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An empirical model to quantify fecal bacterial loadings to coastal areas: Application in a Mediterranean context

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1. Introduction

Coastal water quality is a key driver of seaside tourism economy. Elevated fecal contamination may threaten human health, impair the aquatic environment and lead to prohibition of bathing and shellfish harvesting (Coulliette and Noble, 2008; Dwight et al., 2004). In coastal catchments, the rapid urbanization and the expansion of agricultural land generate increasing levels of pollutants. Consequently,

regulatory bodies are required to actively manage coastal water quality to promote economic development along with the protection of public health and marine environments.

Fecal Indicator Bacteria (FIB), such as thermo-tolerant coliforms and intestinal enterococci are used across the world to detect fecal pollution and set water quality standards. Fecal contamination may come from humans and animals frequenting beaches (Elmir et al., 2007; Wright et al., 2009) and from continental inputs, such as surface leaching, land runoff and sewer discharges (Ahn et al., 2005; Jeong et al., 2005; Reoyo-Prats et al., 2016). Although coastal waters may be contaminated during dry periods (Stein and Ackerman, 2007), numerous studies highlighted the effects of hydroclimatic conditions on

bacterial contamination in seawaters (Boehm et al., 2002; Fiandrino et al., 2003; Parker et al., 2010).

During rainfall events, runoff is generated by different processes. It occurs directly on impervious surfaces and on permeable soils when rainfall intensity exceeds the infiltration rate or when the soil is saturated (Hillel, 2003). Therefore, bacterial contaminants deposited by domestic animals, birds and rodents are conveyed into the watercourses (Causse et al., 2015; Ram et al., 2007). Extreme events also lead to important contamination in urban watercourses due to sewer overflow (Marsalek and Rochfort, 2004). In agricultural areas, microbial pollution is mainly generated by livestock and wild animals (Sigua et al., 2010). Further, Muirhead et al. (2004) showed that sediment resuspension in natural streams and drainage networks highly contributes to bacterial contamination of coastal waterways.

Under semi-arid climates, intense and local storms occur after long dry periods and lead to flash floods (Perrin and Tournoud, 2009; Terranova and Gariano, 2014). In such areas, the major annual rain events are responsible for more than 97% of annual fecal bacterial load in coastal rivers (Chu et al., 2011; Reeves et al., 2004). Precipitations with high intensities and depth are especially characteristic of tropical climates, in particular during the wet season. Consequently, bacterial contamination of coastal waters is highly driven by hydrological conditions in tropical areas (Cho et al., 2010; Rochelle-Newall et al., 2016).

In Europe, the exceeding of the quality thresholds in terms of fecal bacterial contamination is responsible for non-compliance with the European bathing water quality directive (European Environment Agency, 2016). To support coastal water quality management, previous research examined the relationship between environmental conditions and fecal bacterial levels in coastal waters. Strong correlations have been revealed between rainfall amounts and FIB concentrations in many regions, notably in the Flyde coast, UK (Crowther et al., 2001), in California, USA, (Ackerman and Weisberg, 2003) and in Korea (Cha et al., 2010). Although multiple linear regressions were used to link meteorological parameters to bacterial concentrations in urban storm-water runoff (Ekklesia et al., 2015; Farnham and Lall, 2015; Hathaway et al., 2010), little work has been conducted to model bacterial loadings at catchment outlets. However, continental inputs are driven by hydrological conditions and represent the major source of fecal contamination in coastal zones.

In the context of seawater contamination during extreme rainfall events, this paper aims at giving insights into summer storm effects on coastal water quality, by quantifying bacterial loadings from some Mediterranean catchments in Southern France. It intends to provide a simple tool based on rainfall data to characterize potential microbial contaminations of coastal bathing and fishing waters. A better understanding of water quality is essential to support coastal water managers in protecting human health and reducing the socio-economic impacts of such contaminations. The methodology can be conducted in other regions where fecal bacterial contaminations of bathing waters occur after rainfall events, such as touristic destinations in semi-arid and tropical climates.

2. Materials and methods

2.1. Site description

The Gulf of Aigues-Mortes, presented in Fig. 1, is a very attractive site for summer seaside tourism in southern France. The 20 km long coastline is shared by 31 beaches, 6 marinas and many nautical sport clubs. The catchment of the gulf encompasses more than 2300 km² with a mixed land use: 48% of the catchment is agricultural and 13.5% is artificial. The remaining 38.5% are forest, semi-natural areas and wetlands. The population is above 900,000 inhabitants, mainly distributed between the urban areas of Montpellier and Nîmes. According to the national institute of statistics and economic studies (INSEE), the population within the study area averagely increases by 1% per year. In coastal cities, the population increases by up to 40% during summer season. With an average annual rainfall of 672 mm, the climate is semi-arid with the majority of rainfall observed in autumn. A high inter-annual variability of rainfall is characteristic of the Mediterranean climate, along with the occurrence of extreme rainstorms. Consequently, the hydrological regime is extremely variable and leads to the contamination of coastal waters during flood events.

