Modeling of Faecal Contamination in Water from Catchment to Shellfish Growing Area

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During rainstorms, watersheds can introduce large amounts of faecal pollution into the rivers and sea, leading to shellfish contamination. In this study, we assessed *Escherichia coli* fluxes from a catchment, and their impact on estuarine water quality, using two assembled models. For the catchment, the agro-hydrological model SWAT was implemented integrating land uses, soil, topography, rainfall and other climatic data on Daoulas watershed (France). Initially, the SWAT model was calibrated and validated for river flow rates, and results were found satisfactory. Subsequently, different faecal contamination sources were integrated into the model: point sources (WWTP discharges into rivers) and non-point sources (manure spreading on fields). During rainfall events, the major source of contamination was manure spreading, due to the movement of faecal bacteria from fields to streams. For the estuary, the hydrodynamic model MARS-2D was set up, which takes into account realistic wind and tide values. *E. coli* concentrations in water were then calculated, and shellfish contamination derived using different values of bioaccumulation ratio. Results indicated a strong relationship between simulated and measured levels of shellfish contamination. To conclude, this application demonstrates the interest of using models to assess coastal contamination.

Keywords : Modeling, SWAT, MARS, E. coli, Shellfish, Catchment, Estuary

Introduction

Pathogens implicated in shellfish contamination episodes originate from wastewater treatment plants, septic tank effluents and urban and agricultural stormwater. Livestock waste is a primary source of bacteria and pathogens on agriculture land, and *E. coli* levels in streams have been directly related to the presence of livestock (Aitken *et al.*, 2001) and manure spreading on arable land (Crowther *et al.*, 2002). Stormflows are known to flush large amounts of faecal pollution from land sources into river bodies and/or estuaries downstream, leading to degradation of shellfish quality (Davies-Colley and Lydiard, 2008). According to EU regulations, it is of the utmost importance to determine the origin of such contamination and to conduct remedial action. Many studies have been performed to address this issue. Some have taken an empirical approach, using regression models (Kay *et al.*, 2005), distributed models (like the GIS-based transport model Fraser R. H. *et al.*, 1998) or semi-distributed models (Baffaut and Benson, 2003; Benham *et al.*, 2006) to study the origin of the fecal contamination variability in streams. Additionally, in coastal areas, hydrodynamic models have been set up to assess the impact of *E. coli* fluxes on water and shellfish quality (Riou *et al.*, 2007). The applications demonstrated that shellfish quality is the result of mixing conditions between tidal currents, dilution and river input (Pommepuy *et al.*, 2005). In this study we investigated the possibility of associating two models (SWAT on the catchment and MARS 2D in the sea) to assess shellfish contamination in the Daoulas estuary.

Materials and Methods

The Daoulas catchment flows into an estuary devoted to shellfish activities. Daoulas is representative of Brittany catchments and is the subject of long-term shellfish monitoring (REMI) and environmental studies (Pommepuy *et al.*, 2008) to document environmental improvements as best management practices are increasingly adopted (Figure 1).

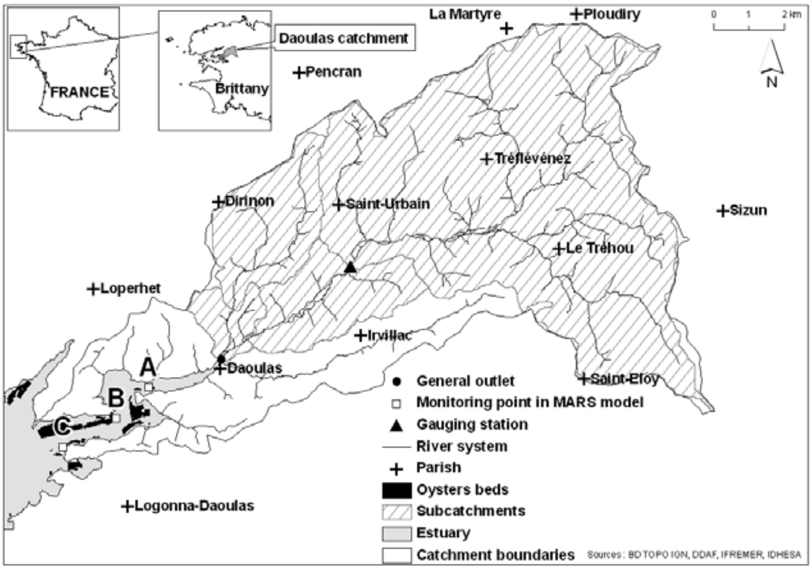

Figure 1. Daoulas catchment and estuary

La Mignonne river (catchment area 113 Km^2) flows into the Daoulas estuary (Bay of Brest) where dilution and currents are governed by oceanic conditions (high tidal ranges from 3 to 5 m, depending on weeks). The catchment has a slightly sloping topography (75

