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Water consumption and wastage behaviour in pigs: implications for antimicrobial administration and stewardship

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A B S T R A C T

Daily water use and wastage patterns of pigs have major effects on the efficacy of in-water antimicrobial dosing events when conducted for metaphylaxis or to treat clinical disease. However, daily water use and wastage patterns of pigs are not routinely quantified on farms and are not well understood. We conducted a prospective, observational 27-day study of the daily water use and wastage patterns of a pen group of 15 finisher pigs reared in a farm building. We found that the group of pigs wasted a median of 36.5% of the water used per day. We developed models of the patterns of water used and wasted by pigs over each 24-h period using a Bayesian statistical method with the brm() function in the brms package. Both patterns were uni-modal, peaking at 1400–1700, and closely aligned. Wastage was slightly greater during hours of higher water use. We have shown that it is feasible to quantify the water use and wastage patterns of pigs in farm buildings using a system that records and aggregates data, and analyses them using hierarchical generalised additive models. This system could support more efficacious in-water antimicrobial dosing on farms, and better antimicrobial stewardship, by helping to reduce the quantities of antimicrobials used and disseminated into the environment.

Implications

Many pig farms that administer antimicrobials to growing pigs to control and treat bacterial diseases use piped drinking water systems in farm buildings. Water wastage by pigs can be a confounding factor when in-water dosing. This study showed that a water metering system could be used to quantify the water consumption and wastage behaviour of groups of pigs. With this knowledge, pig veterinarians and farm managers could better manage in-water dosing events, reducing the quantities of antimicrobials used and disseminated into the environment. The system could also be used to identify and implement water-saving strategies on farms.

Introduction

Pigs must maintain a balance between bodily water inputs and outputs from day-to-day. Most (>75%) of a pig's total daily bodily water input is water consumed by drinking, with smaller quantities from water present in feed and from water formed during protein and fat synthesis and oxidation of feed nutrients (Brooks and Carpenter, 1990). Intensively reared pigs access water ad libitum from drinking appliances (drinkers) within their pen in farm buildings. In buildings accommodating weaner pigs, pens are most commonly fitted with bowls or troughs, while in buildings accommodating grower/finisher pigs, pens are most commonly fitted with bite or nipple drinkers. Pigs might also be able to access water from wet/dry feeders if they are installed. The daily voluntary water use (consumption and wastage) of growing pigs has been measured at between 60 and 117 ml/kg BW with various combinations of drinker types, heights and water flow rates (Little et al., 2019). Water may spill while a pig is drinking or when a pig is playing with a drinker or otherwise releases water from the drinker without consuming it. Water may also leak from a drinker when it is not being used by pigs. Many of the published research studies conducted over the past three decades on water use and drinking behaviour in pigs have not measured the proportion of water that is wasted rather than consumed by pigs, and have often used the terms 'water usage', 'water disappearance' and 'water consumption' interchangeably. The few studies that have measured or estimated water wastage have reported wastage rates ranging from 9 to 60% of the water used per day under different conditions (Li et al., 2005; Meiszberg et al., 2009; Wang et al.,

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2017). (An annotated bibliography of eleven studies is provided in Supplementary Table S1).

Water use of pigs over each 24-h period follows a circadian rhythm, as do many behavioural patterns and physiological/metabolic variations in mammals. This rhythmicity is controlled by the suprachiasmatic nucleus located in the hypothalamus (Li et al., 2021). Pigs mostly drink during daylight hours and their pattern of use is uni-modal or bi-modal, with a peak in the afternoon and a possible secondary peak in the morning (Turner et al., 2000; Brumm, 2006; Misra et al., 2021). This pattern of water use occurs even when pigs are subjected to changes in their environment, such as continuous lighting. Pigs are prandial drinkers, with most of their drinking bouts occurring within 1–2 hours of meals (Bigelow and Houpt, 1988). Pigs drink in frequent bouts (19 to 87 bouts per day), each of which tends to be very small in volume (e.g. 42 ml) and duration (less than 30 seconds) (Andersen et al., 2014).

On many pig farms, antimicrobials are administered to growing pigs for short periods through the water distribution system (**WDS**) in each building for metaphylaxis and, when necessary, to treat clinical disease (Edwards, 2018; Lekagul et al., 2019; Little et al., 2019; O'Niell et al., 2020; Davies and Singer, 2020). Prior to every dosing event, the quantity of antimicrobial required to be administered to a group of pigs to ensure the target dose (mass/weight) is consumed can be calculated using the equation:

$$Da = Dt + \frac{Dt * W}{1 - W}$$

where *Da* is the antimicrobial dose to be administered (mg/kg BW), *Dt* is the target dose to be consumed (mg/kg BW) and *W* is the proportion of water used that will be wasted.

The accuracy of the value for *W* entered in this equation is a powerful lever when dosing, as it sets the level of the entire distribution of systemic exposures to the antimicrobial in the group of pigs relative to the target dose. If the value used for *W* is an over-estimate, then the volume of water that pigs actually consume (1 – *W*) is greater than predicted, and when the group of pigs is dosed, its entire distribution of systemic exposures to the antimicrobial will be shifted higher relative to the target dose, and many pigs will be over-dosed. This is unlikely to confer any additional benefit to most pigs and results in more antimicrobial being used than necessary, at greater cost and greater risk of adverse consequences. Conversely, if the value used for *W* is an under-estimate, (1 – *W*) is less than predicted and the entire distribution of systemic exposures to the antimicrobial will be shifted lower relative to the target dose, and many pigs will be under-dosed. These pigs do not reach the level of systemic exposure to the antimicrobial required to achieve high clinical efficacy, and the risk of selection for and propagation of resistant bacterial pathogens is increased (Lees et al., 2015).

