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A predictive model of the impact of urbanization on bacterial loads in watersheds

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Abstract

Bacterial concentration is one of the most important aspects of water quality. Many regions in the world are affected by increasing urbanization and a potential increase in bacterial concentrations in waters. We used long-term data from 68 stations in eight watersheds in Eastern Thailand to quantify the temporal and geographical variation in total and fecal coliform bacteria. Descriptive statistics showed considerable seasonal, inter-annual, and geographical variation. In order to quantify this multi-level variation, we built a predictive model of bacterial loads. Using fixed- and mixed-effects regression models, we built a model including the effects of urbanization and other significant variables. The best model, fitted by restricted maximum likelihood, included the effects of season, year, urbanization as fixed effects, and of watershed and station as nested, random effects. Temporal variation was related to seasonal and annual variations. Spatial variation had a very significant impact on the bacterial concentrations. Urbanization was an important factor controlling concentrations of bacteria in rivers: we found that the proportion of urban area around a station had a statistically significant effect on log-transformed total coliform bacterial concentration with a slope equal to 1.3 (SE = 0.3), and on log-transformed fecal coliform bacterial concentration with a slope equal to 1.4 (SE = 0.3). Our model predicts that bacterial concentrations would be multiplied by 20 if land is transformed from non-urban to fully urban.

Keywords: Coliforms, Microbiological water quality, Mixed-effect models, Rivers, Thailand

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1. Introduction

The growth of urban areas is a major environmental issue around the world. Conversion of lands into
3 either agricultural lands or urban areas have different consequences with the former case being generally
associated with increased soil erosion and increased chemical inputs in water (particularly nitrogen),
whereas increased human population density is generally associated to increased waste disposal from
6 urban areas which affect directly bacterial concentrations (Cabral and Marques, 2006; Diwan et al., 2018;
Shukla et al., 2018). These issues affect water quality in rivers and waterbodies at different scales and
depending on ecological factors and the management of waste (Causse et al., 2015; Jeong et al., 2019).
9 Furthermore, land use change is a dynamic process taking place at different scales of time and space (Song
et al., 2018), so we may expect the relationship between land use changes and water quality to be complex.

One of the most important components of water quality is the quantity of bacteria in rivers, and
12 particularly coliforms, as some of them are produced by human waste (Abraham, 2011; Rochelle-Newall
et al., 2015). A crucial challenge is to predict the changes in concentrations of coliforms in relation to land
use (Lyautey et al., 2010; St Laurent and Mazumder, 2012; Rochelle-Newall et al., 2016). These
15 predictions are critical for environmental sustainability, but also to be able to take preventive decisions to
avoid negative impacts on human and ecosystem health.

Bacterial contamination is one of the most important issues related to water pollution. The scientific
18 literature on this subject points to two main sources of coliforms in surface waters: agriculture (Lyautey
et al., 2010; St Laurent and Mazumder, 2012) and urbanization (DiDonato et al., 2009). The considerable
ongoing changes in land use and occupation in Southeast Asia result in challenges in the management of
21 environmental resources. Such challenges may be local (Soytong and Perera, 2017) or regional (Taylor,
2010; Paradis, 2018, 2020). Thailand is a country characterized by heterogeneous socioeconomic
development among its provinces, resulting in intense rural-urban migration (Shatkin, 2004; Soytong and
24 Perera, 2017). Eastern Thailand is characterized by highly contrasted land use: it includes large tracks of
tropical forest in its interior, extensive agricultural lands, and fast-growing urban areas on the coast. The
past and current projects of economic development in this area, particularly on the sea coast, raise
27 concerns about water quality and its evolution with respect to changes in land use (Water Environmental
Partnership in Asia, 2018; Eastern Economic Corridor Office, 2019).

In the context of increased urbanization in Eastern Thailand, the risk of water contamination by
30 coliforms could be increased because of the increasing local population densities in industrial areas
(Soytong and Perera, 2014; Water Environmental Partnership in Asia, 2018). Surface waters in Thailand

are classified into five categories according to different quantitative criteria; these categories are labelled
33 as: (1) extra clean, (2) very clean, (3) fairly clean, (4) moderately clean, and (5) unclassified in the previous
classes (http://www.secot.co.th/secot_ww/std-e.html; accessed 2021-01-14). Only the
categories 1–3 are proper for human consumption. The main water quality problems in four major river
36 basins of Thailand are high loads in coliform bacteria (36% of the problems; Simachaya et al., 2000). In
the Eastern Region, fecal coliform contaminations represent 17% of the water quality problems compared
to other parameters such as total solids, turbidity, biochemical oxygen demand, or dissolved oxygen. Fecal
39 coliform bacteria in the Bang Pakong River Basin, a watershed situated in the North of the Eastern
Thailand Region, exceeded surface water standard category 3, which is specified as equal to or less than
4000 bacteria per 100 mL (Simachaya, 2003). This previous study suggested that organic loading caused
42 by human communities, industry, pig farms, and aquaculture were the sources of pollution in this basin.

In this paper, we present a predictive model of bacterial concentrations in rivers and waterways. We
assessed the variability in total and fecal coliform bacteria throughout Eastern Thailand using data from a
45 long-term monitoring program of water quality. Using fixed- and mixed-effects regression models, we
built a model that includes the effects of urbanization and other significant variables. We used this model
to predict changes in bacterial concentrations caused by urbanization taking other effects into account. We
48 conclude with some perspectives on water quality management in the context of growing urban areas.

2. Materials and methods

2.1. Sampling

51 Sampling took place over the Eastern Thailand region in eight watersheds covering a variety of ecological
situations (Fig. 1). In order to consider seasonal variation, sampling was conducted four times each year in
February, May, August, and November which made possible to cover the range of weather regimes in
54 Eastern Thailand: end of dry (cool) season, first peak of rainy season, start of second peak of rainy season,
and start of dry season, respectively (<http://www.climate.tmd.go.th/content/file/75>).
The data used in this paper cover a period from December 2007 until August 2016. For logistic reasons,
57 sampling was done in December instead of November in 2007 and in 2008, and in April 2008 instead of
May 2008. Additionally, several stations were added to the monitoring program in order to increase its
geographical coverage. Four stations (NK01, NK02, PT01, and PT02) were discontinued after four
60 sampling sessions because they could not be accessed continuously to sample water. A total of 68 stations
were sampled between four and 36 times resulting in a total of 1999 samples. Five stations were sampled

four or six times, while the 63 others were sampled at least 19 times. The geographical coordinates

63 (longitude, latitude) of each station were recorded. The water samples were collected in sterile 250-mL plastic bottles and transported on ice to the laboratory of the Regional Environment Office of the Chonburi Province within 24 hours.