Three subcatchments are part of the Gulf of Aigues-Mortes catchment. Firstly, the Vistre–Vidourle (VV) catchment, with a population density of 240 inhabitants/km², covers a surface area of 1389 km² and contains the urban area of Nîmes. The Vistre and the Vidourle rivers join a mesh-type hydraulic system with two outlets, the Grau-du-Roi canal and the Ponant canal. Secondly, the 405 km² area of the Or catchment has a population density of 740 inhabitants/km² and contains a shallow lagoon of 31.7 km². The lagoon interacts with the sea through the Carnon canal. Finally, the Lez-Mosson (LM) catchment covers 709 km² on the west part of the gulf and contains the densely urbanized area of Montpellier. The population density is 691 inhabitants/km². Hydraulic exchanges take place between the Lez River and eight coastal lagoons upstream of the two outlets, the Prevost canal and the Lez River estuary. At the south end of Montpellier, a new wastewater treatment plant, MAERA, is operational since 2006 and collect the wastewaters of 16 municipalities, among which the coastal city of Palavas-les-Flots. The effluents are discharged through a sea outfall 10 km off the coast (Fig. 1). The level of sewage treatment of MAERA is 388,783 population equivalent, representing 64% of the wastewaters in the LM catchment. The remaining 36% of the effluents are discharged into continental waters. In the Or and VV catchments, respectively 142,853 and 409,233 population equivalents are treated, of which are the wastewaters from coastal cities, and the effluents are discharged into rivers and estuaries.

2.2. Sampling and bacterial analyses

Nineteen sampling campaigns were conducted in coastal river outlets and lagoon channels across the Gulf of Aigues-Mortes from June 2008 to January 2015. Hydrological conditions from low flow to high flow and floods

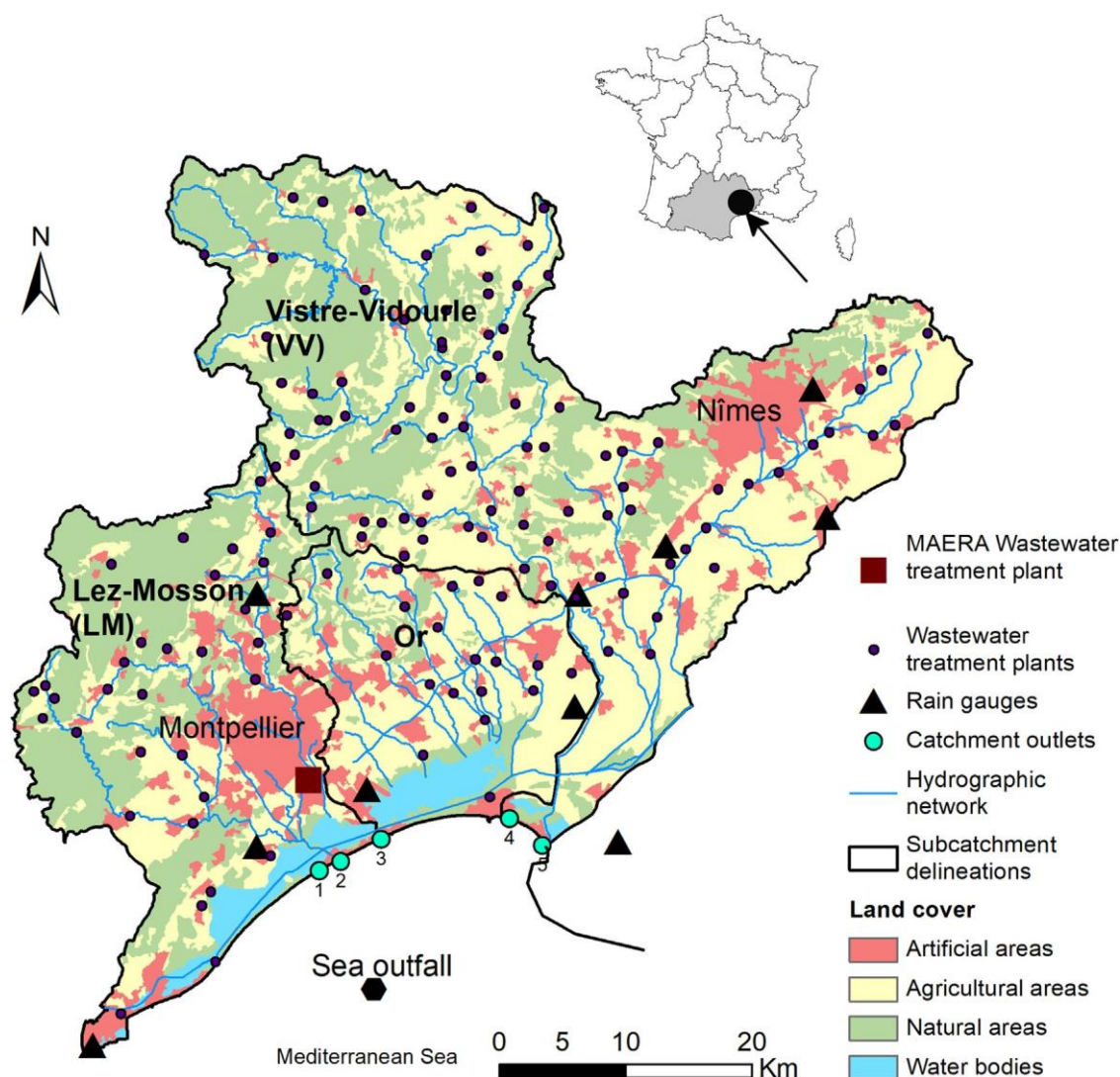


Fig. 1. Catchment of the Gulf of Aigues-Mortes. The outlets are (1) the Prevost canal, (2) the Lez estuary, (3) the Carnon canal, (4) the Ponant canal, and (5) the Grau-du-Roi canal (Vidourle estuary). LM: Lez-Mosson catchment, Or: Or catchment, VV: Vistre-Vidourle catchment.

