgia typically exhibits moderate levels of biotoxins such as PSP and ASP due to several key factors. The Strait of Georgia benefits from more dynamic water circulation compared to enclosed bays, and this effective water exchange helps disperse pollutants and nutrients, reducing the accumulation that supports harmful algal blooms. Tidal flushing and interactions with the open Pacific Ocean prevent nutrient buildup, which is critical in mitigating the proliferation of toxin-producing algae (Praveena et al., 2015). Additionally, many areas along the Strait of Georgia are surrounded by natural vegetation and forested regions that act as buffers, filtering runoff before it enters the marine environment. These natural buffers help maintain lower levels of fecal coliform and reduce nutrient influx, thus limiting conditions that favor harmful algal blooms (Trainer et al., 2012). Agricultural runoff, a significant source of nutrient enrichment, is less intense in many parts of the Strait of Georgia compared to more urbanized coastal regions. Effective land management practices and lower agricultural activities contribute to reduced nutrient loads entering the water (Xu et al., 2019).

In contrast, Nuchatlitz, Esperanza Inlet, and Port Eliza on the west coast of Vancouver Island are relatively undeveloped and experience minimal human impact. The surrounding natural vegetation and forested areas act as buffers, filtering runoff before it enters the marine environment, thereby maintaining low levels of fecal coliforms. Although occasional elevated fecal coliforms have been observed near logging areas, especially when heavy rains lead to rapid flushing, high rates of water exchange with the open Pacific Ocean help disperse potential pollutants, preventing their accumulation (Island Health, n.d.). However, these areas can experience high levels of biotoxins such as PSP and ASP due to several factors. This is probably due to upwelling nutrients and favorable conditions for harmful algal blooms (Ríos-Castro et al., 2023). The strong tidal currents that can bring in nutrient-rich waters favor the growth of harmful algae that produce PSP and ASP toxins, leading to elevated biotoxin levels. Several studies have documented upwelling events off the west coast of Vancouver Island, providing valuable data on this phenomenon (Freeland and Denman, 1982; Jardine, 1990). For instance, Jardine identified wind-driven upwelling near Brooks Peninsula during the summers of 1988 and 1989, utilizing NOAA AVHRR thermal imagery to characterize surface cooling associated with upwelling (Jardine, 1990). Additionally, Freeland and Denman observed a seasonal upwelling center off southern Vancouver

Island over a three-year period, analyzing its dynamics and contributing factors (Freeland and Denman, 1982). Ikeda and Emery further examined a continental shelf upwelling event in this region, employing infrared satellite imagery to track sea-surface temperature patterns during upwelling-favorable winds in the summer of 1980 (Ikeda and Emery, 1984). While upwelling events bring nutrient-rich waters to the surface, promoting the growth of harmful algae, other environmental factors also play critical roles (Smith, 1992). Factors like temperature and salinity significantly affect algal bloom dynamics, with specific ranges favoring toxin-producing algae (Record et al., 2019). Riverine inputs, in addition to upwelling, contribute nutrients to coastal systems, supporting algal blooms. There are several reports of high toxin production associated with low nutrient levels (Lee et al., 2024; Pan et al., 1996). It is most likely that the period of low nutrient levels followed an active growth of the algal population, such as harmful algal blooms that would consume and deplete nutrients. In such a stress condition, the production of biotoxins is triggered (Pan et al., 1998). Organic nutrients, such as dissolved organic nitrogen (DON), may sustain algal proliferation even when inorganic nutrients like nitrate and phosphate are depleted (Anderson et al., 2002). Natural filtration by coastal vegetation, including wetlands, mangroves, and salt marshes, plays a crucial role in mitigating some pollutants by trapping sediments and absorbing excess nutrients and pollutants (Greenfield et al., 2006). These ecosystems stabilize shorelines, provide habitat for wildlife, and contribute to carbon sequestration, but they do not prevent the nutrient inputs from upwelling which can lead to HABs (Richlen et al., 2010). Additionally, effective tidal flushing and water exchange with the open ocean bring nutrients, supporting harmful algal blooms (Leight et al., 2018). These insights highlight the need for holistic nutrient management strategies that consider multiple nutrient sources. Also, these dynamics explain the low levels of fecal coliform but high levels of biotoxins in the west coast regions of Vancouver Island and the contrasting conditions in the Strait of Georgia.