66 2.2. Laboratory analyses

The enumerations of total coliform bacteria (TCB) and fecal coliform bacteria (FCB) were done by means of the multiple-tube fermentation (MTF) method according to the protocols of the American Public Health Association (APHA, 1992). For TCB counts, a series of five fermentation tubes of lauryl sulphate broth (LSB, Merck; also known as lauryl tryptose broth) were inoculated with appropriate volumes of 10-fold dilutions of water samples and incubated at 37 °C for 48 h. The number of five-tube series and the
72 inoculation volumes were chosen depending on the quality and character of the water to be examined (American Public Health Association, 1992, p. 9-46). All gas-positive LSB tubes were subcultured to tubes of brilliant green lactose bile broth (BGLB, Merck) and incubated at 37 °C for 48 h. Gas-positive
75 BGLB tubes were considered positive for the presence of TCB. Gas-positive LSB tubes were subjected to further analysis with *Escherichia coli* broth (ECB, Merck). The EC tubes were incubated at 44.5 °C for 24 h. Gas-positive ECB tubes were considered positive for the presence of FCB. The values of TCB and
78 FCB (expressed in units of most probable number per 100 mL, or MPN/100 mL) were inferred using the following formula (American Public Health Association, 1992, p. 9-50):

$$\text{Bacterial concentration} = \frac{100 \times \text{number of positive tubes}}{\sqrt{\left(\frac{\text{mL sample in}}{\text{negative tubes}}\right) \times \left(\frac{\text{mL sample in}}{\text{all tubes}}\right)}}$$

2.3. Land cover data

81 The land cover data were downloaded from the European Space Agency Climate Change Initiative (ESACCI, <http://maps.elie.ucl.ac.be/CCI/viewer/download.php>, accessed 2018-04-18). These remote sensing data provide land cover and land use from 1992 to 2015 with a
84 resolution of 10'' (ten arcseconds), which is equivalent to a distance of approximately 300 m. Land cover was classified into 38 categories ranging from “No data” to “Permanent snow and ice”. The land cover data were extracted for Eastern Thailand (12.1–14° N, 100.8–102.7° E) and for the years 2007–2015. We
87 calculated an index of urbanization (variable called ‘Urbanization’ below) for each station as the

percentage of land use classified as “Urban areas” one kilometer around the point defined by the coordinates of the station. This index was calculated for each station and each year from 2007 to 2015; its value varied between 0 (no urban area around the station) and 1 (only urban area around the station). We also summarized land use changes, evaluated pixel by pixel, during this period with a focus on urbanization by calculating the proportion of urban areas over Eastern Thailand and land conversion related to urbanization.

2.4. Statistical model-building

We modelled the variation in TCB and FCB with regression models using different approaches, starting from simple linear models and then building more complex models. We first used simple linear regressions to assess the form and the significance of the variation of these relationships. We then performed multiple regression models to test the relative statistical significance of several predictors (‘Year’, ‘Season’, ‘Station’, ‘Urbanization’) using *F*-tests, assessing the significance of each effect while taking others into account. Hereafter, variable names considered as effects in a model are written within single quotes. However, these models must be interpreted with caution because of confounding effects. For instance, it is difficult to test the effects of ‘Station’ and ‘Urbanization’ in the same model because these two effects are mostly confounded (i.e. both variables are geographically linked). Therefore, we used linear mixed-effects (LME) models using ‘Watershed’ and ‘Station’ as random-effect terms. This made it possible to test for the effect of ‘Urbanization’ while considering ‘Watershed’ and ‘Station’ as repeated, nested, correlated measures. Each individual effect was tested with a χ^2 -based likelihood-ratio test where the null hypothesis is that the predictor has no effect on either TCB or FCB concentration while taking the effects of the other predictors in the model into account. Different LME models were compared with their Akaike information criteria (AIC; Akaike, 1973) after fitting the models by maximum likelihood (Pinheiro and Bates, 2000): the model with the smallest AIC was selected as the best one among those considered. TCB and FCB both had strongly skewed distributions so they were $\log_{10}$ -transformed before analyses, as commonly done when analyzing such data (e.g. Lyautey et al., 2010). Since ‘Urbanization’ was a continuous variable, its effect in the model was linear; however, it could be that such an effect might not be linear, for instance, urbanization may have no effect if its index is less than a threshold. Nonlinear effects of ‘Urbanization’ were tested by transforming the urbanization index into two categories: a threshold was chosen and a new categorical variable was defined as “urban” for the stations with ‘Urbanization’ greater than or equal to the threshold, or as “non-urban” if ‘Urbanization’ was less than the threshold. Different values of threshold

were assessed. Predictions for LME models were done with best linear unbiased predictors (BLUP) which include predictions for the random and the fixed effects (Robinson, 1991). The predictive power of a
120 model was calculated as the ratio of its explained variance on the total variance calculated with:

$$R^2 = 1 - \frac{\hat{\sigma}_r^2}{\hat{\sigma}^2},$$

where $\hat{\sigma}_r^2$ is the residual variance of the model, and $\hat{\sigma}^2$ is the total variance.

All data analyses were done with R version 3.5.1 (R Core Team, 2019). The LME models were fitted
123 and analyzed with the package lme4 (Bates et al., 2015). The GIS data were handled with the packages
rgdal (Bivand et al., 2018) and raster (Hijmans, 2018). A file with the commands used for these analyses is
available as supplementary information.

126 3. Results

3.1. Summary of coliform bacterial concentrations

Very low or very large bacterial concentrations could not be quantified precisely in the laboratory with the
129 MTF method because the required numbers of dilutions are not achievable in practice. The detection
thresholds in our study were found to be $18 \text{ MPN/100 mL} \leq \text{bacterial concentration} \leq$
 $160,000 \text{ MPN/100 mL}$. However, presence of bacteria outside of this interval was found in 124 measures
132 of TCB (6.2%) and 134 measures of FCB (6.7%). Out of the 1999 measures of TCB, 47 (2.4%) were
below the lower-bound of the detection threshold (TCB concentration $< 18 \text{ MPN/100 mL}$), and 77 (3.9%)
were above the upper-bound limit (TCB concentration $> 160,000 \text{ MPN/100 mL}$). For FCB, these numbers
135 were 110 (5.5%) and 24 (1.2%), respectively. It is therefore possible to infer the presence of bacteria in
very low or very large concentrations in these 258 measures. In order to include this information in the
subsequent quantitative analyses, these values were replaced by values drawn randomly in the interval [1,
138 17] for those below 18 MPN/100 mL , or in the interval [160,000; 200,000] for those above
 $160,000 \text{ MPN/100 mL}$.

Table 1 gives a summary of the distributions of TCB and FCB. Bacterial concentration exceeded
141 $10,000 \text{ MPN/100 mL}$ in 599 (30%) of the measures of TCB and in 246 measures (12.3%) of those of FCB.
A small number of measures exceeded $100,000 \text{ MPN/100 mL}$: 131 (6.6%) for TCB and 45 (2.2%) for
FCB. The concentrations of FCB were greater than 4000 MPN/100 mL in 405 measures (20%). Both TCB
144 and FCB displayed extensive spatial and temporal variation (Figs. 2 and 3, for TCB and FCB,

respectively). All stations displayed strong seasonal variation in both TCB and FCB with the highest levels measured in summer. Some inter-annual variation were visible for some stations (e.g. BK13, CB02, RY01, TE01). The five stations with four or six measures (BTR01, NK01, NK02, PT01, and PT02) were dropped for the subsequent analyses which were thus done with the 63 stations with at least 19 measures out of the 36 sampling occasions (see Sampling subsection). The mean TCB for each station averaged over years and seasons ranged between 479 MPN/100 mL (Station WR01 located upstream of the River Chantaburi) and 115,576 MPN/100 mL (Station BPT01 near the seamount of the River Bang Pakong). The mean FCB ranged between 48 MPN/100 mL (Station WR01) and 83,659 MPN/100 mL (Station BPT01). Three stations had a mean TCB larger than 100,000 MPN/100 mL: PR04 (upstream of the River Phang Rat on the border of the Provinces Rayong and Chantaburi), TE02 (upstream the River Bang Pakong), and BPT01 (see Table 1). The geographical distribution of the means for all stations showed considerable variation among basins (Fig. 4). Large mean TCB were observed throughout the study area, particularly downstream the rivers close to their seamounts.

3.2. Land cover use and changes between 2007 and 2015

The area considered for the land cover analysis covered 42,031 km² (including 10,323 km² covered by water) and showed little change in land use between 2007 and 2015 with only 287 km² (0.7%) of land that changed during this period. Out of these, 221 km² (77%) were converted into urban areas, mostly from cropland (204 km²). The extent of urban areas changed from 283 km² in 2007, to 504 km² in 2015, an increase of 78%. The three main categories of land use in the study area in 2015 were: rainfed cropland (15,360 km², 48.4%, excluding water), herbaceous cover (5,966 km², 18.8%), and evergreen, broadleaved forest (3,429 km², 10.8%).

