HENRY
Hydraulic Engineering Repository

Ein Service der Bundesanstalt für Wasserbau

Conference Paper, Published Version

Gracia, Luz; Bacon, John; Campos, Carlos

Modelling the fate and transport of faecal bacteria from sewage overflows: The Dart Estuary case study

Zur Verfügung gestellt in Kooperation mit/Provided in Cooperation with:
TELEMAC-MASCARET Core Group

Verfügbar unter/Available at: https://hdl.handle.net/20.500.11970/105179

Vorgeschlagene Zitierweise/Suggested citation:
Gracia, Luz; Bacon, John; Campos, Carlos (2018): Modelling the fate and transport of faecal bacteria from sewage overflows: The Dart Estuary case study. In: Bacon, John; Dye, Stephen; Beraud, Claire (Hg.): Proceedings of the XXVth TELEMAC-MASCARET User Conference, 9th to 11th October 2018, Norwich. Norwich: Centre for Environment, Fisheries and Aquaculture Science. S. 117-122.

Standardnutzungsbedingungen/Terms of Use:

Die Dokumente in HENRY stehen unter der Creative Commons Lizenz CC BY 4.0, sofern keine abweichenden Nutzungsbedingungen getroffen wurden. Damit ist sowohl die kommerzielle Nutzung als auch das Teilen, die Weiterbearbeitung und Speicherung erlaubt. Das Verwenden und das Bearbeiten stehen unter der Bedingung der Namensnennung. Im Einzelfall kann eine restriktivere Lizenz gelten; dann gelten abweichend von den obigen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Documents in HENRY are made available under the Creative Commons License CC BY 4.0, if no other license is applicable. Under CC BY 4.0 commercial use and sharing, remixing, transforming, and building upon the material of the work is permitted. In some cases a different, more restrictive license may apply; if applicable the terms of the restrictive license will be binding.

Modelling the fate and transport of faecal bacteria from sewage overflows: The Dart Estuary case study

Luz García[1], John Bacon[1] Carlos Campos[2]
[1]Centre for Environment, Fisheries & Aquaculture Science, Pakefield Road, Lowestoft, NR33 0HT, UK
[2]Centre for Environment, Fisheries & Aquaculture Science, The Nothe, Barrack Road, Weymouth, DT4 8UB, UK
luz.garcia@cefas.co.uk

Abstract—**In this paper, we present results of a Telemac 3D application developed to investigate the fate and transport of *Escherichia coli* from sewer overflows (SOs) in the Dart Estuary, an important area for fisheries and water-based recreation activities on the south west coast of England. Model simulations were produced to investigate the effects of river discharges and tidal conditions. The results showed that the largest area of *E. coli* contamination in the estuary occurred during neap tides and low river discharges, due to longer persistence of contamination from SOs. This model can be used to investigate the effects of climate change and human population growth on water quality or active management of microbiological contaminants in bivalve shellfisheries.**

I. INTRODUCTION

The Dart Estuary is located in Devon, on the south west of England. It is a macrotidal estuary with range of up to 5.2m during spring tides, and up to 1.8m during neap tides. The tidal flow is ebb dominant and the upper tidal limit of the estuary occurs at Totnes, which is approximately 17 km upstream of the estuary mouth at Dartmouth.

The Dart Estuary is a regionally important center for yachting and boating. Bivalve shellfish, principally Pacific oysters (Crassostrea gigas) and mussels (Mytilus spp.), have been harvested for human consumption on the Dart for centuries.

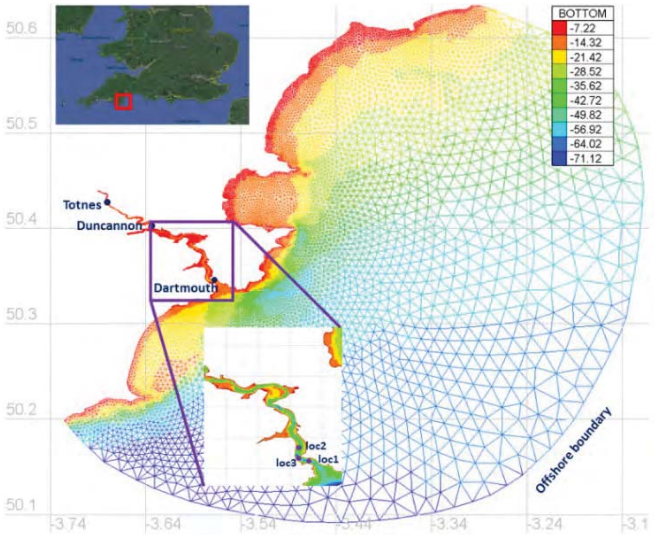

Figure 1: Model domain together with the location of the tidal gauges used for the validation of the water levels and the locations used for the validation of the tidal currents

