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Functional Evaluation of Three Manure-Borne Indicator Bacteria Release Models with Multiyear Field Experiment Data

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Abstract

Modeling the fate and transport of *Escherichia coli* is of substantial interest because of how this organism serves as an indicator of fecal contamination in microbial water quality assessment. The efficacy of models used to assess the export of *E. coli* from agricultural fields is dependent, in part, on submodels they utilize to simulate *E. coli* release from land-applied manure and animal waste. Although several release submodels have been proposed, they have only been evaluated and compared with data from laboratory or small plot *E. coli* release experiments. Our objective was to evaluate and compare performances of three manure-borne bacteria release submodels at field-scale: exponential release (EM), two-parametric Bradford and Schijven (B-S), and two-parametric Vadas-Kleinman-Sharples (VKS); each was independently incorporated and tested as a submodel within the export model KINEROS2/STWIR, using *E. coli*. Dairy manure was uniformly applied via surface broadcasting once a year for six consecutive years on a 0.28 ha experimental field site. Two irrigation events followed each application: the first immediately followed the initial application and the second occurred one week later. Manure and soil samples were collected before and after irrigation, respectively, and manure, soil, and edge-of-field runoff samples were analyzed for *E. coli*. Model performance was evaluated with the Akaike criterion, coefficients of determination (R^2), and root mean squared errors (RMSE) values. The percentage of exported manure-borne *E. coli* varied from 0.1% to 10% in most cases, generally reflecting the lag time between initiation of irrigation and initiation of edge-of-field runoff. The export model performed better when using the VKS submodel which was preferred in 55% of cases. The B-S and EM submodels were preferred in 27% and 18% of cases, respectively. Two-parametric submodels were ultimately preferred over the single parameter submodel.

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1. Introduction

Large numbers of pathogens are applied to fields in manure and have the potential to be released given certain conditions (Borchardt et al. 2014). Pathogens can be transported to water bodies used for recreation, irrigation, aquaculture, or washing produce. Determining pathogen presence and its potential impact is based on concentration of indicator bacteria, the most common being fecal or thermotolerant coliforms and *Escherichia coli* (U.S. EPA 2012; U.S. FDA 2016).

Manure-borne microorganisms must first be released from manure before being removed from fields with runoff or infiltration. Microorganism release from manure appears to be a complex scale-dependent process affected by bacteria concentrations and bacterial cell surface properties, the manure consistency expressed as solids content (%), manure age and weathering, and hydrological factors such as rainfall intensity and duration (Blaustein et al. 2015a). The overall number of manure-borne bacteria removed from the fields depends not only on release from manure or animal waste, but also on continuous interactions between infiltration, storage in soil, and runoff. Several equations were developed to simulate release of bacteria from manure due to rainfall (Bradford and Schijven 2002; Guber et al. 2006, 2014; Kim et al. 2016). These equations have been tested on small vegetated field plots and laboratory soil boxes uniformly covered with manure that underwent simulated rainfall, and their performance was evaluated based on accuracy of reproducing the cumulative export of microbes through the edge of the plot during rainfall-runoff events. In general, these equations have shown a relatively good accuracy in simulating the removal of fecal bacteria (Guber et al. 2006; Kim et al. 2016; Blaustein et al. 2016; Stocker 2017). However, the performance of those equations has not been studied and compared for modeling bacteria export at a larger scale when they are used as components of bacteria export models. The heterogeneity of microorganism transport pathways in overland flow and infiltration may influence the predictive power of release and transport equations applied in field scale settings. These heterogeneity effects are scale-dependent. The runoff coefficient, defined as the percentage of rainfall partitioned to runoff, has been shown to vary considerably in plots versus fields or catchments and also vary largely by surface slope (Cerdan et al. 2004; Delmas et al. 2012).

The KINEROS2/STWIR model to simulate the bacteria transport during the irrigation/runoff event at the field scale was developed and tested by Guber et al. (2011). A few years later Martinez et al. (2014) carried out the model sensitivity analysis. Both works were performed using a single equation developed to simulate the release of bacteria from manure under simulated precipitation. It has been acknowledged that different release equations demonstrate different accuracy at the plot scale but differences between them at the field scale have not been examined. One method to assess a process submodel (in this case, the bacteria release from manure) consists in analyzing the results of the performance of different submodels as a part of a larger model. This method is known as functional evaluation and refers to assessing performance of submodels through the performance of the larger model (Vereecken et al. 1992; Xevi et al. 1997).

The objective of this work was to evaluate three manure-borne bacteria release submodels within the KINEROS2/STWIR manure export model. The assessment utilized the unique dataset from 6 years of *E. coli* export experiments with annual manure applications at the field scale where the overhead irrigation generated edge-of-field runoff.

2. Materials and methods

2.1. Field experiments.

2.1.1. Soil and Manure—The study was carried out at Field A of the Optimizing Production Inputs for Economic and Environmental Enhancement (OPE3) field site at the USDA-ARS Beltsville Agricultural Research Center in Beltsville, MD (Fig. 1). The OPE3 site, where dairy manure is applied every April, is primarily used for corn production research. The soil is a fine-loamy, mixed, semiactive, mesic Aquic Hapludult of the Russett series, with an average bulk density of 1.27 g cm^{-3} and a 2% slope (Gish et al. 2009). The soil profile consists of a coarse loamy sand layer in the top 0–30 cm, a sandy loam layer at the 30–80 cm level, a coarse sand layer at the 80–150 cm level, and a gravelly sand layer at the deepest horizon of 150–250 cm (Guber et al. 2011). Physical and chemical soil properties in the upper 10 cm soil layer were measured in 10 soil samples taken in random locations across the field. Samples were homogenized, and a composite was analyzed by the Penn State Analytical Services Laboratory. In soil samples taken from 2011 and 2016, sand and clay contents varied from 50.7 to 59.6% and from 13.3 to 14.7%, respectively. The organic carbon content varied from 2.4 to 2.7% between all years.

Dairy manure was stockpiled over the course of 3 months prior to each application event. Manure was comprised of excreta and hay bedding material scraped from the feeding pads of heifers and dry cows on a biweekly basis. The average manure solids (%) content as applied between all years was 30 ± 0.20 . Manure was sampled weekly in the month preceding the experiment, and *E. coli* concentrations were in the range of 10^5 to 10^6 CFU (g dry weight)⁻¹.

2.1.2. Experiment Design—Experiments were conducted in April of each year between 2011 and 2016. Manure was spread at a rate of 60 T/ha with a New Holland manure spreader. Soil and manure sampling points were georeferenced with a GPS Total Station 4700 (Trimble, Navigation Limited, Sunnyvale, CA) (Fig. 1). Minor differences in the sampling locations were observed between years, however the locations recorded were all within the circles shown in Fig. 1. During the 2016 event, the number of sampling points was reduced from 33 to 18 and these 18 samples were taken from three rows each containing six sampling points.

On the field, two parallel irrigation pipelines (each 40-m long) provided irrigation to induce release and transport of bacteria from land-applied manure. Each irrigation line contained five sprinkler heads positioned 10 m apart. On the day prior to the experiment and manure application, irrigation pipelines were tested and ran for 30 min to establish consistent antecedent soil moisture contents through all years. In 2016, this “pre-irrigation” event was performed for 10 min. A mason jar was placed at every sampling point to measure water depth and determine the irrigation rate. At the lowest elevation of the field, an H-flume was

outfitted for collection of edge-of-field surface runoff (Fig. 1). The water depth within the H-flume was recorded at each sample collection time. Water depths within the H-flume were later converted to flow rates by using a third-degree polynomial equation with constants determined through a calibration exercise (Gish et al. 2011).