Prior to every dosing event, a dosing commencement time and duration must also be selected by the veterinarian and farm manager. The alignment of the dosing event with the water use and wastage patterns of the pigs within the 24-h period affects the quantity of antimicrobial consumed per hour by pigs from drinkers located throughout the building, and therefore their systemic exposure to the antimicrobial. This is because the building's WDS is driven by the pigs' water demand, so water velocities in each of the main pipe sections of the system vary from hour to hour, altering the patterns of the concentration of the antimicrobial in water available to pigs at drinkers in each pen (Little et al., 2021a).

For veterinarians and farm managers responsible for practising in-water antimicrobial dosing, water wastage can be a confounding factor. If *W* is actually small (e.g. 0.05), then variability in *W* has to be large to have much practical effect on (1 – *W*). Conversely, if *W* is actually large (e.g. 0.65), then variability in *W* is more likely to have a significant effect. Veterinarians and farm managers are aware that a group of pigs may be over-dosed or under-dosed if the value for *W* that they factor into their dosing calculations is inaccurate, and they are also aware that *W* may differ between groups of pigs, even when they are reared in the same building, as it is influenced by many factors, including water flow rates and pressures at drinkers, the type, height and position of each drinker, climatic conditions, levels of competition between pigs, their disease status, the nutrient specifications of their diet, and water quality and palatability. However, veterinarians and farm managers lack systems that provide easily interpretable data for the water consumption and wastage behaviour of each group of pigs (Little et al., 2021b). Given this, and the wide range of wastage rates that has been reported (Supplementary Table S1), it is plausible, and even probable, that, on many occasions on farms when groups of growing pigs are administered antimicrobials and other additives through their drinking water, the estimate for *W* is higher or lower than the actual water wastage rate during dosing, resulting in significant over-dosing or under-dosing. Furthermore, as veterinarians and farm managers have no data on the patterns of water used and wasted over each 24-h period of each target group of pigs to guide their selection of the commencement time of dosing events, it varies widely between 0600 and 1200, as does the duration of dosing, from 4 to 24 hours (Little et al., 2021b). On many occasions, the dosing event may not be well coordinated with the group of pigs' patterns of water used and wasted over each 24-h period. It is also uncertain whether the pattern of water wasted from hour to hour is always well aligned with the pattern of water use or whether, in some circumstances, it diverges.

Our aim in this study was to measure and analyse the water use and wastage patterns of a group of pigs on daily and hourly time scales under farm conditions, with a focus on using these data to guide in-water antimicrobial dosing and improve pig health. This has the potential to increase the effectiveness of in-water antimicrobial dosing practices on farms and reduce the quantities (and cost) of antimicrobial administered, thereby improving antimicrobial stewardship.

Material and methods

We conducted a prospective, observational, cohort pen study in a grower/finisher building on a commercial pig farm in New South Wales, Australia over a period of 27 consecutive days. The study was conducted with the approval of the Rivalea Australia Animal Ethics Committee (authority no. 19B030, approved 12 August 2019 and amended 24 March 2020) and was performed in compliance with its stated requirements. Management of the animals in the study pen was identical to that of pigs in all other pens in the building, except that feed was accessed from a single-space automatic feeder instead of a conventional multi-space feed trough.

Animals, accommodation and facilities

The study was conducted in a naturally ventilated grower/finisher building with concrete floors, side curtains, and a central ridge vent and passage way, accommodating 1 184 female pigs and 2 335 immunologically castrated male pigs in 90 pens. Fifteen immunologically castrated male pigs weighing approximately 88 kg (based on a BW-for-age chart) were arbitrarily selected and placed in a study pen measuring 3.3 m wide by 5.98 m long (19.7 m^2). Approximately 39% of the pen's total floor area was solid concrete and 61% was concrete slats. The pen was equipped with two nipple drinkers positioned one metre apart along the east wall. Each nipple drinker was oriented horizontally, parallel to the fence, and had a stainless steel bowl beneath it to capture water spilled by the pigs. Each drinker had partitions extending 41 cm from the fence into the pen. One of these partitions was a solid material; the other was a metal mesh structure. The pen was also equipped with a Nedap* Prosense single-space automatic feeding station occupying 0.92 m^2 of the pen area, located in the north-east corner of the pen (Fig. 1).

The water source provided to pigs in the building was surface water, pumped from a river and stored in a farm dam. A water sample was collected aseptically from the first drinker during the study for chemical and microbiological analysis at a commercial environmental testing laboratory and found to be well within acceptable standards for all chemical parameters tested (Edwards and Crabb, 2021) (Water quality analysis report is provided in Supplementary Table S2). Pigs were fed ad libitum with a pelleted ration, formulated to meet the nutritional requirements of finisher pigs as specified by the National Research Council (2012).

Water and feed metering systems

A turbine flowmeter with a Hall effect pulse generator (Vision 1005 2F66, 1/4″ connection, Badger Meter Europa GmbH, Neuffen, Germany) was fitted to the water line supplying the two drinkers. The flowmeter had a measurement range of 0.1–2.5 L/min, a K-factor of 22 000 pulses/L, and an accuracy of ±3%. A tipping bucket water gauge with a 40 ml measuring bucket and a dual output reed switch (HyQuest Solutions TB6/40) was positioned on the external side of the east wall of the pen, directly behind each of the two drinkers. A pipe from the bottom of the bowl below the nipple drinker directed spilled water above the tipping bucket (Fig. 2). The water gauges were designed to measure a maximum water flow rate of 3 L/min, well in excess of the flow rate from each drinker (1.25 L/min). Measurement of water wasted in 40 ml increments was adequate for the purpose of calculating water wastage on an hourly timescale. The tipping bucket water gauges were used in preference to a turbine flowmeter, as water spilled by pigs at drinkers was likely to be contaminated with feed particles from their mouths and saliva, which could interfere with the function of the rotor in a turbine flowmeter.