In recent years, concerns have been raised about the impact of sewage discharges on water quality, wildlife and the amenity value of the area. Despite substantial investment made by the water company to reduce point-source pollution in this catchment, the designated shellfish water has never complied with the Guideline (G) microbiological standard of the Shellfish Waters Directive (repealed by the Water Framework Directive in 2013 and transposed to the national legislation through The Shellfish Water Protected Areas Directions (SWPAD) 2016) [9]. Following rainfall events, bivalve molluscs on the Dart are known to rapidly accumulate peak levels of E. coli and maintain these levels for several days [10]. The Cefas sanitary survey reports periodic downgrades in the microbiological classification of bivalve mollusc production areas (BMPAs) suggesting chronic sewage pollution impacts (Cefas, 2010). To achieve the G standard by 2027, the Environment Agency has recommended further pollution remediation work to deliver an average of 10 spills per annum for SOs in the Dart catchment (Environment Agency, 2015). In this context, this modelling study is very timely and can help water resource managers to identify appropriate measures to reduce sewage pollution in this estuary. The focus of this study is bacteria E. coli which is the indicator of faecal contamination prescribed by the relevant European legislation. It is important to acknowledge that, in addition to sewage discharges, the Dart Estuary BMPAs are impacted by diffuse sources of E. coli, from agricultural and urban land. It is estimated that agricultural sources contribute >40% of the total E. coli loading to the estuary [9]. Nevertheless, our interest here lies on the effect of the intermittent sources or, in other words, on the Sewage Overflows (SOs) as these are associated with higher health risk from exposure to enteric pathogens via contaminated water and bivalves. Approximately 70% of waste water in England and Wales is collected via combined sewers, collecting and discharging both foul sewage and surface water runoff. When the amount of sewage and surface water flowing into a combined sewer exceeds the hydraulic capacity of the collection system, the excess flow in the sewage network is discharged in untreated form into the environment via SOs. In this context, the main aim of this paper was to evaluate, by means of numerical modelling tools, the impact of spills from individual identified SOs in the Dart Estuary on the BMPAs under different conditions of river runoff and tidal regime.

II. HYDRODYNAMIC MODEL

A. Model set-up

A three-dimensional hydrodynamic model of the Dart Estuary was built using Telemac 3D (v7p2r2). The model domain extends approximately between 3.114ºW-3.726ºW and 50.08ºN-50.64ºN, and comprises the estuary and the adjacent coastal and offshore waters to allow for a better propagation of the boundary conditions and to investigate the variability of the river plume (see Fig.1). The domain was discretized by means of an unstructured grid with 12054 nodes and 22429 elements in the horizontal and 10 equally spaced layers in the vertical. The refinement in the grid varied spatially, with higher resolution inshore and coarser offshore (13-3843 m is the resolution range). The model bathymetry was mostly obtained from the Department for Environment, Food & Rural Affairs' UK Sea Map 2010, although minor manual modifications had to be done in the upper estuary to be able to properly reproduce the tidal propagation. The boundary conditions for the velocities and surface elevations at the offshore open boundary were obtained from the OSU TPXO European Shelf 1/30º regional model (11 tidal constituents: M2, S2, N2, K2, K1, O1, P1, Q1, M4, MS4 and MN4). Temperature and salinity were kept constant in space and time along the boundary (12.2ºC and 35.1, respectively). The input of fresh water of the Dart river was accounted for in the model by imposing a time series of river runoff obtained from the Austins Bridge station. The river temperature and salinity were prescribed at a constant value of 12.2ºC and 1.0, respectively. It must be noted that, since the temperature inputs are constant and equal along time, and since no atmospheric forcing is considered in this simulation, the temperature will remain constant along time. However, salinity variations seem to dominate the density distribution, being the contribution of temperature negligible [5], therefore this approximation will not affect the modelled circulation in the estuary.

For this study we considered the non-hydrostatic version of the Navier-Stokes equations. The κ-ε turbulence model was selected for the horizontal and vertical dimensions. Flooding and drying was included in the calculations due to the presence of tidal flats. Advection schemes that ensure conservative and monotonic behavior were selected for tracers. The Nikuradse law for bottom friction was considered, with a constant value of roughness length k_x=0.05 applied to the whole computational domain. The time step for the numerical resolution of the model was 1s.