On the day of the experiment, 11 soil samples were taken randomly across the 33 sampling points from a depth of 0 to 5 cm prior to the application of manure using 50-mL conical centrifuge tubes to assess background levels of indicator bacteria. Following manure application, manure samples were taken by filling 10 × 20 cm Whirl-pak bags (Nasco, Fort Atkinson, WI) with manure from the 33 sampling locations across the field. During the 3 h of runoff sampling, surface runoff was collected in sterile 350-mL glass containers from the lip of the H-flume at 5-min intervals for 2 h following initiation of runoff. After 2 h of runoff, the irrigation system was turned off and runoff samples were collected for one additional hour as the field drained. Once the last runoff sample was collected, soil samples were collected from the same sampling depth as before from the 33 sampling locations.

One week after the initial irrigation event, the second irrigation event was performed and sampling of soil, manure, and runoff was performed identically to the first week. Manure was not reapplied in the second week. Because there were some differences between irrigation rates from one event to another, the irrigation depth (mm, computed as the ratio of the volume of irrigation water (L) and the area of the irrigated field (m²), was used to present data on release and export from different events in a compatible form.

2.1.3. Microbiological analysis—Water contents of manure and soil samples were measured by calculating water loss after 10-g samples were oven-dried at 105°C (soil) and 60°C (manure) for 24 h. Wet manure and soil samples were mixed with sterile, deionized water at a rate of 2-g sample per 200 ml of water, and blended at high speed for two minutes to produce a homogeneous slurry mixture. The slurry was allowed to settle for one hour prior to processing. Manure, soil, and runoff samples were analyzed for *E. coli* contents using appropriate serial dilutions. Colilert-18 (IDEXX, Westbrook, MA), ECC agar (CHROMagar, Paris, France), and TBX agar (Neogen, Lansing, MI), were used in 2011–2013, 2014–2015, and 2016, respectively. Runoff concentrations were reported as CFU ml⁻¹ or MPN ml⁻¹, and soil and manure concentrations were reported as CFU gdw⁻¹ or MPN gdw⁻¹ (grams of dry weight).

2.2. Bacteria release and transport model

The runoff and erosion model KINEROS2 (Woolhiser et al., 1990) simulated event-based runoff from agricultural fields. It represented overland flow on an arbitrarily shaped field as one-dimensional flow within an equivalent rectangle described by the kinematic wave equation

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = R - I \quad (1)$$

where h is the depth of ponding [L], q is the water discharge per unit width [L^2T^{-1}], R is the precipitation rate [LT^{-1}], I is the infiltration rate [$L T^{-1}$], t is time [T], and x is the distance along the slope [L]. The depth-discharge relationship is expressed as

$$q = \alpha h^m \quad (2)$$

where $m=5/3$, the parameter α is computed according to Manning's hydraulic resistance law as

$$\alpha = n^{-1} S^{1/2} \quad (3)$$

where S is the surface slope [L^{-1}], and n is the Manning's roughness coefficient for overland flow. The Parlange et al. (1982) equation calculates infiltration rate through the soil surface

$$I = K_s \left[1 + \frac{\sigma}{\exp(\sigma I^*/B) - 1} \right] \quad (4)$$

where K_s is the saturated hydraulic conductivity [LT^{-1}], σ is a dimensionless parameter that represents the soil texture ($\sigma=0.85$ in KINEROS2), I^* is the infiltrated depth [L], $B = (G + h)(\theta_s - \theta_i)$, G is the net capillary drive [L], and θ_s and θ_i are the soil volumetric water contents at saturation and initial condition [L^3L^{-3}], respectively. The one-dimensional flow along the slope gradient was assumed in this work.

Overland transport of manure-borne microorganisms was computed based on advection-dispersion equations, coupled with the kinematic wave equation. The following processes were included in the microbial transport model: microorganism release from surface applied manure; advective-dispersive transport of microorganisms in runoff water; transport of microorganisms into the soil with infiltrating water; straining of microorganisms from infiltrating water by plant litter and vegetation layer; exchange of microorganisms between runoff water and the mixing zone of soil at the surface; and microorganism attachment to and detachment from the soil solid phase.

The add-on module STWIR (Guber et al., 2009, 2011), developed for KINEROS2, employs the advective-dispersive equation for bacteria cells in runoff as

$$\frac{\partial h C_r}{\partial t} + \frac{\partial q C_r}{\partial x} = \frac{\partial}{\partial x} \left(a_L q \frac{\partial C_r}{\partial x} \right) - d(\theta_k a C_r - k_d \rho S_s) - (1 - k_{str}) I C_r + R C_{ir} + R C_m - \mu_r h C_r \quad (5)$$

where C_r and C_s are the microorganism concentration in runoff water and soil mixing zone [$N L^{-3}$], respectively, N is the number of cells, i.e. CFU or MPN, a_L is the dispersivity [L],

C_{ir} is the microorganism concentration in irrigation water [N L^{-3}], C_m is the concentration of microorganisms released from manure [N L^{-3}], k_{str} is the straining coefficient, C_{ir} is the microorganism concentration in irrigation water [N L^{-3}], S_s is the microorganism concentration on the solid phase of soil mixing zone [N M^{-1}], M refers to mass of soil, k_a and k_d are attachment and detachment rates of microorganism at the solid phase [T^{-1}], respectively, ρ is the topsoil bulk density [M L^{-3}], d is the thickness of the mixing zone, i.e. topsoil layer actively interacting with overland flow [L], and μ_r is the rate of microorganism die-off in the runoff water [T^{-1}].

The mass conservation equation of microorganisms in the soil mixing zone is

$$d\rho \frac{\partial S_s}{\partial t} = d(\theta k_a C_r - k_d \rho S_s) + k_f(1 - k_{str})IC_r - d\rho \mu_s S_s \quad (6)$$

where k_f is the fraction of microorganisms which enter the soil mixing zone with infiltrated water and are filtered out within this zone by the soil solid phase, and μ_s is microorganism die-off in the soil mixing zone and solid phase [T^{-1}].

2.3. Models of microorganism release from manure

Three submodels and their modifications were evaluated to simulate microbial release from animal manures due to rainfall or irrigation (Blaustein et al., 2015a). The submodel proposed by Bicknell et al. (1997) has an exponential form

$$C_m(t) = S_{m0} k_e \exp(-k_e R t) \quad (7)$$

where S_{m0} is the initial number of microorganisms in applied manure per unit of area [N L^{-2}], and k_e is the release parameter [L^{-1}]. The analytical expression developed by Bradford and Schijven (2002) is

$$C_m(t) = \frac{S_{m0} \alpha_m}{R} (1 + \alpha_m \beta_m t)^{-(1 + 1/\beta_m)} \quad (8)$$

where α_m [T^{-1}] and β_m are fitting parameters that define the shape of the ‘time versus released number’ graph. The expression following from the Vadas et al. (2004) submodel is

$$C_m(t) = S_{m0} a b (R t)^{b-1} \quad (9)$$

where a and b are release rate parameters. The Bicknell et al. (1997), Bradford and Schijven (2002), and Vadas et al. (2004) submodels are referred to as EM, B-S, and VKS, respectively.