were explored. Four campaigns were performed in summer (2008 and 2014), 11 campaigns took place in autumn (2008, 2009, 2010, and 2014), two campaigns were carried out in winter (2009 and 2015) and the last two were undertaken during a flood event in spring 2011. The measurements were performed in low tide conditions to estimate the bacterial inputs from the continental area and avoid bias due to incoming seawater. At each site, flow velocities across the river channel were measured using an Acoustic Doppler Current Profiler (ADCP). The final discharge estimation was the average of at least four consecutive ADCP transects across the river section. Water samples were collected and stored in sterile 1-L bottles in coolers. To assess the variability of FIB concentrations within the flow section, eight grab samples were collected in eight river subsections and constituted an average sample. Moreover, since intra-storm FIB

concentrations and river flows can be highly variable (Chu et al., 2011), samples were collected by an automatic sampling device and river flow was continuously measured during flood events in 2010 and 2011. Water samples were processed at the laboratory using the reference methods ISO 9308-1 and ISO 7899-2 mentioned in the European bathing water directive 2006/7/EC to enumerate thermo-tolerant coliforms (TTC) and intestinal enterococci (IE), respectively (European Parliament. Council of the European Union, 2006). Water volumes (0.1, 1, 10 and 100 mL) were filtered in duplicate on cellulose nitrate membrane (Whatman filters). TTC were quantified on triphenyl tetrazolium chloride tergitol agar incubated for 24 h at 44.5 °C, and intestinal enterococci were enumerated on Slanetz medium incubated for 48 h at 37 °C. The results are expressed as colony forming units per 100 mL (CFU/100 mL).

2.3. Data

2.3.1. Rainfall data

From ten evenly distributed rain gauge stations, daily rainfall data from 2006 to 2016 were obtained from Météo France in the study area. Spatial rainfall distribution was assessed applying Thiessen interpolation to the rain gauge network. Four weather stations were used to calculate the rainfall over the LM and Or subcatchments whereas 7 rain gauges describe the precipitations over the VV subcatchment. One of them is located in the coastal city of Aigues-Mortes, out of the catchment (Fig. 1).

2.3.2. Water quality data

To compare bacterial inputs from the Gulf of Aigues-Mortes (GAM) catchment and from the sea outfall of MAERA, monthly records of TTC and IE concentrations in the treated effluents of the wastewater treatment plant were provided by the Montpellier-Méditerranée Métropole from 2009 to 2013. Bathing water quality data was provided by the Occitanie regional health agency over the period 2006–2016. TTC and IE concentrations were measured during summer season in bathing waters surrounding the catchment outlets. The beaches surrounding the VV catchment outlets are located on the littoral of “Le Grau-du-Roi” and “La Grande Motte” whereas LM and Or catchment outlets may contaminate the bathing waters of “Palavas-les-Flots” and “Mauguio”.

2.4. Methods for data analysis

There are three main stages to the analysis. Firstly, explanatory relationships are derived between bacterial loadings at the catchment outlets and an Antecedent Precipitation Index (API) calculated from the observed climate datasets. Secondly, measurement uncertainties are included in the linear regression to estimate confidence intervals on model predictions. Finally, these relationships are applied to rainfall data over the period 2006–2016, assuming stationarity in territorial dynamics and rainfall patterns, to simulate bacterial loadings to the coastal area. This period corresponds to the installation of the new wastewater treatment plant of Montpellier. Lastly, the model outputs are compared to the FIB loads measured at the entrance of the sea outfall pipe of the wastewater treatment plant and linked to bathing water quality monitoring data.

2.4.1. Deriving relationships between bacterial loadings to the Gulf of Aigues-Mortes and an Antecedent Precipitation Index

As a first step, FIB concentrations and river flow measurements were used to calculate instant bacterial loadings. Previous research has demonstrated a strong relationship between FIB loads and rainfall accumulation in coastal rivers (Chu et al., 2011; Stumpf et al., 2010). The instant bacterial load is the number of colony forming units flowing per time unit, calculated as:

$$L(t) = C(t) \cdot Q(t) \quad (1)$$

where $C(t)$ is the instant mean concentration of FIB within the section (CFU/100 mL), $Q(t)$ is the instant river flow (m³/s),

and k is the time unit conversion factor, equal to $8.64 \cdot 10^8$. The load $L(t)$ is then expressed as CFU per day. When several values were available for one day, the arithmetic mean was calculated to determine the daily load. For a given subcatchment, bacterial inputs to the sea were computed from the sum of the FIB loadings at each outlet.

In a second phase, the Antecedent Precipitation Index (API) was calculated from daily rainfall datasets. The average rainfall in each subcatchment was calculated from Thiessen polygons delineated from the locations of the weather stations. The API, defined by Kohler and Linsley (1951), has been widely used to link rainfall and runoff across the world (Descroix et al., 2002; Sittner et al., 1969). It results from the sum of weighted rainfall depths of the antecedent days, calculated as following:

$$API = \sum_{i=0}^{d-1} P_i \cdot k^i \quad (2)$$

where API is the Antecedent Precipitation Index of a given day (mm), P_i is the rainfall of the i^{th} antecedent day (mm), and d is the number of antecedent days; k is the weighting coefficient, defined as the rainfall abatement which characterizes the hydrological response of the catchment.

The bacterial loads are not normally distributed hence they were $\log_{10}$ transformed prior to the statistical analysis. Linear relationships between API and bacterial loadings were derived by linear regression for both TTC and EI. The Pearson correlation coefficient was used to assess the statistical significance of the regressions with a confidence level of 95%.