% of the catchment is at less than 6 m) and about 69 % of land cover on the watershed is agricultural (44 % cultivated, 25 % pasture), while 20 % is covered by forest and 10 % by urban areas. This region receives about 700 mm/yr of rainfall and the river export shows a mean flow of 1.45 m^3/s (median flow 1.50 m^3/s). The estuary is classified B for oysters according the European Directive (EC/854/2004 modified by regulation EC/1666/2006) and sustains local economic activity, primarily engaged in shellfish farming. Shellfish quality monitoring has been conducted at monthly intervals for several decades (REMI: wwz.ifremer.fr/envlit/ surveillance/microbiologie_sanitaire). This on-going monitoring was supplemented by a 12-month water assessment campaign of targeted storm-flow sampling for *E. coli* in rivers (Jan 2007-Fev 2008). *E. coli* was analyzed with the technique NF EN-ISO 9308-3. Forecasting information (mainly daily rainfall) was obtained from two local Meteo-France stations (Guipavas and Sizun).

The Soil and Water Assessment Tool (SWAT), is a watershed-scale process-based model developed by the USDA Agricultural Service (Arnold *et al.*, 1998); in this study it was used with the ArcGIS interface. The bacteria transport routine was added to the SWAT model in 2002 (Neitsch *et al.*, 2002), so as to address microbial contamination of water caused by point and non-point sources. The model processes continuously on a daily time step. It was implemented for the Daoulas catchment integrating land use, soil, topography, rainfall and other climatic data.

The microbial survival transport sub-model uses a first decay equation (Moore et al, 1989):

$C_t = C_0 \times e(-K_{20} t \theta^{(T-20)})$, where C_t and C_0: bacterial concentration at t and t_0; K_{20}: decay rate at 20°C (d-1); t: exposition time (day); θ: temperature adjustment factor; and T: temperature (°C).

MARS-2D (Model for Application at Regional Scale), was used for simulating the dispersion and dilution of the plume in the estuary. This is a hydrodynamic model created by IFREMER (Lazure and Dumas, 2008), incorporating realistic wind and tide values and a die-off rate for bacteria (see Riou et al, 2007 for details).

The simulation was realized from 01 February to 31 July 2007. The daily *E. coli* fluxes calculated by SWAT consider point and non point sources. The *E. coli* concentrations from the wastewater treatment plants (four biological treatment plants are located on the watershed) were estimated at a mean of 8.8×10^4 *E. coli*/100 ml. Faecal contamination from agricultural practices was assessed to be mainly linked to run-off from manure spread on fields, and was estimated from quantity of manure produced on local farms and practices that follow the local regulation (no spreading is allowed when rainfall is more than 5mm/day; spreading is forbidden from July to January, 15^{th}). Table 1 shows the main parameters introduced in the model to set up the spreading scenario and to assess bacterial contamination from river to shellfish beds.

In a previous study, the bacterial model was first calibrated and validated for river flow and *E. coli* concentrations in river with good results (Bougeard *et al.*, 2010; Bougeard *et al.*, Submitted); their results showed that the SWAT model has good potential to reproduce the river flow well at different points on the catchment and that it makes a good reproduction of contamination levels.

In this present study, the bacterial model was calibrated with monthly shellfish samples (point B). A frequency analysis method was used to compare measured data (N=162) with predicted data for fecal concentrations in shellfish

Table 1: Input characteristics for E. coli simulation in SWAT and MARS-2D.

Urban sources: WWTP discharges	
E. coli concentrations	8.8×10^4 *E. coli*/100 ml
Discharge flow	From 68 m^3/day (400 inhabitant equivalent) to 324 m^3/day (1900 inhabitant equivalent).
Agricultural sources	
Livestock	
- Bovine	2458 animal population
- Swine	59 877 animal population
- Poultry	293 400 animal population
E. coli concentration in manure	1.42×10^5 *E. coli*/g
Spreading areas (% of entire catchment)	29 %
Quantity of spread manure on field	30T/ha
Spreading conditions	
	- On pastures (6 cm of range-grasses)
	- Days with rainfall below 5 mm
	- From 01/15 to 06/30
Bacterial parameters	
Shellfish/water concentration ratios	10, 30 and 100
Die-off ($days^{-1}$)	0.35

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Results

Figures 2 and 3 show the dispersion plume of *E. coli* in the estuary. Water contamination depends on the flux of the river □ itself influenced by rainfall □ and tidal conditions. Examples of the impact of heavy rainfall are illustrated: these events are rare and rainfall superior to 30mm/day represents only 0.6 % of daily rainfall from 2000 to 2006. Table 2 presents characteristics of two important rainfall events in terms of catchment discharges with quantity of rainfall, river flow and *E. coli* concentrations in the river.
The 2D representation indicates how and when the shellfish beds are impacted during spring or neap tides. On the Atlantic coast, the tidal currents are subject to lunar attraction, which determines the periods of spring tides, when water level between low and high tides ranges more than 5m, and neap tides, when the range is 2 m or less.

