

Influence of climate variables on the concentration of *Escherichia coli* in the Rhine, Meuse, and Drentse Aa during 1985–2010

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Abstract This study evaluates the relationship between the climate variables temperature and precipitation and the concentration of *Escherichia coli* bacteria in the Rhine, Meuse, and Drentse Aa for the period 1985–2010. Data from 4,679 *E. coli* concentration measurements spread over a total of 13 locations in these three river systems were used in this study. The variables water temperature, precipitation, and river discharge were correlated with *E. coli* measurements. Water temperature was found to correlate negatively, and this is in line with expectations that higher temperature increases microorganism die-off. Precipitation and discharge were found to correlate positively, and this is in line with expectations that runoff from agricultural lands brings along pathogens from manure and increases the chance of sewer overflows. The data of the Meuse were fit to a linear model that explained *E. coli* concentrations from a time component, the climate variables and a locations dummy variable, in order to assess the relative contribution of the different variables. This model had an R^2 of 0.49, meaning that climate variables and location can account for nearly half of the observed variation in *E. coli* concentrations in surface water, even when other factors, such as land-use variables, are not taken into account. The effect of the different climate variables was found to differ with scale, with temperature being relatively important at a local scale, and discharge being mainly of importance at larger scales. From our results, we expect that climate change,

mainly the projected increased precipitation, may increase *E. coli* concentrations overall. Other waterborne pathogens that follow similar transmission pathways as *E. coli* may be similarly impacted by climate change.

Keywords Climate change · *E. coli* · Model · Waterborne pathogens

Introduction

Climate change is a recognized threat to society in many different ways. One relatively little researched issue is the impact that climate change could have on the spread of waterborne infectious diseases (Patz et al. 2008; Rose et al. 2001; Schijven and de Roda Husman 2005; Semenza and Menne 2009). The projected changes in surface temperature and more extreme precipitation patterns (Meehl et al. 2007) may affect the concentration of waterborne pathogens in the surface water (Rose et al. 2001) and therefore directly influence the risk of waterborne diseases (Freeman et al. 2009; Hunter 2003). The relationship between climate and these concentrations has been studied for several decades now (e.g., Blum et al. 1987), but quantitative information remains relatively scarce.

The objective of this study is to evaluate the influence of climate variables on the concentration levels of *Escherichia coli* for three river systems in Western Europe: the Rhine, Meuse, and Drentse Aa. The bacterium *E. coli* was selected for this study because, unlike other organisms, it has been extensively studied and is widely used as indicator organism for fecal contamination of water. Its presence may thus indicate the presence of more harmful microorganisms (Wilkes et al. 2009). The main sources of *E. coli* contamination in surface water are sewage and

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manure from farm animals, and also wildlife can contribute (Bach et al. 2002; Wang et al. 1996; Wells et al. 1991; Wu et al. 2011). Western Europe is chosen as a study area, because of the high population density and the intensive agricultural activity in the area, as well as the amount and quality of data that were available.

We study the climate variables, water temperature and precipitation. An increase in the water temperature is expected to decrease the concentration of *E. coli* in the water. Laboratory studies have shown that the die-off of *E. coli* increases with rising temperature (Medema et al. 1997; Wang and Doyle 1998). This effect of temperature could, depending on the study design, also be partly attributed to irradiation, since studies have shown that exposure to UV radiation in sunlight increases inactivation rates, and water temperature is partly regulated by solar intensity (Davies and Evison 1991). Few studies also report growth of *E. coli* outside of a host organism, although under very specific conditions and especially at higher temperatures (Gautam et al. 2011; Vital et al. 2008; Wang et al. 1996). *E. coli* growth is therefore not relevant in this study.

Changes in precipitation patterns can influence *E. coli* concentrations in various ways. Most studies find increased *E. coli* concentrations associated with increased precipitation (Cho et al. 2010; Ferguson et al. 1996; Hong et al. 2010; Tryland et al. 2011; Wu et al. 2011). Especially, increased heavy precipitation events increase runoff from the land, bringing along pathogens from manure, and increase the chance of sewage overflows (Cho et al. 2010; Geldreich et al. 1968; Gibson et al. 1998; Hong et al. 2010; Kistemann et al. 2002). In addition, re-suspension of microorganisms in stream sediment can increase during heavy rainfall events (Cho et al. 2010; Garzio-Hadzick et al. 2010; Stott et al. 2011). River discharge, a variable largely dependent on precipitation (Pfister et al. 2004), has been found to positively correlate with *E. coli* concentrations (Schilling et al. 2009). Nichols et al. (2009) emphasize that not only high precipitation levels but also drought can lead to elevated pathogen concentrations. For example, soil has a lower filtering effect in dry periods, which could increase pathogen concentration during runoff events (Nichols et al. 2009). Furthermore, decreased precipitation may decrease dilution and therefore increase the concentration of *E. coli* in dry periods (Senhorst and Zwolsman 2005).

The climate variables (temperature and precipitation) can influence *E. coli* concentrations in surface waters, but their relative contribution to changes in bacterial concentrations remains unclear. It is important to assess relative influence, to eventually determine the net effect that climate change could have on *E. coli* in this region. Other waterborne pathogens may be similarly impacted by

climate change. If an increase in waterborne pathogens is expected, this can result in an increase in the risk of waterborne diseases.

In this study, we focus on the relationship with climate variables solely and not on the characteristics of the sources of *E. coli* itself. We acknowledge that a variety of other factors influence *E. coli* concentrations in surface water, such as land-use changes and farming practices (e.g., timing of spreading of manure on fields) or the location of waste water treatment facilities (Crowther et al. 2001; Crowther et al. 2002; Kampf et al. 1997; Kay et al. 2008; Schulz and Childers 2011).