2.5. Including measurement uncertainties in the linear regression model

The bacterial load uncertainty is assessed through the spatial-temporal variations of FIB concentration within the flow section during rainfall events and the error on flow measurements. The spatial variability of daily rainfall is assessed through the standard deviation between values of precipitation at the different weather stations within each subcatchment. Then, the uncertainty associated with a given API value is the average of the daily spatial variation of rainfall for the number of antecedent days taken into account in API calculation. Numerous studies highlighted various methods to define the best linear regression when both axes are affected by an error (Burr et al., 2012; Rio et al., 2001). The ordinary least square regression is usually used when the x-axis error is negligible. However, other methods such as the maximum likelihood estimation and the orthogonal distance regression are not found to improve the results when both axes contain uncertainties (Oliveira and Aguiar, 2013; York et al., 2004). Consequently, the ordinary least square regression is used in this analysis to determine the best fitting straight line linking API and bacterial loadings. An associated confidence interval is usually defined by assessing the dispersion of the points around the regression line. Nevertheless, a different method is proposed in this study to include measurements uncertainties. At first, both the x and y errors are assumed

to be normally distributed around the measured value within the uncertainty interval. Ten thousand ensembles of (x, y) points are then generated by Monte Carlo simulations within these distributions. Then the least square method is employed to create an ensemble of 10,000 linear regressions arising from the measurement errors. The confidence interval is defined as the range containing 90% of these linear regressions.

2.6. Simulating bacterial inputs to the Gulf of Aigues-Mortes

The relationships between bacterial loadings and API described in Section 2.4.1 were applied to rainfall datasets on summer season from 2006 to 2016. The model outputs provide the magnitude of bacterial loadings caused by rainfall events in each subcatchment. The bacterial loads in the effluents of the wastewater treatment plant were then compared to the simulated FIB loads at the catchment outlets. Lastly, bathing water quality data of regulatory monitoring was related to bacterial contamination events simulated in the Gulf of Aigues-Mortes.

3. Results

3.1. FIB loads and measurement uncertainties

The samples collected in the Gulf of Aigues-Mortes resulted in 16, 13 and 19 daily loads estimations at the outlets of the LM, Or and VV subcatchment respectively, presented in Fig. 2. The coherence of the results obtained from June 2008 to January 2015 confirms the temporal stationarity of bacterial fluxes dynamics. During the sampling days, the Antecedent Precipitation Index (API) ranged from 0.5 to 118 mm in the three subcatchments. Different hydrological regimes are represented in the data. For instance, the flood of November 2010 was intense and short, with 127 mm rainfall recorded over several hours, whereas a longer event was observed in March 2011 with 135.7 mm of rainfall amount over 4 days.

FIB concentrations and flow measurements in the 8 subsections of each river sampling site were used to assess the spatial heterogeneity of FIB loadings within the flow section. On average, a sample taken from one position within the water column provides an estimation of the mean bacterial load with an accuracy of one log unit CFU/day. This uncertainty is mainly explained by the fluctuation of bacterial concentrations. As an example, the level of TTC in the Lez River section in January 2009 ranged from 4650 CFU/100 mL to 35,000 CFU/100 mL between the eight different subsections (Fig. 3a). Although this variation is different in the five sampling sites, on average bacterial concentrations across the channel sections can vary by one log unit CFU/100 mL for both TTC and EI. The magnitude of the variation is lower for high flow conditions. In a lesser extent, the temporal intra-storm variability may represent a second source of uncertainty. This error is reduced as the extreme events were continuously monitored and the FIB loads are calculated on a daily basis.

The bacterial loads of TTC were found to vary from $5.76 \cdot 10^{10}$ to $1.06 \cdot 10^{17}$ CFU/day at the outlets of the

Gulf of Aigues-Mortes catchment. The loads of EI were lower, ranging from $2.39 \cdot 10^{10}$ to $5.74 \cdot 10^{16}$ CFU/day. The correlation between TTC and IE loads for the 48 observations is significant, with a coefficient of determination of 0.947 at the outlets of the Gulf of Aigues-Mortes catchment when the load of IE is the explanatory variable (Fig. 3b). Microbial loadings are high in the Lez and the Vidourle estuaries, whereas the buffering capacity of the lagoons reduces the FIB loads at the other outlets. In the Or catchment, the observed median loads are one hundred times lower than those measured at the outlets of the two other subcatchments. This is explained by the large buffering capacity of the Or lagoon. Finally, although the microbial loads in the VV and LM subcatchments are of the same order of magnitude during dry periods, the bacterial sources vary spatially in the Gulf of Aigues-Mortes. Whilst the microbial contamination from the VV catchment is due to a mix of urban and agricultural runoff, the major source of FIB in the LM and the Or catchments is the densely urbanized area.

3.2. Correlation between fecal contamination loadings and API

The parameters of the API, which are the duration and the weighting coefficient, were calibrated through a sensitivity analysis. The optimum r-squared coefficient was reached when the duration, d, was 10 days, and the weighting coefficient, k, was 0.85. Consequently, the system status for a given day is characterized by the weighted rainfall recorded during the 10 antecedent days. The weighting factor of 0.85 illustrates a strong rainfall abatement, characterizing the rapid hydrological response of the Gulf of Aigues-Mortes catchment. Therefore, recent precipitations have a major effect on bacterial loadings compared to past rainfall. The results associated with the linear regressions linking API and bacterial loadings are presented in Table 1.

Significant correlations are observed between the explanatory variable, the API, and FIB loadings in the Gulf of Aigues-Mortes, highlighting the influence of hydrological regimes on bacterial dynamics. In the study area, more than 80% of the variance of bacterial loadings is explained by API. Regarding the Or subcatchment, the buffering capacity of the Or Lagoon was considered by calculating API for the day preceding the measurement. Therefore, it is assumed that bacterial contaminants need one more day to reach the catchment outlet than in the other subcatchments. This lag time was determined through statistical calibration, on the basis of daily API and FIB loads observations. The higher value observed for the slope of the linear model at the outlet of the VV subcatchment suggests a larger microbial contaminants load conveyed to the outlet than in the LM and VV subcatchments for increasing API. Fig. 4 shows the linear regressions linking API and TTC loadings at the three subcatchments outlets.