3.3. Linear models

All effects were highly significant when considered alone in a regression model (Table 2). The variable 'Year' was considered either as a continuous variable or as a categorical one: in both cases the relationship was significant, but more variation was explained when 'Year' was a categorical variable, which indicates that TCB and FCB did not increase linearly over time. 'Year' was considered as a categorical variable in the subsequent analyses. 'Station' explained 47% of the variance in both TCB and FCB, whereas 'Watershed' explained 18%. On the other hand, 'Year' or 'Season' explained low quantities of variance. This shows that geographical variation is far more important than temporal variation.

174 A multiple regression model with the effects of ‘Year’, ‘Season’, and ‘Station’, as well as the
interactions between ‘Season’ and ‘Station’ and between ‘Season’ and ‘Year’, was fitted. ‘Watershed’ and
‘Urbanization’ were not considered in this model because they are confounded with ‘Station’ (see
177 subsection Statistical model-building). All effects as well as the interactions were highly significant
(Table 3). This model explained 66% of the variation of TCB, and 64% of FCB.

3.4. Mixed-effects models

180 To further elaborate our models, we fitted an LME model considering ‘Station’ and ‘Watershed’ as random
effects, with the former nested in the latter, and including ‘Season’, ‘Year’, the interaction between these
two variables, and ‘Urbanization’, as main effects. All fixed effects of this model were strongly significant
183 with either TCB or FCB as the response (Table 4). For TCB, the final model with all the above effects had
AIC = 4494. Transforming the urbanization index as a categorical variable did not improve the fit: AIC =
4501 with a threshold of 0.5 (i.e. stations with less than 50% of urban areas around 1 km were considered
186 as “non-urban”), or AIC = 4506 with a threshold of 0. The estimated variance associated with the random
effect of ‘Station’ was $\hat{\sigma}_{\text{Station}}^2 = 0.26$ (SE = 0.52), and the variance associated with ‘Watershed’ was
 $\hat{\sigma}_{\text{Watershed}}^2 = 0.11$ (SE = 0.33), both smaller than the residual variance $\hat{\sigma}^2 = 0.47$ (SE = 0.68).

189 For FCB, the final model had AIC = 4516. Transforming the urbanization index as a categorical
variable did not improve the fit (AIC = 4527 with a threshold at 0.5, or AIC = 4535 with a threshold at 0).
The estimated variances associated with the random effects were $\hat{\sigma}_{\text{Station}}^2 = 0.24$ (SE = 0.49) and
192 $\hat{\sigma}_{\text{Watershed}}^2 = 0.11$ (SE = 0.33), again smaller than the residual variance $\hat{\sigma}^2 = 0.47$ (SE = 0.69).

In order to use this final model for prediction, an artificial data set was built with all possible
combinations of the five predictors (‘Urbanization’, ‘Season’, ‘Year’, ‘Station’, and ‘Watershed’). The
195 predicted value of the response (TCB or FCB) was calculated for each combination of the predictors. This
made it possible to predict the effect of a given predictor while taking into account the effect of the others.
Figure 5 shows the predictions of TCB for each effect in the final model, taking the variation from other
198 effects into account. Since ‘Urbanization’ is a continuous variable, the predicted values of TCB are on
parallel straight lines with a slope equal to the estimated coefficient from the final model. These lines have
different intercepts because they represent the variation in the other predictors. For the other predictors,
201 which are all discrete, the variability from the others is represented with boxplots. This representation
makes it possible to visualize the variability associated with the two random effects, ‘Watershed’ and
‘Station’, which are nested. In particular, some stations which are in the same watershed have different

204 predicted values. Note that the predictions are made on the scale of the transformed response (i.e. $\log_{10}$).
There is clearly considerable variability outside of each significant effect, meaning that a single effect
explains only a portion of the global variability. Figure 6 shows the predictions for FCB which are very
207 similar to those for TCB. The plots of the predicted values against the observed ones show that the
predictions were best in the range between 1000 MPN/100 mL and 10,000 MPN/100 mL (Fig. S3).
Predictions tended to be overestimated for concentrations less than 1000 MPN/100 mL, and
210 underestimated for concentrations above 10,000 MPN/100 mL. The largest discrepancies were (on the
log-scale) 3.6 and 2.8 for TCB and FCB, respectively.

The slope of the parallel lines associated with the effect of 'Urbanization' was estimated to be equal to
213 1.3 (SE = 0.3) for TCB and 1.4 (SE = 0.3) for FCB. Therefore, the process of urbanization in this region
(increase of 'Urbanization' from 0 to 1) is predicted to result in a 20-times increase in TCB and 25-times
increase in FCB (since the responses were $\log_{10}$ -transformed).

216 To further assess the precision of these predictions, we focused on three stations with contrasting
features: a station characterized by an urbanization index equal to one (RY03), a station with an
urbanization index equal to zero but in the same watershed than the first one (RY02), and a station in an
219 area with increasing urbanization during the study period (WR02). This makes it possible to formulate
predictions without the additional effects of the predictors 'Watershed' and 'Station'. Furthermore,
focusing on a specific station is likely to be more meaningful for management purposes. Figure 7 shows
222 the predicted values of TCB for each year and each season for these three stations. Since the effect of
'Urbanization' is linear in the final model, the predicted effect of this variable is to simply shift the
temporal curves downwards (decreasing 'Urbanization') or upwards (increasing 'Urbanization'). For
225 simplicity, only the predictions for Urbanization = 0 (continuous curve) and for Urbanization = 1 (dashed
curve) are displayed. Clearly, the predictions for RY03 and for RY02 are very similar. In the case of
WR02, the urbanization will increase the values of TCB, although not reaching the values predicted for the
228 two other stations. For the three stations, the observations are well predicted by the model. Figure 8 shows
the predictions of FCB.

4. Discussion

231 In this study of bacterial concentrations in waters of Eastern Thailand, we showed that total and fecal
coliform bacteria showed considerable variation in the area studied both spatially and temporally. Several
studies have shown similar extensive variation in bacteria in Portugal (Cabral and Marques, 2006), Canada

234 (Lyautey et al., 2010), and India (Shukla et al., 2018). Temporal variation in our study was related to both
seasonal and annual variation: the highest levels of TCB/FCB were measured in summer which could be
explained by the highest temperatures over the year during this season. However, Vermeulen and Hofstra
237 (2014) observed that concentrations of *Escherichia coli* in several major rivers in Netherlands and Belgium
decreased with increasing temperatures because of bacterial die-off. On the other hand, summer in
Thailand is also the season with high precipitation which could lead to increased transport of bacteria. We
240 also observed considerable inter-annual variation in both TCB and FCB with no obvious trend. It is not
clear what caused these variations, though a potential candidate explanation could be weather. This is
currently under further investigation.

243 Spatial variation had a huge impact on the measured TCB and FCB. It is complicated to assess this
variation because of the nestedness of the effects (e.g. ‘Station’ and ‘Watershed’). This nestedness implies
that these effects must be included as random effects in a mixed model. The variance associated with the
246 effect of ‘Station’ was estimated to be twice as large than the one associated with the effect of ‘Watershed’.
This was apparent also when plotting the predicted values associated with each effect (Figs. 5 and 6).
Interestingly, urbanization appeared as a distinct effect from these two variables since the urbanization
249 index was strongly significant even after including ‘Station’ and ‘Watershed’ as random effects. It is still
unclear what could explain the important variation among stations and we are currently investigating other
potential variables (e.g. distance to the shore, land use around the stations).