The runoff flow rate at the time of runoff samples collection and the time between each sample collection were used to compute the cumulative number of *E. coli* cells (N) removed with runoff during each irrigation event. The cumulative number was then divided by the estimated number of *E. coli* applied in the manure (N_0). The number of *E. coli* applied to the field in manure was calculated as the product of the average concentration of *E. coli* in manure [CFU (gram wet weight)⁻¹], the manure application rate (60 ton ha⁻¹), and the area of the field (2772 m²) with appropriate unit conversion factors. The cumulative number of *E. coli* removed during an irrigation event was then divided by the number of *E. coli* applied in the manure to produce the export ratio N/N_0 . In the second irrigation event in each year, the same method was used except N_0 was calculated based on concentrations of *E. coli* in the manure just prior to the second event instead of those measured prior to the first event.

2.4. Model application procedure

The mathematical model was calibrated for each event separately, and for each submodel of microorganisms released from manure. The PEST software (Doherty, 2005) solved the inverse problem by minimizing mean-least-squared differences between observed and simulated values of chosen variables. The overland flow component of KINEROS2 was calibrated to observed discharge dynamics (q). Actual and simulated cumulative water amounts passing the flume within each runoff event were compared to ensure simulation correctness. The following parameters were calibrated: Manning's roughness coefficient (n), saturated hydraulic conductivity (K_s), net capillary drive (G), soil saturation before irrigation ($S_i = \theta_i/\theta_s$), and soil volumetric water content at saturation (θ_s).

The transport component of the model was calibrated using cumulative *E. coli* export in runoff, obtained by integrating measured *E. coli* concentrations over the measured runoff water. The objective function also included a squared residual of average measured and simulated *E. coli* concentrations in the soil mixing zone after each irrigation event. The calibration determined values for the following parameters: dispersivity (α_L); attachment rate of microorganism at the solid phase (k_d); detachment rate of microorganism from the solid phase (k_d); as well as parameters describing microorganism release from manure: k_e for EM, α_m and β_m for B-S, and a and b for VKS submodels.

Following Guber et al. (2011), we set the straining coefficient $k_{str}=1$. Since bacteria transport in this study was modeled for single runoff events that lasted less than 6.5 h, microorganism die-off in the manure, runoff water, soil mixing zone, and soil solid phase was disregarded in simulations ($\mu_i=0$). Thickness of the soil mixing zone was set to $d=1$ cm (Sadeghi and Arnold, 2002; Guber et al., 2011). The uniform initial concentration of microorganisms in manure and soil mixing layer along the slope were assumed equal to average values of measured concentrations prior to each irrigation event. The concentration of microorganisms in irrigation water and at the slope inlet was assigned a value of zero.

In all simulations the size of the numerical grid cell was one meter, and the time step during numerical simulations was set to have the Courant number less than 0.5. Additional simulations were performed to assess the effect of non-uniform initial microorganism contents in the manure. Based on experimental data from the first 2013 irrigation, five

random spatial series of *E. coli* content in manure along the slope were generated according the cumulative probability distribution function of initial microorganism content. These spatial series were used as the initial conditions for five simulation runs.

The determination coefficient (R^2) and standard error (SE) assessed model performance. The corrected Akaike information criterion (Burnham and Anderson, 2002) was used to compare model performance. The criterion was computed as

$$AICc = 2p + N \left[\ln \left(\frac{RSS}{k} \right) \right] + \frac{2p(p+1)}{k-p-1} \quad (24)$$

where RSS is the residual sum of squares, k is the total number of data points, and p is the number of parameters. The preferred model had the lowest $AICc$ value

The probabilities of the difference in median concentrations of *E. coli* in soil and manure before and after irrigation were determined by using Mann-Whitney test for equal medians with α set at 0.05. The one-way Kruskal-Wallis test to compare the model performance metrics of the three submodels was applied with values from different years treated as replications. Correlations between hydrological variables were assessed using Pearson R^2 values.

3. Results

3.1. Experimental data.

3.1.1. Hydrologic conditions—An overview of hydrological variables and controls in the experiment is given in Table 1. Coefficients of variation (CV %) for all variables were generally low (< 40 %). No correlation between time to runoff initiation and the antecedent soil moisture was found ($R^2 = 0.033$, $p = 0.637$). There was a low correlation between time to runoff initiation and manure moisture content; however, this was not significant ($R^2 = 0.22$, $p = 0.144$). Correlations between sets of other hydrological data provided very low correlations ($R^2 < 0.1$). The percentage of applied water removed as runoff was generally low and ranged from 3.2 to 15.2 % between all years with an average of 10.4 %. Antecedent gravimetric soil water contents were not consistently higher or lower prior to irrigation in the first or second week of the experiment. Manure water content on the field always declined between irrigation events with an average decrease by approximately 7% in 2011, and by 65 to 68% in 2012 through 2016.

3.1.2. Bacteria in soil and manure—*E. coli* was not always detected in the soil prior to the start of an experiment (Table 2). The average concentration of *E. coli* in soil prior to manure application and the first irrigation event across the study period was $(4.6 \pm 4.11) \cdot 10^2$ CFU or MPN gdw⁻¹. *E. coli* concentrations in soil after manure application and the first irrigation event averaged $(1.7 \pm 0.67) \cdot 10^4$ CFU or MPN gdw⁻¹, showing the 37-fold increase. *E. coli* concentrations slightly declined to $(1.5 \pm 0.85) \cdot 10^4$ CFU or MPN gdw⁻¹ between the first and second irrigation events, although this decrease was statistically significant only in 2012 ($p < 0.01$). After the second irrigation event, *E. coli* concentrations in

soil averaged $(1.4 \pm 0.84) \cdot 10^4$ CFU or MPN gdw⁻¹. Overall decreases in soil concentrations of *E. coli* following the second irrigation events were greater in some years than others. For example, this decrease was significant in 2015 ($p = 0.035$), yet decreases in *E. coli* concentrations in the soil after the second irrigation, compared to pre-irrigation levels, were not significant in 2012 ($p = 0.222$) and 2016 ($p = 0.096$). In 2013, concentrations related to the second irrigation event remained relatively stable and were not significantly different ($p = 0.765$), with an overall increase from pre-irrigation to post-irrigation of only 2% (25.1 MPN gdw⁻¹).

E. coli concentrations in manure samples prior to each irrigation event are presented in Table 2, showing decreases from the first to the second events in all years except for 2012. Average *E. coli* concentration in manure prior to the first irrigation event was $(5.0 \pm 0.27) \cdot 10^6$ CFU or MPN gdw⁻¹. This was in accord with the data from manure monitoring during stockpiling when concentrations were found in the 10^5 - 10^6 range. Prior the second irrigation event, *E. coli* concentrations were $(5.1 \pm 2.60) \cdot 10^5$ CFU or MPN gdw⁻¹. Median concentrations of *E. coli* in manure prior to the second irrigation events were significantly lower than the initial concentrations in 2011, 2013, 2015 and 2016 ($p < 0.001$, $p < 0.001$, $p < 0.001$, $p = 0.003$, respectively). In 2012, however, *E. coli* concentrations in manure were substantially greater prior to the second irrigation event, compared to the initial event ($p = 0.116$). Over the course of the multi-year study, average coefficients of variation (CV) for *E. coli* in manures prior to the first and second irrigation events were 260 ± 21 and 172 ± 62 , respectively.