The system recorded a timestamp with water in-flow in pulses/min from the turbine flowmeter and out-flow in the number of tips/min from each tipping bucket water gauge. These data were stored locally and periodically uploaded to a remote data server as a.csv file for processing. In-flow (ml/min) was calculated by dividing the number of pulses/min recorded by the turbine flowmeter by 22 000. Out-flow (ml/min) at each tipping bucket was calculated by multiplying the number of tips/min by 40. The single-space automatic feeding station contained an RFID reader, feed trough and weighing platform. Each time a pig entered the feeder, it was identified by its RFID ear tag, and its BW, feeding duration and feed intake were recorded. Data were transmitted in real time to Nedap's proprietary data management system, Nedap Velos. After an adaption period of 14 days, the water input and output from the two drinkers and feed consumption from the automatic feeding station were recorded over a period of 27 days. At the completion of the study, the mean BW of the pigs was approximately 109 kg.

Data aggregation and analysis

Water used for each hour of each day was calculated as the sum of water used for each minute of that hour. Data on water wasted for each of the two tipping bucket water gauges were combined, and total volumes tipped for the pen were calculated for each time period. Where tips occurred in consecutive minutes, total volume tipped in the pen was calculated for these minutes combined. For each time period with tips, total water usage since the previous tip was calculated and the proportion of that water that was wasted was calculated. Water wasted in each minute of the day was then calculated, assuming the proportion wasted was constant since the previous tip. Water wasted for each hour of each day was then calculated as the sum of water wasted for each minute of that hour. Water consumed in each hour of each day was then calculated as water used less water wasted in that hour. All feed dispensed by the feeding station was assumed to have been consumed by pigs. Feed consumed for the pen group was recorded for each time period when feed was dispensed, with the feeding period start time (hour and minute of day) and duration of feeding in seconds recorded. Feed used in each hour of the day was estimated from these data. The rate of feed consumption (g/sec) was assumed to be constant throughout each feeding period. Temperature and humidity data, and times of sunrise and sunset on each day of the study, were obtained from a weather station 7 km from the farm (Australian Government Bureau of Meteorology, 2021).

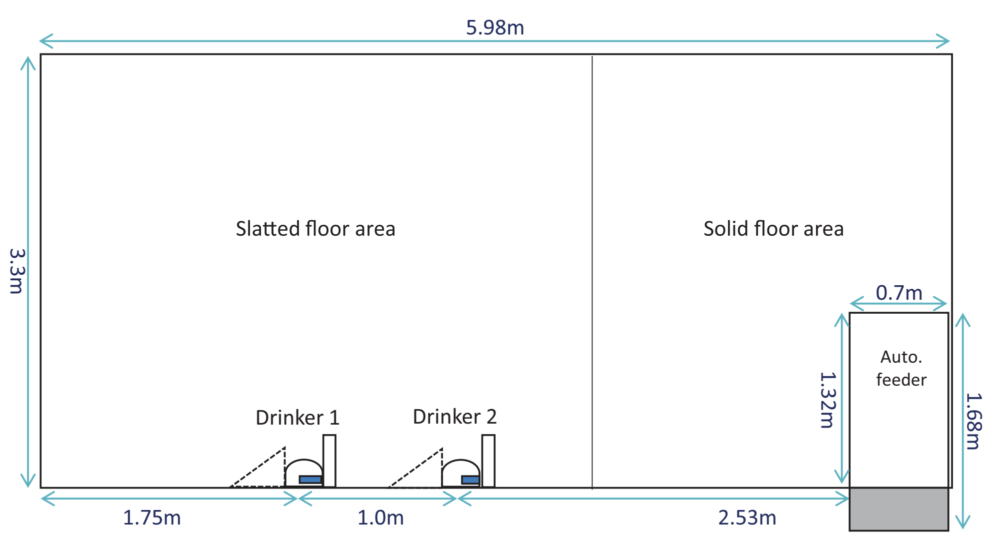

Fig. 1. Layout of study pen accommodating the group of 15 pigs, showing the dimensions and positions of the drinkers and feeder*. *Nedap Livestock Management, Parallelweg 2, 7141 DC Groenlo, The Netherlands.

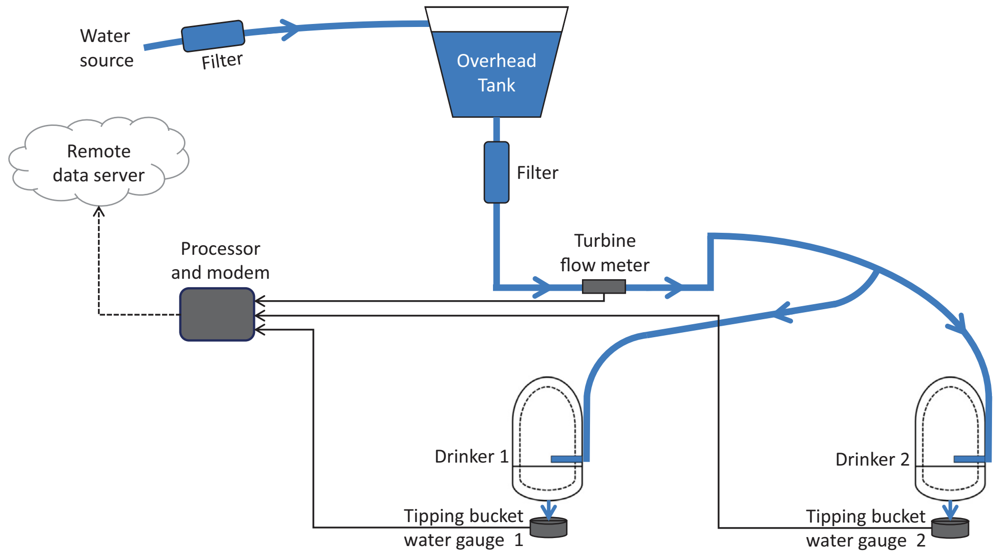

Fig. 2. Water metering system used in the study pen to measure the water consumption and wastage behaviour of the group of 15 pigs.