252 It is difficult to compare our results with those from the literature because of possible (unreported)
differences in the field and laboratory protocols, which could add some systematic or random variation in
the data. Furthermore, the different methods may have different specificities towards bacterial species. On
255 the other hand, the particularities of different studies (e.g. climate, landscape) may help to better
understand the mechanisms controlling bacterial concentrations in rivers. Keeping in mind these caveats,
previous studies reported maximum values of MPN equal to 2420 MPN/100 mL in Canada (Butler et al.,
258 2014), 5172 MPN/100 mL in Ecuador (Rao et al., 2015), 8000 MPN/100 mL in Belgium (de Brauwere
et al., 2011), and 10,000 MPN/100 mL in Netherlands (Vermeulen and Hofstra, 2014) or in a rural area of
Laos (Causse et al., 2015). Lyautey et al. (2010) reported 2004 measures of *E. coli* concentration in
261 Ontario (Canada) with annual means between 10 MPN/100 mL and 1000 MPN/100 mL (global median:
64 MPN/100 mL) and only three measures larger than 10,000 MPN/100 mL. Jeong et al. (2019) found that
67% of the *E. coli* in a watershed in Texas (U.S.A.) was contributed by wildlife. However, increase in
264 wastewater discharges and urban lands due to population growth resulted in increased concentration of *E.*

coli (Jeong et al., 2019). By contrast with these values from the literature, our results showed large values of MPNs, particularly for TCB, with 38 out of 63 stations (60%) showing a mean TCB above
267 10,000 MPN/100 mL. Most of the studies cited above were conducted in temperate countries or in rural tropical areas (Laos and Ecuador), which could explain these differences. Besides, our study covered several watersheds and a substantial geographic area and thus the data we analyzed were probably more
270 heterogeneous than those in these studies. As an illustration of this point, our models predicted a mean TCB around 100 MPN/100 mL for some stations (CB01, WR01) and above 50,000 MPN/100 mL for others (e.g. BPT01). Nevertheless, it might be very useful to further assess the precision of the measures
273 reported here by analyzing some samples with different methods. Because of its location, BPT01 receives impacts from several land use activities, mainly shrimp and fish aquaculture, compared to CB01 and WR01 where agriculture is the main activity.

276 Urban growth and its environmental impacts are very general issues in many countries. Several studies have shown that the growth of urban areas is not random and usually follows a dendritic pattern known as urban sprawl (Pan et al., 2020; Xu et al., 2020). Studies in China, North America, and Europe showed that
279 the impact of urbanization is very likely to have different impacts on different areas (Tang et al., 2005; Du and Huang, 2017). This impact is also very likely to differ with respect to sociological factors, for instance in relation to commuting behaviours which is typical of many large European and North American urban
282 systems (Pan et al., 2019). The growth of urban areas is expected to increase the proportion of impervious surfaces as well as surface water runoff (Tang et al., 2005).

In the present study, we used a statistical approach based on linear mixed-effect models which was
285 motivated by the geographical spread of the stations which covered several watersheds. The inclusion of random effects (here ‘Station’ and ‘Watershed’) makes it possible to fit complex models that would be impossible to fit with standard linear models. Additionally, linear models, even with random effects, make
288 it possible to formulate predictions in a straightforward way which are easily interpretable.

An important result from our analyses is the importance of urbanization as a factor controlling concentrations of bacteria in rivers. Our models predict that TCB and FCB would be multiplied by 20 and
291 25, respectively, if land is transformed from non-urban to fully urban (i.e. urbanization index changed from zero to one). One motivation of monitoring water quality in this study area is its control in relation to the development of the Eastern Seaboard (ESB) or the Eastern Economic Corridor (EEC). The
294 transformation of the area started in 1982 and ESB has now the largest number of industrial estates in Thailand (i.e. 18 out of 38; Soyong and Perera, 2017). ESB, together with the Bangkok area, is a recipient

of rural migrants from other regions of Thailand (Jampaklay et al., 2007). Special economic zones (SEZ) with extensive industrial and urban development have undeniable social and economic benefits, but their environmental sustainability is generally questionable (see review in Ślusarczyk and Grondys, 2018). Previous studies have focused on social conflict arising from industrialization in ESB (Soytong and Perera, 2017). Zhang and Tripathi (2018) found a relationship between atmospheric pollution by fine particulate matter and lung cancer in Eastern Thailand (actually a subset of the area considered in the present study). Therefore, health hazard is likely to be a general concern in ESB as in other SEZs. Other studies showed the importance of urban areas in the concentrations of bacteria in rivers (Wu and Jackson, 2016), lakes (Newton and McLellan, 2015), or creeks (DiDonato et al., 2009).

5. Conclusions

The present study shows that coliform bacterial concentrations in waters of Eastern Thailand varied considerably both spatially and temporally. Temporal variation was related to both seasonal and annual variation with the highest levels of bacterial concentrations measured in summer. These concentrations varied extensively among stations and among watersheds. The concentrations of fecal coliforms were greater than 4000 MPN/100 mL, the upper limit for consumable surface water, in 20% of the measures. The study also shows that urbanization is a very significant driver of bacterial concentrations in the rivers of Eastern Thailand and is predicted to cause a 20-fold increase of these concentrations. These results bring important information for land management. First, wastewater treatment in urban areas is a crucial element in improving water quality. Second, it is crucial to investigate the proximate, causal factors that affect TCB and FCB as a consequence of urbanization. Other components such as cleaner production, legal framework, institutional and financial arrangements, monitoring and enforcement, and cooperation with related agencies and local communities, should be taken into account as well. Most of all, an ecosystem approach is the key to development planning strategies as rivers themselves provide several basic ecosystem services.

Declaration of interest statement

None.

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Table 1: Distribution summaries of total coliform bacteria (TCB) and fecal coliform bacteria (FCB).

	Number of measures greater than* (in MPN/100 mL)			Number of stations with mean greater than† (in MPN/100 mL)		
	10,000	50,000	100,000	10,000	50,000	100,000
TCB	599	248	131	38	7	3
FCB	246	84	45	14	2	0

*Out of 1999 measures from 68 stations. †Out of 63 stations.

Table 2: Simple linear regressions of total coliform bacteria (TCB) and fecal coliform bacteria (FCB); cont.: continuous; cat.: categorical. F : value of the F -statistic testing the effect of the predictor, df : numbers of degrees of freedom of the test (d_1, d_2), P : P -value of the test, R^2 : proportion of explained variance.

Predictor	TCB				FCB			
	F	df	P	R^2	F	df	P	R^2
Year (cont.)	5.28	1, 1997	0.021	0.00	46.04	1, 1997	< 0.001	0.02
Year (cat.)	5.47	9, 1989	< 0.001	0.02	9.41	9, 1989	< 0.001	0.04
Season	27.27	3, 1995	< 0.001	0.04	18.42	3, 1995	< 0.001	0.03
Station	25.79	67, 1931	< 0.001	0.47	25.80	67, 1931	< 0.001	0.47
Watershed	63.71	7, 1991	< 0.001	0.18	64.51	7, 1991	< 0.001	0.18
Urbanization	282.83	1, 1997	< 0.001	0.12	300.40	1, 1997	< 0.001	0.13

Table 3: Multiple linear regressions of total coliform bacteria (TCB) and fecal coliform bacteria (FCB). The F -tests are for the effect of each predictor taking the effects of the others into account. F : value of the F -statistic testing the effect of the predictor, df : numbers of degrees of freedom of the test (d_1, d_2), P : P -value of the test.

Predictor	TCB			FCB		
	F	df	P	F	df	P
Year (cat.)	9.70	8, 1695	< 0.001	14.30	8, 1685	< 0.001
Season*	46.47	3, 1919	< 0.001	29.94	3, 1919	< 0.001
Station	12.36	67, 1695	< 0.001	9.60	67, 1685	< 0.001
Season $\times$ Station	2.27	201, 1695	< 0.001	1.99	201, 1695	< 0.001
Season $\times$ Year	8.25	23, 1695	< 0.001	6.56	23, 1695	< 0.001

*Effect tested in a model without interactions.