The model was run for a two-month period, starting the 1st of December 2015, aiming at capturing periods of high and low river discharge during different tidal phases. The first days of the simulations were considered the spin-up period and hence, discarded from the analysis.

B. Model validation

The water levels were validated against observations at three tidal gauges (Totnes, Duncannon and Dartmouth, https://www.valeport.co.uk/InsideValeport/DartNetTides). In Fig. 2 the model results are shown for the Dartmouth gauge in comparison with the observations and the predictions from the UK Hydrographic Office (UKHO). The model reproduces well the observations both for spring and neap tide, showing a reasonable fitting in terms of amplitude and phase.

Owing to the lack of direct measurements of current velocities, the model was validated with velocity values found in the literature. According to [8] the characteristic flow velocities on the flood tide are 0.6m/s during spring tide at the mouth and 0.3m/s during neap tide. Tidal velocities at three different locations in the mouth of the estuary were extracted (Fig. 1) and very similar values to those reported in the literature during the flood phase of the tide were found (Fig. 2).

Salinity data available for the upper part of the Dart Estuary show that, as expected, the variability in the salinity range increases as we approach the estuary mouth. However, these data correspond to a period of very low river discharge during March 2003, and therefore could not be directly compared with the model results. The simulation period comprises low and high river discharge periods, in which the response of the model shows a similar behavior to the observations.

In any case, our model shows a similar behavior and, since the simulations last long enough to consider high and low river discharge periods, the response in the salinity levels can be seen. For the purposes of the model salinity validation, Fig.3 depicts the

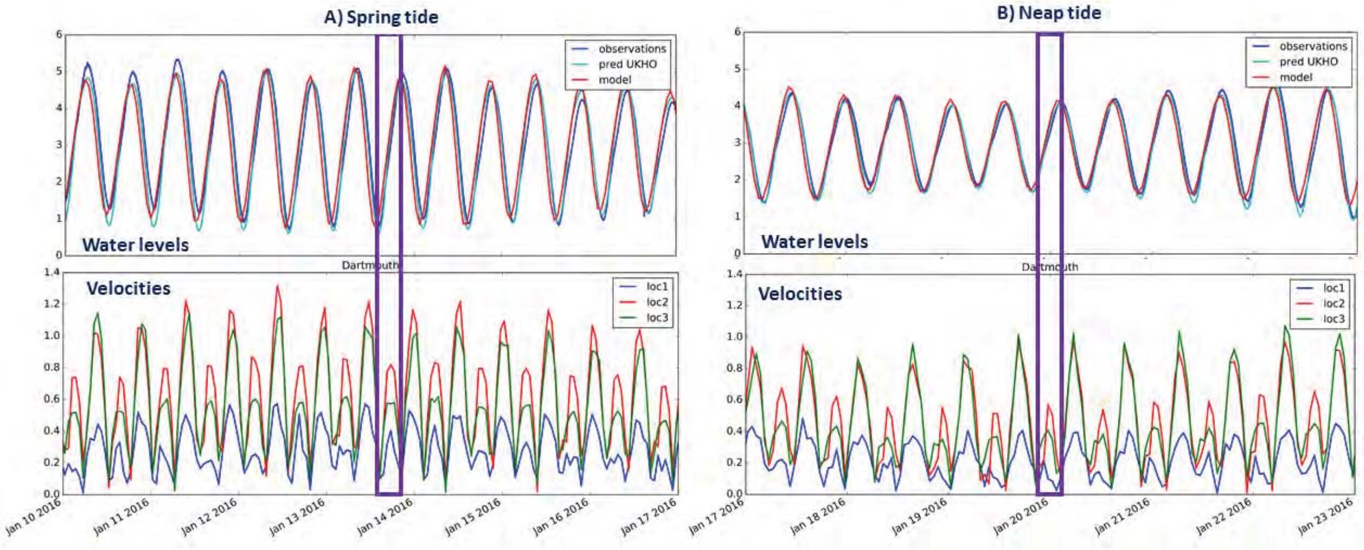

Figure 2: Validation of the water levels at Dartmouth (top panel) and current velocities (bottom panel) at locations 1, 2 and 3 (see Figure 1)

daily averaged salinity at the estuary mouth (C) at the surface and bottom layers, together with the tidal regime (A) and the river discharge (B). According to the literature, the Dart Estuary is partially mixed and experiences a complete stratification/destratification cycle with the neap/spring transition ([8]). In Fig. 3 we show that the model reproduces an increase in the stratification during neap tide. However, this stratification is modulated by the river discharge. In this sense, the stratification is stronger if the river discharge is higher (compare periods 1 and 2, both corresponding to neap tide conditions). The stratification can be strong in spring tide too if the river discharge is high enough. This is the case of the period highlighted as 3, that is characterized by stronger stratification than the previous neap tide (around 20th January).