The uncertainty related to API corresponds to the average of the daily standard deviation between the precipitations observed at the weather stations for each subcatchment. This uncertainty varies among the API values according to the spatial extension of the rainfall events. The 90% confidence intervals presented in

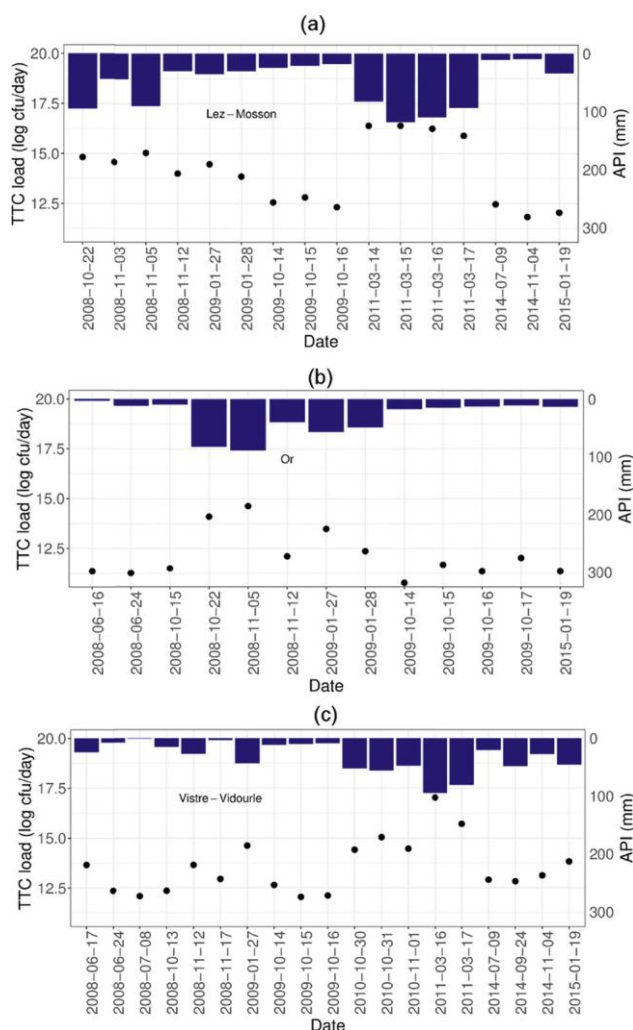


Fig. 2. Daily loads estimations of thermo-tolerant coliforms (TTC) and associated uncertainties between June 2008 and January 2015 in (a) the Lez-Mosson catchment; (b) the Or catchment; (c) the Vistre-Vidourle catchment. The histogram represents the Antecedent Precipitation Index (API) corresponding to each measurement.

long-dashed lines in Fig. 4 take into account the uncertainties estimated from bacterial load measurements and the spatial variability of API. The method used to consider measurement errors through Monte Carlo simulations captures a broader range of bacterial loadings variability than the only consideration of the dispersion of the points around the regression line, represented in dotted lines in Fig. 4. Consequently, the measurement errors have a significant impact on the variation range of bacterial loadings to the coastal area for a given API value.

3.3. Simulation of FIB loadings

FIB loadings at the catchment outlets were simulated using the empirical model during summer seasons from 2006 to 2016 (Fig. 5). The base load is significantly lower in the Or subcatchment (< 11 log CFU/day) than in the LM and VV subcatchments (> 12 log CFU/day). The latter two

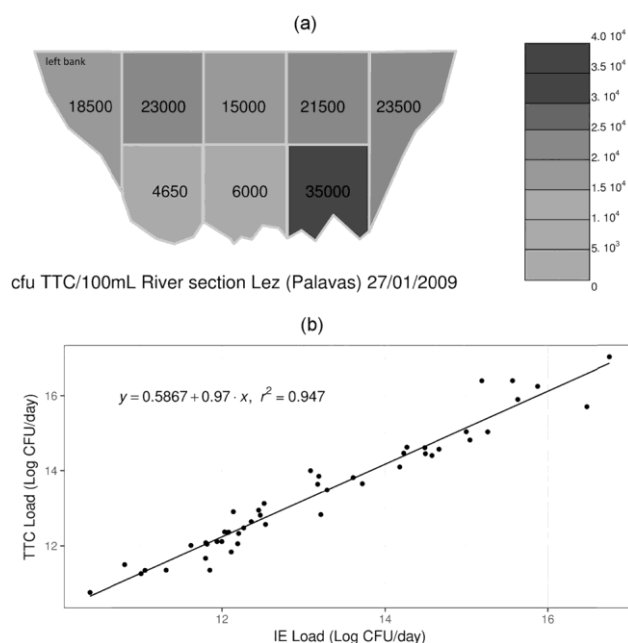


Fig. 3. a: spatial variability of thermo-tolerant coliforms (TTC) concentration in the Lez river section on January 27th, 2009; b: linear regression between thermo-tolerant coliforms (TTC) and intestinal