Data on the daily water use and wastage of pigs and their association with feed consumption were subjected to statistical analysis in R and visualised using ggplot2 in R. Models for pigs' water use and wastage patterns over each 24-h period were estimated using the software package brms (Bürkner, 2017), which provides an interface to fit Bayesian generalised (non-) linear multivariate multilevel models in R using the probabilistic programming language Stan (Chatzilena et al., 2019). We opted to use a Bayesian inference method, as used in some previous studies of pig water use patterns (Madsen and Kristensen, 2005; Jensen et al., 2017; Dominiak et al., 2019a), rather than a frequentist method, as it offered several advantages. These included a hierarchical structure that offered great flexibility, with the ability to readily use datasets of varying sizes and to specify and analyse complex hierarchical models, and a more coherent expression of uncertainty. As it was a hierarchical generalised additive model (**HGAM**) (Pedersen et al., 2019), brms assumed that the water usage and wastage of pigs in a given hour were dependent on their water usage and wastage in previous hours, and identified changes in patterns of water used and wasted within each 24-h period over 27 successive days as pigs gained weight. The HGAM enabled the relationships between the explanatory variable (hour of day) and the response variables (water used and wasted) to be described as smooth curves ("smoothers"). For water usage per kg pig BW per hour, we generated a single common smoother plus group-level smoothers (each of the 27 days of the study) for all observations. Each group-specific smoother had its own smoothing parameter and therefore its own wiggliness (Pedersen et al., 2019). The same approach was also used for water wastage per kg pig BW per hour.

The model is characterised by the general equation:

$$\log_e(y) \sim f(Time) + f(Time, Day) + \gamma_{Day}$$

A gamma HGAM with a log link was selected for the response. The model was implemented for two response variables (y), these being water usage and water wastage. The two functional terms in the equation represent thin plate regression splines. γ_{Day} is the day-level intercept, representing inter-day variability. Observations of unobservable low value were defined as left-censored, with an arbitrarily nominated left-censoring limit of 1 millilitre per pig per hour. This was implemented to ensure that observations of unobservable low value were retained in the model (Canales et al., 2018). The effective sample sizes were evaluated and increased as necessary and the 'adapt_delta' argument was altered to ensure that divergent transitions did not occur in the results. For each model run with brms, for each smooth term, group and population-level effects, chain convergence was assessed with the Rhat statistic and a value of 1.00 was achieved, indicating that the chains had converged to a common distribution (Vehtari et al., 2021). The final version of the code used to fit the models with brms in R is provided in Supplementary Material S1.

In-water antimicrobial dosing events (days 8 and 9)

Periodic, metaphylactic in-water dosing events were routinely conducted in the building. Two of these events coincided with days 8 and 9 of the study. All pigs (including those in the study pen) were administered an antimicrobial, lincomycin, by the farm manager according to the consulting veterinarian's prescription, applying dosing practices routinely used on the farm. On each day, dosing commenced at approximately 0700 and ceased at 1500 (8 h duration). A value for water wastage of 45% was factored into the dosing calculations performed prior to the dosing event, as was done routinely for all grower/finisher buildings on the farm fitted with nipple drinkers. To achieve the prescribed target dose of 8 mg/kg BW of active lincomycin, an antimicrobial dose of 14.55 mg/kg BW was therefore administered, assuming that 6.55 mg/kg BW (45%) would be wasted.

All components of the water metering system installed in the pen for this study functioned reliably for the study period, without any interruption to data flow. Particulates in the dam water supplying the pig building were prevented from disrupting the rotor within the turbine flowmeter by two screen filters installed in the water line, before the water holding tank and between the water holding tank and the turbine flowmeter (Fig. 2). The model of turbine flowmeter selected for the study proved to be capable of measuring short flows at very low flow rates so that all volumes of water drawn by pigs when interacting with the two drinkers in the pen were recorded. The tipping bucket water gauges remained in position under the spout of the pipe draining water from the bowl beneath each drinker, ensuring that nearly all volumes of water wasted were recorded. Feed particles and saliva present in water collected by the tipping bucket flow gauges did not disrupt their function.

Results

Daily pig water usage and wastage and association with daily feed consumption

Water usage per pig per day increased slightly over the study period, as was expected as the pigs gained weight. The water used per kg BW per day was steady over the study period (median, 84.7 ml; interquartile range, 10.9; range, 49.4–123 ml/kg) (Fig. 3a). Water wasted per kg BW per day was also steady (median, 29.3 ml; interquartile range, 5.3; range, 15–41.1 ml/kg). The proportion of water used by pigs daily that was wasted (median, 36.5%) was moderate compared to those reported in previous studies (Supplementary Table S1) and quite stable from day-to-day (interquartile range, 3.5%) (Fig. 3b).

The proportion of the total daily water usage of pigs that occurred during daylight hours (i.e. between sunrise and sunset) was greater (median, 72.8%; interquartile range, 7.2%; range, 66.2–91.3%) than that of feed consumption (median, 60.7%; interquartile range, 8%; range, 35.5–67.6%) (Fig. 4a). While feed consumption per pig per day trended upward slightly over the study period as the pigs gained weight, median feed consumption per kilogram BW was more steady (median, 24.8 g; interquartile range, 5.9; range, 14.5–31.5 g/kg). The water used:feed ratio (median, 3.5; interquartile range, 0.5; range, 2.8–6.4) and water consumed:feed ratio (median, 2.3; interquartile range, 0.4; range, 1.8–4.1) were also similar to those reported in a previous study (Bigelow and Houpt, 1988) and were very consistent from day-to-day (Fig. 4b).