III. MODELLING FAECAL BACTERIA RELEASED THROUGH SEWAGE OVERFLOWS

A. Characterization of SOs in the Dart Estuary

As mentioned in the Introduction, SOs are intermittent discharges that spill untreated sewage at different points of the shoreline, with variable duration and volume. In the UK, the Environment Agency (EA) applies a set of standards to the determination of consent applications for discharges that impact on shellfish waters. For shellfish waters impacted by multiple SOs, the EA recommends aggregating spills by frequency and volume so that the combined impact of the aggregated spills does not exceed 10 spills per annum or 3% of the time on average. However, sometimes spills occur beyond the regulations.

Fig. 4 shows SOs spill data for the period 1st of April 2006 to 31st of March 2016 into the Dart Estuary. The colour scale shows in blue spills of less than 12h, in green spills between 12-24h, in yellow those lasting between 24-72h and in red spills of more than 72h. From Fig. 4 it is clear that six SOs (Totnes STW-SO, Stoke Gabriel SPS-PSCOEO, Mill Creek SPS-PSCOEO, Kiln Road SPS-PSCOEO, Ferry Boat SPST-PSCOEO and Dittisham STW-SO) have been more active than the others, specially from 2012 on, showing multiple long-lasting periods of spills and a certain degree of overlapping among the different SOs. In this study, we focused on the six SOs above, being the average duration of the spills compiled in Table 1.

TABLE 1. AVERAGE DURATION OF SOS SPILLS

SO	*Average duration*	*Number of data*
Totnes STW-SO	71.62	144
Stoke Gabriel SPS-PSCOEO	58.57	50
Mill Creek SPS-PSCOEO	9.51	143
Kiln Road SPS-PSCOEO	19.64	123
Ferry Boat SPST-PSCOEO	29.98	185
Dittisham STW-SO	27.92	195

Not much information is available on the SOs runoff. Indeed, among the selected ones, only data for Ferry Boat and Mill Creek were available, with flow rates of 23 and 17 m^3/day, respectively. Therefore, we decided to consider a baseline runoff for all the SOs of $20m^3$/day. A test was done to evaluate the impact of higher discharges ($200m^3$/day).