present similar levels of bacterial contamination in dry periods, even though the population is significantly higher in the LM subcatchment. Consequently, the MAERA wastewater treatment plant contributes to reducing the continental inputs of Fecal Indicator Bacteria under dry conditions. After rainfall events, bacterial loadings increase suddenly in the three subcatchments and return to baseline conditions in several days. On average, 2.4 rainfall events per summer season lead to an increase of simulated FIB loads by more than one log unit CFU/day. These events, illustrated in Fig. 5a, may have severe consequences on bathing water quality and marine environments. Whereas under dry weather conditions, the simulated loads are found significantly lower at the catchment outlets than at the sea outfall of the MAERA wastewater treatment plant, intense summer rainstorms elevate bacterial loadings such as continental inputs become the major source of Fecal Indicator Bacteria in the coastal area. This phenomenon is illustrated in Fig. 5b during the 23.7 mm storm event on July 1st, 2012, which led to a significant increase of TTC loadings at the outlets. Regarding the VV subcatchment, highly elevated bacterial loads during rainfall events may be due to significant sewer overflows, as many wastewater treatment plants discharge their effluents in this catchment. Also, land runoff occurs over horse and bulls breeding areas and the urban area of Nîmes. The storm event on July 1st, 2012 coincides with a “poor” water quality classification in Palavas-Les-Flots on July 2nd, as illustrated in Fig. 6.

4. Discussion

This study analyses the impact of intense summer rainstorms on fecal contaminations in a coastal area under

Table 1

Characteristics of the linear regressions linking the Antecedent Precipitation Index (API) and Fecal Indicator Bacteria (FIB) loadings for both thermo-tolerant coliforms (TTC) and intestinal enterococci (IE) in the three subcatchments of the Gulf of Aigues-Mortes (Lez-Mosson, Or, and Vistre-Vidourle). In the Or subcatchment, the API was calculated for the day preceding the measurement as bacterial contaminants need one more day to reach the catchment outlet because of the buffering capacity of the Or lagoon.

	Lez-Mosson		Or		Vistre-Vidourle	
	TTC	IE	TTC	IE	TTC	IE
Intercept						
Estimate	12.1	12	10.9	10.8	12	11.6
Std error	0.323	0.24	0.17	0.214	0.192	0.187
Pr (> t)	1.89E ⁻¹⁵	2E ⁻¹⁶	1.61 ⁻¹⁵	2.33E ⁻¹⁴	2E ⁻¹⁶	2E ⁻¹⁶
Slope						
Estimate	0.038	0.035	0.039	0.039	0.048	0.056
Std error	0.005	0.004	0.004	0.005	0.005	0.005
Pr (> t)	2.46E ⁻⁰⁶	1.97E ⁻⁰⁷	1.18E ⁻⁰⁶	1.08E ⁻⁰⁵	8.93E ⁻⁰⁹	6.36E ⁻¹⁰
R ²	0.805	0.864	0.892	0.84	0.864	0.9
Pearson coefficient	0.9	0.93	0.94	0.92	0.93	0.95

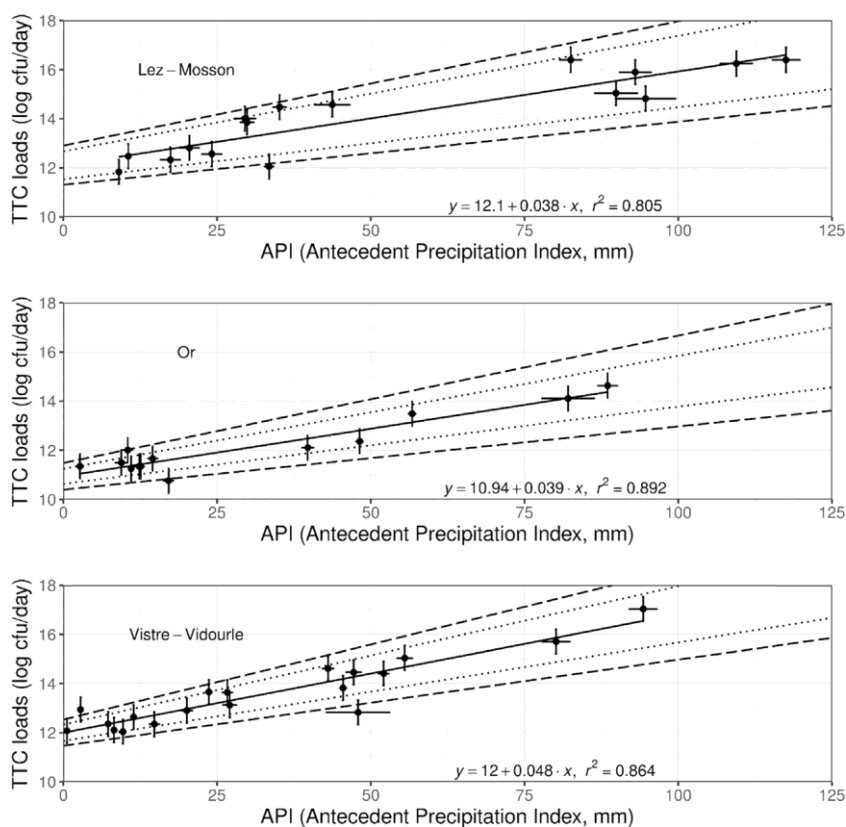


Fig. 4. Explanatory relationships between API and thermo-tolerant coliforms (TTC) loads in the Gulf of Aigues-Mortes. The 90% confidence intervals arising from measurement uncertainties are represented in long-dashed lines. The 90% confidence intervals arising from the dispersion of the points are represented in dotted lines.

the Mediterranean climate. Our results show significant increases in thermo-tolerant coliforms and intestinal enterococci loadings at the catchment outlets in response to intense rainfall events, consistent with previous studies conducted under semi-arid and tropical climates (Ackerman and Weisberg, 2003; Causse et al., 2015; Cho et al., 2010; Rochelle-Newall et al., 2016). Microbial loadings were found to be highly correlated with the Antecedent Precipitation Index (API) at the outlets of the three

subcatchments, regarding TTC as much as IE. Although other meteorological criteria such as solar irradiation could impact FIB loads at the catchment outlets (Cha et al., 2010; Chan et al., 2015; Hathaway et al., 2010; Rochelle-Newall et al., 2015), antecedent rainfall is the main indicator influencing microbial contamination in the Gulf of Aigues-Mortes.