We assess the contribution of the climate variables temperature and precipitation to the observed variation in *E. coli* concentrations using statistical modeling. Statistical modeling enables us to assess the net effect of temperature and precipitation on *E. coli* concentrations. Statistical modeling of pathogen loads has been attempted mostly at local scales and with varying results (Crowther et al. 2003; Kay and McDonald 1983; Kay et al. 2005; Olyphant and Whitman 2004). Different variables are taken into account in these models; often, precipitation or discharge is included, some focus on temperature. Few studies use a comprehensive set of climate variables including precipitation, discharge, or runoff as well as temperature in their statistical models. In this study, we assess the effect of temperature and precipitation on *E. coli* by (I) establishing the correlation between observed climate variables and the concentration levels of *E. coli* in three selected river systems and (II) estimating the relative contribution of the different climate variables to the observed variation in *E. coli* concentrations by fitting the data of the river Meuse to a linear model. We discuss the results in the context of climate change.

Methods

Study site description

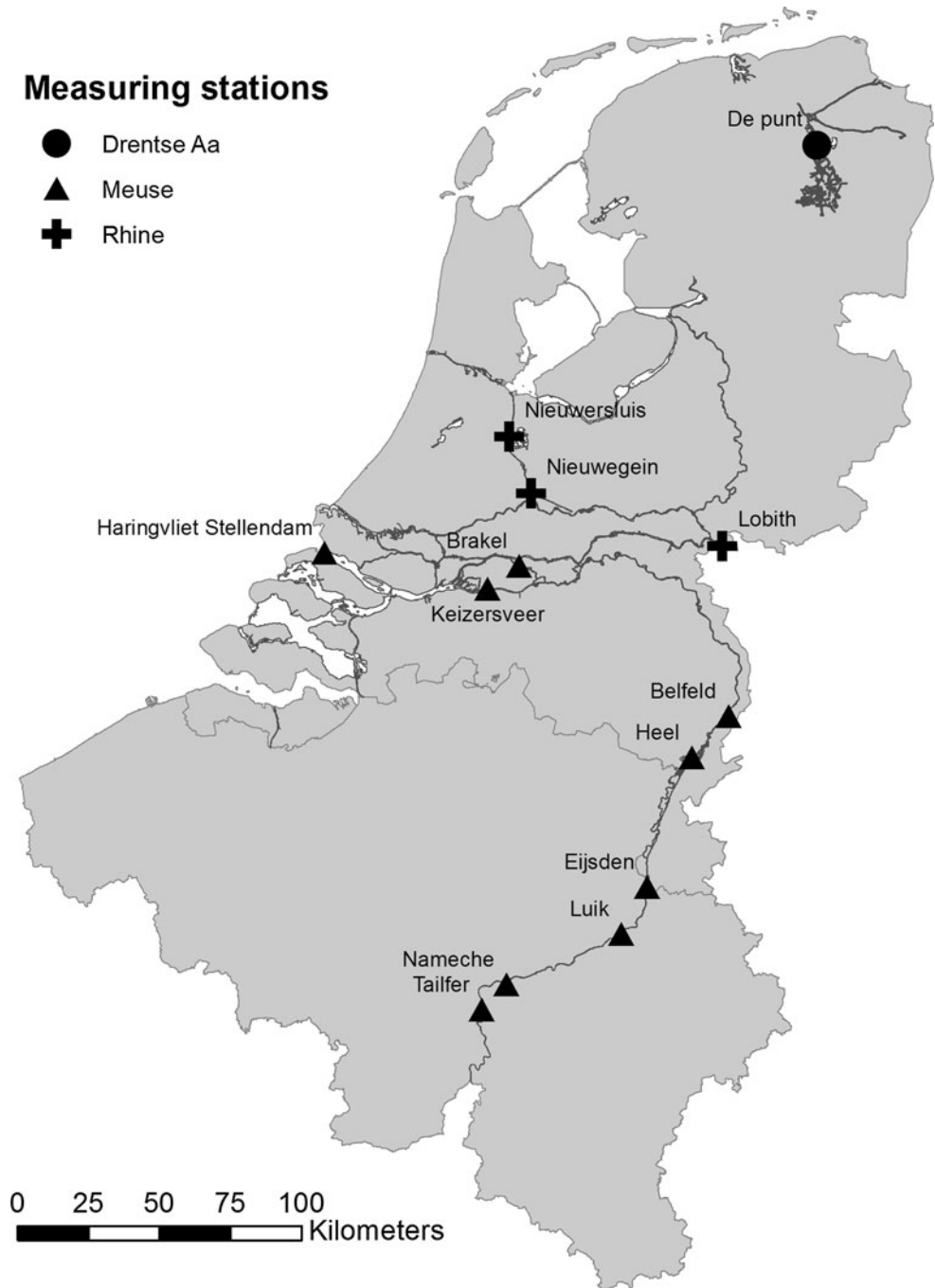
This study uses data of three different river systems in the Netherlands and Belgium: Drentse Aa, Rhine, and Meuse. These three river systems differ in their characteristics. The Rhine originates in the Alps and receives water both from snowmelt and rainfall. The Meuse originates at a much lower altitude and is a predominantly rain-fed river (Pfister et al. 2004). The Drentse Aa is a small river lying entirely in the north of the Netherlands and is fed by rainwater and groundwater seepage (De Jong 2006). Within these river systems, 13 measurement locations are situated. Nine locations are along the Meuse, three along the Rhine, and one in the Drentse Aa. The Meuse locations Luik, Nanche, and Tailfer are located in Belgium, and the remaining

ten locations are in the Netherlands. Figure 1 shows a map of the study area.