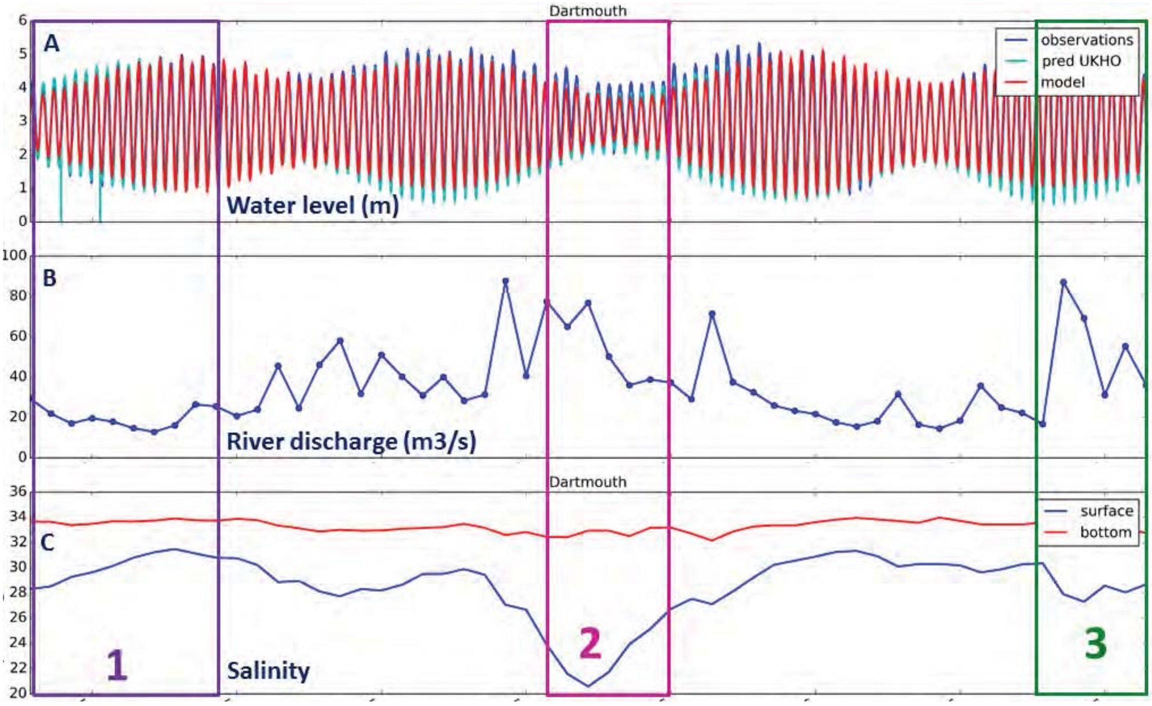

Figure 3: A) Observed and predicted water levels at Dartmouth, B) River discharge in m^3/s and C) Daily averaged surface (blue line) and bottom salinity (red line). The periods marked by 1, 2 and 3 are explained in the text.

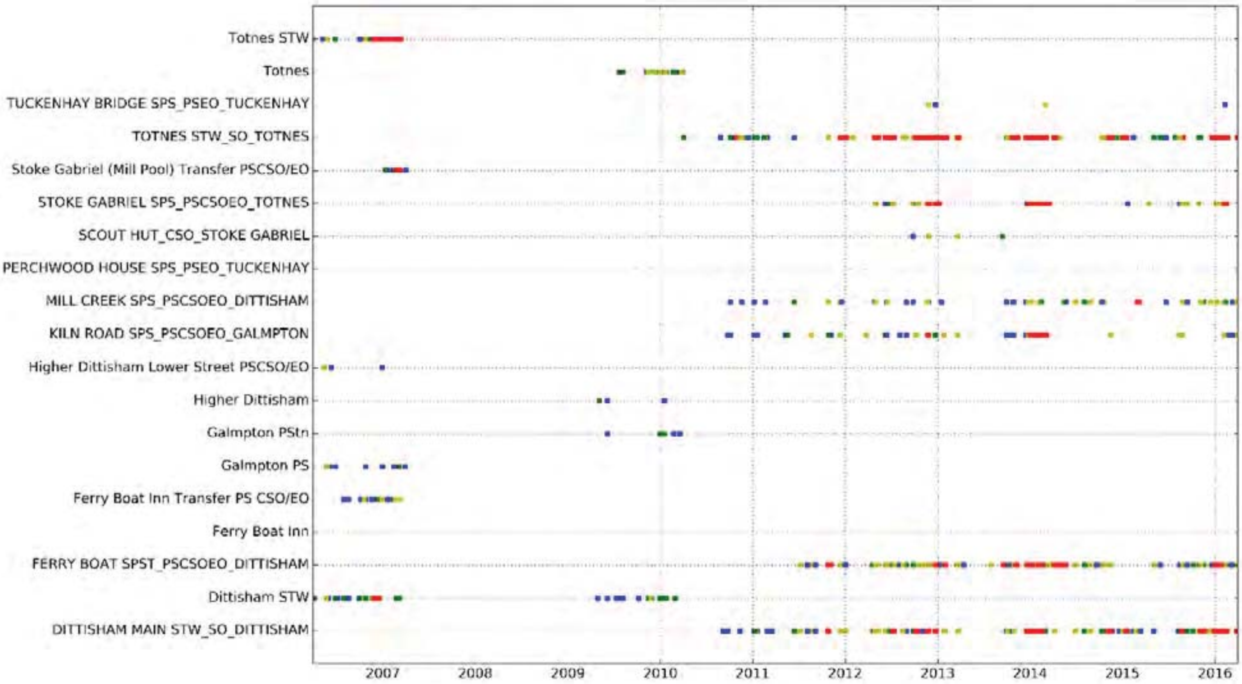

Figure 4: Spills of several sewage overflows in the Dart Estuary. Blue colours correspond to spills of less than 12h, green between 12-24h, yellow between 24-72h and red > 72h

Monitoring of concentrations of *E. coli* in effluents from SOs is not required under the EA discharge consenting policy. However, [4] published reference concentrations for different treatment levels and individual types of sewage-related effluents under different flow conditions. In this sense, Totnes STW-SO and Dittisham STW-SO were assigned a concentration of $8x10^5$cfu/100ml, corresponding to stored settled sewage, whereas for the rest of the SOs we used $2.5x10^6$cfu/100ml, which was Kay's characterization for storm sewage overflows.

