



Effects of Cattle Grazing on Microbial Pollution at the Watershed Scale: Field Observation, Laboratory Analyses, and Fate and Transport Modeling

Yael Gilboa¹ · Ofer Snir¹ · Gal Rozenberg¹ · Firas Talhami² · Yohay Carmel¹ · Guy Dovrat³ · Eran Friedler¹

Received: 3 December 2025 / Accepted: 4 May 2026
© The Author(s) 2026

Abstract

Cattle grazing near and inside watercourses may potentially contribute fecal coliform (FC) to surface water (streams, lakes, etc.), posing risks to both ecosystems and public health. This study presents a novel approach for estimating the impact of grazing cattle on watercourses under diverse conditions and to assess the effects of mitigation measures. The approach is based on a conceptual framework integrating field observations, long-term laboratory analysis, and FC fate and transport prediction modeling. The field survey revealed uniform distribution of dung across the plots, irrespective of distance to water. Microbial fate in the cattle dung over time under varying temperatures describes growth followed by a decline. The developed predictive process-based model showed that indirect FC load reaching the stream after dry grazing days ($\sim 10^{10}$ CFU per cow per rain event) was approximately two orders of magnitude higher than FC load by direct in-stream deposition ($\sim 10^8$ CFU per cow per day). These loads were significantly reduced by creating a buffer zone of 50 m between the watercourse and grazing areas or by cattle exclusion from the watercourses for a limited time - at least during sensitive periods, i.e., when heavy rain is expected after several dry weeks and especially during the tourist period. The model results can help policy makers to quantify the effectiveness of management practices and will assist in identifying ways of revising existing measures to improve this effectiveness. The developed model can be adapted to different cases, considering the conditions prevailing on the sites.

Highlights

- We assessed the impact of cattle grazing on watercourse microbial loads.
- Microbial fate and transport model was developed based on field and lab observations.
- Uniform dung distribution was observed irrespective of distance from watercourse.
- Rain after dry period is predicted to increase fecal coliform load at watercourses.
- The model may serve policymakers to derive effective grazing management.

Extended author information available on the last page of the article

Keywords Grazing beef cattle · Grazing management policy · Dung distribution · Fecal coliform aging experiment · Microbial fate and transport model · Microbial quality of surface water

1 Introduction

Presence and fate of fecal indicator bacteria (FIB) in the environment have received increasing interest in recent years. The US Environmental Protection Agency was called for identifying impaired water sources due to fecal contamination and developing strategies to control and manage these pollution sources (USEPA 2014). Today, beef cattle are recognized as important contributors of environmental fecal contamination, specifically in surface water (streams, lakes, etc.). The main fecal contamination pathways of surface water are direct and indirect release of human and animal feces, when the main sources are categorized as point sources or non-point/diffuse sources originating through surface runoff (e.g.: Hassan-Vásquez et al. 2022; Afolabi et al. 2022; Paruch and Paruch 2022). Specifically, there has been increased concern regarding the impacts of beef cattle grazing near- and inside watercourses (O’Callaghan et al. 2019; Afolabi et al. 2022). In many regions, grazing cattle are allowed to access watercourses as they provide low-cost and low-maintenance water source for livestock, in addition to shade and palatable vegetation in the riparian zone. Hence, wherever cattle are present in the watershed, and particularly if they have access to the water, FIB and pathogens might be washed readily to the streaming surface waters and thus, present environmental challenges.

Previous studies report that where cattle have access to streams, they spend approximately 0.5–2.5% of their time in the stream water (e.g.: Haan et al. 2010; Schwarte et al. 2011; Bond et al. 2012; Conroy et al. 2016). A value of 1% was adopted widely in modelling the proportion of daily fecal matter deposited directly in streams by cattle with unimpeded access to watercourses (Wilcock 2006).

Fecal coliforms (FC) are indicators of the hygienic status of aquatic environments. When high concentrations are detected in water, FC is correlated with increased human health risk (Cho et al. 2016; Paruch and Paruch 2022) and is utilized as a universal standard for water quality. Thus, closure of recreational areas to the public is required when high FC counts are detected, both from animal feces runoff and from discharge of improperly treated sewage (Shakya et al. 2022). Yet the dynamic distribution of pathogens in watersheds was rarely quantified and most of the studies to date were conducted in temperate regions (Grudzinski et al. 2020; Islam et al. 2021; Afolabi et al. 2022; Cheong et al. 2024).

Knowledge of animal contribution to the distribution of FIB contamination as well as factors that affect microbial dynamics is required to mitigate health risks associated with surface water for domestic, agricultural and recreational purposes (Islam et al. 2021). Previous studies examined the environmental factors that promote the presence of livestock, in particular cattle, near streams/ivers and thus increase the potential for contamination. They found that the most effective tool for minimizing grazing cattle presence near streams/ivers was constructing drinking water points away from the streams (Ganskopp 2001; Yoshitoshi et al. 2020).

After excrement, manure fecal-borne bacteria survival is affected by many factors including temperature, moisture content, rainfall, pH, animals diet, UV or solar radiation, in-soil

predation by other microorganisms, the physiological status of the organisms and strain variability, organisms being washed away via precipitation as well as their growth and death and type of soil (Crane and Moore, 1986; Avery et al. 2004; Van Kessel et al. 2007; Alegbel-eye and Sant'Ana 2020; Dean and Mitchell 2022; Devane et al. 2022).

Recent field studies in the United States demonstrated that grazing within integrated crop-livestock systems can temporarily increase soil contamination by FIB, with bacterial persistence strongly influenced by temperature and regional climatic conditions (Cheong et al. 2024). The authors underscore the need for improved predictive frameworks that account for environmental drivers and transport mechanisms across diverse grazing systems and climatic regions. In addition to persistence, laboratory studies have demonstrated that FIB mobilization from fecal deposits is strongly influenced by fecal sources, ageing time, and temperature, with significant variation in the proportion of bacteria transferred into hydrological pathways (Afolabi et al. 2022). These results emphasize the importance of explicitly representing mobilization processes when developing predictive models of microbial fate and transport.

To reduce the potential microbial impact of grazing cattle on surface water, several mitigation measures are available: reducing the time that cattle spend in riparian watercourses, constructing troughs as alternative water sources, and full exclusion or fencing and establishing buffer zones (Tiedemann et al. 1987; Harmel et al. 2010; Wagner et al. 2012; Grudziński et al. 2020).

Microbial fate and transport modelling may serve policymakers to derive effective grazing management policy. A prediction model could evaluate and compare management practices under different conditions and prescribe optimal management practices. Several types of models were reported in the literature, including statistical models, best management practices, decision-support systems, and mechanistic, process-based models of microbial fate and transport (e.g.: Agouridis et al. 2005; Cho et al. 2016; Weiskerger and Phanikumar 2020; King et al. 2021; Naloufi et al. 2021; Young et al. 2023). However, many existing mechanistic watershed-models are computationally complex and require extensive calibration and detailed hydrological and microbiological datasets. Similarly, statistical models typically rely on large historical databases for reliable prediction. Such data-intensive approaches are often impractical in Mediterranean grazing watersheds, where predictive records might be limited and hydrological regimes are characterized by prolonged dry periods followed by short, intense rainfall events.

The objectives of this study are: (i) to assess the effect of grazing beef cattle on FC contamination of watercourses under Mediterranean climate conditions; (ii) to develop a simplified, parsimonious process-based model that captures the dominant mechanisms of fecal accumulation, decay, and runoff-driven transport without relying on extensive historical datasets; and (iii) to evaluate and compare the effectiveness of grazing management practices using a scenario-based modeling framework, to support decision making for recreational water quality management.

We hypothesize that under Mediterranean climate conditions, indirect runoff-driven transport following prolonged dry periods contributes more significantly to peak in-stream FC loads than continuous daily direct deposition. In addition, we hypothesize that both source-based (e.g., short-term cattle exclusion) and transport-based (e.g., buffer zones) mitigation strategies can reduce FC loads under Mediterranean hydrological conditions.

In this research, we propose a conceptual framework for integrating field observations, laboratory analysis and experiments, and FC fate and transport prediction model. Cattle dung distribution was estimated by a field survey. FC fate over time under varying temperatures was quantified under controlled laboratory experiments. The results obtained from these two stages were used to quantify and calibrate the model developed. Then the model was used to simulate the effectiveness of specific management options that can provide insight for decision makers for managing recreational water quality to ensure public health.

Beyond its local context, this study proposes a transferable and data-efficient framework for watershed-scale microbial pollution modelling, integrating field data, laboratory-derived decay functions, and a simplified process-based approach applicable to grazing systems worldwide.

2 Methods

2.1 Study Area

Lake Kinneret watershed has a total area of 2,730 km². Its climate is Mediterranean, with hot, (completely) dry summers and cool, wet winters. Mean rainfall is 700 mm/y, mostly between October and March. The watershed is inhabited by ~200,000 people and visited by ~2–3 million tourists every year. Intensive agriculture is practiced in the catchment including beef cattle raising in rangelands (Zohary et al. 2014). The total area of rangeland in the watershed is 1,250 km², sustaining about 60,000 cattle heads. The Jordan River, the dominant outflow in the watershed is the major water source for Lake Kinneret.

2.2 Mapping Dung Distribution

Seasonal observation surveys were performed from May 2022 to September 2023 at Lake Kinneret watershed. Five rangeland plots were surveyed, each containing a flowing stream. The plots ranged from 10 to 80 hectares, differing in grazing density and herd size. In some plots grazing spanned over the entire year, in others grazing was seasonal, while in few grazing durations were very short with high cattle density (Table 1). The surveys were carried out in plots located northeast of Lake Kinneret, either where cattle were present in the plot or immediately after the cattle left the plot (Fig. 1).