As mentioned before, important sources of *E. coli* in surface water are manure and sewage. Belgium and the Netherlands are situated in a region of Western Europe with concentrated agricultural activities. Half of the land area of Belgium is agricultural, and in the Netherlands, this is around two-thirds of the land area (CBS Statistics Netherlands et al. 2011; FOD Economie 2010a). Part of this land is used for cattle grazing, and on pastures and

cropland, manure is often used as fertilizer, meaning that there are many diffuse sources of *E. coli* throughout the study region. In the Netherlands, the far majority of sewage is treated in centralized sewage treatment plants before discharge to the surface water takes place: in 1990, around 95 %, and in 2008, 99.6 %, respectively, of household wastewater was treated (CBS Statistics Netherlands et al. 2012; Directoraat-Generaal Water and Directoraat-Generaal Milieubeheer 2010). The remaining 0.4 % is treated with on-location facilities (Directoraat-Generaal Water and

Fig. 1 Map showing measurement locations along the Rhine, Meuse, and Drentse Aa in the Netherlands and Belgium. *E. coli* concentrations, water temperature, and discharge measurements were obtained at the indicated locations. Precipitation data were obtained from nearby rain gauges, on average no further than a few kilometers away (not shown on the map, as gauge locations mostly overlap with currently shown locations)



Directoraat-Generaal Milieubeheer 2010). Although in some areas along the Meuse in Belgium discharge of untreated sewage still occurs (Aquafin, personal communication, November 7, 2012), overall Belgian treatment rates are relatively high. In 2008, 87.5 % of the Belgian population was connected to the public sewage system and also on-site treatment systems are used (FOD Economie 2010b). Owing to the high treatment rates in both countries, especially overflows of untreated sewage during heavy precipitation events are a potentially important source of *E. coli* in surface water in the Netherlands and Belgium.

Data

E. coli data

Table 1 gives an overview of the data used in this study. *E. coli* measurements were obtained from Waterlaboratorium Noord (Drentse Aa), RIWA Association of River Waterworks, and Rijkswaterstaat Waterdienst (Rhine and Meuse). In this study, we statistically analyzed a total of 4,679 *E. coli* measurements spread over the 25-year period from 1985 to 2010, three river systems and 13 locations. *E. coli* measurements are often taken once every 2 weeks, but for some locations, data are taken with a higher or lower frequency.

The data were collected by different laboratories of the aforementioned organizations according to the standardized methods issued by the Dutch normalization institute NEN (providing NEN protocols), which works in the context of international norms (such as ISO protocols). Due to the long time period and the combination of data from 13 locations, several measurement methods for *E. coli* have contributed to these data. From the start of our data in 1985 until approximately 1993, the data concern thermotolerant bacteria from the coligroup (mostly *E. coli*) which were measured using the membrane filtration method according to NEN 6570 on Teepol agar. Around 1987, the medium was switched to laurylsulphate agar (LSA). From approximately 1993, the data concern *E. coli* specifically and the direct plating method according to NEN 6261 was used. Not all laboratories started this at exactly the same time. In 2001, NEN 6261 was switched to ISO 9308-1 rapid test, but these follow the same protocol. In 2001, several laboratories switched to ISO 9308-3, a microplate method giving most probable number values. Also in the Belgian part of the Meuse, ISO norms are used in water quality measurements, reportedly ISO 9308-1 and since 2008 ISO 9308-2. We acknowledge that using data obtained by different laboratories and methodologies can lead to inhomogeneities in the dataset and consequent biased results (Schets et al. 2002), which is especially relevant when

performing safety checks on drinking water or surface water used for recreation and comparing these to norms. We have checked the data and did not observe jumps that could indicate method changes. Based on Schets et al. (2002), who show that results of different measurement methods are typically in the same order of magnitude, we conclude that peaks in *E. coli* concentration that are typically logs higher than average concentrations are barely influenced by changes in measurement methods. Since we are studying how *E. coli* measurements relate to climate variables and are not looking at absolute values of *E. coli* measurements per se, we have decided to still use these data together. It is rare to have such a long period of *E. coli* measurements together with climate data available; this analysis could otherwise not have been performed.

The *E. coli* measurements range from 0 to 83,000 colony-forming units (cfu)/100 ml. The mean of the data is 1,847 cfu/100 ml, and the median value is 410 cfu/100 ml. The distribution of the values is strongly positively skewed, and it was found that a log transformation of the data provided a more normal distribution. Therefore, *E. coli* data were always log transformed during this study. The aforementioned total of 4,679 *E. coli* measurements exclude zero values or values reported below the detection limit, because surface water in an agricultural area unlikely actually contains zero *E. coli* and because only approximately 1 % of the data were reported zero values or below detection limit. Since our study does not focus on absolute values of *E. coli* but on the behavior relative to climate variables, we do not expect this to significantly impact our study. Table 1 also shows the mean and maximum *E. coli* concentrations per measurement location. The *E. coli* concentrations in the Meuse, Rhine, and Drentse Aa fall within the same range. Meuse Eijsden shows the highest concentrations and Meuse Haringvliet Stellendam the lowest. Eijsden is located near the border of the Netherlands and Belgium, approximately 20 km downstream of the Belgium city of Luik, where the second highest mean *E. coli* concentrations are observed in our dataset. Sewage discharge in Luik may therefore be an explanation for the elevated *E. coli* concentrations in this part of the river. Haringvliet Stellendam is a measurement location near the sluices where the Meuse enters the North Sea. Possibly, dilution or increased sedimentation rates in this part of the river could lead to the observed lower *E. coli* concentrations here.