Simulated bacterial loadings are systematically associated with a confidence interval emerging from measure-

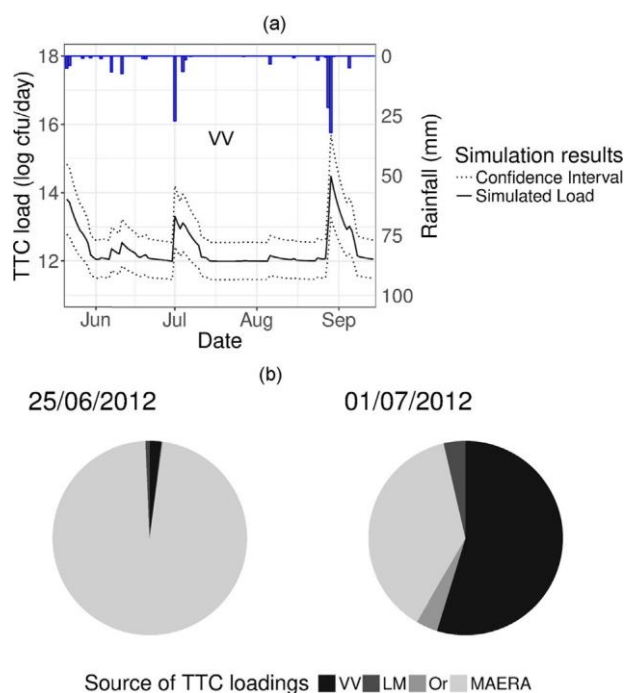


Fig. 5. a: simulated loads of thermo-tolerant coliforms (TTC) at the Vidourle–Vistre (VV) subcatchment outlets during summer 2012. The histogram represents the daily precipitation; b: apportionment of thermo-tolerant coliforms (TTC) loadings (CFU/day) to the Gulf of Aigues-Mortes under dry conditions (total load of $1.96 \cdot 10^{14}$ CFU/day) and during a rainfall event (total load of $2.87 \cdot 10^{14}$ CFU/day). LM: Lez-Mosson catchment, Or: Or catchment, VV: Vistre–Vidourle catchment, MAERA: wastewater treatment plant.

ment uncertainties. Whilst standard statistical methods assess uncertainties through the dispersion of the points around the regression line, this study provides a methodology to take into account the difficulties of precisely measuring FIB concentrations and river discharges, especially during extreme events. These errors mainly depend on the spatial-temporal variability of microbial concentrations within the river section, even though sample storage and laboratory methods may also generate uncertainties (McCarthy et al., 2008). Thereby including measurement errors in the modelling process, the order of magnitude of bacterial loadings is estimated along with an accurate range of variation. Therefore, significant increases in FIB loads can be detected and distinguished from negligible variations within the 90% confidence interval.

Over the period 2006–2016, the model outputs highlight frequent summer rainstorms leading to an increase of bacterial loadings by more than one log unit CFU/day at the catchment outlets. Although the spread of contamination depends on numerous factors such as salinity, dissolved oxygen, temperature, marine currents and solar irradiation (Boehm et al., 2002; Gonzalez et al., 2012), massive inputs of microbial contaminants to the coastal area may affect human health and cause bathing prohibition. Several events of bathing water quality degradation were recorded by the Occitanie regional health agency from 2006 to 2016 during rainy sampling

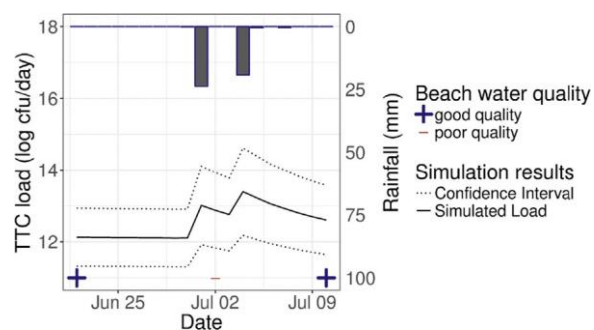


Fig. 6. Thermo-tolerant coliforms (TTC) loadings at the Lez-Mosson catchment outlets and bathing water quality in Palavas-Les-Flots during summer 2012. The histogram represents the daily precipitation.

days. Notwithstanding that the majority of regulatory samples classify bathing waters as “excellent” in the Gulf of Aigues-Mortes, only a few samples were collected during rainfall events and the associated API never exceeded 50 mm. Consequently, none of samples were collected during extreme summer rainstorms, which are nonetheless the most likely conditions to degrade recreational water quality.

