



# A GIS-based software for forecasting pollutant drift on coastal water surfaces using fractional Brownian motion: A case study on red tide drift



Rufu Qin<sup>a</sup>, Liangzhao Lin<sup>a,\*</sup>, Cuiping Kuang<sup>b</sup>, Tsung-Chow Su<sup>c</sup>, Xiaodan Mao<sup>b</sup>, Yusheng Zhou<sup>a</sup>

<sup>a</sup> State Key Laboratory of Marine Geology, Tongji University, Shanghai, China

<sup>b</sup> Department of Hydraulic Engineering, College of Civil Engineering, Tongji University, Shanghai, China

<sup>c</sup> Department of Ocean & Mechanical Engineering, College of Engineering & Computer Science, Florida Atlantic University, Boca Raton, FL 33431, USA

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## ABSTRACT

For ocean pollution emergencies, decision-makers need to quickly know the location of the pollutant for quick assessment and response strategies. In this study, an integrated operational forecasting model coupling a non-Fickian particle-tracking diffusion model based on fractional Brownian motion and geographic information system (GIS) has been developed to implement an operating system for pollutant drift forecasting. The software was developed in C# and C++ language using ArcGIS Engine functions which provides improved visualization and user-friendly and automatic tools for simulation in a geographically referenced environment. The capabilities and effectiveness of the developed software were illustrated by predicting red tide drift through calibration with field observations. This visualized operational forecasting software provides a quick and easy deployable tool for decision-makers in quick response to emergency ocean pollution events.

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## Software availability:

Name of software: Pollutant Drift Forecast GIS (PDFGIS)

Version: 1.0

Software required: MS Windows (tested on Windows 7), ArcGIS Engine 10.1 Runtime License, Net Framework4.0

Programming language: MS visual studio 2010.net C#, C++

Availability: Restricted. Contact authors for details

## 1. Introduction

In recent years, pollution emergencies in coastal waters have become an important environmental issue that affects coastal and marine life causing ecological degeneration and economic loss. In

order to give response teams an opportunity to respond rapidly to an incident and minimize the environmental and economic impact of a pollutant, a fast simulation with trends for the spread of the pollutant is needed.

The problem of efficient methods for predicting and visualizing pollutant diffusion and drift trajectories in water using numerical models have obtained increasing attention from researchers in the marine science community (Pollani et al., 2001; Daniel et al., 2005; Carracedo et al., 2006; Hackett et al., 2006; Liu and Weisberg, 2011; Minguez et al., 2011; Sayol et al., 2014). In this work, we focus on providing a very fast pollutant drift prediction and an interactive visualization tool.

The types of pollutant concerned in this study can be classified in two categories: (a) substances continuously released from a pollution source for a relatively long duration; (b) substances that are instantaneously released, i.e., a pollutant load is abruptly discharged over a very short period of time (Mainardi Fan et al., 2015). Although pollutants in both categories are released differently, accurate modeling for both requires knowledge of the physical conditions in the ocean, chiefly currents (Hackett et al., 2006). Neglecting viscous effects, researchers have indicated that the

\* Corresponding author. State Key Laboratory of Marine Geology, Tongji University, Shanghai 200092, China.

E-mail addresses: [qinrufu@tongji.edu.cn](mailto:qinrufu@tongji.edu.cn) (R. Qin), [86774994@qq.com](mailto:86774994@qq.com) (L. Lin), [cpkuang@tongji.edu.cn](mailto:cpkuang@tongji.edu.cn) (C. Kuang), [su@fau.edu](mailto:su@fau.edu) (T.-C. Su), [daniel\\_071103@163.com](mailto:daniel_071103@163.com) (X. Mao), [zhou-yusheng@foxmail.com](mailto:zhou-yusheng@foxmail.com) (Y. Zhou).

diffusion of pollutants in coastal waters mainly involve two movements: advection and turbulent diffusion (Qu, 2003; Sayol et al., 2014).

In the course of a simulation, in general, the pollutant can be represented as a set of particles. A particle-tracking model based on advection-diffusion is commonly used for describing pollutant drift. However, the prediction of turbulent diffusion on the coastal water surface is a complex with uncertainties, and one way of accounting for uncertainties is using a stochastic framework. A number of research studies have employed a Lagrangian stochastic model by means of a Brownian random walk process to establish the particle-tracking model to simulate turbulent diffusion of particles (Proehl et al., 2005; Abascal et al., 2009; Minguez et al., 2011; Sayol et al., 2014; Otero et al., 2015). Such models assume that particle tracks are neutrally persistent, i.e. the particles execute simple random walks, which can only be modeled by Fickian diffusion. However, some studies and field observations have demonstrated that particle movement is persistent on the ocean surface (Qu, 2003). To simulate persistent motion, a non-Fickian diffusion model based on fractional Brownian motion (fBm) has been integrated to predict the diffusion of particle clouds. It has been found that the shape of trajectories are better represented by the fBm particle-tracking model as opposed to the ordinary Brownian model (Guo et al., 2012).