Cowpats were mapped at each plot by 2–6 straight transects with varying length of 100–500 m and a width of 2 m. Transect location was selected at random. For each dung within the transect the following was recorded: location (coordinates), cowpat dimensions (length,

Table 1 Grazing data of the surveyed plots

Plot	Grazing density (1,000 m ² /cows)	Number of grazing cows	Type of grazing	Grazing period (Number of days a year)
1	25	~100	Continuous	365
2	4	85	Freq. Chng *	~14
3	4	85	Freq. Chng	~14
4	~25	Unknown	Continuous	365
5	~25	~50	Continuous	365

* Freq. Chng – High animal density for a short time period with frequent changing of plots

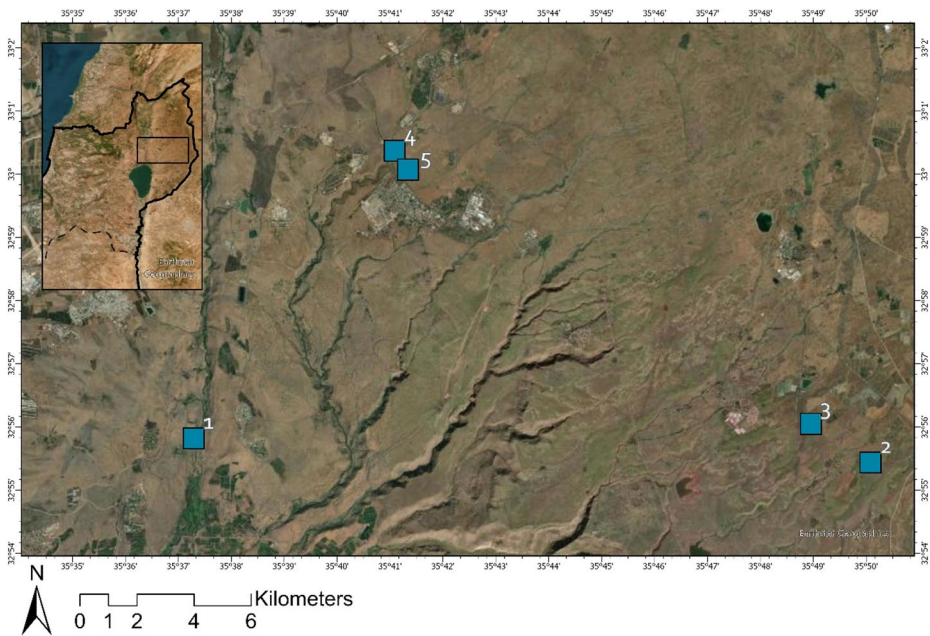


Fig. 1 Study area - Lake Kinneret watershed. Blue squares indicate the surveyed grazing plots

width, depth), site characteristics (vegetation shadow, hill, track, etc.) and age-group. Cowpats age-groups were classified visually into three categories: (1) Fresh – up to one week; (2) Medium – 1–3 weeks and (3) Old – over three weeks, based on: color, crust formation, and cracking. Cowpat samples (~15 g) were taken in an ice box to the laboratory, where water content and FC concentration were measured (Sect. 2.3).

Dung density was characterized as a function of distance from water. The minimum distance between the marked cowpat and the nearest watercourse was calculated using ArcGIS Pro 3.1 software (ESRI, Redlands, CA, USA). As the study focused on potential impact on stream water quality, distance to the watercourse was selected as the primary spatial control. Additional terrain-related variables (e.g., slope) were not explicitly incorporated in order to maintain a simplified framework centered on stream-relevant transport pathways.

Each plot was divided into 10 m wide strips from the stream (0–10, 10–20 m, etc.). Cowpat density at each strip was calculated as:

$$d_i = \frac{Num_i}{A_i} \quad (1)$$

where: d_i is cowpat density in strip i (# cowpats/m²), Num_i is total number of cowpats at strip i (cowpat #), and A_i is total area of transects located at strip i (m²).

To represent the relative spatial distribution of dung, we calculated P_i as the normalized proportion of cowpats in strip i relative to the total number of cowpats observed in the plot (Eq. 2). Thus, P_i reflects the relative probability of dung occurrence within each distance strip across the plot.

$$P_i = \frac{d_i \cdot A_i}{\sum d_i \cdot A_i} \quad (2)$$

2.3 Dung Analysis

Water content of the dung samples was measured by gravimetric methods at 60 °C (FAO 2023).

FC concentration: A cowpat sample (~3 g) was weighed and placed inside a sterile Falcon tube, 30 ml of phosphate buffered saline (PBS) was added and then the tube was shaken (TS-400 orbital shaker, MRC, Israel) for 0.5 h to release all bacteria to the liquid phase. After 0.5 h sedimentation, the upper liquid was analyzed. FC concentration was determined by Spread Plate Method (method 9215 C; APHA/AWWA/WEF 2017), samples were seeded on HiCrome Agar (HiMedia, India) Petri dishes, incubated for 24–48 h at 44 °C and colonies were counted. FC concentrations were normalized to dry weight based on gravimetric determination of water content.

2.4 Controlled Aging Experiments - Fate of Fecal Coliforms over Time

Aging experiments were performed to determine FC fate in cowpat over time. Temperature was controlled and varied to match the diurnal temperature cycle. Three aging experiments were conducted to imitate winter, spring and summer conditions in Mediterranean climate (one for each season), each lasting 100 days. The results were used for fitting a kinetic fate model of FC growth and decay (Sect. 3.1).

Freshly excreted cowpats were collected on three different dates in 2023: February (winter), May (spring) and August (summer). About 10 cowpats were collected, which is comparable to sample sizes reported in similar studies (e.g., ~12 samples; Afolabi et al. 2022). The cowpats were placed in a sterile bag and kept refrigerated until arriving at the laboratory, where they were homogenized for 15 min (Blakeslee F-20T mixer, USA) to equalize factors related to manure characteristics (FC concentration, volume, shape, density, organic matter content, humidity, etc.).

The homogeneous mixture was divided into 8 “pies” with the typical dimensions (diameter 22 cm, height 2.5 cm) as measured at the field campaign. The “dung-pies” were placed in a heating-cooling incubator (Thermo Scientific Precision, USA) connected to a temperature controller (Shinko Technos. Co. Japan), which simulated the diurnal near-ground temperature profile, as measured at Avney Eitan meteorological station located in Lake Kinneret watershed (Israel Meteorological Service). The diurnal temperature profile changed seasonally; during winter temperature ranged between 8 and 17 °C, while for spring and summer the profiles spanned from 13 to 25 and 19 to 41 °C respectively (Supplementary Material (SM), Figure SM1).

Four thermocouples (National Instruments, USA) were placed inside the incubator to monitor temperature. One was placed at the bottom of the incubator, another at the top shelf of the incubator, the third close to the surface of the dung-pie and the last thermocouple inside the dung-pie. Relatively uniform temperatures were measured at the different parts of the incubator. Due to the heat transfer, the temperature inside the dung-pie was less sensitive to changes in the environment temperature, showing two hours lag, and smaller amplitude

(maximum temperature inside the dung-pie was 2 °C lower than the environment maximum temperature; data not shown).

Samples were taken from the upper and the bottom part of the dung-pie for water content and FC concentration analyses (Sect. 2.3). On the first week, samples were taken daily then weekly.

2.5 Statistical Analysis

Field and the laboratory data were examined by analysis of variance (ANOVA). Spatial distribution of dung and modelling the fate of FC concentrations over time were examined using goodness-of-fit test. P-values < 0.05 were considered as significant. Statistical analyses were performed with *JMP Pro* statistical software.

3 Development of FC Fate and Transport Model

The model aims to assess FC daily load reaching the watercourse resulting from cattle grazing by direct and indirect dung deposition into the water (Fig. 2). The model was developed to be simple, containing only a few local specific parameters, allowing it to be easily applied on different watersheds.

During summer (no rain in Israel), FC load was calculated based on direct deposition only (excretion in the watercourse). During winter, both direct and indirect depositions were considered, when the latter was calculated based on rainwater intensity, spatial distribution of dung, and fate and transport models.

3.1 Modelling the Fate of FC over Time

Results obtained by the aging experiments were used for fitting a five parameters bi-exponential kinetic model of FC growth and die-off (Eq. 3; Crane and Moore 1986; Jolicoeur and Pontier 1989; Fidalgo et al. 2011).

$$\log(N_t) = a + b \cdot e^{(-c \cdot t)} + d \cdot e^{(-f \cdot t)} \quad (3)$$

where: N_t is number of bacteria in the cowpat at day t after excretion day (cfu/g_{dung}); t is the time after excretion day (d); a is the asymptote (residual bacteria concentration; cfu/g_{dung}); b and d are scale factors; c and f are decay rates (1/d).

At $t=0$ (day of excretion) $a+b+d=N_0$. t days after excretion the bacterial load (BLC_t ; cfu/cow) per cow is:

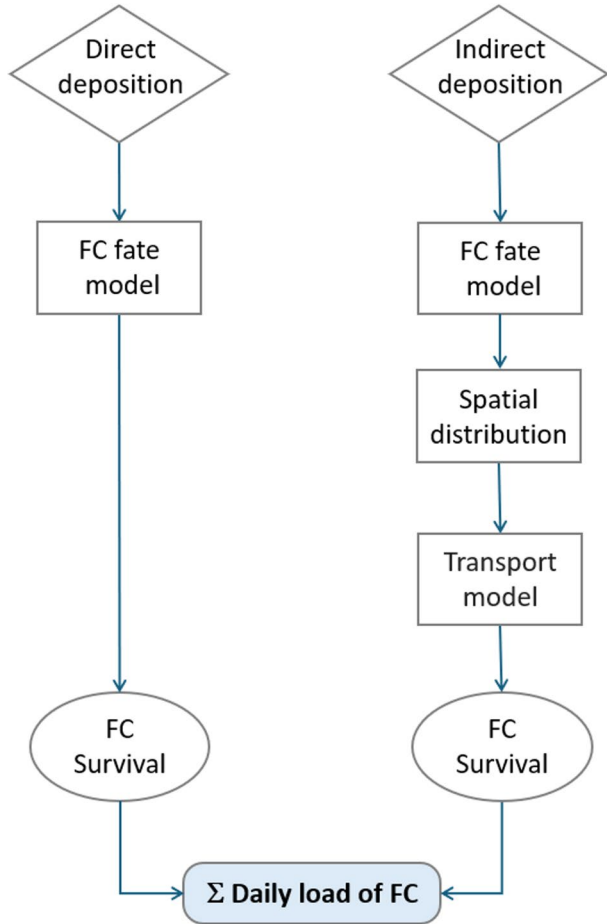
$$BLC_t = N_t \times FW \quad (4)$$

where: FW is the average feces weight excreted daily by a single cow (4 kg/cow; Aharoni et al. 2009).

Every day all BLC_t s in the plot were inventoried, and when a day passes, N_t (and BLC_t) becomes N_{t+1} (and BLC_{t+1}).