Table 4: Linear mixed-effects model of total coliform bacteria (TCB) and fecal coliform bacteria (FCB). The χ^2 -based tests are likelihood-ratio tests where the null hypothesis is that the predictor in the first column has no effect on either TCB or FCB as response while taking the effects of the others into account. χ^2 : value of the χ^2 -statistic testing the effect of the predictor, df : number of degrees of freedom of the test, P : P -value of the test.

Effect	TCB			FCB		
	χ^2	df	P	χ^2	df	P
Year (cat.)	78.02	9	< 0.001	89.58	9	< 0.001
Season	135.21	3	< 0.001	88.34	3	< 0.001
Urbanization	16.55	1	< 0.001	20.96	1	< 0.001
Season $\times$ Year	159.92	23	< 0.001	132.06	23	< 0.001

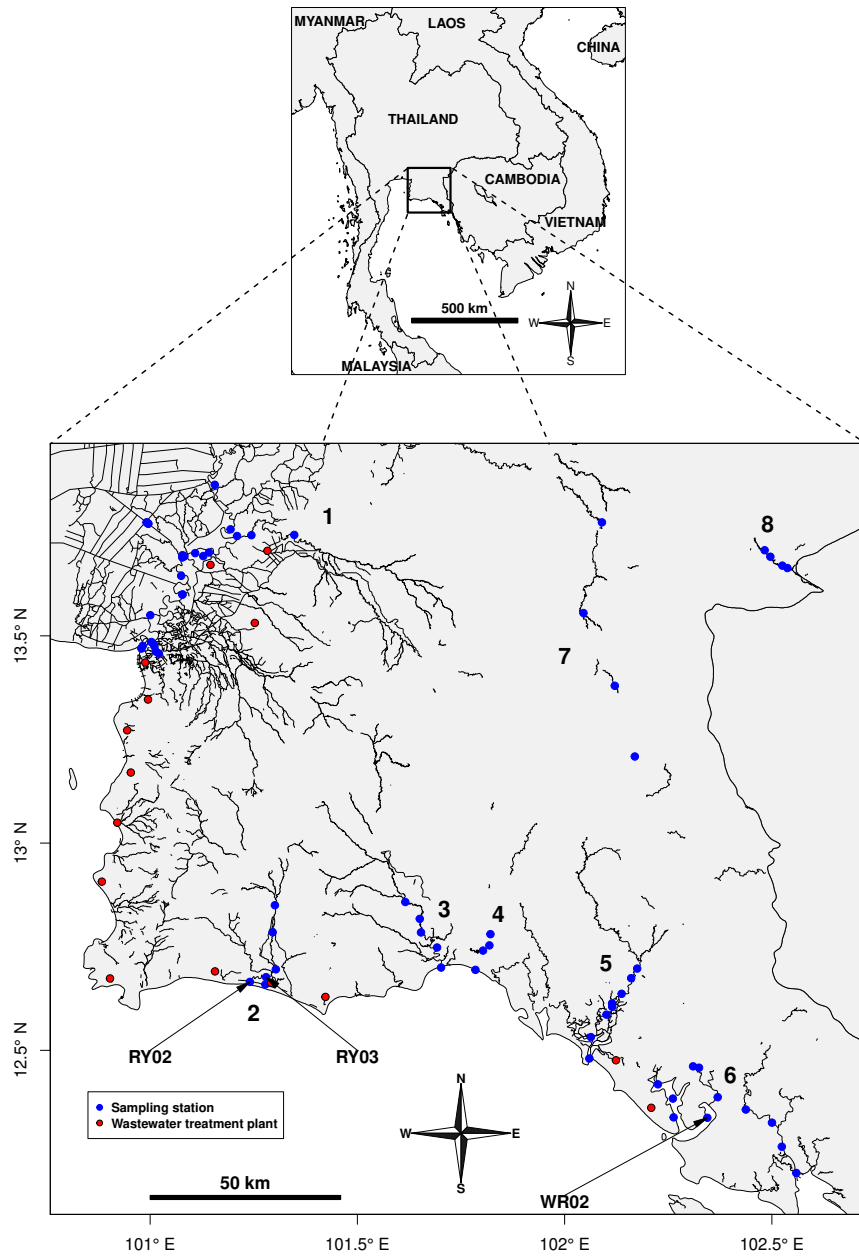


Figure 1: Geographical distribution of sampling stations displayed with the main waterways in Eastern Thailand and the wastewater treatment plants. The bold numbers indicate the watersheds used in the analyses. The stations RY02, RY03, and WR02, which are used in Figures 7 and 8, are shown with arrows. The locations of the wastewater treatment plants are from Dumrongthai (2019).

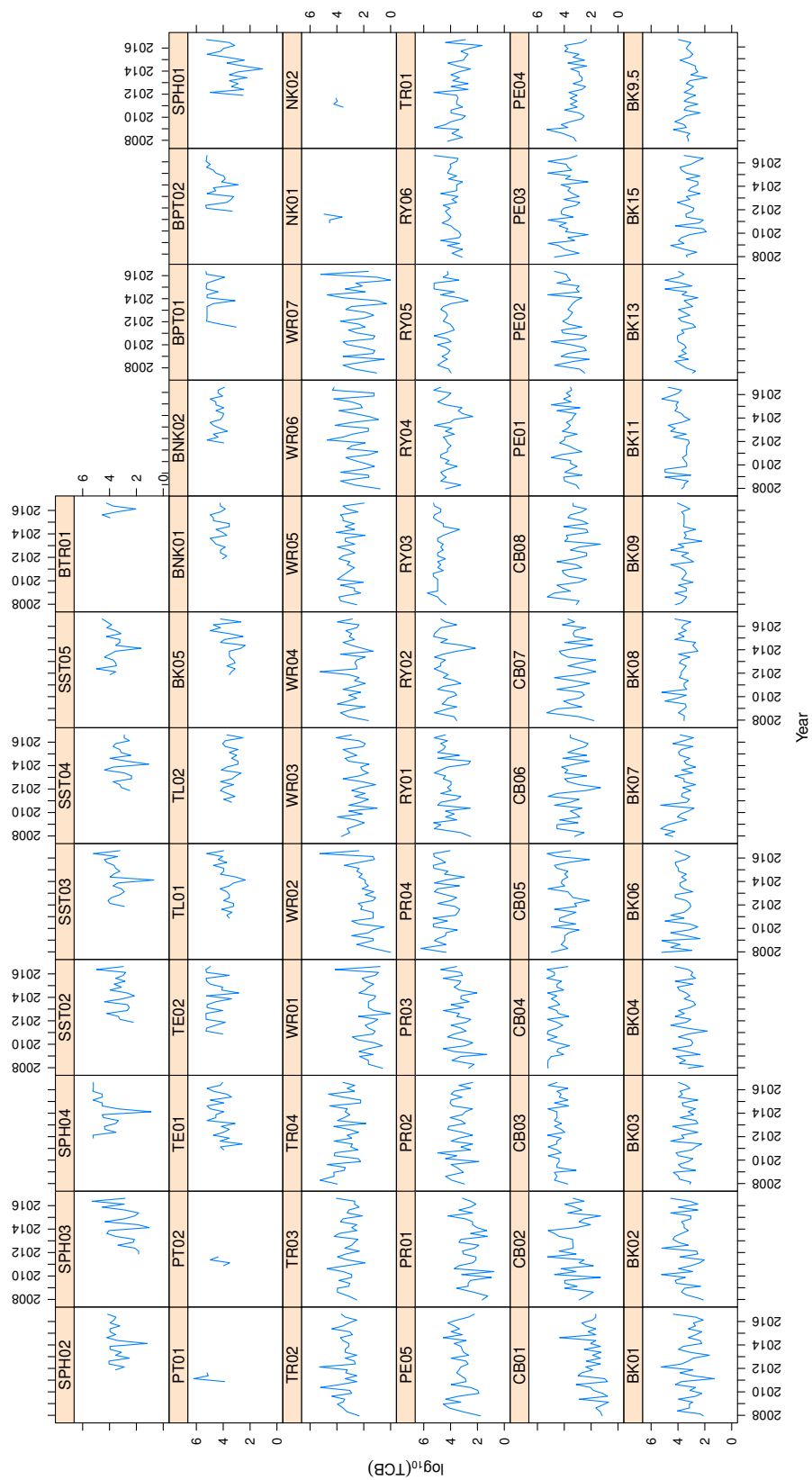


Figure 2: Temporal variation in abundance of total coliform bacteria (TCB, in MPN/100 mL) in 68 stations in Eastern Thailand