Figure 2 presents the *E. coli* concentration plume on 06/25/07; this occurred during a neap tide, one day after there was a rainfall event of 45.4 mm/day. During neap tide, estuarine water covers the oyster beds for longer than during spring tide. Thus, this situation leads to a longer exposure of shellfish to contaminated water. Figures 2a and 2b present the plume at high tide (midday) and low tide (6:00 pm), respectively.

Table 2: Catchment discharges characteristics for two important rainfall events

	Date	Rainfall amount	River flow (m^3/s)	*E. coli* concentrations (log10 cfu/100 ml)	*E. coli* loads (log 10 cfu/day)
Figure 2 Neap tide	06/24/2007	45.4	9.54	4.11	9.09
	06/25/2007	7.8	11.9	4.01	9.09
Figure 3 Spring tide	03/05/2007	30.8	12.9	3.74	8.85
	04/05/2007	6.2	11.6	3.53	8.59

At high tide, the upper estuary is impacted by the river discharge. Upstream, at point A, the concentration reaches 10^4 to 10^5 *E. coli*/100 ml and in the middle of estuary the concentration ranges from 10^2 to 10^4 *E. coli*/100 ml. This level of water contamination is very high compared with levels recommended by USA regulations to ensure good shellfish sanitary quality (14 cfu/100 ml). At point C, there is no impact at high tide considering that contamination levels are about 10^{-1} to 10^0 *E. coli*/100 ml. At low tide, however, as the plume moves toward the downstream area of the estuary, an increase in *E. coli* concentration is observed up to 10^2 to 10^3 at point C. This level of contamination represents a risk for shellfish quality.

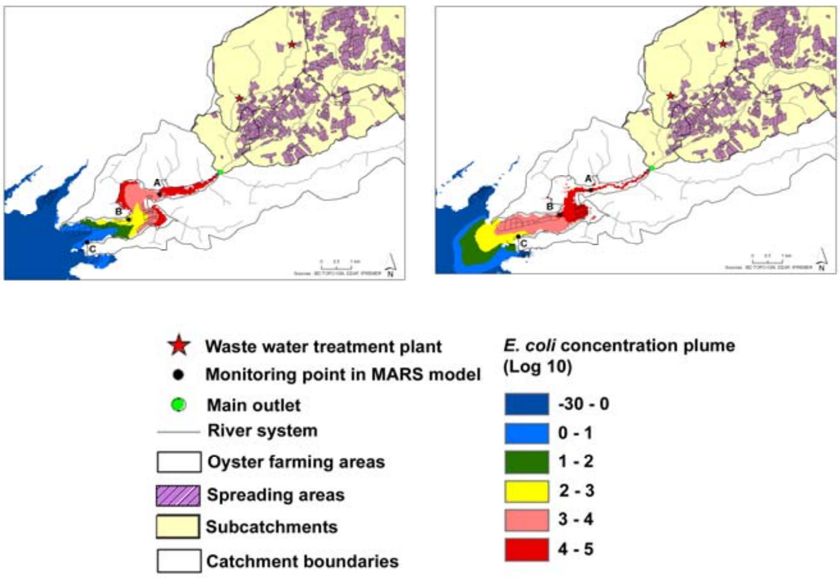
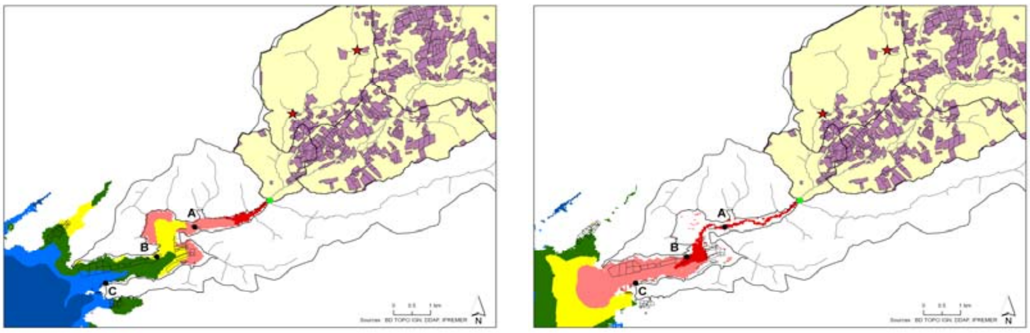