The total bacterial load is given by:

Fig. 2 Schematic flowchart of the developed model



$$Total\ bacteria\ load = \sum_{i=t_first}^{i=t_last} BLC_i \tag{5}$$

where: t_first is the day that the cows entered the plot; t_last is the day that the cows were taken out from the plot.

Note that from the date the cows are taken out from the plot, no new load is added, yet the cowpats remain in the plot and continue to age. For example: number of bacteria present at a plot where a cow grazed for 20 days and was taken out from the plot 10 days ago, will generate: $t_last=10$ days and $t_first=10+20=30$ days. Equation 5) will be applied on time

step $t=30, 29, 28, \dots, 10$ and the received results will be sum up ($\sum_{30}^{10} BLC_i$).

The proposed model was applied to assess FC fate in dung vs. time from excretion in different seasons.

3.2 Spatial Analysis of the Watershed

To quantify bacteria transport through the watershed, spatial analysis of dung distribution is required. All water paths in the watershed were marked, and a grid of 50×50 m “cells” was laid on top of the watershed. Each cell’s center point was assumed to contain the bacteria “associated” with the cell, then its distance to the nearest watercourse was calculated.

The number of bacteria in each 50×50 m cell was calculated as dung density proportion to be located in a specific cell (P_i) multiplied by the total number of bacteria excreted into the environment during grazing period generated by a single cow (Eq. 6).

$$Bac_load_cell(i) = P_i \times \sum BLC_t \quad (6)$$

where $Bac_load_cell(i)$ is bacteria load in cell i (cfu/cow).

As aforementioned, P_i represents the normalized spatial distribution of dung across distance strips and was used as a weighting factor to allocate total bacterial load among watershed grid cells. In case of a uniform cowpats density, the number of bacteria in each cell is calculated by dividing the total number of bacteria excreted into the environment during grazing period by the number of cells.

3.3 Surface Transport Mechanism

FC transport model was adapted from Collins and Rutherford (2004) and was based on runoff calculation using SCS curve number (CN) method; in this study CN value was 75 (Bosznay 1989). A CN value of 75 represents soils with moderate to low infiltration capacity, supporting runoff generation during significant rainfall events. This study focuses on surface runoff as the primary transport pathway. Under Mediterranean climatic conditions characterized by prolonged dry periods and short, high-intensity rainfall events, runoff generation is typically event-driven and dominates microbial mobilization from surface-deposited dung. Subsurface flow pathways were not represented in the model.

Number of FC transported though the watershed due to surface runoff generated within a storm event is calculated by Eq. (7):

$$FC_{wash_off}(i) = \begin{cases} Bac_load_cell(i) \times \frac{R}{R_{min}}, & R < R_{min} \\ Bac_load_cell(i), & R \geq R_{min} \end{cases} \quad (7)$$

where $FC_{wash_off}(i)$ is bacteria load wash-out from cell i (cfu/cow), R is surface runoff (mm; calculated by SCS curve), R_{min} is the runoff coefficient (mm) set as 25 mm, similar to Collins and Rutherford (2004).

The potential of transported bacteria to reach the waterbody decreases with travel distance to the flow path. Hence, a negative exponential relationship between the number of bacteria and distance from water body was assumed (Eq. 8).

$$FC_{watercourse}(i) = FC_{wash_off}(i) \cdot e^{(-k_x \cdot x_i)} \quad (8)$$

where: $FC_{watercourse}(i)$ is bacteria reaching the stream from cell i (cfu/cow); k_x is stream-proximity-coefficient (m^{-1}), x_i is the distance from a given cell to the nearest stream (m).

Two values of k_x , 0.023 and 0.007, were considered, representing a 50% decline in the number of bacteria after 30 and 100 m transport, respectively. These values were selected to represent contrasting yet realistic attenuation scenarios under field conditions, representing short and longer effective transport distances reported in the literature (Collins and Rutherford 2004).

Summarizing bacteria $FC_{\text{watercourse}}(i)$ for all cells in the watershed and considering the herd size yields the bacteria load from herd of grazing cows reaching the watercourse (*Herd load*, cfu; Eq. 9).

$$\text{Herd load} = \text{herd} \times \sum_{i=1}^n FC_{\text{watercourse}}(i) \quad (9)$$

where: *herd* is the number of cows grazing in the watershed (# cows), *n* is the number of cells (#).

The herd load presents the total contamination of bacteria deposited in the plot by herd of cows, during the grazing period and is transported to the stream by surface runoff. Dividing the herd load by the flowrate yields an assessment of the in-stream bacteria concentration (cfu/100 ml) generated by indirect deposit of grazing cattle.

3.4 Sensitivity Analysis

A one-at-a-time sensitivity analysis was performed to assess the influence of key model parameters, including *CN* (65 and 85), R_{\min} (10, 20, 30 and 40 mm), and k_x . Baseline k_x values of 0.023 and 0.007 m^{-1} were used in the model (representing a 50% decline in bacterial load over 30 m and 100 m, respectively). For sensitivity purposes, k_x was varied to represent shorter and longer effective transport distances (10–200 m). Each parameter was varied within reasonable ranges based on literature values while keeping other parameters constant. The resulting changes in predicted FC loads were quantified as percentage differences relative to the baseline scenario.

3.5 Model Application - Grazing Policy

The model was applied on the Meshushim watershed (drainage area of 160 km^2) located at the Golan Heights (Fig. 3) and draining to Lake Kinneret. The stream is part of a national nature reserve, and a variety of hiking trails cross the stream. The reserve is highly visited, especially during spring and summer.

FC concentration generated by direct and indirect dung deposits was estimated for the Meshushim stream using the model. Indirect deposition was calculated for different rain events intensities (25, 50, 70–100 mm/event) generating surface runoff, at different times of the year.

Three grazing management policies were simulated: (1) “Business as usual” (BAU) - no limits on grazing cattle. (2) Buffer zones (fence) between the watercourses and the grazing areas. (3) Removal of grazing cattle from plots adjacent to the watercourses for different durations prior to a rain event.

Fig. 3 Spatial analyses of the Meshushim watershed. Water paths at the Meshushim watershed are marked



The area is cold and rainy during winter. The tourism period is between spring and summer, thus high in-stream FC concentrations during these months might increase the risk to human health. The potential human health risk considered in this study refers to recreational exposure (e.g., bathing, swimming, or direct contact with stream water) rather than drinking water supply. In the study area, streams are used for tourism and recreational activities, and direct contact with contaminated water may result in incidental ingestion or dermal exposure. The above grazing management policies were examined for spring and summer for the following scenarios:

1. The dry summer season was 150 d long and followed by significant rainfall of 25, 50, 70–100 mm/event. FC contamination reaching the stream was estimated based on four buffer zones: no buffer, 10, 50 and 100 m between the watercourse and grazing areas. Obviously buffer zones limited the grazing area, yet the number of cows and hence the dung spread over the grazing area, remained the same (higher grazing pressures).
2. The effect of spring rainfall (25, 50, 70–100 mm/event) at the beginning of tourism period after sixty dry days (common in this season), was estimated by simulating cattle exclusion from the watercourses. Scenarios included no exclusion, full cattle exclusion of one, two or four weeks before the rain event.

4 Results and Discussion

4.1 Field Campaign

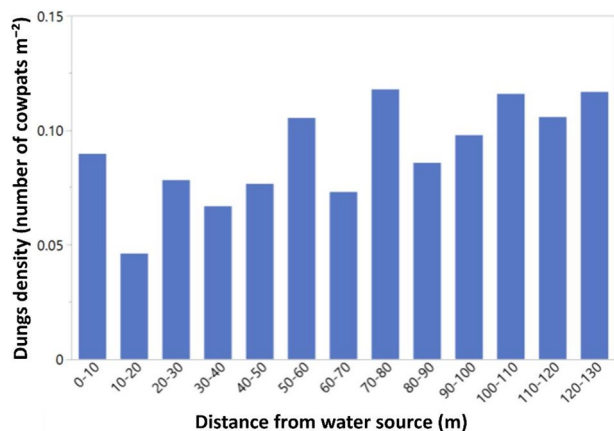
4.1.1 Spatial Dung Distribution

Cattle dung mapping was performed ten times over 16 months and served to calculate dung density at strips of 10 m from the stream. Dung density ranged from 0.04 to 0.19 (dung-piles/m²), with an average of 0.10 ± 0.03 dung-piles/m²; Fig. 4), with no statistically significant effect of distance from the watercourse ($p > 0.05$). Several candidate models (linear, exponential, and polynomial) were tested, but none provided a statistically significant fit. Therefore, dung density was represented by its overall mean value, and the spatial pattern was considered approximately uniform across distance strips for modelling purposes. This result implies that other factors may have affected cattle distribution within the plots surveyed rather than just the watercourse. For example, relatively high areas (topographically), with cooling effects of wind, shaded areas that are used by the cattle as resting places, or plot size (small in our case) may also affect the location of cattle. This result contradicts the common knowledge in this field but is consistent with four different studies that reported uniform- or nearly uniform distribution of dung in cattle grazing plots (Hassan-Vásquez et al. 2022; Bagshaw et al. 2008; White et al. 2001; Parsons et al. 2003). Interestingly, all four studies indicated that cattle concentration near streams was observed only on hot days, and mentioned vegetation cover and temperature as having significant effects on the spatio-temporal dynamics of dung deposition. Conversely, Shine et al. (2025) using multispectral sensor or unmanned aerial vehicle report that most dung was clustered near watercourses, in corners, and near supplement feeders.

Field observations indicated a relatively uniform spatial distribution of dung within the grazing plots; therefore, a uniform bacterial load was assigned to all grid cells in the spatial implementation of the watershed equation (Eq. 6).

Worth noting that Fig. 4 presents the distance from watercourse up to 130 m, whereas only a few transects were surveyed beyond that distance. Yet the density observed at further distances (above 130 m) was not different than the trend found for distances of up to 130 m from the watercourse.