3.1.3. Export dynamics—The percentage of water removed from the field as runoff relative to the volume applied was similar between the first and second irrigation events, with multiyear averages of 11.0% and 9.7%, respectively. Most of the applied water infiltrated or remained in pools at the surface of the field (Table 1). Dependencies of the overland export of *E. coli* on the irrigation depth are shown in Fig. 2. In general, the later runoff started, the smaller the fraction of *E. coli* was exported from the field in runoff. Relative to starting content of *E. coli* in the land-applied manure (i.e., prior to the first irrigation event), overall numbers of exported bacteria were not large, with 2012 being the exception (Table 3). With the exception of 2012, the cumulative export of *E. coli* from manure to edge-of-field in runoff varied from 0.9 to 8.4% during the first irrigation, and from 0.2 to 10.5 % during the second irrigation. Comparison of *E. coli* export after the first and second irrigation events in the same year showed that *E. coli* fractions exported after three hours of runoff collection were larger in the second irrigation event in 2011 and 2013 and smaller in 2012, 2015, and 2016.

3.2. Simulation results

3.2.1. Runoff simulations—Comparisons of simulated and observed runoff discharge time series and cumulative runoff volume for each year and irrigation event are presented in Figure 3. The final values of KINEROS2 parameters following calibration, determination coefficient (R^2), and standard error (SE)] are shown in Table 4. The determination coefficient for discharge values varied from 0.943 to 0.988 with a standard error of 0.106 to 0.320 L s^{-1} , which is within the range from 2% to 8% of maximum observed discharge values. Simulation results capture the shapes of runoff discharge and cumulative runoff

volume, as shown in Figure 3; in most cases, however, the simulated irrigation depth when runoff started was smaller than that observed (see cumulative runoff volume in Fig. 3). The largest time gap between the start of irrigation and start of runoff generation was detected in 2013, during the second irrigation event, which resulted in an overestimation of simulated runoff volume compared to what was measured. Values of the KINEROS2 parameters exhibited low-to-moderate magnitude of coefficient of variation (5.4 % to 31.1 %) (see CV values in Table 4). For example, Manning's roughness (n) values varied between 0.111 and 0.304, which corresponds to chisel plow soil conditions (Woolhiser et al., 1990). Soil hydraulic conductivity (K_s) values did not vary much among years, ranging from about 8 cm to 15 cm hr⁻¹ (Table 4). Values of the capillary drive parameter (G) varied between 8.7 and 26.1 cm which corresponds to soil textures varying from sandy loam to sandy clay loam (Woolhiser et al., 1990). The initial saturation of soil (S_i) was smaller in 2016 compared to other years probably because of a shorter irrigation pipeline testing time (10 min versus 30 min in 2011–2015) one day before the runoff experiment started. Saturated water contents (θ_s) exhibited a relatively low variation between 0.385 and 0.432.

3.2.2. Transport model comparison—The simulated and measured *E. coli* concentrations and cumulative numbers in runoff are shown in Fig. 4. The simulations capture the shapes of the observed time series, especially when using the B-S and VKS submodels, compared to the EM submodel which often underpredicted *E. coli* export. In most cases, simulated export of *E. coli* started earlier than the observed one. These discrepancies are partly because the simulated runoff starts 15–45 min before the observed discharge begins. Also, after runoff initiation, the model simulates very small water discharge values that cannot be measured, and concentrations in it. This explains why the simulated export starts before the observed. However, the total number of bacteria during this time gap is generally less than 1% of their total number exported during each event.

Simulated and measured average *E. coli* concentrations in soil after each irrigation event are presented in Fig. 5. The comparison was favorable for most years except the first irrigation in 2012 when observed concentrations in soil were 4.7–7.7 times greater than those simulated. Model performance in simulating soil concentrations of *E. coli* was consistently better for the B-S and VKS submodels, compared to the EM submodel (Fig. 5).

The calibrated transport parameters and goodness-of-fit criteria for the EM, B-S, and VKS equations in the STWIR transport model are presented in Tables 5, 6 and 7, respectively. While average determination coefficients were similar for the B-S and VKS equations, the average standard error was around 12% greater for the former. When using the EM equation, the average standard error was more than an order of magnitude greater than when using either the B-S or VKS equation. The one-way ANOVA on ranks showed that mean standard errors were not significantly different between the submodels ($p = 0.224$). Similarly, the ANOVA on ranks showed that AICc values from the models did not significantly differ ($p = 0.596$). Average R^2 values for the VKS and B-S submodels were 0.988 while the average value for the EM model was 0.964. While the coefficient of determination was high for the EM submodel, this submodel consistently under predicted *E. coli* export (Fig. 4). The ANOVA on ranks showed that values of R^2 significantly differed between the three

submodels ($p = 0.007$). Pairwise testing showed that mean values of R^2 between the EM submodel and VKS submodel significantly differed ($p = 0.010$) but the EM and B-S submodel did not significantly differ ($p = 0.060$). The VKS and B-S submodels did not significantly differ ($p = 0.792$). The most significant deviations of simulated concentrations from observed ones were found with the EM submodel predictions for events in 2011, 2012, 2014, and 2015. The average $AICc$ value was lower with the VKS equation, compared to the B-S equation, and both were lower than the EM equation. Based on $AICc$ values, the KINEROS2/STWIR model performed best in 55%, 27%, and 18% of cases with the VKS, B-S, and EM submodels, respectively. A one-way ANOVA revealed that $AICc$ values for the three submodels were not significantly different ($p = 0.552$).

Calibrated dispersivity (a_L) values (Tables 5, 6, and 7) varied from 0.1 m to 1.2 m and were similar for all three submodels, with average values at 0.37–0.42 m. The calibrated attachment (k_a) and detachment (k_d) rates were different when different release equations were used (Tables 5, 6, and 7), and exhibited significant variability between weekly irrigation events. Average values of attachment and detachment rates using the B-S and VKS equations were very similar ($k_a = 0.998 \text{ h}^{-1}$, $k_d = 0.609 \text{ h}^{-1}$ and $k_a = 1.143 \text{ h}^{-1}$, $k_d = 0.594 \text{ h}^{-1}$, respectively). When using the EM equation, however, the average rates were $k_a = 1.227 \text{ h}^{-1}$ and $k_d = 0.140 \text{ h}^{-1}$, respectively. The more substantial differences in attachment and detachment rates when using the EM equation, compared to the B-S or the VKS equation, suggest better performance of the latter two.

The estimated EM submodel parameter k_e values ranged from 0.002 to 0.259 cm^{-1} with an average value of 0.048 cm^{-1} (Table 5), which was an order of magnitude smaller than the values obtained in small-scale experiments of fecal coliform release from manure (Guber et al., 2006). For the B-S submodel, values of α_m and β_m ranged from 0.76 to 38.04 h^{-1} and from 0.17 to 4.77, respectively (Table 6). Unlike in the work of Guber et al. (2006), no significant relationship was determined between parameter α_m and the irrigation rate in this work (Pearson $r = -0.255$, $p = 0.449$). For the VKS submodel, parameters a and b ranged from 0.04 to 19.72 and from 0.14 to 0.99, respectively (Table 7).