We checked whether significant trends over time could be observed in the datasets of the different locations. The *E. coli* time series of some locations showed a slight general increase, some a general decrease. Possible explanations for reduced *E. coli* concentrations over time include the building of waste water treatment plants and removal of sewer overflows during the period covered by

Table 1 Overview of data used in this study

Location	Timespan <i>E. coli</i> measurements	<i>N. E. coli</i> measurements	<i>T</i> water	Precipitation	Discharge	Longitude	Latitude	Mean <i>E. coli</i> concentration (cfu/100 ml)	Maximum <i>E. coli</i> concentration (cfu/100 ml)
<i>Meuse</i>									
Belfeld	1988–2000	321	×	×	×	6.11	51.32	1,351	19,500
Brakel	1987–1990, 1996–2010	303	×	×	– ^a	5.05	51.80	188	12,000
Eijsden	1987–2009	410	×	×	×	5.70	50.78	7,566	83,000
Haringvliet Stellendam	1986–2010	498	×	×	– ^a	4.06	51.83	49	2,400
Heel	2002–2010	99	×	×	– ^a	5.93	51.19	548	6,900
Keizersveer	1985–2010	578	×	×	×	4.90	51.72	639	18,000
Luik	1991–2001	271	×	×	×	5.57	50.63	3,499	16,400
Nameche	1991–2001	271	×	×	×	5.00	50.47	2,725	18,800
Tailfer	1985–1992, 2003–2009	438	×	×	×	4.88	50.39	2,198	27,000
<i>Rhine</i>									
Lobith	1985–2007	541	×	×	×	6.09	51.86	3,109	30,000
Nieuwegein	1987–2010	579	×	×	– ^a	5.11	52.02	415	4,300
Nieuwersluis	2001–2010	92	×	×	– ^a	5.00	52.20	585	8,400
<i>Drentse Aa</i>									
De Punt	1995–2010	278	×	×	×	6.61	53.12	1,043	25,000

In the first column, the different locations in the three different river systems which were studied are given. The second column shows from which years *E. coli* data were available for these locations. The third column shows how many *E. coli* measurements in total were available for a specific location. The following three columns show whether for a given location, data of the climate variables water temperature, precipitation, and discharge were used in this study. × Data were used, – data were not available. The next columns show the latitude and longitude coordinates of the locations where *E. coli*, water temperature, and discharge data come from. Precipitation observations are taken from meteorological stations nearby. The last two columns show the mean and maximum observed *E. coli* concentration at a certain measurement location

^a Discharge data not meaningful (measurement location is side channel or sluice)

the data series. In general, water treatment levels have increased during the period of study (Directoraat-Generaal Water and Directoraat-Generaal Milieubeheer 2010; FOD Economie 2010b). Reasons for increased average *E. coli* concentrations could be climatic changes, as well as changes in land use or farming practices, such as increased use of land for agriculture and spreading of more manure during the period covered by the data series (Crowther et al. 2002; Kampf et al. 1997) or an increased urbanization and population density (Mallin et al. 2000). In most of our measurement locations, *E. coli* concentrations were highest during the winter months (December–February). However, the differences between seasons were not always significant.

Climate data

The climate data that we use are water temperature, precipitation at nearby rain gauges, and discharge. Water temperature and discharge measurements were provided by the same organizations and for the same locations as the

E. coli measurements (see above and Fig. 1). Precipitation data for the Netherlands were obtained from the European Climate Assessment & Dataset (ECA&D) (Klein Tank et al. 2002). Belgian precipitation observations were provided by the Royal Meteorological Institute (RMI) of Belgium. Rain gauges were selected as close as possible to *E. coli* measurement locations, on average no further than a few kilometers away. The water temperature measurements, like the *E. coli* measurements, are often taken once every 2 weeks, but for some locations, data from periods with more or less intensive measurement frequencies are available. Precipitation and discharge data are mostly daily data.

Discharge is used in addition to precipitation, because it is affected by precipitation changes in the entire upstream area of the river basin and could be seen as a more long-distance precipitation effect, dependent on cumulative rainfall in the upstream catchment. Taking only discharge and excluding precipitation, as was done in a similar study by Schilling et al. (2009), means that the effect of precipitation events and runoff events at a time of low discharge

can be missed, as Schilling et al. (2009) also recognized in their discussion. Therefore, we include both variables in this study.

Water temperature, unlike air temperature, was found to follow a bimodal distribution. This can be explained by various factors including meltwater and groundwater seepage and has been reported in the literature (Senhorst and Zwolsman 2005; Smith 1968). Precipitation follows a gamma distribution. Discharge was found to be log normally distributed and is therefore, like *E. coli*, always log transformed in this study. For 8 of the 13 locations, the datasets are complete for all variables. For the others, the data are not fully complete, mainly due to the lack of discharge measurements of some locations that are on side channels instead of along the actual river, making discharge measurements here not meaningful for this study (see Table 1).