A model provides a way to understand and predict the behavior of natural systems. However, adopting some models may be difficult due to hard to understand outputs, which limits further analysis on the model results. Thus, models cannot be fully utilized by a non-expert. The outputs of model mostly involve spatial data. Therefore, in the past few decades, significant effort has been devoted to make pollutant dispersion modeling applications more accessible by integrating them with geospatial technologies such as GIS. Naoum et al. (2005) designed a GIS pre-processor within ArcView GIS to produce inputs for pollutant transport modeling to simulate the currents and pollutant transport in lakes and coastal areas. Tuama and Hamre (2007), Kulawiak et al. (2010) developed web-GIS for marine pollution monitoring and forecasting to facilitate the integration, visualization and distribution of multi-source monitoring data and results from numerical model. Zhang et al. (2011) proposed a GIS framework coupled with a water quality model to simulate the temporal-spatial changes of pollutant concentration. Liu et al. (2014) coupled a distributed diffuse pollution model with a GIS and concluded that the fully integrated approach can avoid tanglesome data exchange and more robust than loose coupling approaches. Maantay et al. (2009) and Xu et al. (2013) integrated virtual geographic environment to facilitate air pollution simulation.

The fBm model has a primary focus on pollutant dispersion modeling while GIS is a powerful tool for spatial data visualization and management. By combining the fBm model and GIS into a single framework, it is possible to provide a visualization tool for quick drift forecasting. However, up to now, the two systems have not been well integrated and there has been no work on developing such a GIS-based software. One key goals of this study is combine these two technologies to create a software tool able to support the simulation of pollutant drift. The software application for the temporal-spatial simulation of particle-tracking, named Pollutant Drift Forecast GIS (PDFGIS), was developed in a Windows system environment based on Component GIS technology. This provides an interactive and user-friendly interface for pollutant drift simulation in a geographically referenced environment, in the form of time-varying thematic layers overlaid on background marine and land data.

The remainder of this paper is organized as follows: Section 2 gives a general description of the mathematical equations used to

simulate the drift processes of a pollutant. Section 3 discusses the integration methodologies and outlines the general framework of the GIS integration with a fBm particle-tracking diffusion model as well as develops and implements the software. Section 4 conducts a case-based efficiency and operation test of the software. Section 5 summarizes the conclusions.

## 2. The fBm particle-tracking diffusion model formulation

A brief description of the fBm particle-tracking diffusion model is provided in this section; for more details refer to citations presented in each of the subsections. The fractional Brownian motion is defined by its stochastic representation in Mandelbrot and van Ness, 1968.

$$B_H(t) = \frac{1}{\Gamma(H + 1/2)} \int_{-\infty}^t (t-s)^{H-1/2} dB(s) \quad (1)$$

where  $\Gamma$  represents the Gamma function  $\Gamma(a) = \int_0^{\infty} \exp(-x) dx$  and  $0 < H < 1$  is called the Hurst parameter. The integrator  $B$  is a stochastic process representing ordinary Brownian motion (Dieker, 2004). Some authors have proposed a more practical fractional Brownian motion model developed from Eq. (1). This is defined by (Addison, 1996; 1997, 2000; Qu, 2003):

$$B_H(i) - B_H(i-1) = \frac{1}{\Gamma(H + 1/2)} \left\{ \sum_{j=i-M}^{i-2} [(i-j)^{H-1/2} - (i-j-1)^{H-1/2}] R(j) + R(i-1) \right\} \quad (2)$$

$$B_H(t_i) - B_H(0) = \sum_{i=1}^{t_i} [B_H(i) - B_H(i-1)] \quad (3)$$

here  $B_H(t_i)$  is the  $i$ th discrete approximation to the fBm at time  $t_i = \Delta t \cdot i$ , and  $\Delta t$  is the discrete time step used.  $M$  is the limited memory used in the approximation of the fBm.  $R(i)$  are the random steps discretely sampled from a Gaussian probability distribution.

In the fBm model, the drift process of pollutant on the coastal water surface is controlled by horizontal advection and turbulent diffusion. At each time step, the position of particle is computed by the superposition of the advective component (induced by current and wind) and the turbulent diffusive component, i.e. the increment of fBm. For an individual particle, which represents a certain amount of the simulated substance, the numerical model solves the following equations (Qu, 2003; Guo et al., 2012; Otero et al., 2015):

$$\Delta x(i) = u_c(i)\Delta t + C_d u_w(i)\Delta t + \Delta B_x(i) \quad (4)$$

$$\Delta y(i) = v_c(i)\Delta t + C_d v_w(i)\Delta t + \Delta B_y(i) \quad (5)$$

$$x_{i+1} = x_i + \Delta x(i) \quad (6)$$

$$y_{i+1} = y_i + \Delta y(i) \quad (7)$$

where  $\Delta x(i)$  is the increment of the particle's position, and  $u_c(i)$ ,  $v_c(i)$  are the current velocities in  $x$  and  $y$  directions respectively, and  $u_w(i)$ ,  $v_w(i)$  are the wind velocities at 10 m above the water surface in  $x$  and  $y$  directions respectively.  $C_d$  is the wind drag coefficient. Generally, the wind drag coefficient  $C_d$  takes a value between 0.025

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