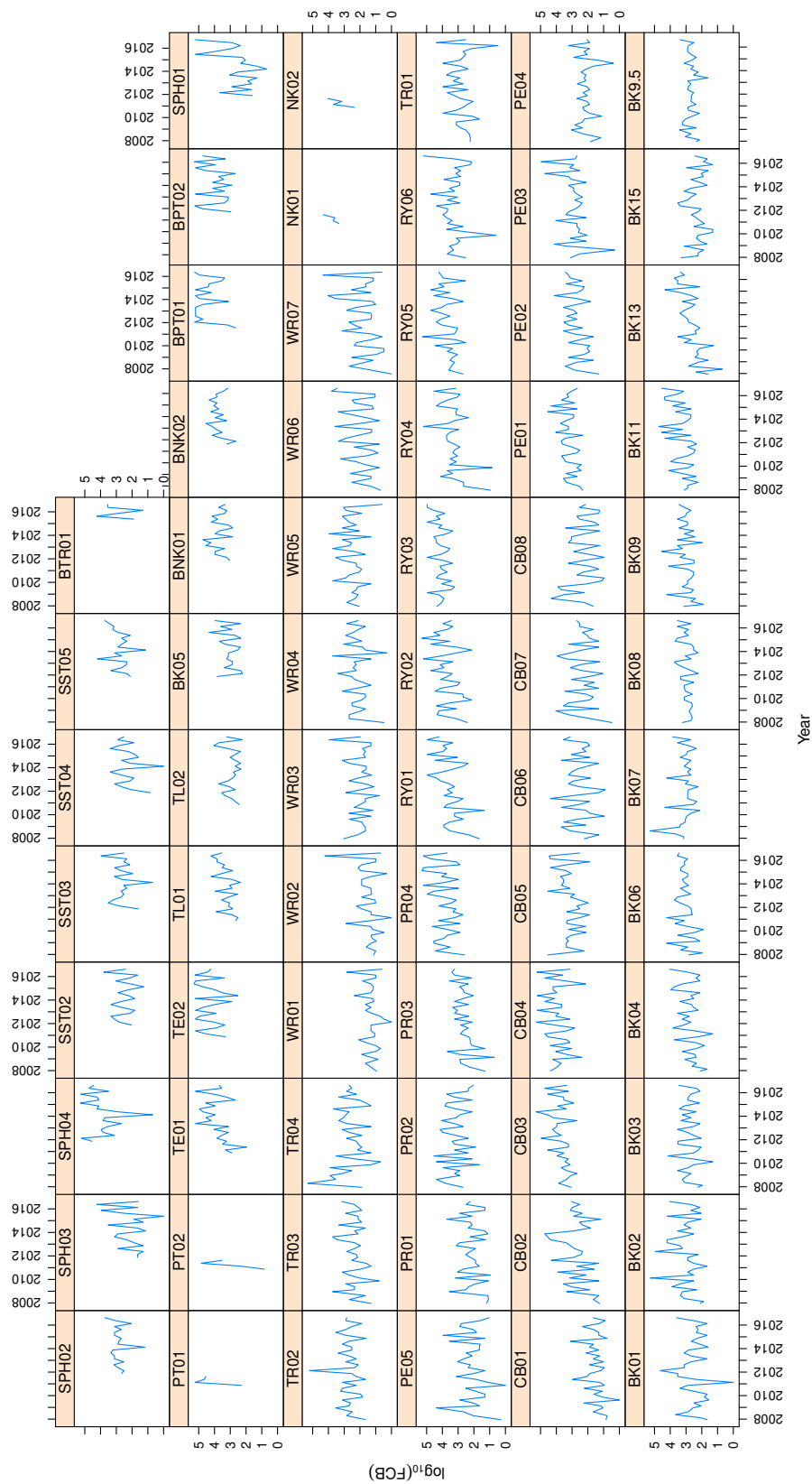


Figure 3: Temporal variation in abundance of fecal coliform bacteria (FCB, in MPN/100 mL) in 68 stations in Eastern Thailand.

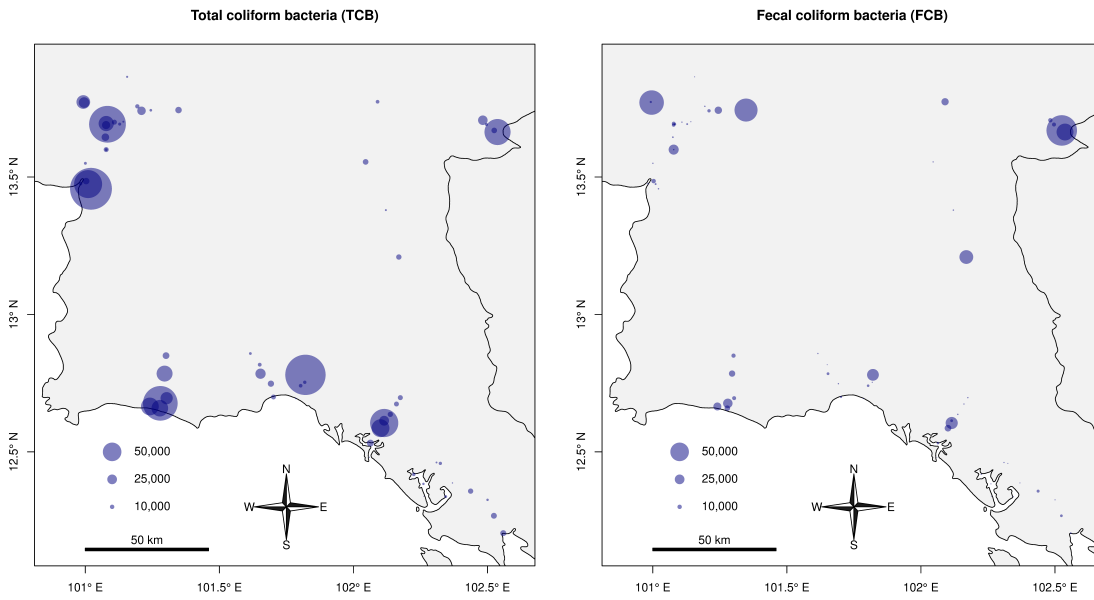


Figure 4: Abundance of total and fecal coliform bacteria (in MPN/100 mL) in Eastern Thailand averaged over all sampling occasions for each station.