We checked whether significant trends over time could be observed in the datasets of the different locations. Water temperature generally increased during 1985–2010 (significant in 5 out of 13 locations), but this represents only a small part of the observed variation in data (R^2 values <0.01). A positive trend in water temperature is in line with the observed warming that has taken place in Europe over the past few decades, as reported by the IPCC and the Dutch RMI (KNMI 2011b; Solomon et al. 2007). Similarly, observed trends in precipitation and discharge only explained a small part of the observed variation (R^2 values <0.01). Precipitation shows a positive trend (significant in 5 out of 13 locations), which is in line with the general findings of the Dutch RMI, reporting an increase in precipitation in the Netherlands over the past century (KNMI 2011a). According to Tu et al. (2004), discharge trends in the Meuse have shown an increase in winter and a decrease during summer with no significant long-term change in annual discharge. In this study, we found a negative discharge trend in the Meuse (significant for 5 out of 6 locations), and the Rhine and Drentse Aa both show a positive trend in discharge; however, for the Rhine, this result was not significant. For the Rhine, a positive trend would be in line with findings reported by the International Commission for the Hydrology of the Rhine basin (CHR) (Belz 2010). Increasing discharges in the Drentse Aa have also been reported in the literature (De Jong 2006).

Statistical analysis

The data were analyzed using the statistical software package R. First, standard Pearson product–moment correlation analyses between *E. coli* concentrations and water temperature and discharge, and Spearman's rank correlation analysis between *E. coli* concentrations and precipitation were performed. Spearman's rank correlation, which

does not require the variables to be normally distributed, was used for correlation analysis between *E. coli* concentrations and precipitation, because precipitation data are gamma distributed. We studied the precipitation data required, because the expectation was that using precipitation data from the same day as *E. coli* would not be meaningful as precipitation needs some time to percolate through the system. A sensitivity analysis was performed in which summation of precipitation of different sets of days was tested. We use precipitation summed over three days, because it provided best correlations. Slight variations were observed among the different locations, presumably due to local landscape conditions. Summing precipitation with similar results has been done in other studies (Nichols et al. 2009; Schulz and Childers 2011; Tryland et al. 2011).

We study the observed variation in *E. coli* concentration levels in surface water further by fitting the Meuse data to a linear regression model, combining the different variables and locations together. This is done to assess the relative contributions of the climate variables to the observed variation in *E. coli* concentration. We focus on assessing the relationship of *E. coli* with climate variables only, allowing for local differences (e.g., in land use, location of sewage treatment plants, etcetera) by including a locations dummy variable (index h).

The model has the following form:

$$\log(Y) = \beta_0 + \beta_1 t + \beta_2 T + \beta_3 p + \beta_4 \log(D) + \beta_{5,h} + \varepsilon$$

$Y = E. coli$ concentration in cfu/100 ml, β_i are constants, $t =$ time in days (counting from start of measurements), $T =$ water temperature in $^{\circ}\text{C}$, $p =$ precipitation summed over 3 days in 0.1 mm, $D =$ discharge in m^3/s , $h =$ index for location, $\varepsilon =$ residual error.

For six locations along the Meuse, information was available on all variables and these were therefore included in the model. These locations were Meuse Belfeld, Meuse Eijsden, Meuse Keizersveer, Meuse Luik, Meuse Nameche, and Meuse Tailfer. The Rhine and Drentse Aa were left out, as it was felt that not enough complete datasets were available for these river systems to make a meaningful analysis. As independent variables, we have taken time, temperature, precipitation, and discharge. Time was included in order to account for long-term trends that do not originate from a relation with climate variables, but for example from a general increase in sewage treatment rates over time. Locations were included as dummy variable.

After running the model with the complete dataset, we studied the effect of leaving the temperature data out of the model and the effect of incorporating all first-order interactions in the model. Analysis of variance (ANOVA) was performed to assess the relative contribution of different

model components to explain the observed variation. The model was also run for all locations individually. In that case, the index h is no longer included in the model. The coefficient of determination (R^2), adjusted for degrees of freedom, determines how well the models explain the observed variation in *E. coli* concentrations. All statistical tests were assessed for significance at the 95 % confidence level ($p < 0.05$).

One might expect to find autocorrelation in the Meuse data, meaning that the measurements are dependent on each other in space or time. However, since our measurements are usually taken no more often than once every 2 weeks and water flows through the river Meuse from start to finish in approximately 4 days during average discharge conditions (Rijkswaterstaat, personal communication), we believe temporal autocorrelation is not an issue. Spatial autocorrelation, meaning that measurements at subsequent locations in a river are depending on each other, could not be conclusively shown nor excluded from our data, because similar processes operate at the different measurement locations (e.g., similar climate variation is present at the different locations). In any case, even if present, spatial autocorrelation should not influence model goodness of fit, and considering the large amount of data points in this study, also model significance should not be largely impacted.

Results

Correlations

To assess the effect of the separate climate variables on the *E. coli* concentration, each of the variables water temperature, precipitation, and discharge was correlated with the corresponding *E. coli* concentration measurements for all locations separately. Note that correlation itself does not prove a cause–effect relationship. Table 2 gives an overview of the results. Figure 2 graphically shows the correlations for the locations Meuse Luik and Meuse Keizersveer, as examples of what the results look like for a location with significant correlations (Keizersveer) and without significant correlations (Luik). We find for all but two locations significant negative correlations between *E. coli* and water temperature. For all but one location, *E. coli* significantly correlates positively with precipitation, and for six out of eight locations, also a significant positive correlation is found between *E. coli* and discharge.

Model

To assess the effect of the climate variables combined on the *E. coli* concentration, we fit the Meuse data to the linear

regression model explained in “[Statistical analysis](#)” section. Running the model gave an adjusted R^2 of 0.49 and all independent variables contributed significantly ($p < 0.001$). The model parameter estimates are given in Table 3. Location Meuse Belfeld is taken as reference level for the dummy variable, which is why it has value 0. Performing an ANOVA indicated that temperature has a relatively minor contribution to the explained variance in the model. Therefore, we next tried to run this model with only time, precipitation, discharge, and locations as variables. This led to a model with an adjusted R^2 of 0.48, a result surprisingly close to the 0.49 of the complete model. We expected that temperature would be more influential, since the correlation analysis in “[Correlations](#)” section has shown that significant correlations between *E. coli* concentrations and temperature exist at almost all locations. The effect of temperature on *E. coli* die-off rates is also confirmed in the literature, as described earlier in “[Introduction](#)” section.