Aberrations in water use by the pigs were seen in association with malfunction of the automatic feeder on days 11–13 and 20–21 of the study (Fig. 3a). At 0648 on day 11, the feeder became totally inoperative for a period of 51 h 6 min until it was repaired and returned to normal operation on day 13. During this period, pigs were fed manually 3 kg of the pelleted ration per pig on the floor at 0730 each day. On days 11 and 12, a reduction in the volume of water used by the pigs was observed. On day 13, following manual feeding of pigs at 0730, the feeder returned to normal operation at 0954. Pigs' feed consumption on day 13 was therefore greater than normal and corresponded with the highest daily water usage measured during the study. Restriction in the quantity of feed available to pigs occurred again on day 20 due to malfunc-

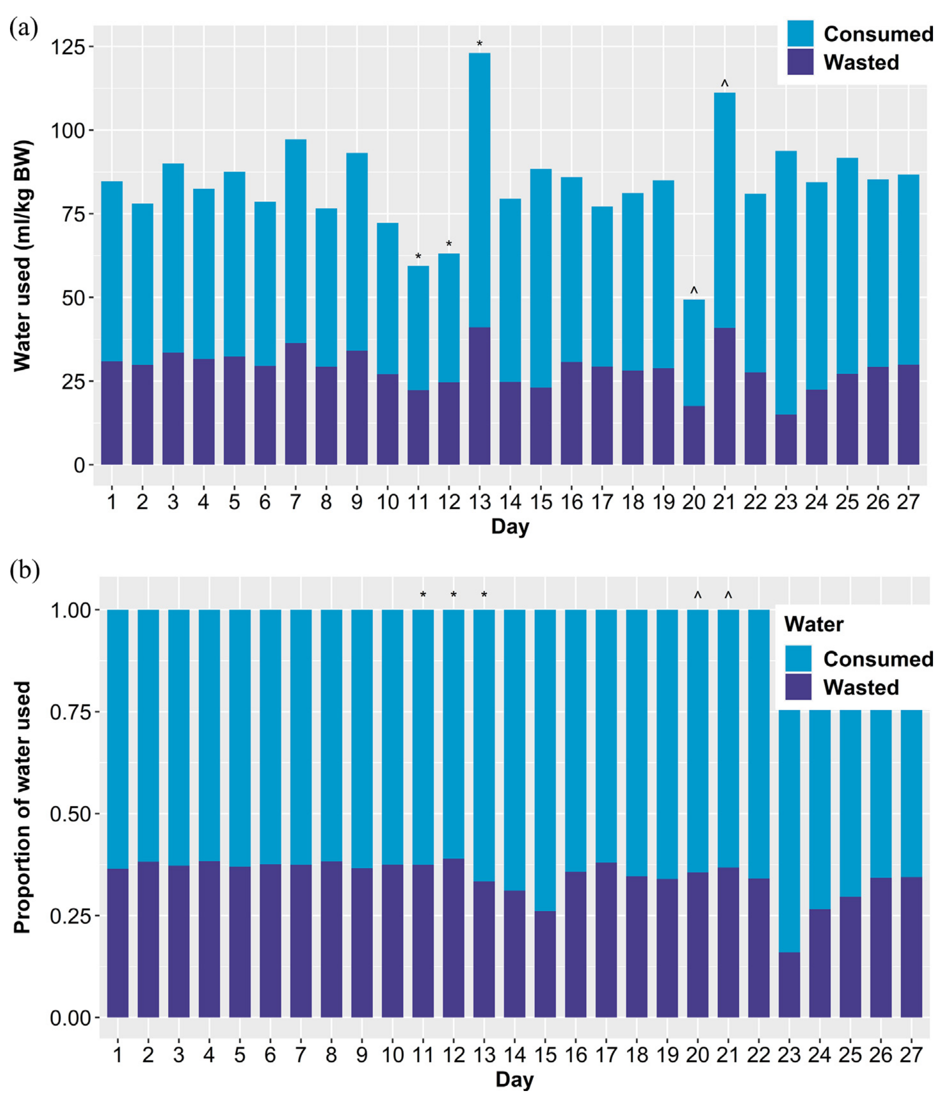

Fig. 3. (a) Water wasted and consumed by the pen group of 15 pigs per day of the 27-day study period (ml/kg BW); (b) Proportions of water used by the pen group of 15 pigs per day of the 27-day study period that were wasted and consumed. *Feeder malfunction on days 11–13. ^Feeder malfunction on days 20–21.