An additional assessment was performed by simulating different initial distributions of *E. coli* in manure along the slope, using a uniform distribution with simulations based on five different random realizations of initial concentrations drawn from the experimental cumulative probability distribution function (Fig. 6). Most differences between the *E. coli* concentration in manure and cumulative export in runoff occurred during the early stages of each runoff event (Fig. 6); the differences among total numbers of *E. coli* transported with runoff were within 5% for different realizations.

4. Discussion

Large inter-annual differences were found for irrigation-induced runoff export of manure-borne *E. coli* from the manured field. The cumulative bacterial export changed with the lag time between initiation of irrigation and initiation of edge-of-field runoff (Fig. 2). This may partially explain the observations of large variability of bacterial indicator release from other types of manure or animal waste for the same depth of irrigation water applied (Kim et al.,

2016; Blaustein et al., 2015a). The infiltration and storage capacity of soil might be exhausted at different times, and the exported amounts would reflect concentrations of *E. coli* released earlier.

Various release and transport studies have indicated that the numbers of fecal indicator organisms (FIOs) exported from fields amended with liquid manure could be predicted from the rainfall depth, but this was not the case for solid manure (Blaustein et al., 2015a). For example, at the rainfall depth of 26.6 mm, Stout et al. (2005) observed 27% to 46% fecal coliform export from solid dairy cattle manure whereas Larsen et al. (1994) reported 10% export. At the rainfall depth of 35 mm, Thurston-Enriquez et al. (2005) observed exports from 0.01% to 0.7% of fecal indicator organisms from beef cattle manure. These numbers are similar to the numbers reported by Ferguson et al. (2007), who delivered 25 mm of rainfall to fresh cattle fecal pats on field soil and observed from 0.5% to 0.9% release of *Cyptosporidium parvum* oocysts, from 1.3% to 1.4 % release of *E. coli*, and from 0.03% to 0.06% release of PRD1 bacteriophage. Thus, rainfall depth cannot be the sole predictor of FIO export from fields with solid manure applications. Although many factors affect FIO release and export from solid manure (consistency, storage conditions, bedding, etc.), our results indicate that soil conditions that control water infiltration and soil storage must be included in predictive models as a strong factor controlling the fraction of exported manure-borne FIO.

Overall numbers of exported *E. coli* were not large compared to total numbers in applied manure (Table 3), indicating that it was not released from the manure, infiltrated prior to edge-of-field, or was stored in soil at the field. For example, Kim et al. (2016) computed the fraction of *E. coli* released from fresh cattle pats in 36 rainfall-runoff experiments and found values ranging from 0.8 to 2.6%. The sandy soil in this study provided somewhat favorable conditions for transport of bacteria downward into soil, with a limited potential for overland lateral movement. Indeed, the percentage of applied water recovered as runoff was low and ranged from 2.6 to 15.2 % (Table 1). Spatial variation of concentrations of *E. coli* in manure on the field was high throughout the study, highlighting the importance of taking a large number of samples to assess the number of bacteria applied adequately.

Functional evaluation of FIO release models showed that when the EM submodel was included in the KINEROS2/STWIR model, it did not perform as well as the VKS or B-S submodels. These results agree with results of Guber et al. (2006), who evaluated the release of fecal coliforms from manure slurry applied to small-scale grass-covered plots in the field and observed a larger Root Mean Square Error (RMSE) of the EM submodel than the VKS or B-S submodel. Given the uniqueness of our study as the one performed on a full scale field, the similarity between Guber et al. (2006) and the present study is particularly interesting because it suggests that the B-S and VKS submodels perform better than the EM submodel regardless of scale. Similarly, Blaustein et al. (2016) simulated rainfall-induced release of different indicator bacteria from solid manure applied over grass in soil boxes. In that study, the EM submodel had a poor overall performance at simulating bacterial release, whereas the B-S submodel was preferable for simulating release of both *E. coli* and enterococci, and the VKS submodel was preferable for simulating release of total coliforms. The EM submodel simulated the release rate as simply being proportional to the amount of

irrigation water and concentration. On the contrary, the VKS and B-S submodels were able to better reflect the difference in dominant mechanisms of FIO release. Added flexibility in VKS and B-S models is beneficial for simulating the existence of different stages of bacteria release from solid manure. Blaustein et al. (2015b) noted that dilution with mixing was only one mechanism that might be important during the first stage of FIO release from manure. The “late” release of bacteria originally associated with the manure solid phase might be because (1) manure solid contents provided surfaces for bacterial attachment; (2) mechanical straining of bacteria in manure aggregates could have negative effects on bacterial leaching through manure; and/or (3) manure particulates containing attached bacteria could be strained. Edwards et al. (2000) stated that two-stage release behavior may be caused by initial flushing of biological material, followed by dilution and/or decreasing availability for biological material transport. The mass transfer rate of microbes from manure solids to the leaching liquid phase may decrease with time because the surface area of manure exposed to flow is depleted of finer colloidal materials over time (Bradford and Schijven, 2002).

Comparison of KINEROS2/STWIR performance with the VKS and B-S submodels did not demonstrate a clear advantage of either of the two. The KINEROS2/STWIR performance metrics (R^2 , corrected Akaike criterion, and standard error) were very similar in simulations with both (Tables 6 and 7). One reason could be that the fractions of the exported *E. coli* were very small and differences between the nonlinear models could not be manifested clearly. On average, the VKS submodel had lower standard error and *AICc* values than the B-S submodel, although the two submodels had approximately the same R^2 .

Model parameter values substantially varied from year to year. That reflected differences both in soil structure and in soils surface properties which in turn could be caused by year-specific presence or absence of crop residues, water repellency of sandy soils which dominated in this work, presence or absence of emerged weeds, history of freezing-thawing as soil structure factor, pressure in irrigation pipelines, wind and radiation as irrigation water droplet size controls, and other factors. This work, due to unusually large number of experimental years encompasses conditions that can be encountered but does not pretend to explain the specific differences between specific parameter values for specific years. The observed variation in parameter values can be used to generate statistically equiprobable sets of parameter values to assess the uncertainty of modeling results.

The average value of the exponent in the VKS submodel was 0.583, which is very close to the exponent in the MUSLE developed for sediment loss (Williams et al., 1975; USBR, 2006), and later assumed as the default exponent value in the manure erosion model (Williams et al., 2012). Indeed, similar erosive action occurs on solid manure, as the overhead irrigation breaks the fecal matrix. This results in a steady number of bacteria being released when new sections of manure interior are exposed. Kim et al. (2016) note that release efficiency increases as manure structure breaks down, although fewer microbes are available over time. Based on the results of this study, it would seem the latter dominates as evidenced by the sizeable decrease in *E. coli* export during the second irrigation event as compared to the first. Nevertheless, in 2 of 6 years the fraction of *E. coli* released increased during the second irrigation event indicating that the weathering and bioturbation of manure structure may allow for enhanced export of fecal bacteria.

5. Conclusions

Six years of field-scale runoff experiments demonstrated large spatio-temporal variability despite maintaining the same experimental design and similar conditions. Substantial numbers of manure-borne *E. coli* were removed from the field in both irrigation events every year. The *E. coli* die-off in soil was always observed between irrigation events, but this was not always the case in manure. After the second irrigation event, concentrations in soil generally declined, except in one instance where pre- and post-irrigation levels were nearly the same. Relative increases and decreases in concentrations in soil and manure were statistically significant in some years and not in others.