In New Brunswick, Baie De Shippagan is characterized by a variety of marine habitats, including estuaries, salt marshes, and sandy shorelines, which support diverse aquatic life such as fish, shellfish, and seabirds (Nature Trust of New Brunswick, n.d.). The area also hosts human activities such as fishing, aquaculture, tourism, and small-scale shipping, all of which can contribute to pollution pressures (Leroux, 2013). Also, temperature influences fecal coliform dynamics, warmer seasons promote bacterial growth and persistence, while colder conditions limit microbial activity (Shaheduzzaman et al., 2016). Despite these influences, the fecal coliform levels in Baie De Shippagan remain moderate, largely due to a robust water quality monitoring system that enables timely interventions and effective management practices, helping to maintain water quality (Government of New Brunswick, n.d.), upgrading and replacing aging septic systems is critical to prevent leaks and improve wastewater treatment in residential areas, implementing stricter regulations and providing financial incentives for homeowners to modernize their systems can reduce pollution. Similarly, Hills Island on the Atlantic coast, known for its relatively pristine environment, benefits from natural filtration systems like wetlands and dense seagrass beds, which help to keep fecal coliform levels low. Hills Island's extensive vegetation and undisturbed landscapes act as natural filters, maintaining low fecal coliform levels. However, this region experiences high biotoxin levels. Petrie and Drinkwater examine upwelling phenomena along the Atlantic coast, including regions adjacent to New Brunswick, which bring nutrient-rich waters to the surface, fueling the growth of harmful algae that can produce toxins (Petrie and Drinkwater, 1993). Although the interaction between the Gulf Stream and the Labrador Current ensures regular flushing and nutrient dispersal reducing fecal pollution but creating favorable conditions for harmful algal blooms. Competing phytoplankton and zooplankton can sometimes suppress harmful algae, but when conditions favor toxic species, biotoxins can become concentrated (Ohio Water Resources Center, 2021). These dynamics explain the low levels of fecal coliforms but high levels of biotoxins observed in these regions. These use cases illustrate a comprehensive overview of the variation patterns of the pollutants in relation to regional environmental and climate conditions. This provides a support to managemental decision-making in scheduling shellfish harvesting and recreation activities.

4. Concluding remarks

The OPMS web application offers an interactive visualization for analyzing the suitability of coastal business development. It provides an integrated platform that combines environmental monitoring with advanced statistical analysis, facilitating a deeper understanding of the factors influencing pollutant levels. The dynamic mapping and data visualization capabilities of OPMS enable users to identify pollution hotspots, track seasonal and spatial trends, and correlate pollutant levels with environmental variables.

Understanding pollutant levels at various coastal locations is crucial for environmental management. Monitoring fecal coliforms and biotoxins helps pinpoint potential pollution risks. Environmental experts can utilize this data to identify highly affected areas and potential sources of pollution such as sewage system failures or agricultural runoff, versus those which are primarily influenced by seasonal environmental and climate variability. Effective identification of these sources facilitates targeted interventions and remedial measures. Moreover, recognizing areas with elevated levels of pollution enables authorities to issue health advisories, close shellfish harvesting areas, and educate the public on associated risks, thus protecting health and guiding policy development.

Future enhancements to the Ocean Pollution Monitoring System (OPMS) could significantly improve its utility for users by incorporating several functional upgrades. One key improvement would be to encourage government agencies to provide more dynamic access to their datasets through APIs. This would automate calculations and statistics, ensuring that the tool delivers the most recent and up-to-date results. By enabling researchers to access real-time data, this feature would foster deeper analysis and a better interpretation of ecological phenomena. Additional enhancements could include an option for users to select and focus on specific sites by entering a Site ID, facilitating more detailed and site-specific analysis. Users could also benefit from a feature that allows them to filter and view groups of sites based on specific fecal coliform and biotoxin (FPC) scores, making it easier to target areas of concern. Moreover, a dynamic map selection tool could allow users to select a portion of the map to focus on, enabling more geographically specific analysis. These proposed improvements aim to provide users with greater control over the data they view and analyze, thereby increasing the OPMS's effectiveness in environmental monitoring and management.

By providing access to comprehensive environmental datasets and visualizing key pollution trends, OPMS serves as a transformative platform that empowers stakeholders to make informed decisions, enhancing coastal water quality management, reducing pollution risks, and protecting public health. Beyond its immediate applications in monitoring fecal coliforms and biotoxins, OPMS sets a precedent for leveraging data-driven tools in broader environmental management contexts. The methodologies and insights presented in this paper provide an example for other regions with historic monitoring data, fostering comparative studies and cross-regional collaborations. Moreover, OPMS highlights the importance of integrating science with policy, bridging the gap between data collection and practical implementation. It can influence future developments in marine monitoring programs by demonstrating the value of centralized, publicly accessible platforms for environmental data. In summary, OPMS not only addresses pressing challenges in marine pollution in Canada but also provides a scalable framework for tackling broader environmental issues. It represents a significant step toward fostering innovation in environmental monitoring, empowering diverse stakeholders, and influencing related

research and policy initiatives to achieve sustainable coastal management.

CRediT authorship contribution statement

Zhaoze Liu: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis. **Shuai You:** Writing – review & editing, Formal analysis. **Li Xing:** Writing – review & editing, Supervision, Conceptualization. **Guillaume Durand:** Writing – review & editing, Resources. **L. Paul Moccia:** Writing – review & editing, Data curation. **Vincent Mercier:** Writing – review & editing, Resources. **Youlian Pan:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization. **Xuekui Zhang:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

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Declaration of competing interest

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Data availability

The data that has been used is confidential.

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