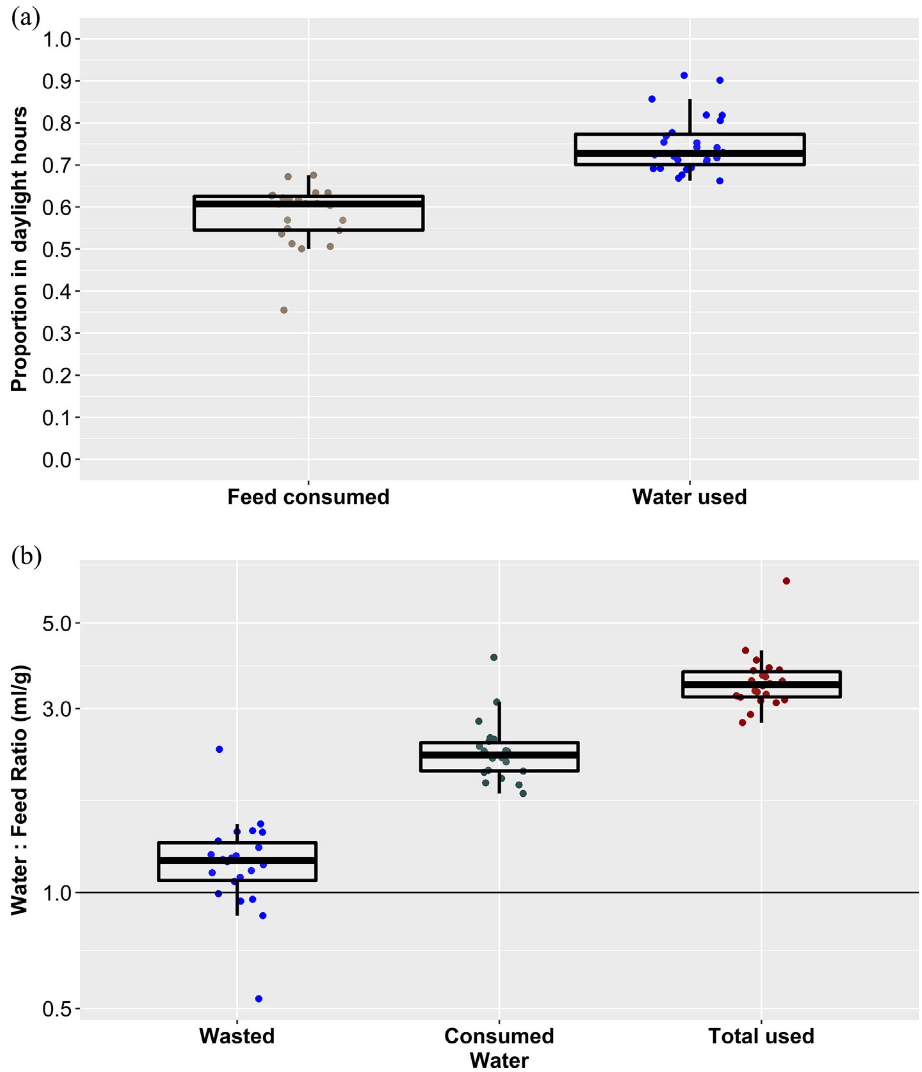

Fig. 4. (a) Proportions of water used and feed consumed by the pen group of 15 pigs per day over the 27-day study period during daylight hours#; (b) Water:feed ratios, based on water wasted, water consumed and total water used (sum of water consumed and water wasted) by the pen group of 15 pigs per day over the 27-day study period (ml/g). Days 11–13 and 20–21 were excluded from analysis as the feeder malfunctioned on these days, so accurate feed consumption data were not available. #based on sunrise and sunset times for Corowa airport, Australian Government Bureau of Meteorology (7 km from farm).

tion of the automatic feeder. As was seen on days 11 and 12, a reduction in the volume of water used by the pigs was observed on day 20. The next day (day 21), following manual feeding of pigs at 0730, the feeder returned to normal operation at 0916. Pigs' feed consumption on day 21 was therefore greater than normal, and corresponded with the second-highest recorded water usage during the study.

Patterns of water used and wasted over each 24-h period

Smoothers generated in brms for pigs' water use and wastage observations for the 27 days by time of day showed that both had uni-modal patterns, peaking in the mid-late afternoon at approximately 1400–1700 (Fig. 5). Over the 27-day study period, peaks for water used and water wasted of pigs tended to shift 1–2 hours earlier in the afternoon. During the mid-late afternoon, when water use was higher, a slightly greater proportion of the water used was wasted. Overall, the model fit was sound (R^2: 0.67; 2.5th credible limit: 0.60; 97.5th credible limit: 0.72). While the model did not perform well on days 13 and 21, the two days of aberrantly high water use during the study, this did not impact on the R^2 and 2.5th and 97.5th credible limits of the model.

In-water antimicrobial dosing events (days 8 and 9)

The median water wastage rate measured in the study pen over the 8-hour dosing period (0700–1500) on days 8 and 9 was 38%, which was 7% less than the value of 45% factored into the dosing calculations by the farm veterinarian and farm manager prior to the in-water dosing event conducted in the building. Pigs would therefore have consumed 9 mg/kg of the antimicrobial instead of the target dose of 8 mg/kg, equating to 1.125 of the target dose, an over-dose of 12.5% (Fig. 6).

Discussion

There were three main findings from this study: (1) that water wasted by the group of pigs each day, as a proportion of the total water used, was stable day-to-day over the study period, as were the ratios of water used:feed consumed, and water consumed:feed