Fig. 4 Dung density vs. distance from watercourse, aggregated across five surveyed plots in the Lake Kinneret watershed. Values represent aggregated total counts across all surveyed plots (total cowpats divided by total surveyed area in each distance strip); therefore, no error bars are shown



4.1.2 Dung Analysis

Water content in the cattle dungs collected from the field, ranges from ~3 to ~80% (Fig. 5a). Dung water content was found to correlate with the visual classification of the dungs to three age categories. (statistically significant ANOVA, $p < 0.0001$; Fig. 5a). On the other hand, no significant effect of age categories on dung FC was found (ANOVA, $p > 0.05$; Fig. 5b). FC concentrations obtained in the three categories ranged between 10^3 and 10^8 CFU/g_{dry dung}. The results indicate that the FC concentration in fresh dungs (category #1) were slightly lower than in dungs classified at category #2, while lower FC concentrations were observed in age category #3. Sinton et al. (2007) report on initial increase in dung bacteria concentrations, due to favorable conditions (moisture, temperature, organic matter, etc.) and noticeable reduction only after resources reduce and competition between the microorganisms intensifies.

4.2 Laboratory Controlled Aging Experiment

4.2.1 Water Content

Water content of fresh dung (day 0) was influenced by cattle nutrition and ranged from 0.79 to 0.88 (Fig. 6). Initial water content was highest in winter, when green grass was prevalent (0.85 ± 0.02), whereas lower mean values were observed in spring (0.79 ± 0.001) and summer (0.79 ± 0.002), when cattle grazed mostly on dry herbaceous vegetation. The seasonal differences were statistically significant (ANOVA, $p < 0.0001$).

Throughout the aging experiments, water content in the dung asymptotically decayed to a minimum value (Fig. 6). The minimum water content measured during the simulated winter and spring conditions was ~8%, while in simulated summer the minimum reached was ~5%. In addition, the time needed to reach the minimum water content was 43 and 36 days during the simulated winter and spring (respectively), and merely 17 days during summer. The decay rate of water content (i.e.: evaporation) was higher during the simulated summer conditions (0.1%/d, exponential decay, statistically significant, $p < 0.0001$; $R^2 > 0.95$) and lower for the winter and spring (0.04 and 0.05%/d, respectively; statistically significant, $p < 0.0001$; $R^2 > 0.9$).

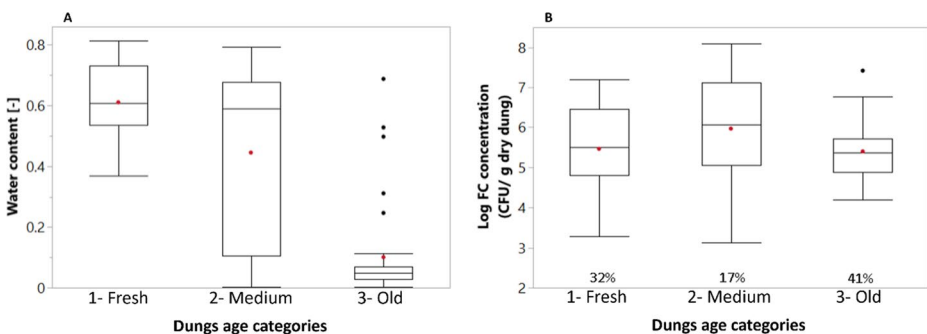


Fig. 5 Dung water content and log FC concentration vs. dung age categories (set by visual observation). Total sample size ($n=90$); red points – average values; Percentages indicate the proportion of samples that were below the detection threshold

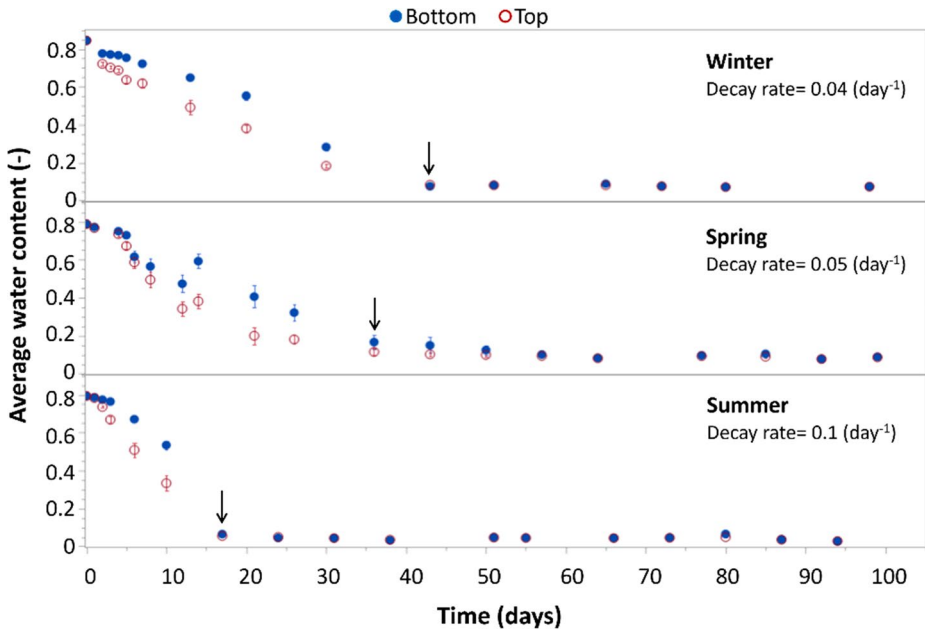


Fig. 6 Average water contents in cattle dung, over time under three temperature profiles in controlled environmental conditions. Blue solid circles - average water content inside the dung-pie; Red circles-average water content at the surface of the dung-pie ($n=8$ per time point; Error bars indicate \pm standard error). Arrows- minimum water content

The decay rate of water content, measured at the surface of the dung, was faster than inside the dung (bottom), which was less exposed to the ambient temperature variation. At the beginning of the experiment the water content at the surface and inside the dung-pie were identical, since the dung-pies were homogeneous, then the difference grew and gradually disappeared towards reaching the minimum water content (Fig. 6).

4.2.2 Fecal Coliforms

Initial FC concentrations in the fresh homogenized dung-pies was 10^6 – 10^8 CFU/g_{dry dung}. During the first week of the aging experiments, about one order of magnitude increase in FC was observed (for all examined seasons), for both surface and inside the dung-pies. This phenomenon confirms the field survey results, in which higher FC concentration was measured in dung-pies classified in age category 2 (~week) compared to dung classified in category 1 (fresh). About a week into the aging experiment the trend changed and a decline in the bacterial concentration was observed (Fig. 7).

Initial growth of 1–3 orders of magnitude in dung-pies bacteria counts, for up to 7 days, followed by a decrease, under different temperatures, has been well documented in the literature both under field and laboratory conditions (e.g.: Sinton et al. 2007; Van Kessel et al. 2007; Oladeinde et al. 2014). It is likely that the initial increase in bacteria concentrations is due to favorable conditions (water content, moisture, temperature, organic matter content, etc.) and/or to reduction of environmental stresses factors (i.e., change in oxygen level, lower levels of toxic compounds etc.; Crane and Moore 1986). A reduction in bacteria

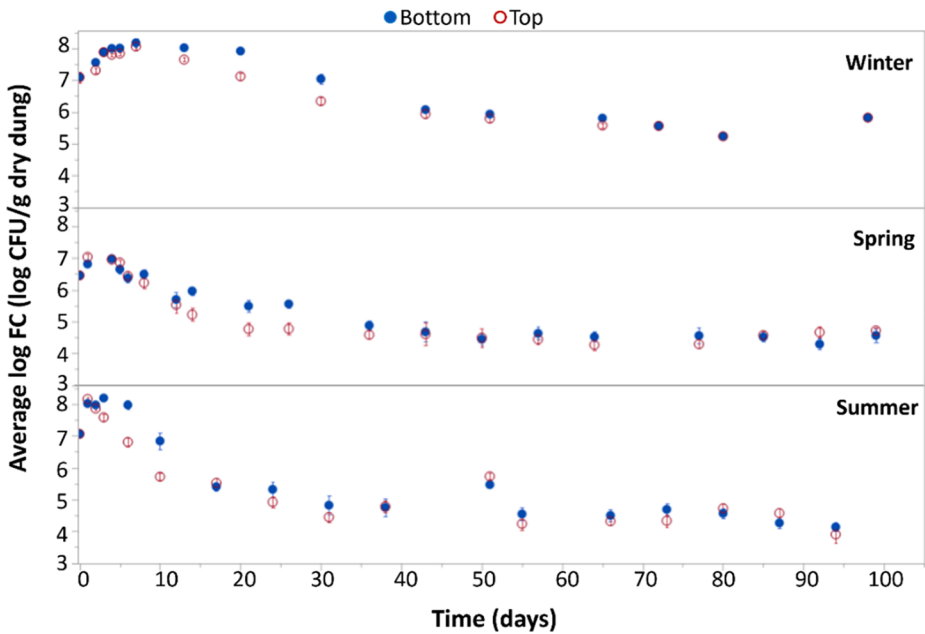


Fig. 7 Average log FC concentration in cattle dung-pies, over time, under three temperature profiles in controlled experimental conditions. Blue solid circles - average log FC concentration measured inside the dung; red circles - average log FC concentration measured at the surface of the dung ($n=8$ per time point; Error bars indicate \pm standard error)

concentration is noticed probably only after resources reduce and competition between the microorganisms intensifies.

Although FC concentration in the incubated dung-pies decreased, it remained substantial for at least 100 days after the onset of the experiment and maybe much longer, with average concentration of about 10^4 CFU/g_{dry dung}. Similarly, Bolton et al. (1999) reported a concentration of about 10^3 CFU/g_{dry dung} for cattle feces kept in the field for 99 days. Topalcengiz et al. (2020) showed concentration of about 10^4 CFU/g_{dry dung} a year after excretion, when the dung was kept at room temperature in the laboratory.

In the present study, temperature was considered the primary environmental driver of FC decay. This assumption is supported by a meta-analysis synthesizing results from 42 studies, which identified temperature as the dominant factor governing *E. coli* decline rates in manure-amended soils under field conditions (Tran et al. 2020; Cheong et al. 2024). Other field-related factors, including solar radiation, dung-soil interactions, in-soil predation by other microorganisms, the physiological status of the organisms and strain variability, organisms being washed away via precipitation as well as their growth and death and type of soil (Crane and Moore, 1986; Avery et al. 2004; Van Kessel et al. 2007; Alegbeleye and Sant'Ana 2020; Dean and Mitchell 2022; Devane et al. 2022), were not represented. While this simplification enhances model simplicity and applicability under data-limited conditions, it may influence prediction accuracy. Notably, many of these omitted processes are expected to accelerate FC decay under field conditions compared to controlled laboratory experiments. Therefore, the experimentally derived decay rates likely represent conservative estimates, and in-field FC persistence may be lower. Similar findings of higher

FC survival under laboratory conditions compared to field conditions have been reported in previous studies (e.g., Van Kessel et al. 2007).