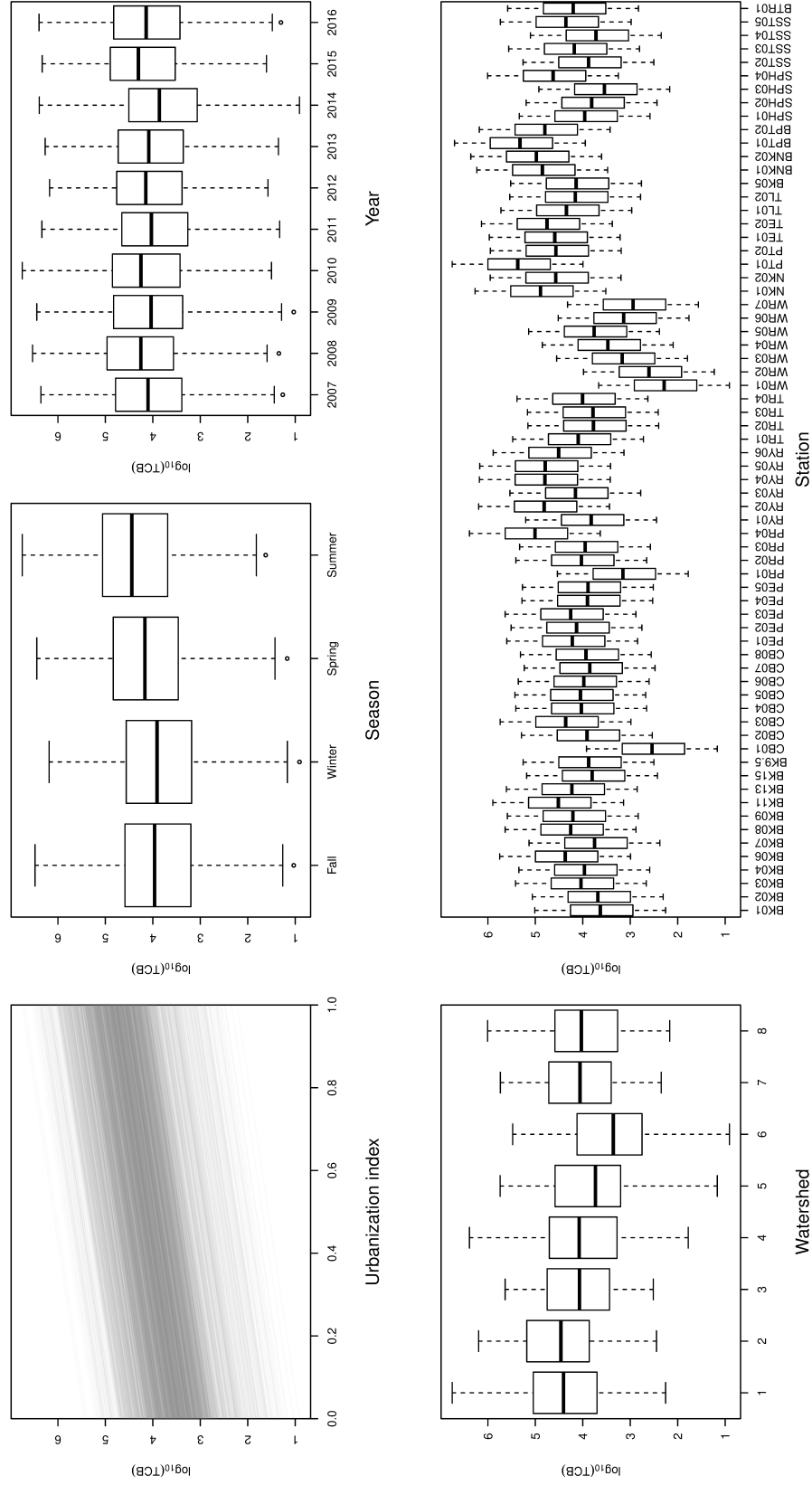


Figure 5: Predictions of TCB (in MPN/100 mL) from the final mixed-effects model. Each panel shows the partial predictions for each effect included in the model; the displayed variation is due to the other effects

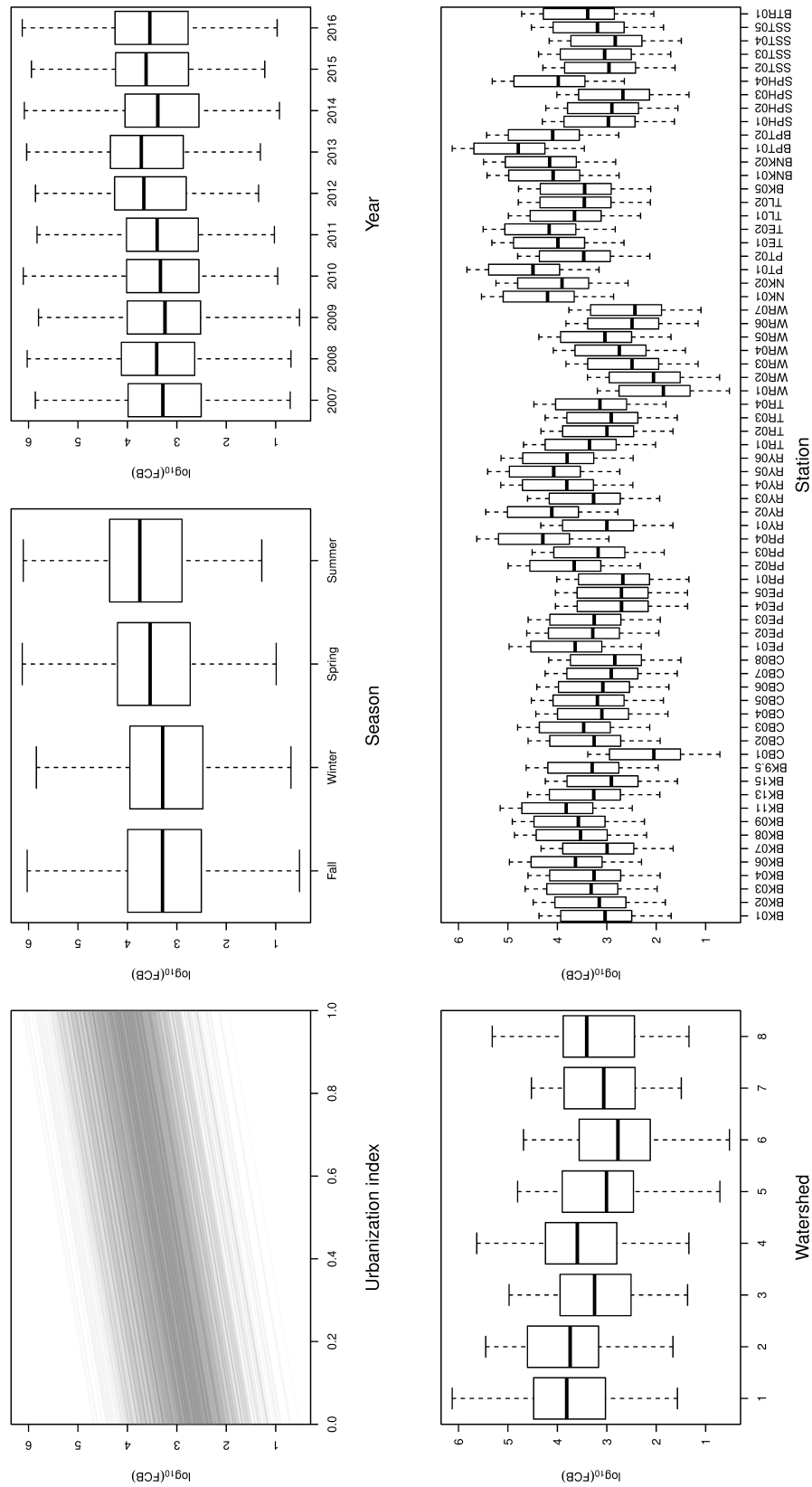


Figure 6: Predictions of FCB (in MPN/100 mL) from the final mixed-effects model. Each panel shows the partial predictions for each effect included in the model; the displayed variation is due to the other effects.