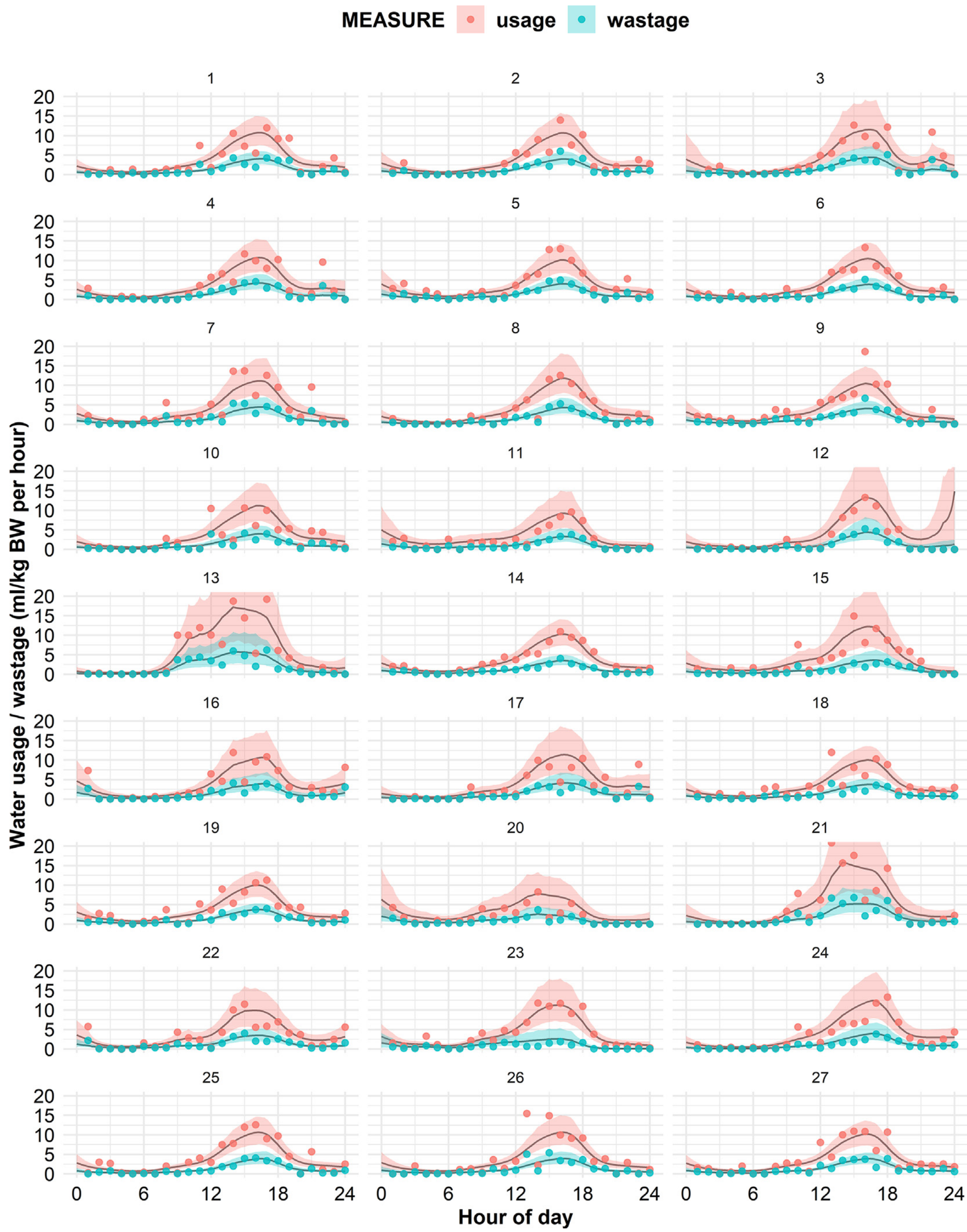

Fig. 5. Smoothers showing estimated water usage and water wastage by the pen group of 15 pigs (ml/kg BW per hour) within each day over the 27-day study period, in chronological order. In each smoother, the band edges indicate the limits of a 95% credible interval. Observed data for water used and water wasted in each hour of each day are represented by dots.

consumed; (2) that patterns of daily water use and wastage of pigs, which were accurately modelled with the Bayesian method used in this study, were closely aligned and uni-modal, peaking at 1400–1700, with a slightly greater proportion of the water used wasted during hours of higher water use; and (3) that it is feasible to quantify the daily water use and wastage patterns of a group of pigs and use them prior to each in-water dosing event to perform more accurate dosing calculations and optimise the dosing regimen, thereby improving in-water antimicrobial dosing efficacy and stewardship on pig farms.

Patterns of water used and wasted over each 24-h period

Water use patterns within each 24-h period of cohorts of pigs reported in published studies have varied widely in the timing and the amplitude of the peak(s) (Turner et al., 2000; Madsen and Kristensen, 2005; Brumm, 2006; Villagra et al., 2007; Kashiha et al., 2013; Rousseliere et al., 2016; Chimainski et al., 2019; Muniz et al., 2021; Misra et al., 2021). This may be for three reasons. First, the behavioural patterns of a particular cohort of pigs reared in a particular building, including its drinking pattern,

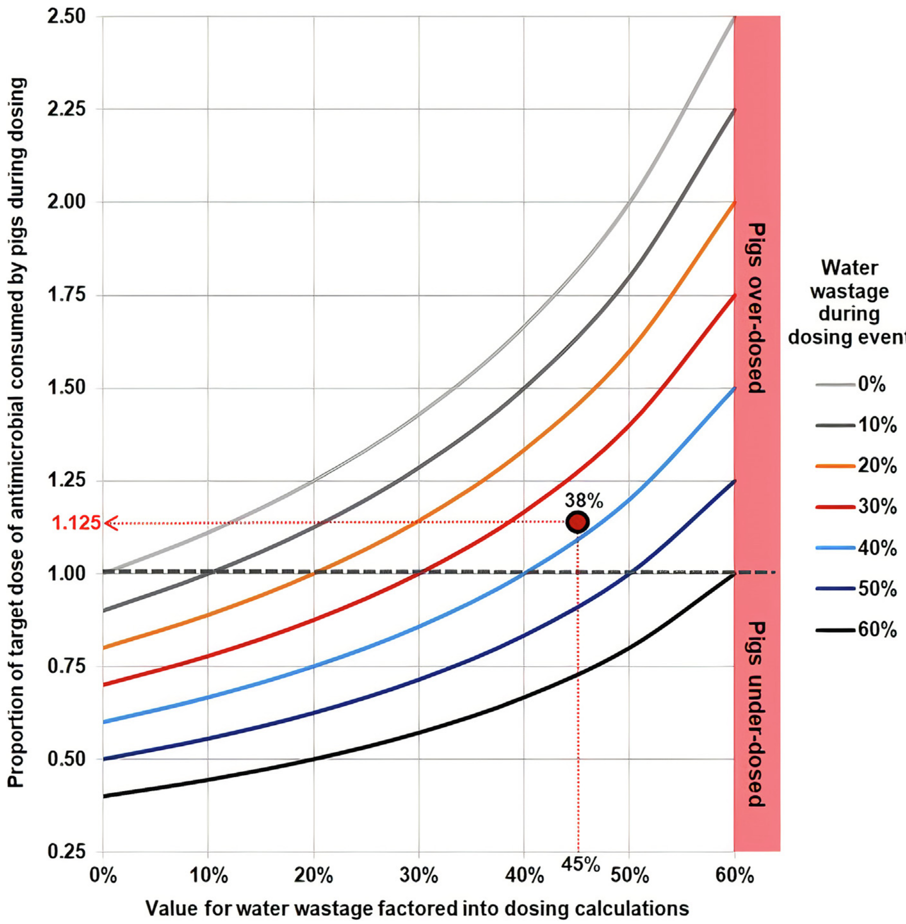

Fig. 6. Proportion of target dose of antimicrobial consumed by the pen group of 15 pigs at alternative actual water wastage rates during a dosing event, based on the value for water wastage (% of water used) factored into the dosing calculations prior to the event. The value for water wastage factored into the dosing calculations by the farm veterinarian and farm manager prior to the in-water dosing event conducted in the building was 45%. The circle indicates the median water wastage rate of 38% that was measured in the study pen over the 8-hour dosing period (0700–1500) on days 8 and 9 (38%).