Three bacterial release submodels were incorporated into KINEROS2/STWIR to simulate release of *E. coli* using data from 11 runoff experiments performed under similar conditions. The one-parameter exponential submodel performed acceptably in simulating manure-borne *E. coli* export; however, it was clearly inferior to both two-parametric submodels (Vadas-Kleinman-Sharpley and Bradford-Schijven models), according to values of AICc, R^2 , and standard error. Both two-parametric submodels were nearly equivalent in accuracy in agreement with what other authors have observed in smaller-scale experiments (Blaustein et al. 2016; Guber et al. 2006). According to AICc, R^2 , and standard error, VKS was favored in 61% of cases, while B-S was only favored in 39%. The AICc criterion favored VKS in 55% of cases and B-S in 45% when these two were compared to each other. ANOVA on ranks showed that the model standard error and AICc metrics did not significantly differ when implementing different submodels. However, ANOVA on ranks showed that significantly higher values of R^2 were achieved by implementing the VKS and BS submodels over the EM submodel.

Overall, this work highlights the inherent variability in forecasting water quality affected by runoff from manure-amended fields. The KINEROS2/STWIR model equipped with either the VKS or B-S release submodel is a powerful tool for these simulations despite large variability. The results of this study are useful for the field of microbial water quality forecasting since manure-borne bacteria export data from field scale runoff events are essentially lacking in the current literature. Effects of changing the submodel were noticeable within the results of the model which indicates that release model selection should not be an arbitrary decision.

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References

- Bicknell BR, Imhoff JC, Kittle JL, Jr., Donigan AS, Jr., & Johanson RC (1997). Hydrological simulation program—FORTRAN user's manual for version 11. Environmental Protection Agency Report No. EPA/600/R-97/080 U.S. Environmental Protection Agency, Athens, Ga.

- Blaustein RA, Hill RL, Micallef SA, Shelton DR, & Pachepsky YA (2016). Rainfall intensity effects on removal of fecal indicator bacteria from solid dairy manure applied over grass-covered soil. *Science of the Total Environment*, 539, 583–591. [PubMed: 26386449]
- Blaustein RA, Pachepsky YA, Shelton DR, & Hill RL (2015a). Release and removal of microorganisms from land-deposited animal waste and animal manures: a review of data and models. *Journal of environmental quality*, 44(5), 1338–1354. [PubMed: 26436252]
- Blaustein RA, Pachepsky YA, Shelton DR, & Hill RL (2015b). Solid manure as a source of fecal indicator microorganisms: release under simulated rainfall. *Environmental Science and Technology*, 49 (13), 7860–7869. [PubMed: 26011817]
- Bradford SA, & Schijven J (2002). Release of *Cryptosporidium* and *Giardia* from dairy calf manure: impact of solution salinity. *Environmental science & technology*, 36(18), 3916–3923. [PubMed: 12269743]
- Burnham KP, & Anderson DR (2003). *Model selection and multimodel inference: a practical information-theoretic approach* Springer Science & Business Media.
- Doherty J 2005 PEST, Model-Independent Parameter Estimation, User's Manual: 5th Edition, Watermark Numerical Computing, Australia.
- Edwards DR, Larson BT, & Lim TT (2000). Runoff nutrient and fecal coliform content from cattle manure application to fescue plots. *Journal of the American Water Resources Association*, 36 (4), 711–721.
- Ferguson CM, Davies CM, Kaucner C, Ashbolt NJ, Krogh M, Rodehutsors J, & Deere DA (2007). Field scale quantification of microbial transport from bovine faeces under simulated rainfall events. *Journal of water and health*, 5(1), 83–95. [PubMed: 17402281]
- Goodrich DC, Bums IS, Unkrich CL, Semmens DJ, Guertin DP, Hernandez M, & Levick LR (2012). KINEROS 2/AGWA: Model use, calibration, and validation. *Transactions of the ASABE*, 55(4), 1561–1574.
- Guber AK, Yakirevich AM, Sadeghi AM, Pachepsky YA, & Shelton DR (2009). Uncertainty evaluation of coliform bacteria removal from vegetated filter strip under overland flow condition. *Journal of environmental quality*, 38(4), 1636–1644. [PubMed: 19549940]
- Guber AK, Pachepsky YA, Yakirevich AM, Shelton DR, Sadeghi AM, Goodrich DC, & Unkrich CL (2011). Uncertainty in modelling of faecal coliform overland transport associated with manure application in Maryland. *Hydrological processes*, 25(15), 2393–2404.
- Guber AK, Pachepsky YA, Dao TH, Shelton DR, & Sadeghi AM (2013). Evaluating manure release parameters for nonpoint contaminant transport model KINEROS2/STWIR. *Ecological modelling*, 263, 126–138.
- Guber AK, Shelton DR, Sadeghi AM, Sikora LJ, & Pachepsky YA (2006). Rainfall-induced release of fecal coliforms, chloride, phosphorus and organic carbon from surface-applied dairy manure. *Applied and Environmental Microbiology*, 72, 7531–7539. [PubMed: 17028232]
- Kim K, Whelan G, Molina M, Purucker ST, Pachepsky Y, Guber A, Cyterski M, Franklin D, & Blaustein RA (2016). Rainfall-induced release of microbes from manure: model development, parameter estimation, and uncertainty evaluation on small plots. *Journal of water and health*, 14(3), 443–459. [PubMed: 27280610]
- Larsen RE, Miner JR, Buckhouse JC, & Moore JA (1994). Water-quality benefits of having cattle manure deposited away from streams. *Bioresource Technology*, 48(2), 113–118.
- Parlange JY, Lisle I, Braddock RD, & Smith RE (1982). The three-parameter infiltration equation. *Soil Science*, 133(6), 337–341.
- Randle T, Yang C, & Daraio J, (2006). *Erosion and Reservoir Sedimentation*, USBR Erosion and sedimentation Manual, Ch2.
- Sadeghi A, & Arnold JG (2002). A SWAT/microbial submodel for predicting pathogen loadings in surface and groundwater at watershed and basin scales. In: *Total Maximum Daily Load (TMDL) Environmental Regulations*, Proceedings of the Conference, Fort Worth, TX, USA March 11–13, pp. 56–63.
- Stout WL, Pachepsky YA, Shelton DR, Sadeghi AM, Saporito LS, & Sharpley AN (2005). Runoff transport of faecal coliforms and phosphorus released from manure in grass buffer conditions. *Letters in Applied Microbiology*, 41(3), 230–234. [PubMed: 16108912]

- Thurston-Enriquez JA, Gilley JE, & Eghball B (2005). Microbial quality of runoff following land application of cattle manure and swine slurry. *Journal of water and health*, 3(2), 157–171. [PubMed: 16075941]
- U.S. FDA (2016). Food and Drug Administration. FSMA Final Rule on Produce Safety Available at <http://www.fda.gov/Food/GuidanceRegulation/FSMA/ucm334114.htm>
- U.S. EPA (2012). Recreational Water Quality Criteria. Office of Water 820-F-12-058 Available at <https://www.epa.gov/sites/production/files/2015-10/documents/rwqc2012.pdf>
- Vadas PA, Kleinman PJA, & Sharpley AN (2004). A simple method to predict dissolved phosphorus in runoff from surface-applied manures. *Journal of Environmental Quality*, 33(2), 749–756. [PubMed: 15074829]
- Vereecken H, Diels J, Van Orshoven J, Feyen J, & Bouma J (1992). Functional evaluation of pedotransfer functions for the estimation of soil hydraulic properties. *Soil Science Society of America Journal*, 56(5), 1371–1378.
- Williams JR (1975). Sediment-yield prediction with universal equation using runoff energy factor, pp. 244–252. In: *Present and prospective technologies for predicting sediment yield and sources*. ARS-S-40 Agricultural Research Service USDA. 1975.
- Williams JR, Izaurralde RC, & Steglich EM (2012). Agricultural Policy / Environmental eXtenderModel. Theoretical Documentation. Version 0806 Agrilife Research Temple, Texas Available at <http://apex.tamu.edu/media/72000/the-apex0806-theoretical-documentation.pdf>
- Woolhiser DA, Smith RE, & Goodrich DC (1990). KINEROS, A Kinematic Runoff and Erosion Model: Documentation and User Manual ARS-77. USDA, ARS, Washington, DC.
- Xevi E, Christiaens K, Espino A, Sewnandan W, Mallants D, Sørensen H, & Feyen J (1997). Calibration, validation and sensitivity analysis of the MIKE-SHE model using the Neuenkirchen catchment as case study. *Water Resources Management*, 11(3), 219–242.