If the model is run for all locations separately, adjusted R^2 values between 0.04 and 0.57 are found. The model estimates from these runs can be found in the Appendix. A schematic summary of the model estimates is given in Table 4. ANOVA of these runs showed great variability among locations as to which variables significantly contribute to explaining the observed variation in *E. coli* concentrations at the different locations. For example, temperature is a significant variable in four of the six locations individually, yet leaving it out altogether in the complete model does not make a great difference, as described above.

Running the model including all first-order interactions improved the adjusted R^2 to 0.55 but it was felt that this improvement did not weigh up to the added complexities interactions bring to the model, since overfitting of our data may occur. An ANOVA showed that interactions play a relatively minor role in explaining the observed variation.

Discussion

Correlations

A negative correlation of *E. coli* with water temperature agrees with findings from other studies that *E. coli* survives longer in water with lower temperatures (Medema et al. 1997; Wang and Doyle 1998). The observed positive correlations of *E. coli* concentration with both precipitation and discharge are also observed in other studies (e.g., Schilling et al. 2009; Tryland et al. 2011; Wu et al. 2011). This can be attributed to a combination of factors according to previous studies: increased runoff from farm pastures bringing along pathogens from manure, re-suspension of

Table 2 Overview of correlations between *E. coli* and climate variables in the different datasets

Locations	<i>r</i> value correlation log <i>E. coli</i> — water temperature	<i>N</i>	<i>r</i> value correlation log <i>E. coli</i> —precipitation	<i>N</i>	<i>r</i> value correlation log <i>E. coli</i> —log discharge	<i>N</i>
Meuse Belfeld	-0.36*	228	0.47*	321	0.68*	111
Meuse Brakel	0.14*	299	0.33*	303	—	—
Meuse Eijsden	-0.27*	392	0.13*	257	0.38*	410
Meuse Haringvlietstellendam	-0.26*	410	0.19*	498	—	—
Meuse Heel	-0.39*	96	0.32*	99	—	—
Meuse Keizersveer	-0.42*	480	0.36*	578	0.53*	565
Meuse Luik	0.02	270	0.09	271	0.08	268
Meuse Nameche	-0.19*	195	0.30*	271	0.23*	266
Meuse Tailfer	-0.36*	432	0.18*	438	0.38*	436
Rhine Lobith	-0.19*	389	0.24*	541	0.00	541
Rhine Nieuwegein	-0.20*	575	0.23*	578	—	—
Rhine Nieuwersluis	-0.38*	91	0.26*	90	—	—
Drentse Aa	-0.17*	249	0.31*	278	0.30*	270

The left column shows the locations, the *r* value columns show the *r* value of the correlation of *E. coli* measurements with measurements of a specific climate variable, the *N* columns show how many *E. coli* measurements and how many corresponding climatic measurements were used to compute the correlation. Standard Pearson's product-moment correlation was used for correlating *E. coli* with water temperature and discharge, and for precipitation, Spearman's rank correlation was used. *E. coli* data and discharge data were log transformed. Precipitation data were summed over 3 days previous to the dates of the *E. coli* measurement. Values indicated with * are significant at $p < 0.05$. A ndash (—) indicates discharge data were not available for this location

* Significant at $p < 0.05$

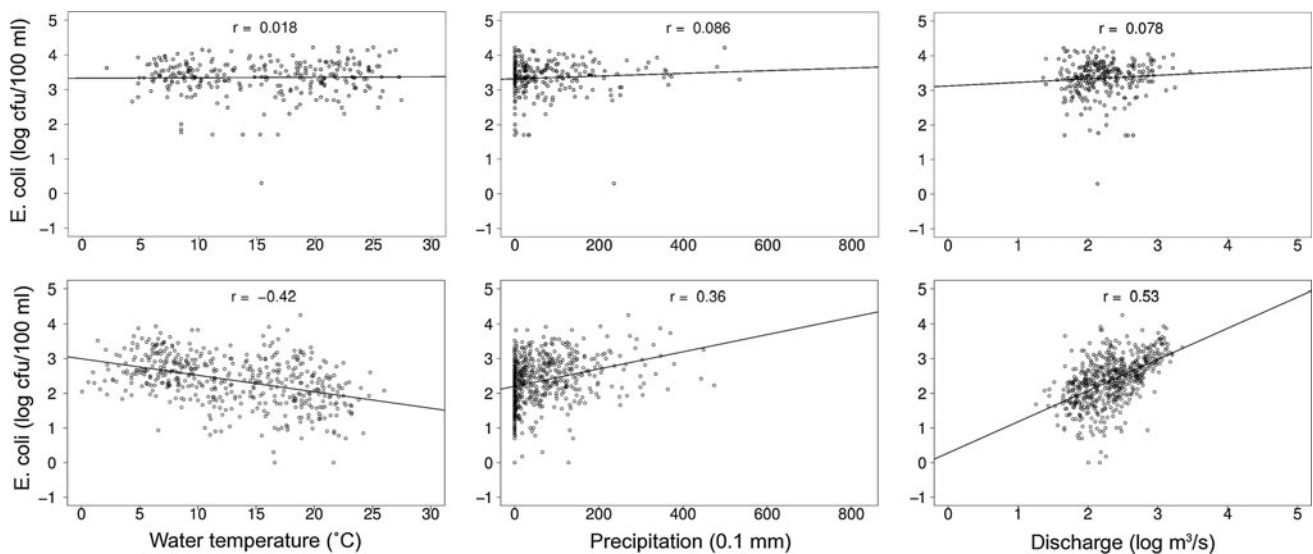


Fig. 2 Examples of correlation of log *E. coli* concentration with water temperature, precipitation, and log discharge, shown for the locations Meuse Luik (top row) and Meuse Keizersveer (bottom row). Precipitation is taken summed over 3 days, as explained in