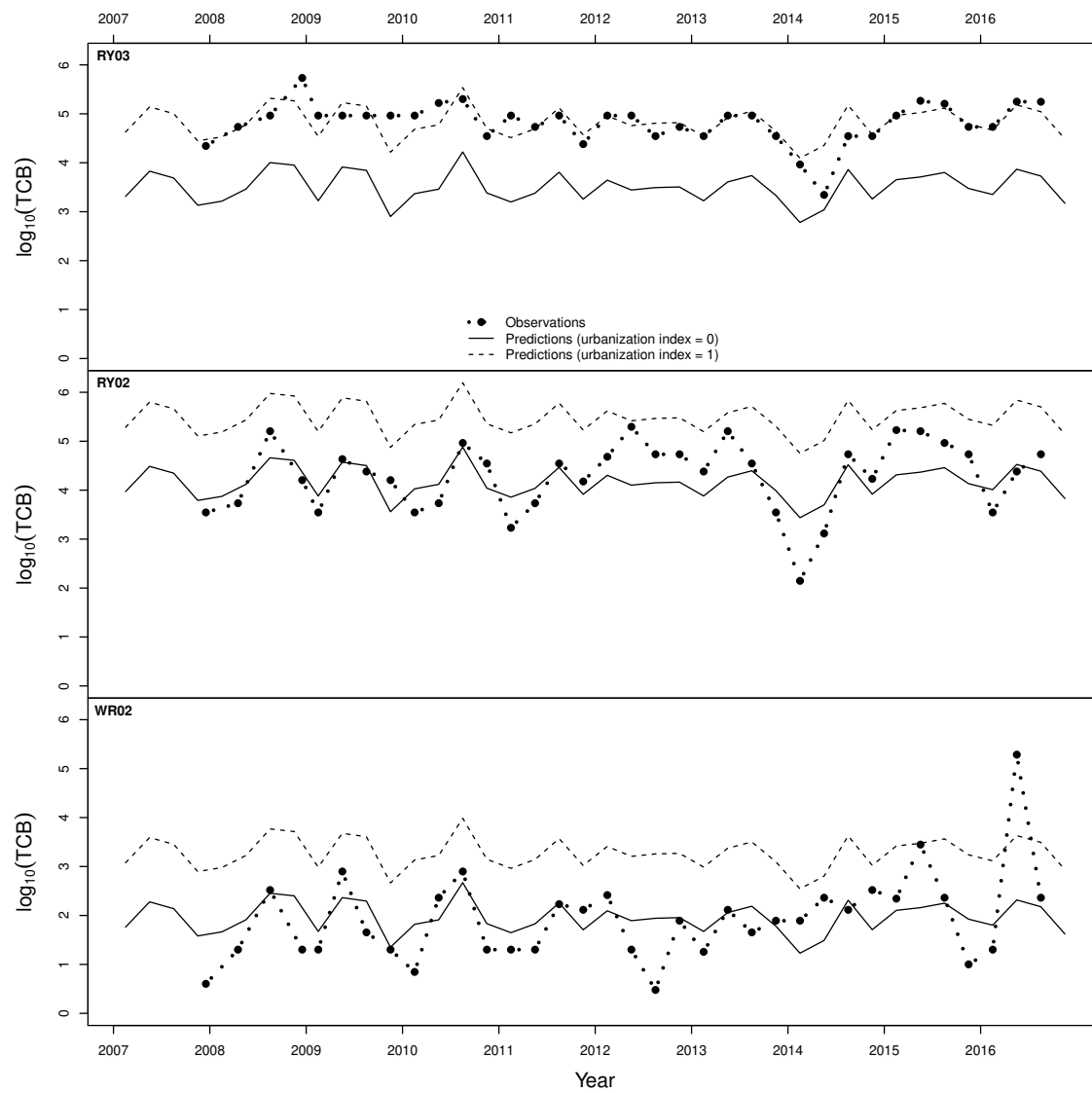


Figure 7: Predicted values of TCB (in MPN/100 mL) for three stations.

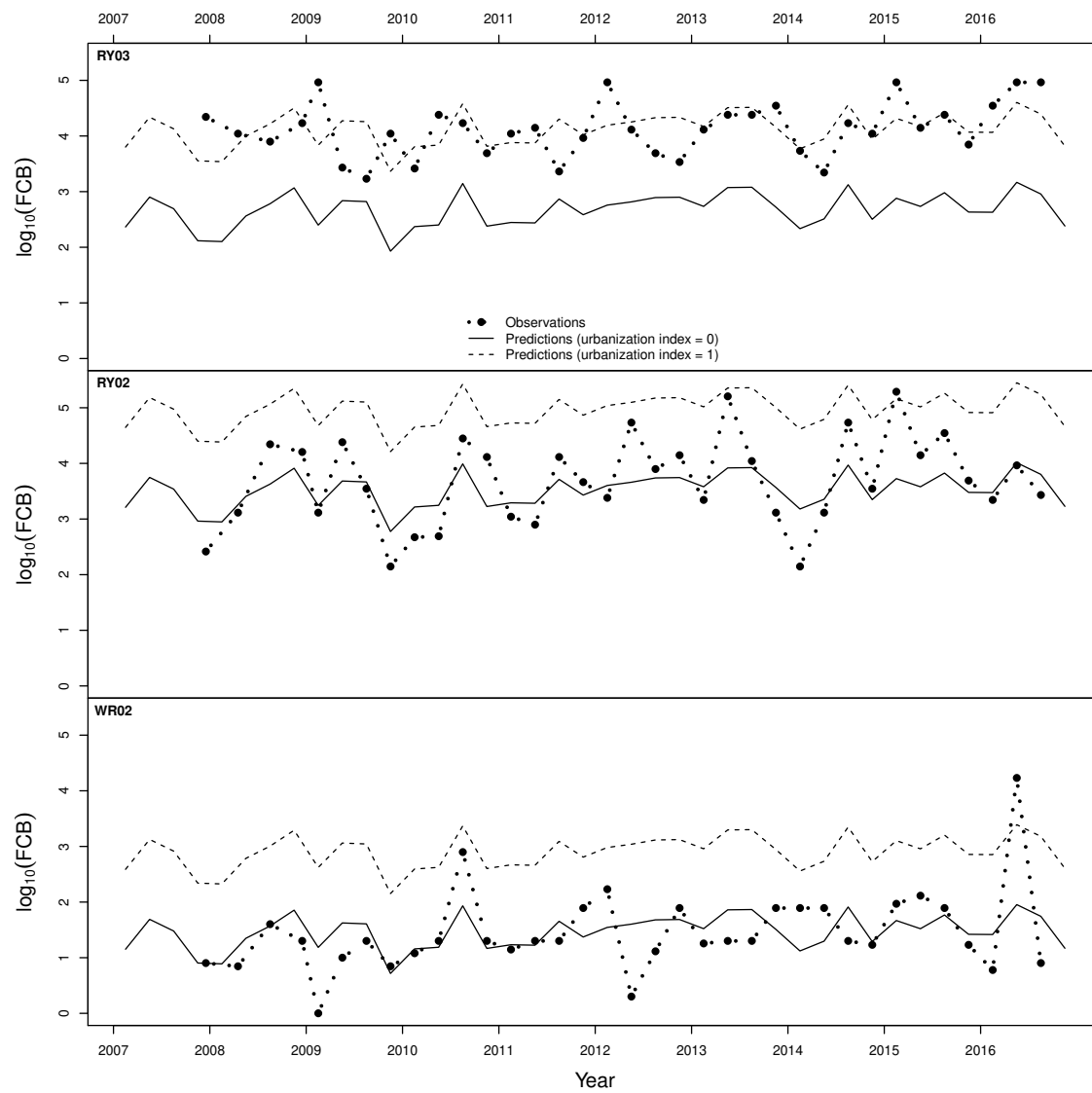


Figure 8: Predicted values of FCB (in MPN/100 mL) for three stations.