In addition, FC concentration was found to be linearly correlated with the water content ($R^2 > 0.75$, $p < 0.0001$; Figure SM2).

4.3 Fate of Fecal Coliforms in Dung-pies over Time

Growth and decay rates were estimated by the parameterized non-linear biexponential model (Eq. 3; Table 2). Although uncertainty in parameter estimation may affect the exact predicted FC concentrations, the model was mainly applied to compare management scenarios. Hence, the comparative trends are expected to be more robust than the absolute predicted values. The five-parameter biexponential equation exhibited a biphasic pattern with a period of faster decay followed by a period of slower decay. This model generates a decline after reaching a single maximum and describes population growth followed by a decline. During summer, population growth phase was extremely short, hence an exponential model (3 parameters) fitted the data better.

The environmental conditions (different temperature ranges) as well as the different diets which the cattle are fed during the year certainly affected the concentration and rate of decay of the bacteria. Exposure to temperature variation affected the survival of FC. However, regardless of the environmental conditions, the average FC concentrations at the surface of the dung-pies were lower than the concentrations inside of it, and FC decay rate at the surface was higher than inside the dung-pies. However, these differences were not statistically significant ($p > 0.05$).

4.4 Effects of Direct Deposition

According to Aharoni et al. (2009) a single beef cow excretes daily an average of 4 kg_{dry feces}. Using the measured initial FC concentration (Sect. 4.2.2), the daily FC load is: 6.6×10^{10} , 1.1×10^{10} , 4.6×10^{10} CFU/(cow×d) for winter, spring and summer (respectively).

Assuming that 1% of cattle feces are dropped daily directly into the streams (Sect. 1 above), the in-stream FC concentration can be calculated using the flowrate and number of grazing cows in the watershed. For example, the average flowrate at the Meshushim stream is ~ 0.75 m³/s (based on flowrates during 1983–2023, monitored by Israel Water Authority and Mekorot, Israel's National Water Company; Asheri et al. 2024). Assuming 100 grazing cows that have unrestricted access to the stream, FC concentration due to direct deposition, is estimated at ~ 100 cfu/100 ml during winter and somewhat lower during spring (Table 3). It should be noted that during winter the cows tend to spend less time near the stream (Vidon et al. 2008), but this factor was not considered.

Table 2 FC concentrations over time - Parameter estimates of the non-linear bi-exponential model (5 parameters)

Parameters / Values	Winter	Spring	Summer
Asymptote (a)	4.3	4.4	4.5
Scale 1 (b)	4.46	3.15	3.72
Decay rate 1 (c)	0.019	0.06	0.07
Scale 2 (d)	-1.70	-1.10	n.s*
Decay rate 2 (f)	0.287	1.02	n.s*
R ²	0.89	0.76	0.83

All parameters are statistically significant $p < 0.0001$

*n.s not significant $p > 0.05$

Table 3 Seasonal FC concentration predicted by direct deposition

	Winter	Spring	Summer	Assumptions
FC concentration (cfu/gr _{dry} dung)	1.7×10^7	2.9×10^6	1.2×10^7	Based on aging experiments (Fig. 7)
FC load (cfu/d×cow)	6.6×10^{10}	1.1×10^{10}	4.6×10^{10}	4 kg feces/cow × day
FC load (cfu/d×cow)	6.6×10^8	1.1×10^8	4.6×10^8	1% of feces deposit directly in streams
Herd FC load (cfu/d)	6.6×10^{10}	1.1×10^{10}	4.6×10^{10}	100 grazing cows
In-stream FC concentration (cfu/100 mL)	102	18	107	Flowrate at the Meshushim stream: Average: 0.75 m ³ /sec Summer: 0.5 m ³ /sec

During summer (literarily dry), the only mechanism by which cows contribute to the in-streams bacterial concentration is by direct excretion. Hence, considering summer the flowrate at the Meshushim stream (0.5 m³/s), the in-stream FC concentration is also ~100 cfu/100 ml (Table 3).

It should be noted that this approach does not consider stream internal FC contamination, that might be caused by antecedent direct defecation of cattle in the water. Previous studies indicate that FC often becomes incorporated into stream sediments after deposition into stream water and survive in the sediments for long periods (e.g.: O'Callaghan et al. 2019 and references therein). Therefore, stream sediments are recognized as potential FC reservoirs, acting not only as sinks but also as sources of fecal contamination when resuspension events occur (Nagels et al. 2002). Hence, the actual in-stream FC concentration may be higher.

In-stream FC, even at concentrations lower than the maximum allowed by the regulations, might emphasize a threat to human health, as it is an indicator for other pathogens. According to Israel Ministry of Health permitted-bathing water guidelines, the maximum threshold for fecal coliform concentrations in recreational waters is 400 cfu/100 ml. This risk is particularly relevant when pasture areas are close to recreational- tourist areas and there is direct contact between humans and the contaminated water.

4.5 Effect of Indirect Deposition

Rain event followed by surface runoff is the driving force of bacteria transport into the stream by the indirect pathway. Indirect FC load estimated at a certain area is affected by daily FC excreted by a single cow, the time that the cow spends at the basin and by bacteria growth and decay processes inside the dung-pies. These are influenced by various environmental factors such as temperature and rainfall and therefore are season dependent. In addition, grazing management policies, e.g. buffer zone and cattle exclusion durations, can shape the contamination wash-out.

4.5.1 Buffer zone- bacteria transport after long dry summer

Smolders et al. (2015) demonstrated that eliminating direct contact between cattle and watercourses, using physical barrier of livestock bridging, reduced in-stream pollution and prevented the occurrence of pathogenic microbial outbreaks. However, adopting solely the physical barrier policy did not ameliorate the potentially chronic pollution arising from diffuse sources by cattle as they graze across the surrounding catchment.

Three buffer zones between the watercourse and the grazing area were simulated in addition to no buffer scenario. For these scenarios, the accumulation of dung-pies under summer aging conditions was calculated by applying Eqs. 3, 4 and 5 for the summer season and yielded FC load of 1.05×10^{12} cfu/g_{dry dung} generated by one cow grazing unimpededly at the watershed area in the course of this grazing period (150 d). As aforementioned, dung distribution was uniform and unaffected by distance from the watercourse (Fig. 4), therefore we assumed identical bacteria load in each cell (i.e.: the total number of bacteria excreted into the environment during grazing period was divided by the number of cells). Larger buffer zone reduced the grazing area, yet the amount of dung spread over the grazing area remained the same (higher grazing pressures). Hence, FC loads in each cell were higher for larger buffer zones.

FC load washed-out into the stream from each cell was determined based on surface runoff generated by the rain events (Eq. 7) and the transport distance to the stream (Eq. 8). Four rain events volumes were simulated under two stream-proximity-coefficients representing a 50% decline in the number of bacteria transported 30 m, or 100 m, respectively (Eq. 8). Table 4. (upper part) presents the summary of bacteria estimated to be transported

Table 4 FC transport to the stream after 150 and 60 dry days under different rain events volumes and grazing management policies

Stream proximity coefficient (m ⁻¹)	Env. condition	Grazing management policies	FC survival rate (cfu/cow)			
			Rain event (mm/event)			
			25	50	75	100
0.023	First rain after 150 dry days under summer conditions	No buffer	6.5×10^9	8.6×10^{10}	2.2×10^{11}	2.3×10^{11}
		10 m buffer	5.5×10^9	7.2×10^{10}	1.8×10^{11}	1.9×10^{11}
		50 m buffer	2.3×10^9	3.0×10^{10}	7.6×10^{10}	8.0×10^{10}
		100 m buffer	9.8×10^8	1.3×10^{10}	3.3×10^{10}	3.5×10^{10}
0.007		No buffer	1.6×10^{10}	2.2×10^{11}	5.5×10^{11}	5.8×10^{11}
		10 m buffer	1.6×10^{10}	2.0×10^{11}	5.3×10^{11}	5.5×10^{11}
		50 m buffer	1.2×10^{10}	1.7×10^{11}	4.2×10^{11}	4.5×10^{11}
		100 m buffer	1.0×10^{10}	1.4×10^{11}	3.5×10^{11}	3.7×10^{11}
0.023	First rain after 60 dry days under spring conditions	No buffer/excl.	1.5×10^9	2.0×10^{10}	5.1×10^{10}	5.4×10^{10}
		50 m buffer	5.3×10^8	7.0×10^9	1.8×10^{10}	1.9×10^{10}
		1 week excl.	2.8×10^8	3.7×10^9	9.4×10^9	9.9×10^9
		2 weeks excl.	9.9×10^7	1.3×10^9	3.3×10^9	3.5×10^9
0.007		4 weeks excl.	3.2×10^7	4.2×10^8	1.1×10^9	1.1×10^9
		No buffer/excl.	3.8×10^9	5.0×10^{10}	1.3×10^{11}	1.4×10^{11}
		50 m buffer	2.9×10^9	3.9×10^{10}	9.9×10^{10}	1.1×10^{11}
		1 week excl.	6.9×10^8	9.2×10^9	2.4×10^{10}	2.5×10^{10}
		2 weeks excl.	2.5×10^8	3.3×10^9	8.3×10^9	8.8×10^9
		4 weeks excl.	7.8×10^7	1.1×10^9	2.7×10^9	2.8×10^9

from the whole watershed and reach the stream after being deposited by one cow over 150 dry grazing days.