“Statistical analysis” section. The *E. coli* measurements at Meuse Luik do not correlate significantly with the climate variables, the *E. coli* measurements at Meuse Keizersveer do

pathogens in sediments, and sewage overflows during especially heavy rainfall events (Cho et al. 2010; Garzio-Hadzick et al. 2010; Gibson et al. 1998; Hong et al. 2010; Senhorst and Zwolsman 2005), as was discussed in the introduction. The relationship with discharge may be attributable to similar mechanisms as the effect of

precipitation, but taking into account *E. coli* sources from the upstream part of the basin. Since only positive correlations between precipitation and *E. coli* were found, we have not observed the possible enhancing effect of dry periods on *E. coli* concentrations as described by Nichols et al. (2009).

Table 3 β_i estimates of the model $\log(Y_h) = \beta_0 + \beta_1t + \beta_2T + \beta_3p + \beta_4\log(D) + \beta_{5,h} + \varepsilon$

	β_i estimate
β_0	2.38
Time (β_1)	-3.28×10^{-05}
Temperature (β_2)	-1.18×10^{-02}
Precipitation (β_3)	7.78×10^{-04}
Log(discharge) (β_4)	3.64×10^{-01}
Location Meuse Belfeld ($\beta_{5,1}$)	0
Location Meuse Eijsden ($\beta_{5,2}$)	1.44
Location Meuse Keizersveer ($\beta_{5,3}$)	0.56
Location Meuse Luik ($\beta_{5,4}$)	2.08
Location Meuse Nameche ($\beta_{5,5}$)	2.44
Location Meuse Tailfer ($\beta_{5,6}$)	2.80

This model takes into account all three climate variables temperature, precipitation (cumulative over 3 days previous to the date of the *E. coli* measurement), and discharge. Furthermore, a time component is included and the different measurement locations are taken into account as a dummy variable. The estimates for the latter ($\beta_{5,h}$) are relative to the reference location, in this case the Meuse Belfeld. The $\beta_{5,h}$ values do not affect the slope of the graph, only the intercept

Model performance

Our linear regression model shows that only taking into account climate variables and a locations factor can account for almost half of the observed variation in *E. coli* concentrations in the Meuse ($R^2 = 0.49$, see “Model” section). When looking at comparable statistical modeling efforts in the literature, a great variety in R^2 values is reported. The variation depends on which variables were added, the amount of data used, and which organism is looked at, among others. Examples include land-use-based models of fecal indicators of Kay et al. (2005) with reported R^2 values of 0.49–0.68 for 40 sub-catchments of the river Ribble drainage basin in the United Kingdom, and the model of Olyphant and Whitman (2004) that includes hydrological, meteorological, and water quality parameters for *E. coli* contamination of a lake beach in

Chicago, accounting for 71 % of the observed variation in log *E. coli* concentrations ($R^2 = 0.71$).

Our model performs worse than the listed models. However, these studies include more variables, such as hydrological or land-use variables, in their linear regression models. Furthermore, these models mostly concern locations that are close together (e.g., on one beach), likely improving model fit. Further specifying the model for local landscape and land-use conditions, seasonality, singling out of extreme precipitation events, and low flow conditions could possibly improve results. However, lack of sufficient data density prevented us from doing so in this study.

Climate projections and *E. coli* in surface water

According to the climate change scenarios developed by the Dutch RMI (KNMI), overall the air temperature in the Netherlands is expected to rise (Van den Hurk et al. 2006). Air temperature and water temperature correlate quite well, although the relationship is not linear, especially at both low and high temperatures (Mohseni and Stefan 1999). We found negative correlations between water temperature and *E. coli* concentrations, so we would expect this aspect of climate change to decrease *E. coli* concentrations in surface water. However, since leaving out temperature from the model altogether did not reduce the model goodness of fit strongly, as was discussed in “Model” section, the magnitude of this effect is questionable. The issue of scale (local vs. multiple river systems) also plays a role here, since for some individual locations, temperature appeared to be a more important determinant of *E. coli* concentrations than at the full model scale. From our study, it is difficult to draw conclusions on this matter, more detailed research into including appropriate processes at different modeling scales is required, as is for example indicated in a paper by Oliver et al. (2009).

According to the KNMI climate scenarios, the amount of precipitation is for all scenarios expected to increase in

Table 4 This figure schematically gives an overview of the model estimates of the different model runs of the 6 locations individually

	Meuse Belfeld	Meuse Eijsden	Meuse Keizersveer	Meuse Luik	Meuse Nameche	Meuse Tailfer
(Intercept)	+	+	+	+	+	+
Time	-	-	-	+	+	+
Precipitation	+	+	+	+	+	+
Temperature	-	-	-	+	-	-
log10(Discharge)	+	+	+	+	+	+
Adjusted R^2	0.57	0.15	0.44	0.04	0.11	0.17