Sewer overflow and land runoff are the main phenomena occurring during rainfall events that engender microbial contaminations. Even with the MAERA wastewater treatment plant located in the catchment since 2006, wet weather conditions generate continental bacterial loadings that may impair coastal water quality. However, during dry periods, MAERA discharges 64% of the LM catchment effluents through the sea outfall and thus reduces the continental inputs of Fecal Indicator Bacteria. Consequently, whereas the population is significantly higher in the LM catchment than in the VV catchment, bacterial loadings are similar under dry weather conditions. Moreover, the modelling of the Gulf of Aigues-Mortes hydrodynamics showed that the effluents from the sea outfall do not contaminate coastal bathing waters (Leredde et al., 2007; Monfort et al., 2012). Despite this beneficial effect of MAERA in the LM subcatchment, regulatory monitoring data underlines the impact of urbanized catchments on continental bacterial inputs to coastal waters, even under dry weather conditions. Among the observed events of bathing water quality degradation, 64% were recorded around the LM and Or catchment outlets, while 36% were recorded close to the VV subcatchment outlets. Consequently, urbanized catchments seem to generate the most important part of microbial contaminations, which is coherent with recent research (Cho et al., 2010; Kang et al., 2010; Paule-Mercado et al., 2016). Also, more frequent bathing water quality degradation was observed around the Lez and the Vidourle outlets than in the remote recreational sites. During dry periods, the sources of Fecal Indicator Bacteria may be sewer leakage in coastal cities, animals frequenting beaches and the bathers themselves (Elmir et al., 2007; Wright et al., 2009).

In the Gulf of Aigues-Mortes, bacterial contamination of coastal waters may affect the local economy by causing the prohibition of bathing and nautical activities, leading to a

decrease in tourist numbers. At a wider scale, tourism industry is the largest business sector in the world economy and highly depends on coastal and marine destinations. By highlighting the impact of rainfall events on bacterial loadings to the coastal area, this study emphasizes the need of considering hydrological conditions in the monitoring of bathing and fishing water quality to avoid severe economic losses. The collection of bathing water quality data representative of different hydrological regimes could enable water quality managers to maximize monitoring efficiency and to build a stronger predictive model. Such statistical tool has been developed in North Carolina, USA (Gonzalez et al., 2012) to detect water quality degradation in recreational and high priority shellfish waters from antecedent rainfall, salinity, dissolved oxygen and temperature.

The methodology presented in this study can also be applied in developing countries, where public health is threatened by the use of water of poor quality. In such areas, land runoff and latrines overflow are the prevalent factors driving bacterial contaminations of surface waters during rainfall events (Causse et al., 2015; Rochelle-Newall et al., 2016). Indeed, the lack of sanitation induces the defecation of humans and animals on the top of the soils. The statistical model linking bacterial loadings to antecedent precipitations could support wastewater managers in estimating the timing and magnitude of serious contamination events. Further, such analysis is cost effective and can be applied in areas where little knowledge is available about the morphology and hydrology of the catchment.

To build the empirical regressions in other environments, the demography and water management practices must stay stationary during the sampling and simulation periods. Also, the measurements of bacterial loadings should represent the different hydrological conditions of the area. Additional measurements can validate the statistical regressions after the sampling campaigns. Regarding the choice of the dependent variable, TTC and IE are used worldwide to detect fecal contamination. However, under certain climatic conditions such as in tropical areas, the persistence of these indicators is increased (Ekklesia et al., 2015), and FIB may not be suitable to identify recent fecal contamination from humans and animals. According to Rochelle-Newall et al. (2015), the development and proliferation of FIB in tropical environments are promoted by high and stable temperatures, high light intensities and high relative humidity. The empirical regressions developed in this study can then be applied for other aquatic pathogens or tracers of fecal contamination, as the calibration process only depends on the size of the catchment, the land use and the hydrological regime through API calculation.

Finally, our results showed that the frequency of assessing bathing and fishing water quality is essential to detect bacterial contamination events following intense rainstorms. A monthly sampling conducted under dry weather conditions and the incubation time for FIB enumeration limit the capacity of regulatory authorities to assess bathing water quality in a timely manner, as showed by Leecaster and Weisberg (2001) in southern California. While the authors observed only 5% of

exceedance of bathing water quality standards during monthly sampling, this frequency reached 25, 55 and 80% for sampling once a week, three times per week and five times per week, respectively. Consequently, more frequent FIB measurements, following peaks of microbial inputs predicted by the linear model could specify the link between high bacterial loadings at the catchment outlets and contamination events in surrounding recreational waters.

5. Conclusion

In semi-arid and tropical regions, intense rainstorms drive bacterial contaminants transfer through hydrographical networks to seawaters. Consequently, maintaining good water quality in recreational and fishing areas is a crucial issue facing coastal water managers. This study analyses the impact of intense summer rainstorms on fecal bacterial loadings to a coastal area under the Mediterranean climate. A linear regression model was developed to quantify thermo-tolerant coliforms and intestinal enterococci loadings at a catchment outlet in relation to an Antecedent Precipitation Index. The API results from the sum of weighted rainfall depths of the antecedent days. The model is based on temporal stationarity in territorial dynamics and rainfall patterns, assuming no major changes during the modeling period due to land use planning or climate change. Measurement uncertainties are included in the linear model to assess confidence interval of the outputs. Observed fecal bacterial loadings were found to increase significantly with API, and the highest loads were recorded during two flood events in 2010 and 2011. Moreover, river estuaries were the main sources of microbial inputs compared to the outlets of coastal lagoons, which offer important buffering capacities. The spatial heterogeneity of FIB loads within the flow section was the major source of uncertainty associated with fecal bacterial loads measurements.

The model outputs showed that (i) more than 80% of the variance of microbial loadings is explained by antecedent precipitation, (ii) on average 2 rainfall events per summer season lead to an increase of fecal bacterial inputs to the coastal area by more than one log unit CFU/day, (iii) continental inputs to the sea become the major source of fecal bacterial contaminants during rainfall events compared to the sea outfall of the wastewater treatment plant.

The advantages of the statistical model for estimating the bacterial loadings at the catchment outlets are its simplicity and its robustness. The only requirement is to have rainfall data available. The estimation of FIB loads and the associated confidence interval arising from measurement uncertainties expand the ability of coastal water managers to anticipate potential contamination of bathing and fishing waters and therefore maximize monitoring efficiency.

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