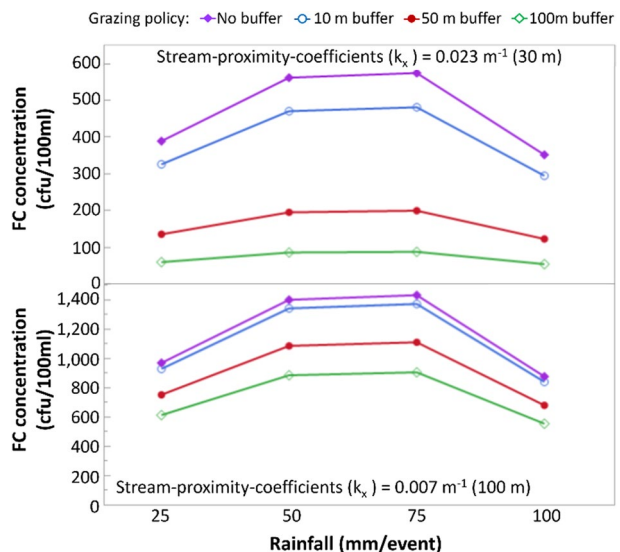
As expected, the results indicate that rain volume has a significant effect on bacteria transported to the watercourse, with higher volumes generating higher surface runoff which washes-out the dung-pies and detaches more bacteria. When rain intensity varied between 25 and 100 mm/event, the number of transported bacteria that reached the stream increased by up to two orders of magnitude for the same grazing management policy (Table 4., upper part). This result is in line with Nagels et al. (2002) who indicated positive correlation between FC concentrations in rivers and surface runoff, with the highest concentrations usually associated with flood events. Furthermore, using host-specific markers Wagner et al. (2021) identified fecal pollution at impaired waters and showed that concentration of cattle markers was higher at grazed sites and were correlated with stocking rate and runoff events.

Stream proximity coefficient (FC transportation decay factor), as expected, also had significant effect, with lower stream proximity coefficient results in higher FC load reaching the stream. The results obtained for $k_x = 0.007$ 1/m were 2–10 times higher than the ones received for $k_x = 0.023$ 1/m (Table 4., upper part).

Indirect FC load reaching the stream after 150 grazing days was at least two orders of magnitude higher than in-stream direct deposition of FC (Table 3), hence, in this case direct deposition is negligible.

In-stream FC concentration generated by grazing cattle was estimated by solving Eq. 9) assuming 100 grazing cows and a stream flowrate of 0.65 m³/s and under the 4 grazing management policies of buffer zone and the two values of stream proximity coefficients (Fig. 8). The surface runoff flowrate has a significant effect on the stream microbial water quality. Like the trend obtained for transported bacteria load, high runoff detaches higher number of bacteria, thus the in-stream FC concentration increases. A similar mechanism was described by Afolabi et al. (2022), who noted that rainfall events provide the energy required to physically disrupt fecal deposits and initiate bacterial mobilization. Moreover, rainfall characteristics such as intensity and volume have been identified as key determinants of microbial

Fig. 8 FC in the Meshushim stream due to transported FC originating from beef cattle dung as a function of rainfall volume and under different grazing management policies and stream proximity coefficients after 150 dry summer days. Two stream-proximity-coefficients (k_x) scenarios representing a 50% decline in the number of bacteria transported 30 m (upper figure), or 100 m (bottom figure). Note: different y-axes scale



water quality. However, very heavy rains produce opposite outcomes due to dilution of the transported bacteria, as shown in Fig. 8 for a 100 mm rain event.

Implementing buffer zones had a significant impact on FC concentration originating from cow dung washed to the stream. The difference in removal between the “no buffer” and all three buffer zones management policy was found to be 5–85%. Thus, buffer zones can potentially reduce human health risk. This result is consistent with a previous literature review that highlighted the effectiveness of riparian enclosure fencing in mitigating the negative impacts of cattle on water quality, particularly with respect to fecal indicator bacteria (Grudzinski et al. 2020). However, that review focused on temperate forest and temperate grassland streams, and the authors emphasized the need for further research in semi-arid regions. It is important to note that the optimum buffer width is specific to the case study (i.e.: type of pollutant, stream flow, typical surface runoff, soil type etc.). Large buffers, particularly when the adjacent land is cultivated, may not be economically viable, as the buffer itself is usually left unfarmed (Cole et al. 2020).

The buffer-zone scenarios simulated the first rain events after a long dry period that are likely to extract most bacteria from the watershed. Thus, following rain events would encounter a much lower dung stock in the watershed, exposing the remaining dung and new dung deposited after the previous event.

A comparison between the two transport pathways highlights their different temporal dynamics and magnitudes. Direct deposition represents a daily input to the stream, reaching approximately 6×10^8 CFU per cow per day (assuming 1% direct defecation). In contrast, indirect transport reflects cumulative bacterial buildup in dung deposited across the watershed during dry periods. During a 150-day dry summer period, FC accumulate across the watershed, reaching about 10^{12} CFU/cow in deposited dung. A single rainfall event can mobilize 10^9 – 10^{11} CFU/cow into the stream (Table 4.), depending on rainfall intensity and transport distance. Thus, the first-flush indirect load delivered during one runoff event may exceed the daily direct input by two to three orders of magnitude. Therefore, direct deposition governs background contamination during dry-flow periods, whereas indirect transport dominates peak contamination events following prolonged dry conditions.

This dominance of rainfall-driven indirect transport during peak rain events is consistent with previous laboratory-based findings describing microbial mobilisation as a hydrological continuum, in which bacteria are first detached from faecal deposits and subsequently conveyed to receiving waters during runoff events (Afolabi et al. 2022). This study emphasizes that rainfall acts as the primary trigger transforming accumulated microbial loads into episodic faecal contamination downstream.

4.5.2 Cattle Exclusion Duration - FC Transport during Spring Rains

The model was applied to evaluate the effect of cattle exclusion from the watershed, for different durations, before the beginning of the tourism season in the region. Removing the cattle from the watershed results in no new dung deposited, while in the existing dung-pies the number of FC available for transport to the stream decreases.

Four exclusion durations were simulated: no exclusion, exclusion of 1, 2 and 4 weeks before the tourism season. Similar to the buffer zones simulation, FC load was estimated by applying Eqs. 3, 4 and 5 considering dung accumulation for 60, 53, 46 and 32 dry days under spring aging conditions, i.e.: the cattle were excluded for 0, 7, 14 and 28 days respectively.

The ongoing grazing scenario (no buffer zone/no exclusion) yielded FC load of 2.45×10^{11} cfu/g_{dry dung} for a single cow grazing for 60 dry days during spring.

The aging experiment has shown that FC concentration increases during the first week and then declines, with ca. two orders of magnitude decline into the experiment (Fig. 7). Thus, the most significant period is the days just after dung dropping. Hence, based on the model scenarios cattle exclusion for 1, 2 and 4 weeks before arrival of travelers to the area, generated lower FC concentrations (4.5×10^{10} , 1.6×10^{10} and 5.1×10^9 cfu/g_{dry dung} respectively). Although the above results are theoretical, they are in line with observations reported by Wagner et al. (2012), who measured *E. coli* concentrations in grazed pastures and found that *E. coli* levels decreased by more than 88% when runoff occurred more than two weeks after grazing, compared with runoff that occurred during, or shortly after, grazing. Despite being conducted in a different region, these findings align well with the trend predicted by the model.

Bacteria load washed into the stream was calculated under uniform dungs distribution, for 25, 50, 70 and 100 mm rain events and using the two stream-proximity-coefficients. Like the buffer zones scenarios, high rain intensity and low stream-proximity-coefficient increased the number of bacteria washed to the stream (Table 4, lower part). Cattle exclusion significantly reduced FC load reaching the stream by surface runoff, with a reduction of up to two orders of magnitude between the no exclusion and the 4 weeks exclusion.

Cattle exclusion one week before the hiking season reduced FC concentration by 82% for both stream-proximity-coefficients (Fig. 9). Longer exclusions yielded higher reductions (over 90%). On the other hand, in the same environmental conditions, a buffer zone of 50 m led to a reduction of only 60% and 22% for stream-proximity-coefficients of 0.023 and 0.007 m^{-1} ; respectively.

To enable a comparison between these two mitigation strategies, their effectiveness was evaluated under identical rainfall and stream-proximity transport conditions. One-week cattle exclusion reduces the bacterial source by preventing fresh dung deposition and allowing die-off of recently deposited feces, whereas a buffer zone reduces transport efficiency without affecting the source strength. Under the modeled spring conditions, short-term exclusion resulted in comparable or greater FC load reduction than a 50 m buffer. However, the relative effectiveness of these measures depends on rainfall intensity, transport distance, and grazing pressure. These results suggest the benefits of excluding cattle from watershed, even for one week before the beginning of hiking season, rather than using buffer zones, and limiting the cattle from accessing the watercourses.

Various measures are available for removing cattle away from streams, including artificial shade, alternative water sources, and provision of additional food far from the stream. However, most studies reported little-, if any effect of water troughs on cattle distribution (Kaucner et al. 2013; Haan et al. 2010; Rawluk et al. 2014; Bagshaw et al. 2008). We are aware of only one study that tested the effects of artificial shade and food provision, in addition to water troughs, on cattle distribution (Dolev et al. 2010) who found that the combination of these three measures effectively removed cattle away from watercourses.

4.6 Sensitivity Analysis

To evaluate the robustness of the modelling results to key parameter assumptions, a one-at-a-time sensitivity analysis was conducted for major hydrological and transport parameters,