A + is denoted when the sign for that variable in the model is positive, a – when it is negative. The boxes in gray show significant results ($p < 0.05$ when performing analysis of variance on model run), white boxes are not significant. The bottom row gives the R^2 values of the respective runs

winter and for some scenarios in summer as well. Summer precipitation is expected to decrease in several other scenarios. The amount of precipitation on a wet day, so the intensity of rainfall events, is expected to increase for both winter and summer in all scenarios (Van den Hurk et al. 2006). Research on the impact of climate change on the flow conditions of the Rhine indicates that due to increased winter precipitation and snowmelt, winter discharges will increase. Summer discharge will likely decrease due to the reduced snow storage and increased evaporation (Middelkoop et al. 2001). Due to climatic change, the water source of the Rhine is expected to shift from a combination of rain and snowmelt toward a mainly rain-fed regime (Pfister et al. 2004). For the Meuse, no changes have been observed for average annual discharge levels; however, it is thought that peak flow occurrence as well as low flow occurrence will increase due to climatic factors (Tu et al. 2004). We have found that *E. coli* concentrations increase with higher precipitation and discharge. Therefore, climate change may be expected to have an increasing effect on *E. coli* concentrations in Western European surface waters. This study took precipitation cumulative over 3 days and looked at the complete range of precipitation values, not specifically at dry periods or heavy precipitation events. It would be interesting to go more into detail in this topic in future research, especially in light of climate change which could increase both the occurrence of dry periods and the occurrence of heavy precipitation events.

From *E. coli* concentrations to risk of disease

Escherichia coli concentrations do not directly represent risk of disease, since it is merely an indicator of fecal pollution. However, an increase in *E. coli* concentration may indicate an increase in pathogens in the surface water. Risk of waterborne disease depends on a number of factors additional to the concentration of the organism in the water. These include parameters specific for different pathogen types, such as survival and reproductive capacity in the environment, but also societal factors, such as water usage and human behavior in recreation and consumption, among others (Bosch 1998; Schijven and de Roda Husman 2005). Via quantitative microbial risk assessment (QMRA) estimations can be made to risk of disease, this requires data (or assumptions) about the concentration of pathogens in river water (Van Lieverloo et al. 2007). Our study indicates an increase in *E. coli* concentration due to climate change, which could lead to an increased risk of disease. A relationship between climate change and increased risk of disease is indicated in the literature, in the field of waterborne diseases as well as other types of health risks (e.g., Campbell-Lendrum and Woodruff 2006; Harvell et al.

2002; Nichols et al. 2009). Data on pathogen concentrations is much more sparse than *E. coli* data. We therefore believe that a challenge for further research lies in quantifying and modeling the link between *E. coli* concentrations in surface water and risk of infection with waterborne pathogens, in light of climate change.

Conclusions

Based on our analysis of 4,679 *E. coli* samples, water temperature, discharge and precipitation data of a total of 13 locations along three different river systems in the Netherlands and Belgium, the Rhine, Meuse, and Drentse Aa, spread over the period 1985–2010, we conclude the following:

- Water temperature was found to correlate negatively with *E. coli* concentrations.
- Both precipitation summed over 3 days and river discharge were found to correlate positively with *E. coli* concentrations.
- Combining the Meuse data of *E. coli*, water temperature, precipitation and discharge into a linear model together with a time component and a locations dummy variable gave a fit with R^2 of 0.49, meaning that climate variables and location can account for a substantial part of observed variation in *E. coli* concentrations in surface water, even when other factors such land-use variables are not taken into account. Other models, incorporating more variables, have reported higher R^2 values.
- The effect of the different climate variables appears to differ with model scale, with temperature being relatively important for some individual measurement locations, but less so when the data of different measurement locations are combined.
- From our results, we expect that climate change, mainly the projected increased precipitation, may increase *E. coli* concentrations in Western European surface waters. Waterborne pathogens that follow similar transmission pathways as *E. coli* may be similarly impacted by climate change.

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Appendix

See Table 5.

Table 5 Coefficient estimates of model runs of individual locations

	β_i estimate
<i>Meuse Belfeld</i> ^a	
(Intercept)	0.940522
Time	-0.00742*
Precipitation	0.002695*
Temperature	-0.00462
Log10 (discharge)	0.849424*
β_i estimate	
<i>Meuse Eijsden</i> ^b	
(Intercept)	3.27E + 00*
Time	-8.42E - 05
Precipitation	1.39E - 04
Temperature	-1.51E - 02*
Log10 (discharge)	2.87E - 01*
β_i estimate	
<i>Meuse Keizersveer</i> ^c	
(Intercept)	1.717185*
Time	-0.0016*
Precipitation	0.001997*
Temperature	-0.02509*
Log10 (discharge)	0.536864*
β_i estimate	
<i>Meuse Luik</i> ^d	
(Intercept)	2.944871*
Time	0.001363*
Precipitation	0.00031
Temperature	0.003317
Log10 (discharge)	0.068034
β_i estimate	
<i>Meuse Nameche</i> ^e	
(Intercept)	3.104699*
Time	0.002421*
Precipitation	0.000856
Temperature	-0.01647*
Log10 (discharge)	0.012741
β_i estimate	
<i>Meuse Tailfer</i> ^f	
(Intercept)	2.75E + 00*
Time	8.15E - 05
Precipitation	6.49E - 04*

Table 5 continued

	β_i estimate
Temperature	-1.79E - 02*
Log10 (discharge)	2.53E - 01*

* Significant at $p < 0.05$ in analysis of variance

^a Adjusted $R^2 = 0.57$

^b Adjusted $R^2 = 0.15$

^c Adjusted $R^2 = 0.44$

^d Adjusted $R^2 = 0.04$

^e Adjusted $R^2 = 0.11$

^f Adjusted $R^2 = 0.17$

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