B. *Modelling E. coli transport and decay*

In Telemac, the transport and decay of *E. coli* (EC) is modelled through (1)

$$\frac{\partial EC}{\partial t} + \vec{u}.\nabla(EC) = div\left(\vec{K}.\nabla(EC)\right) - k_d EC, \qquad (1)$$

with the left-hand side representing the advection of the faecal coliform, the first term on the right-hand side showing the diffusion and, finally, the last term representing the exponential decay. It is known that k_d for E. coli is a function of temperature, salinity and irradiation (see, for instance, [1] and [3]). However, for this study we have started by only considering a temperature dependence given by

$$k_d = k_{20}\theta^{(T-20)}, \qquad (2)$$

with $k_{20} = 0.036\text{h}^{-1}$, $\theta = 1.07$ and T the temperature [6]. Notice that since the temperature is kept constant in the model, the decay rate will be constant as well.

C. *Modelling scenarios*

To evaluate the effect of the river discharge and the tidal phase on the dispersal of *E. coli* in the estuary, four scenarios were considered:

- Scenario 1: Neap tide and high river discharge. The simulation starts the 4th of January 2016 and lasts for 5 days.

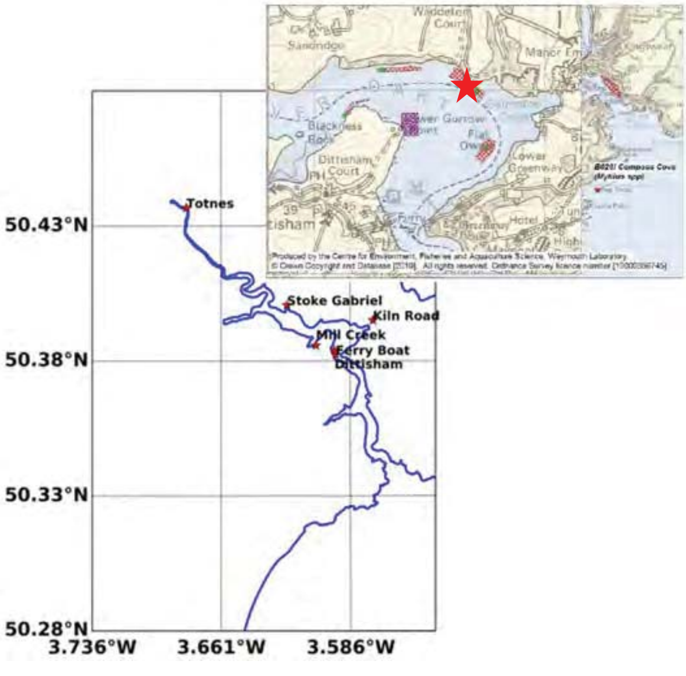

Figure 5: Location of the sewage overflows considered in this study and map showing the location of the BMPAs in the Dart Estuary (extracted from [2])

- Scenario 2: Neap tide conditions and low river discharge. The simulation starts the 19th of January and lasts for 5 days. This scenario was repeated for a spill discharge of 200m^3/day.
- Scenario 3: Spring tide and low river discharge. The simulation starts the 26th of January and lasts for 5 days.
- Scenario 4: Spring tide and high river discharge. The simulation starts the 13th of January and lasts for 5 days.

The different periods and conditions, although not explicitly indicated, can be seen in Fig. 3. The considered SOs, their duration and discharge are shown in Section III.A.

The location of the six considered SOs together with the BMPAs in the Dart Estuary is shown in Fig. 5.

IV. RESULTS

The concentration of *E. coli* one day after the beginning of the spill in the neighbourhood of the BMPAs of the Dart Estuary for the four studied scenarios is shown in Figure 6. The red colour in the map represents *E. coli* levels of > 10cfu/100ml (estimated mean concentration equivalent to G standard of the SWPAD). According to the model results, the area of exceedance is larger for scenario 2 (see Figure 6 B), followed by scenario 1 (Figure 6, A) at this time, with the BMPAs located in the areas of exceedance. This result is reasonable considering that retention of the spill increases at neap tide and low river discharge, whereas flushing increases in spring tide. The time series shown under each map represents the evolution of the concentration of the BMPA highlighted with a red star in Fig. 5. Higher concentrations are obtained for scenario 2 (Figure 6, B), although the maximum value is observed for scenario 1.