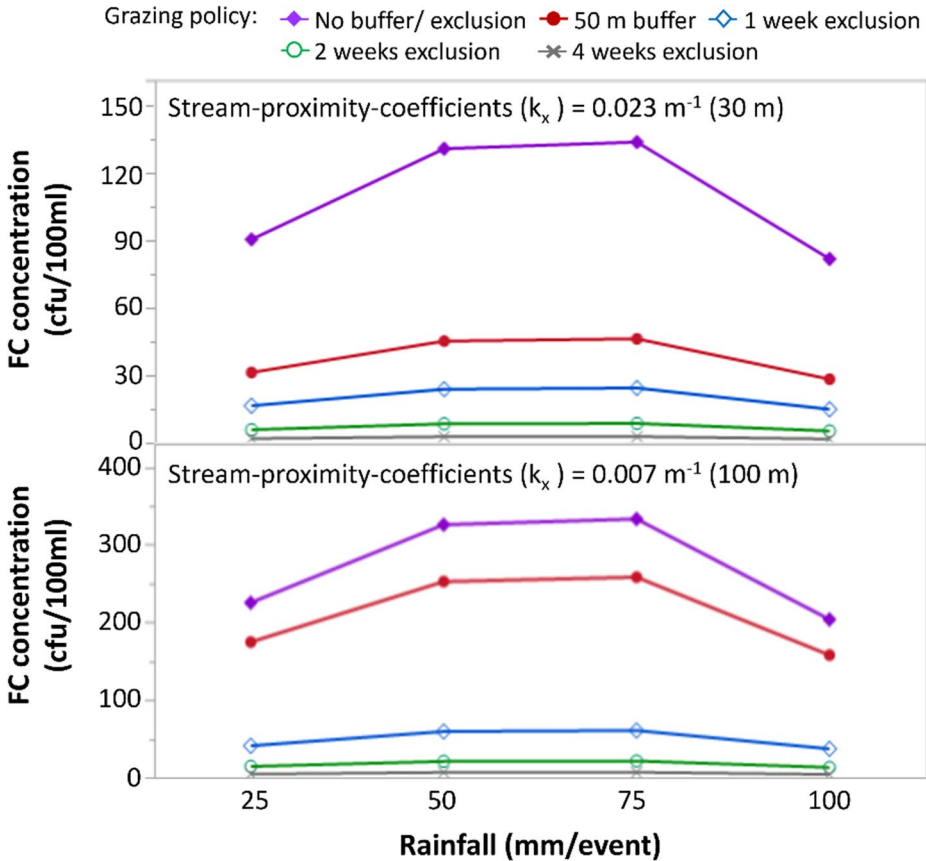


Fig. 9 FC in the Meshushim stream due to transported FC originating from cow dung as a function of rainfall volume and under different grazing management policies and stream proximity coefficients following sixty dry days during spring. Two stream-proximity-coefficients (k_x) scenarios representing a 50% decline in the number of bacteria transported 30 m (upper figure), or 100 m (bottom figure). Note – Different y-axes scales

including CN (65–85), R_{min} (10–50 mm), and k_x (corresponding to a 50% bacterial reduction over transport distances of 10–200 m).

The analysis showed that predicted absolute FC concentrations were most sensitive to runoff generation parameters, particularly CN . Variations in CN resulted in changes ranging from a decrease by a factor of up to 6.3 ($CN=65$) to an increase by a factor of 1.6 ($CN=85$) relative to the baseline scenario. Changes in k_x produced concentration variations between a decrease by a factor of 3.3 (transport distances of 10 m) and an increase by a factor of 1.6 (transport distances of 50 m). Adjustments in R_{min} resulted in concentration changes between a decrease by a factor of 2 ($R_{min}=50$ mm) and an increase by a factor of 2.5 ($R_{min}=10$ mm). Despite variation in absolute magnitudes, the relative ranking of management scenarios remained consistent across tested parameter ranges. These results indicate that while hydrological assumptions strongly influence predicted concentration magnitudes, the comparative conclusions regarding mitigation effectiveness are robust.

4.7 Model Scope, Innovation and Limitation

Compared to existing data-intensive watershed models that require extensive calibration and long-term monitoring records, the proposed framework provides a simplified, process-based alternative to grazing systems. While it does not explicitly simulate all hydrological pathways, its simplified structure enables application under limited data availability and enables comparison of management scenarios. This balance between process representation and practical applicability constitutes the primary innovation of the present study.

While the findings provide useful insight for management and decision-making, several modelling assumptions and data limitations should be acknowledged. The model was developed as a process-based scenario analysis tool and was parameterized using field measurements and literature data; however, full watershed-scale validation against long-term in-stream FC monitoring data has not yet been conducted. Independent watershed-scale validation was limited by the availability of monthly FC monitoring data without source attribution, preventing direct comparison between predicted cattle-derived loads and total observed in-stream concentrations. Therefore, the model should be interpreted as a comparative scenario framework rather than a fully calibrated predictive tool. Future event-scale monitoring and source-tracking analyses would enable more rigorous validation.

5 Conclusions

A novel approach for assessing the impact of grazing beef cattle on watercourses under diverse conditions is presented. The approach is based on field measurements and long-term laboratory experiments that were used for developing a predictive model. The field survey revealed uniform distribution of dung across plots, irrespective of distance from the watercourse. This finding may contrast common knowledge but is supported by other studies. Even studies that found greater cattle distribution near streams indicate that this was apparent only on hot days.

A simplified scenario-based model was developed using a limited set of site-specific parameters, enabling application to different watersheds with appropriate calibration. Sensitivity analysis indicates that model predictions are primarily governed by runoff-generation parameters (particularly CN), followed by bacteria transport distance (k_x), while R_{min} has a moderate influence. These findings emphasize the importance of accurate local hydrological characterization and support the need for site-specific calibration prior to model transfer.

The model, when applied to the Meshushim stream, indicates that for most of the year there are no abnormal cattle-borne FC concentrations in the watercourse. However, the model predicts that during heavy rain events after long dry periods, the in-stream FC concentrations will be orders of magnitude higher than the average ones. The model shows that these loads can be significantly reduced by applying an appropriate grazing management policy such as creating a buffer zone of 50 m between the watercourse and grazing areas or by keeping the cattle away from the streams for a limited time - at least during sensitive periods, i.e. heavy rain is expected after several weeks without significant rain and especially during the tourism period. Based on these scenario-based model results, the Israel Water Authority decided to consider and implement these management measures (Friedler et al. 2024). While the model is intended primarily as a comparative scenario framework

rather than a fully calibrated predictive tool, future event-scale monitoring and further field research are required to evaluate the effectiveness of these grazing management practices and would enable further validation and improvement.

The model results can support policy makers in evaluating and improving grazing management practices. Beyond the specific study area, the proposed framework is transferable to other watersheds, provided that local hydrological conditions are adequately characterized and calibrated.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s40710-026-00839-w>.

Acknowledgements The research was supported by Israel Water Authority.

Author contributions Conceptualization: F. T., Y. C., G. D. and E. F.; Data collection and Data Curation: Y. G., O. S., G. R., Y. C., G. D. and E. F.; Methodology: Y. G., Y. C., G. D. and E. F.; Writing – Review and Editing: Y. G., O. S., G. R., F. T., Y. C., G. D. and E. F.; Funding Acquisition: F. T., Y. C., G. D. and E. F.; Supervision: Y. G. and E. F. All authors have read and approved the final manuscript.

Funding Open access funding provided by Technion - Israel Institute of Technology. The research was supported by Israel Water Authority.

Data Availability The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Ethical approval Not applicable.

Competing interests The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- APHA/AWWA/WEF (2017) Standard methods for the examination of water and wastewater. 23rd Edition, American Public Health Association, American Water Works Association, Water Environment Federation
- Afolabi EO, Quilliam RS, Oliver DM (2022) Time since faecal deposition influences mobilisation of culturable *E. coli* and intestinal enterococci from deer, goose and dairy cow faeces. *PLoS One* 17:e0274138. <https://doi.org/10.1371/journal.pone.0274138>
- Agouridis CT, Workman SR, Warner RC, Jennings GD (2005) Livestock grazing management impacts on stream water quality: a review. *JAWRA J Am Water Resour Assoc* 41:591–606. <https://doi.org/10.1111/j.1752-1688.2005.tb03757.x>
- Aharoni Y, Henkin Z, Ezra A et al (2009) Grazing behavior and energy costs of activity: a comparison between two types of cattle1,2. *J Anim Sci* 87:2719–2731. <https://doi.org/10.2527/jas.2008-1505>

- Alegbeleye OO, Sant'Ana AS (2020) Manure-borne pathogens as an important source of water contamination: an update on the dynamics of pathogen survival/transport as well as practical risk mitigation strategies. *Int J Hyg Environ Health* 227:113524. <https://doi.org/10.1016/j.ijheh.2020.113524>
- Asheri T, Rom M, Berger D et al (2024) Lake Kinneret watershed Report. Mekorot, Israel's National Water Company. (in Hebrew)
- Avery SM, Moore A, Hutchison ML (2004) Fate of *Escherichia coli* originating from livestock faeces deposited directly onto pasture. *Lett Appl Microbiol* 38:355–359. <https://doi.org/10.1111/j.1472-765X.2004.01501.x>
- Bagshaw CS, Thorrold B, Davison M et al (2008) The influence of season and of providing a water trough on stream use by beef cattle grazing hill-country in New Zealand. *Appl Anim Behav Sci* 109:155–166. <https://doi.org/10.1016/j.applanim.2007.03.004>
- Bolton DJ, Byrne -C, Sheridan -JJ et al (1999) The-survival-characteristics-of-a-non-toxicogenic-strain-of-*Escherichia coli*-O157:H7. *J Appl Microbiol* 86:407–411. <https://doi.org/10.1046/j.1365-2672.1999.00677.x>
- Bond TA, Sear D, Edwards M (2012) Temperature-driven river utilisation and preferential defecation by cattle in an English chalk stream. *Livest Sci* 146:59–66. <https://doi.org/10.1016/j.livsci.2012.02.022>
- Bosznay M (1989) Generalization of SCS curve number method. *Journal of Irrigation and Drainage Engineering* 115:139–144. [https://doi.org/10.1061/\(ASCE\)0733-9437\(1989\)115:1\(139\)](https://doi.org/10.1061/(ASCE)0733-9437(1989)115:1(139))
- Cheong S, Chandler-Khayd C, Williams SR et al (2024) Evaluation of environmental risk factors associated with survival of generic *E. coli* in organic integrated crop-livestock systems in California and Minnesota. *Front Sustain Food Syst*. <https://doi.org/10.3389/fsufs.2024.1464018>
- Cho KH, Pachepsky YA, Oliver DM et al (2016) Modeling fate and transport of fecally-derived microorganisms at the watershed scale: state of the science and future opportunities. *Water Research* 100:38–56. <https://doi.org/10.1016/j.watres.2016.04.064>
- Cole LJ, Stockan J, Helliwell R (2020) Managing riparian buffer strips to optimise ecosystem services: a review. *Agriculture, Ecosystems & Environment* 296:106891. <https://doi.org/10.1016/j.agee.2020.106891>
- Collins R, Rutherford K (2004) Modelling bacterial water quality in streams draining pastoral land. *Water Research* 38:700–712. <https://doi.org/10.1016/j.watres.2003.10.045>
- Conroy E, Turner JN, Rymaszewicz A et al (2016) The impact of cattle access on ecological water quality in streams: examples from agricultural catchments within Ireland. *Science of The Total Environment* 547:17–29. <https://doi.org/10.1016/j.scitotenv.2015.12.120>
- Crane SR, Moore JA (1986) Modeling enteric bacterial die-off: a review. *Water Air Soil Pollut* 27:411–439. <https://doi.org/10.1007/BF00649422>
- Dean K, Mitchell J (2022) Identifying water quality and environmental factors that influence indicator and pathogen decay in natural surface waters. *Water Research* 211:118051. <https://doi.org/10.1016/j.watres.2022.118051>
- Devane M, Dupont P-Y, Robson B et al (2022) Mobilization of *Escherichia coli* and fecal source markers from decomposing cowpats. *Science of The Total Environment* 853:158509. <https://doi.org/10.1016/j.scitotenv.2022.158509>
- Dolev A, Carmel Y, Yehuda Y, Henkin Z (2010) Optimizing the location of water and feeding sites to decrease cattle contamination of natural streams. *Options Mediterr* 92:55–58
- FAO (Food and Agriculture Organization) (2023) Standard operating procedure for soil moisture content by gravimetric method
- Fidalgo JL, Ortiz Rodríguez IM, Wong WK (2011) Design issues for population growth models. *J Appl Stat* 38:501–512. <https://doi.org/10.1080/02664760903521419>
- Friedler E, Carmel Y, Gilboa Y et al (2024) Assessing the impacts of animals on streams microbial quality and ways to reduce them: Measuring and modeling fecal coliforms concentrations as an indicator of microbial contamination. Final report. Israel Water Authority. (in Hebrew)
- Ganskopp D (2001) Manipulating cattle distribution with salt and water in large arid-land pastures: A GPS/GIS assessment. *Appl Anim Behav Sci* 73:251–262. [https://doi.org/10.1016/S0168-1591\(01\)00148-4](https://doi.org/10.1016/S0168-1591(01)00148-4)
- Grudzinski B, Fritz K, Dods W (2020) Does riparian fencing protect stream water quality in cattle-grazed lands? *Environ Manage* 66:121–135. <https://doi.org/10.1007/s00267-020-01297-2>
- Haan MM, Russell JR, Davis JD, Morrical DG (2010) Grazing management and microclimate effects on cattle distribution relative to a cool season pasture stream. *Rangel Ecol Manage* 63:572–580. <https://doi.org/10.2111/REM-D-09-00045.1>
- Harmel RD, Karthikeyan R, Gentry T, Srinivasan R (2010) Effects of agricultural management, land use, and watershed scale on *E. coli* concentrations in runoff and streamflow. *Trans ASABE* 53:1822–1841
- Hassan-Vásquez JA, Maroto-Molina F, Guerrero-Ginel JE (2022) GPS tracking to monitor the spatiotemporal dynamics of cattle behavior and their relationship with feces distribution. *Animals Basel* 12:2383. <https://doi.org/10.3390/ani12182383>