Figure 2. Simulated E. coli concentration plume in Daoulas estuary during neap tide 06/25/07 after a rainfall event (45.4 mm on 06/24/07)

When the rainfall event occurs during a spring tide (03/05/07, 30.8 mm), the shape of the plume is slightly modified (Figure 3). At low tide, the impact of river discharges is slightly greater than during neap tide, with a concentration of 10^4-10^5 *E. coli*/100 ml at points A and B (10^3-10^4 at point C). Indeed, during neap tides, the tidal range is lower than during spring tides (5 m versus 2 m) and, therefore, the time during which shellfish beds are covered by estuarine water is longer. On the other hand, during low tide, the dilution is not efficient enough to avoid contamination. At high tide, high bacterial concentrations re-enter the estuary: 10^3-10^4 are observed at point A, 10^2-10^3 at point B, and 10^0-10^1 at point C.



3a. High tide (6:00 am) *3b. Low tide (12:00)*

Figure 3. Simulated E. coli concentration plume in Daoulas estuary during spring tide 03/06/07 after a rainfall event (30.8 mm on 03/05/07)

E. coli concentration was then assessed in shellfish using different bioaccumulation ratios. Indeed *Crassostrea gigas,* like other molluscs, concentrates microorganisms present in the water overlying shellfish beds. It is currently accepted that bioaccumulation varies with the species of shellfish, type of microorganism, environmental conditions and season (Burkhardt and Calci, 2000 ; Lees, 2000). Figure 4 presents a comparison between the measured and calculated values. A frequency curve analysis method was used to compare measured data from the Ifremer network REMI with predicted data for *E. coli* concentrations in shellfish calculated with three different bioaccumulation ratios (10, 30 and 100) chosen according to the literature (Burkhardt and Calci, 2000 ; Riou *et al.*, 2007). The results showed that a ratio of 30 was more appropriate than 10 or 100. These results are slightly different to those found by Burkardt and Calci (2000) with *Crassostrea virginica*, and could be explained by the differences observed between the two studies in terms of oyster species and climatic conditions. In Daoulas, the results obtained with the model (ratio set at 30) reproduce the REMI classification according EU regulation fairly well: this area is classified 'B', *i.e.*; 90% of the values are lower than 4600 *E.coli*/100g, and 10% are between 4600 and 46000 *E.coli*/100g.

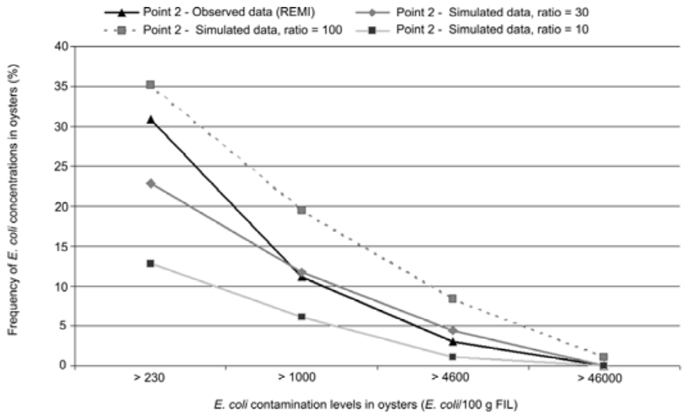


Figure 4. Frequency of E. coli concentrations in oysters (%)
Point B - Measured data (REMI); Point B - Simulated data, ratio=30; Point B - Simulated data, ratio=100; Point B - Simulated data, ratio=10

Conclusion

This paper describes an innovative approach for coastal management applications by coupling watershed and marine models. The benefits of such model combination are numerous and now need to be investigated. For example, concerning hydrodynamics, further studies would allow to analyse fluctuations in residence time considering not only tide, waves, and wind, but also freshwater inflow fluctuations. In general, it is recognized that oscillations in estuaries are mainly due to tide, but taking into account real large flux fluctuation as observed during rainfall period, would modify this finding. From a microbial point of view, the better understanding of residence time will also permit to better appreciate the role of biological factors - i.e. T90 and shellfish cumulative ratio - for managing shellfish areas. This first application represents important progress compared with current modelling approaches. Nevertheless, further investigations are necessary to improve the results. In particular, a larger data base is needed to better validate the bacterial results. Moreover, the possibility to assess the most representative point in estuary would help managers to choose an adequate monitoring point representative of extreme or mean contamination conditions. Once validated, the models would provide managers with decision-making tools that could reduce pollution at its sources. They could also be used to predict events that could otherwise seriously degrade water quality and lead to shellfish contamination and thus help to anticipate any risk to human health by consumption of contaminated shellfish.

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