Figure 1.
Layout of the manure application field. Left: location of the Field A irrigated area at the OPE3 field site. Right: Irrigation system distribution and sampling point distribution.

Figure 2. Dependencies of the exported fraction of *E. coli* on the irrigation depth. N is the total number of exported bacteria, N_0 is the total number of applied bacteria. An experiment label includes the year, “1” for the first irrigation, and “2” for the second irrigation.

Figure 3. Measured (first irrigation - black circles, second irrigation - blue circles) and simulated (first irrigation - continuous lines, second irrigation -dashed lines) runoff

Figure 4. Measured (first irrigation - black circles, second irrigation - blue circles) and simulated (first irrigation - continuous lines, second irrigation - dashed lines) *E. coli* concentrations in runoff. Pink, red and green curves show results of simulations with exponential, Bradford-Schijven, and Vadas-Kleinman-Sharpley submodels, respectively.

Figure 5. Measured vs simulated average *E. coli* content in soil after irrigation events. KINEROS2/STWIR was run with the exponential release (a), Bradford-Schijven (b), and Vadas-Kleinman-Sharp (c) submodels.

Figure 6.

Simulated *E. coli* in runoff for five random realizations of spatial distributions of *E. coli* concentration in manure (year 2013, first irrigation). The left panel shows *E. coli* concentration in runoff throughout the removal event (CFU ml⁻¹) and the right panel shows cumulative *E. coli* cells removed during the event (CFU). Black curve shows the simulation with the uniform initial distribution of *E. coli* in manure; circles show measured values.

Table 1.

Hydrologic data and manure water content for irrigation events.

Year	Irrigation duration (min)	Irrigation rate (mm min ⁻¹)	Total runoff volume (L)	Antecedent soil water content (g H ₂ O / g wet soil)	Manure water content (g H ₂ O g ⁻¹ manure)	Time to runoff initiation (min)	Irrigation depth when runoff starts (mm)	Percentage (%) of irrigation water removed as runoff
2011/1	186	0.31	24053	-	0.72	69	21.3	10.5
2011/2	185	0.28	24749	-	0.67	69	19.1	12
2012/1	214	0.21	25536	0.26	0.7	85	17.9	12.8
2012/2	214	0.2	18413	0.21	0.24	89	17.8	9.9
2013/1	255	0.18	18467	0.22	0.64	138	27.8	9.9
2013/2	274	0.21	28129	0.21	0.2	151	32.2	12.4
2014/1	206	0.22	24315	0.23	0.68	86	19.8	14.9
2015/1	217	0.19	20595	0.22	0.73	96	18.8	15.2
2015/2	246	0.17	14951	0.25	0.25	125	21.7	10.4
2016/1	272	0.26	6241	0.2	0.74	151	39.5	2.6
2016/2	282	0.26	8925	0.25	0.25	162	42.1	3.6

Table 2.

Pre- and postirrigation *E. coli* concentrations in manure and soil samples.

Year/Irrigation	Manure CFU or MPN/gdw	SE	Preirrigation Soil	SE	Postirrigation Soil	SE
2011/1	1.43·10 ⁶	4.56·10 ⁵	n.d	n.d	3.29 · 10 ²	2.10 · 10 ²
2011/2	1.67·10 ⁵	3.46·10 ⁴	n.d	n.d	1.88 · 10 ³	9.26 · 10 ²
2012/1	3.88·10 ⁴	1.91·10 ⁴	2.09·10 ³	1.98·10 ³	1.45 · 10 ⁴	3.74 · 10 ³
2012/2	2.40·10 ⁵	2.27·10 ³	3.17·10 ³	2.83·10 ³	4.82 · 10 ²	2.19 · 10 ²
2013/1	3.73·10 ⁶	1.74·10 ⁶	1.88·10 ²	7.86·10 ¹	1.06 · 10 ³	1.88 · 10 ²
2013/2	8.70·10 ³	2.27·10 ³	9.31·10 ²	3.71·10 ²	9.56 · 10 ²	2.19 · 10 ²
2014/1	2.43·10 ⁶	1.05·10 ⁶	0	0	3.71 · 10 ³	1.14 · 10 ³
2015/1	1.44·10 ⁷	5.91·10 ⁶	0	0	4.20 · 10 ⁴	8.75 · 10 ³
2015/2	1.47·10 ⁶	1.01·10 ⁶	3.77·10 ⁴	1.46·10 ⁴	6.87 · 10 ³	1.16 · 10 ³
2016/1	9.6·10 ⁶	7.76·10 ⁶	0	0	2.42 · 10 ⁴	9.48 · 10 ³
2016/2	6.41·10 ⁵	2.62·10 ⁵	1.88·10 ⁴	5.75·10 ³	8.50 · 10 ³	1.54 · 10 ³

SE-standard error; n.d.- not determined. A /1 or /2 after the year indicate the first and second irrigation events for that year, respectively. Pre- and post-soil refers to concentrations of *E. coli* in the soil before and after irrigation, respectively.

Table 3.

Total numbers of *E. coli* that were in the land-applied manure before irrigation began (N_0) and that were collected in the edge-of-field runoff (N)

<i>E. coli</i> Year/Irrigation	N_0 CFU or MPN	N CFU or MPN	N/N_0 %
2011/1	$9.26 \cdot 10^{12}$	$4.80 \cdot 10^{11}$	5.18
2011/2	$8.33 \cdot 10^{11}$	$6.80 \cdot 10^{10}$	8.16
2012/1	$1.88 \cdot 10^{11}$	$1.09 \cdot 10^{11}$	58.10
2012/2	$2.46 \cdot 10^{12}$	$1.20 \cdot 10^{10}$	0.49
2013/1	$2.13 \cdot 10^{13}$	$1.94 \cdot 10^{11}$	0.91
2013/2	$1.13 \cdot 10^{11}$	$1.19 \cdot 10^{10}$	10.54
2014/1	$1.27 \cdot 10^{13}$	$5.92 \cdot 10^{11}$	4.68
2015/1	$5.89 \cdot 10^{13}$	$4.93 \cdot 10^{12}$	8.37
2015/2	$2.44 \cdot 10^{13}$	$3.61 \cdot 10^{10}$	0.15
2016/1	$3.48 \cdot 10^{13}$	$4.66 \cdot 10^{11}$	1.34
2016/2	$7.30 \cdot 10^{12}$	$2.04 \cdot 10^{10}$	0.28
Average	$1.65 \cdot 10^{13}$	$6.90 \cdot 10^{11}$	9.79

Table 4.