- Islam MMM, Iqbal MS, D'Souza N, Islam M (2021) A review on present and future microbial surface water quality worldwide. *Environ Nanotechnol Monit Manag* 16:100523. <https://doi.org/10.1016/j.enmm.2021.100523>
- Jolicoeur P, Pontier J (1989) Population growth and decline: a four-parameter generalization of the logistic curve. *J Theor Biol* 141:563–571. [https://doi.org/10.1016/S0022-5193\(89\)80237-1](https://doi.org/10.1016/S0022-5193(89)80237-1)
- Kaucner CE, Whiffin V, Ray J et al (2013) Can off-river water and shade provision reduce cattle intrusion into drinking water catchment riparian zones? *Agric Water Manage* 130:69–78. <https://doi.org/10.1016/j.agwat.2013.08.012>
- King J, Ahmadian R, Falconer RA (2021) Hydro-epidemiological modelling of bacterial transport and decay in nearshore coastal waters. *Water Res* 196:117049. <https://doi.org/10.1016/j.watres.2021.117049>
- Nagels JW, Davies-Colley RJ, Donnison AM, Muirhead RW (2002) Faecal contamination over flood events in a pastoral agricultural stream in New Zealand. *Water Sci Technol* 45:45–52
- Naloufi M, Lucas FS, Souihi S et al (2021) Evaluating the performance of machine learning approaches to predict the microbial quality of surface waters and to optimize the sampling effort. *Water Basel* 13:2457. <https://doi.org/10.3390/w13182457>
- O'Callaghan P, Kelly-Quinn M, Jennings E et al (2019) The environmental impact of cattle access to water-courses: a review. *J Environ Qual* 48:340–351. <https://doi.org/10.2134/jeq2018.04.0167>
- Oladeinde A, Bohrmann T, Wong K et al (2014) Decay of fecal indicator bacterial populations and bovine-associated source-tracking markers in freshly deposited cow pats. *Appl Environ Microbiol* 80:110–118. <https://doi.org/10.1128/AEM.02203-13>
- Parsons CT, Momont PA, Delcurto T (2003) Cattle distribution patterns and vegetation use in mountain riparian areas. *J Range Manage* 56:334–341
- Paruch L, Paruch AM (2022) An overview of microbial source tracking using host-specific genetic markers to identify origins of fecal contamination in different water environments. *Water Basel* 14:1809. <https://doi.org/10.3390/w14111809>
- Rawluk AA, Crow G, Legesse G et al (2014) Off-stream watering systems and partial barriers as a strategy to maximize cattle production and minimize time spent in the riparian area. *Animals Basel* 4:670–692. <https://doi.org/10.3390/ani4040670>
- Schwarte KA, Russell JR, Kovar JL et al (2011) Grazing management effects on sediment, phosphorus, and pathogen loading of streams in cool-season grass pastures. *J Environ Qual* 40:1303–1313. <https://doi.org/10.2134/jeq2010.0524>
- Shakya SK, Rawat NS, Mishra AK et al (2022) Livestock waste management practices to strengthen the farm profitability. *J Entomol Zool Stud* 10:321–326. <https://doi.org/10.22271/j.ento.2022.v10.i5d.9075>
- Shine AE, Mamo M, Abagandura GO et al (2025) Unmanned aerial vehicle-based remote sensing of cattle dung: detection, classification, and spatial analysis of distribution. *Rangeland Ecol Manage* 98:192–203. <https://doi.org/10.1016/j.rama.2024.06.002>
- Sinton LW, Braithwaite RR, Hall CH, Mackenzie ML (2007) Survival of indicator and pathogenic bacteria in bovine feces on pasture. *Appl Environ Microbiol* 73:7917–7925. <https://doi.org/10.1128/AEM.01620-07>
- Smolders A, Rolls RJ, Ryder D et al (2015) Cattle-derived microbial input to source water catchments: an experimental assessment of stream crossing modification. *J Environ Manage* 156:143–149. <https://doi.org/10.1016/j.jenvman.2015.03.052>
- Tiedemann AR, Higgins DA, Quigley TM et al (1987) Responses of fecal coliform in streamwater to four grazing strategies. *J Range Manage* 40:322. <https://doi.org/10.2307/3898729>
- Topalcengiz Z, Jearnsriping S, Spaninger PM et al (2020) Survival of Shiga toxin-producing *Escherichia coli* in various wild animal feces that may contaminate produce. *J Food Prot* 83:1420–1429. <https://doi.org/10.4315/JFP-20-046>
- Tran DTQ, Bradbury MI, Ogtrop FFV et al (2020) Environmental drivers for persistence of *Escherichia coli* and *Salmonella* in manure-amended soils: A meta-analysis. *J Food Prot* 83:1268–1277. <https://doi.org/10.4315/0362-028X.JFP-19-460>
- USEPA (2014) Clean Water Act Sect. 303(d): Impaired Waters and Total Maximum Daily Loads (TMDLs). <https://www.epa.gov/tmdl>
- Van Kessel JS, Pachepsky YA, Shelton DR, Karns JS (2007) Survival of *Escherichia coli* in cowpats in pasture and in laboratory conditions. *J Appl Microbiol* 103:1122–1127. <https://doi.org/10.1111/j.1365-2672.2007.03347.x>
- Vidon P, Campbell MA, Gray M (2008) Unrestricted cattle access to streams and water quality in till landscape of the Midwest. *Agric Water Manage* 95:322–330. <https://doi.org/10.1016/j.agwat.2007.10.017>
- Wagner KL, Redmon LA, Gentry TJ, Harmel RD (2012) Assessment of cattle grazing effects on *E. coli* runoff. *Trans ASABE* 55:2111–2122
- Wagner KL, Gentry TJ, Harmel RD et al (2021) Grazing effects on bovine-associated and background fecal indicator bacteria levels in edge-of-field runoff. *Water* 13:928. <https://doi.org/10.3390/w13070928>

- Weiskerger CJ, Phanikumar MS (2020) Numerical modeling of microbial fate and transport in natural waters: review and implications for normal and extreme storm events. *Water* 12:1876. <https://doi.org/10.3390/w12071876>
- White SL, Sheffield RE, Washburn SP et al (2001) Spatial and time distribution of dairy cattle excreta in an intensive pasture system. *J Environ Qual* 30:2180–2187
- Wilcock RJ (2006) Assessing the relative importance of faecal pollution sources in rural catchments. Technical report no. TR 2006/41. Environment Waikato, Hamilton, New Zealand. 30p
- Yoshitoshi R, Watanabe N, Lim J (2020) Spatial distribution of grazing sites and dung of beef cows in a sloping pasture. *Japan Agric Res Q* 54:299–306
- Young C-C, Liu W-C, Liu H-M (2023) Uncertainty assessment for three-dimensional hydrodynamic and fecal coliform modeling in the Danshuei River estuarine system: The influence of first-order parametric decay reaction. *Mar Pollut Bull* 193:115220. <https://doi.org/10.1016/j.marpolbul.2023.115220>
- Zohary T, Sukenik A, Berman T, Nishri A (2014) *Lake Kinneret: Ecology and Management*. Springer

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Authors and Affiliations

Yael Gilboa¹ · Ofer Snir¹ · Gal Rozenberg¹ · Firas Talhami² · Yohay Carmel¹ · Guy Dovrat³ · Eran Friedler¹

✉ Yael Gilboa
ygilboa@technion.ac.il

¹ Faculty of Civil and Environmental Eng, Technion – Israel Institute of Technology, Haifa 32000, Israel

² Water Authority of Israel, POB 623, Zahar Industrial Area, Rosh Pina 12000, Israel

³ Department of Natural Resources, Neve-Ya'ar Research Center, Agricultural Research Organization – Volcani Institute, Ramat-Yishay, Israel