Table 2 compiles the averaged and maximum concentration of *E. coli* along the simulation period in the considered BMPA, together with the number of hours for which the concentration exceeds the standard of 10cfus/100ml. It is clear that scenarios 1 and 2 represent the worst-case scenarios of contamination, with scenario 2 showing a longer exposure to high concentrations (24h). The results for the test case considering higher discharges (200m^3/day) are also included in Table 2. In this case the

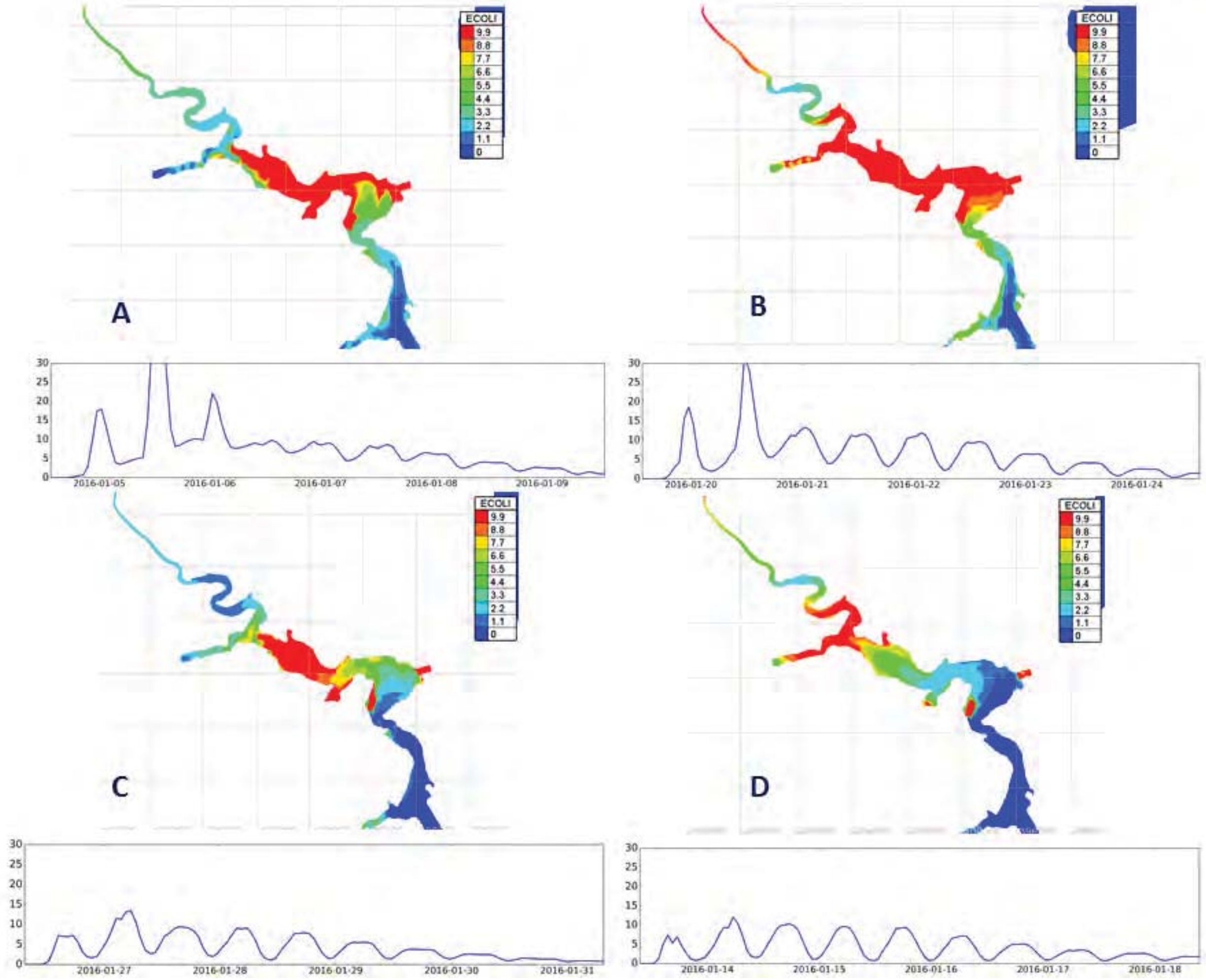

Figure 6: Model results corresponding to one day after the beginning of the spill. A) Scenario1, B) Scenario 2, C) Scenario 3 and D) Scenario 4. The time series below each plot represent the evolution of the concentration of E. coli at the BMPA indicated with a red star in Fig. 5.

averaged concentrations greatly exceed the G standard (56.08cfu/100ml), being this standard exceeded for most of the simulation time (4.45 days).