Parameters found for the KINEROS2 runoff model. n

Year/irrigation	n	K_s cm ^{-h}	G cm	S_i	θ_s	R^2	SE L/sec
2011/1	0.111	15.36	8.7	0.731	0.391	0.970	0.217
2011/2	0.143	13.84	11.4	0.771	0.426	0.988	0.149
2012/1	0.304	8.14	14.6	0.834	0.432	0.978	0.183
2012/2	0.238	7.19	24.6	0.809	0.410	0.984	0.131
2013/1	0.270	7.82	22.1	0.776	0.429	0.962	0.245
2013/2	0.234	7.06	26.1	0.741	0.391	0.976	0.197
2014/1	0.277	7.71	24.1	0.806	0.401	0.976	0.320
2015/1	0.238	7.93	15.0	0.833	0.439	0.964	0.192
2015/2	0.141	7.53	18.0	0.8	0.438	0.949	0.157
2016/1	0.268	12.47	18.9	0.613	0.383	0.955	0.107
2016/2	0.185	11.45	23.4	0.604	0.385	0.943	0.164
Average	0.219	9.68	18.8	0.756	0.411	0.968	0.187
CV, %	29.3	31.1	30.9	10.6	5.4	1.5	31.3

n is the Manning's roughness coefficient, K_s is the saturated hydraulic conductivity, G is the net capillary drive, S_i is the soil saturation before irrigation, and θ_s is the soil volumetric water content at saturation.

CV=coefficient of variation, R^2 =determination coefficient, SE=standard error

Table 5.

Parameters^s for STWIR transport model using the M release equation.

Year/Irrigation	a_L	k_a	k_d	k_e	SE	R ²	AICc
	m	h ⁻¹	h ⁻¹	cm ⁻¹	CFU or MPN		
2011/1	0.100	0.013	0.120	0.016	$1.56 \cdot 10^{11}$	0.949	2206
2011/2	0.100	0.003	0.090	0.019	$3.25 \cdot 10^{10}$	0.974	2377
2012/1	0.471	0.086	0.024	0.025	$6.41 \cdot 10^{10}$	0.986	2812
2012/2	0.253	0.226	0.017	0.002	$1.19 \cdot 10^8$	1.000	1906
2013/1	0.524	0.154	0.401	0.037	$1.01 \cdot 10^{10}$	0.991	2314
2013/2	0.765	0.040	0.044	0.020	$2.79 \cdot 10^9$	0.995	2185
2014/1	0.100	1.805	0.183	0.023	$2.87 \cdot 10^{11}$	0.960	1803
2015/1	0.100	0.025	0.046	0.020	$2.40 \cdot 10^{12}$	0.815	2020
2015/2	1.172	5.851	0.051	0.100	$1.80 \cdot 10^9$	1.000	1508
2016/1	0.100	0.021	0.213	0.009	$1.20 \cdot 10^{11}$	0.939	1796
2016/2	0.356	5.275	0.353	0.259	$1.29 \cdot 10^9$	0.994	1603
Average	0.367	1.227	0.140	0.048	$2.79 \cdot 10^{11}$	0.964	2048
CV, %	94.7	180.1	95.3	154.6	253.6	5.6	18.5

^s a_L is the dispersivity, k_d is the detachment rate of microorganisms at the solid phase, k_d is the detachment rate of microorganisms from the solid phase, and k_e describes the microorganism release from manure.

Table 6.

Parameters[§] for STWIR transport model using B-S release equation.

Year/Irrigation	a_L	k_a	k_d	a_m	β_m	SE	R ²	AICc
	m	h ⁻¹	h ⁻¹	h ⁻¹	-	CFU or MPN		
2011/1	0.101	1.491	2.647	22.953	0.271	3.34 · 10 ¹⁰	0.995	2052
2011/2	0.150	0.779	0.186	5.968	4.770	7.82 · 10 ⁸	0.999	2014
2012/1	0.260	1.477	0.986	0.758	0.249	6.64 · 10 ⁹	0.997	2573
2012/2	0.234	3.566	0.011	18.510	0.278	1.28 · 10 ⁸	1.000	1997
2013/1	0.840	0.076	0.436	29.743	0.652	1.10 · 10 ¹⁰	0.988	2325
2013/2	0.203	1.848	0.202	30.460	1.004	3.38 · 10 ⁸	0.999	1933
2014/1	0.981	0.673	0.605	13.471	0.166	1.50 · 10 ¹⁰	1.000	1605
2015/1	0.100	0.168	0.237	15.296	7.005	5.22 · 10 ¹⁰	0.999	1739
2015/2	0.911	0.582	0.005	58.667	0.699	4.67 · 10 ⁸	1.000	1488
2016/1	0.100	0.133	0.003	23.262	3.568	1.93 · 10 ¹⁰	0.998	1811
2016/2	0.334	0.185	1.382	38.038	0.392	4.30 · 10 ⁸	0.998	1593
Average	0.383	0.998	0.609	23.375	1.732	1.27 · 10 ¹⁰	0.998	1921
CV, %	90.8	105.48	132.38	68.4	134.0	132.5	0.349	16.9

[§] a_L is the dispersivity, k_d is the detachment rate of microorganisms at the solid phase, k_d is the detachment rate of microorganisms from the solid phase, and a_m and β_m describe the microorganism release from manure.

Table 7.

Parameters for STWIR transport model using VKS release equation

Parameter	a_L	k_a	k_d	a	b	SE	R ²	AICc
Year/Irrigation	m	h ⁻¹	h ⁻¹	-	-	CFU or MPN		
2011/1	0.224	1.890	5.648	1.149	0.989	6.44 · 10 ⁹	1.000	1904
2011/2	0.208	0.039	0.020	2.857	0.804	7.38 · 10 ⁸	0.999	2016
2012/1	0.100	0.401	0.057	21.159	0.971	6.65 · 10 ⁹	0.986	2557
2012/2	0.461	0.888	0.247	1.517	0.278	1.05 · 10 ⁸	1.000	1934
2013/1	0.477	0.049	0.088	2.499	0.296	9.59 · 10 ⁹	0.997	2311
2013/2	1.228	0.903	0.069	3.817	0.980	2.48 · 10 ⁸	1.000	1903
2014/1	0.198	0.285	0.112	6.540	0.471	1.28 · 10 ¹⁰	1.000	1594
2015/1	0.176	0.099	0.035	19.715	0.301	4.95 · 10 ¹⁰	0.999	1735
2015/2	0.958	4.583	0.015	8.457	0.142	7.93 · 10 ⁸	1.000	1523
2016/1	0.105	0.336	0.008	2.147	0.854	2.30 · 10 ¹⁰	0.995	1824
2016/2	0.498	3.100	0.232	0.040	0.328	1.32 · 10 ⁹	1.000	1610
Average	0.421	1.143	0.594	6.354	0.583	1.01 · 10 ¹⁰	0.998	1901
CV, %	87.1	129.2	282.7	116.0	57.5	146.7	0.4	16.4

a_L is the dispersivity, k_a is the detachment rate of microorganisms at the solid phase, k_d is the detachment rate of microorganisms from the solid phase, and a and b describe the microorganism release from manure.