TABLE 2. AVERAGED AND MAXIMUM CONCENTRATION OF E. COLI FOR THE DIFFERENT SCENARIOS. NUMBER OF HOURS FOR WHICH THE CONCENTRATION EXCEEDS 10CFUS/100ML

Scenarios	Average concentration	Maximum concentration	Hours conc.>10cfus/100ml
Scenario 1	7.2	58.1	16
Scenario 2	6.1	31.33	24
Scenario 2-HD	56.08	313.8	107
Scenario 3	3.99	13.5	5
Scenario 4	3.99	12.0	4

V. SUMMARY AND CONCLUSIONS

In this paper, we have shown the first stages of the implementation of a hydrodynamic model of the Dart Estuary that is able to reproduce the water levels and current velocities along the estuary, as well as the stratification/destratification periods promoted by the tides and the variability of the river discharge. In this sense, we have a model that is suitable to investigate the fate and transport of faecal bacteria released through sewage overflows. The characterization of sewage overflows in terms of frequency of discharge and run-off is complex, therefore we have used the available data to define a constant run-off and an average spill duration applied to four simple scenarios from which we concluded that the worst conditions (higher exposure to *E. coli* in the BMPAs) in terms of tides and river discharge occur at neap tide when the river discharge is low.

Although beyond the scope of this initial study, further studies analysing the correlations between rainfall and the spill occurrence, frequency and duration would provide additional information to inform the identification of appropriate pollution remediation measures through the WFD Programmes of Measures process and/or support initiatives to proactively manage microbiological risks in BMPAs. Thus, this model constitutes a useful predictive tool available to better characterise episodes of poor water quality following intermittent discharges. A similar study, although based on statistical models, has been recently published (see [7]). This model could also be used to study the effects of climate change and population growth on the microbiological quality of the waters and shellfish.

ACKNOWLEDGEMENT

This study was funded by Cefas Seedcorn Project ‘Impact and evaluation of combined sewer overflow discharges in shellfish waters’ (DP407).

REFERENCES

[1] R.A Blaustein, Y. Pachepsky, R.L. Hill, D.R. Shelton and G. Whelan. Escherichia coli survival in waters: Temperature dependence. Water research, 47, 2013, pp. 569-578

[2] Cefas, 2010. Sanitary survey of the Dart Estuary (Devon). Cefas report of behalf of the Food Standards Agency, to demonstrate compliance with the requirements for classification of bivalve mollusc production areas in England and Wales under regulation (EC) No. 854/2004

[3] G.Gao, R.A. Falconer, B. Lin. Modelling the fate and transport of faecal bacteria in estuarine and coastal waters. Marine Pollution Bulletin 100, 2015, pp. 162-168.

[4] Kay D, Crowther J, Stapleton CM, Wyer MD and others (2008) Faecal indicator organism concentrations and catchment export coefficients in the UK. Water Res 42: 2649−2661

[5] Priestley, A.D., 1998. The Dart Observatory: an estuarine monitoring system. International Ocean System Design 2, 5-9

[6] Selvakumar, a., m. Borst, and s. D. Struck. Microorganisms die-off rates in urban stormwater runoff 2007. Presented at 2007 TMDL Conference, Bellevue, WA, June 24 - 27, 2007.

[7] W. Schmidt, H.L. Evers-King, C. Campos, D.B. Jones, P.I. Miller, K. Davidson and J.D. Shutler. A generic approach for the development of short-term predictions of Escherichia coli and biotoxins in shellfish. Aquaculture Environment interactions, vol. 10, 2018, pp. 173-185

[8] R.H. Thain, A.D. Priestley and M.A. Davidson. The formation of a tidal intrusion front at the mouth of a macrotidal, partially mixed estuary: a field study of the Dart Estuary, UK. Estuarine, Coastal and Shelf Science, 61, 2004, pp. 161-172

[9] Environment Agency, 2015. Shellfish water action plan. Issued Sep 2015.

[10] C.J. Campos, S. Kershaw, R.J. Lee, O.C. Morgan and K. Hargin. Rainfall and river flows are predictors for beta-glucuronidase positive Escherichia coli accumulation in mussels and Pacific Oysters from the Dart Estuary (England). Journal of Water Health, 2011, 9(2). Pp. 368-381