may be influenced by intrinsic factors such as the pigs' gender, genetics, BW and health status, and many extrinsic factors such as the building type and design, pen group size and stocking density, drinker type, the number of drinkers and feeders in each pen and their spatial arrangement, water flow rates from drinkers, water quality, diet specifications, day-length, building temperature, humidity and air quality and flow (Villagra et al., 2007). Second, the method used to collect water use data varied between studies (equipment used, frequency of data measurements). Third, the statistical approach (frequentist or Bayesian) and specific method used to estimate each cohort of pigs' water use pattern varied between studies.

In agreement with other researchers (Madsen and Kristensen, 2005; Dominiak et al., 2019a; 2019b), we found that aggregating data on water used and wasted per minute into hourly data points was a good compromise between losing excessive data points and having so many data points that the computational load was too great for a mid-specification personal computer to perform Bayesian inference through simulation. The use of group-level smoothers (each of the 27 days of the study) with the common smoother enabled the model to capture variation between days in the patterns of water used and wasted.

The two occasions during the study when the automatic feeding station malfunctioned highlighted the close association that exists between pigs' water use and feed consumption. The close alignment of the uni-modal patterns of total water use and wasted water was expected. In other cohorts, we have observed shifts in peak water use of up to 3 hours over their occupancy in a building (unpublished studies). The study was conducted under cool to mild conditions in late winter (median minimum daily ambient temperature of 4 °C, median maximum daily ambient temperature of 16 °C). If the study had been conducted under warm to hot summer conditions (i.e. above the thermal comfort zone of finisher pigs of 10–25 °C), the proportion of the water used that was wasted may have been substantially higher in the afternoon and early evening than at other times, if pigs spent increased time using drinkers to wet their skin as an evaporative heat loss strategy. This warrants further investigation. If an in-water antimicrobial dosing event was conducted under such circumstances, many pigs would be under-dosed unless a higher, accurate value for wastage (W) was used in calculation of the quantity required to be administered prior to the event.

Aligning dosing events with pigs' patterns of water used and wasted over each 24-h period

A water metering system could be used to continuously measure the volumes of water used and wasted per minute of a representative number of pigs in a weaner building or grower/finisher building. In conventional weaner and grower/finisher buildings, in which pigs are accommodated in small pen groups (typically holding 20–100 pigs), drinkers in two or more pens could be fitted with the water metering system. In 'eco-shelters', in which pigs are accommodated in larger pen groups (typically 250–500 pigs), a sub-set of all drinkers could be fitted with the system. Each day, per minute data for the previous 7 days could be aggregated into hourly data points and a software package such as brms used to fit Bayesian models of the water use and wastage patterns of the pigs. These 7-day models could then be used by veterinarians and farm managers prior to each dosing event to more accurately calculate the quantity of antimicrobial required to ensure pigs consume the target dose. The proportion of water used that was wasted over the intended dosing period could be used in the dosing calculations rather than that over the entire 24-h period.

The 7-day models could also be used to ensure that each dosing event commenced in the hour when water use was ascending and approaching its main peak, and water velocities in pipe sections were therefore increasing. For example, for the group of pigs in this study, this would be between 1100 and 1200 (rather than at 0700). Commencing the dosing event at this phase of the daily water use pattern helps to reduce differences between drinkers located throughout the building in the initial lag after commencement of dosing before antimicrobial first reaches the drinker, and in the duration over which the antimicrobial is available to pigs at the drinker. As a consequence, between-animal variability in the quantity of antimicrobial consumed over time by pigs is reduced, and antimicrobial consumption by pigs over the first few hours of the dosing period is increased, leading to earlier attainment of the pharmacokinetic-pharmacodynamic target for the antimicrobial that best predicts its efficacy (Little et al., 2019; 2021a). Ultimately, a higher proportion of pigs in the group dosed should attain the systemic exposure to the antimicrobial required for high clinical efficacy and suppression of emergent antimicrobial resistance.

Reducing water wastage and quantities of in-water antimicrobials used and disseminated into the environment

Water metering systems fitted in pens to help manage antimicrobial dosing could also be used to evaluate potential water-saving strategies and identify those that could be effective in reducing water wastage. Given that drinking water represents 80% of the total water use of a pig farm and 75% of total water used on pig farms is in weaner and grower/finisher buildings (Muhlbauer et al., 2010), the capacity to identify and implement effective water-saving strategies may contribute substantially to reducing the water footprints of pig farms, i.e. the quantity of water required per tonne of pig meat produced. This is becoming more important as concerns grow in many countries about the sustainability of water use for the production of pig meat and other foods of animal origin, given the increased demands imposed by human population growth and changes in diets, and the effects of climate change on water availability. Pig production is 19% of the total global water footprint of farm animal production (Mekonnen and Hoekstra, 2012).

If effective water-saving strategies in weaner and grower/finisher buildings were implemented, the quantity of antimicrobial required to be administered in each dosing event could be reduced, as could the proportion of the antimicrobial administered that passes into the effluent management system of the farm, and may ultimately lead to reductions in the concentrations of bacteria containing antimicrobial resistance genes applied to soils and discharged into surface water and groundwater (He et al., 2020). Strategies that may help to reduce water wastage in a particular building on a particular farm might include: reducing the water flow rate at the drinkers if it exceeds the generally recommended maximum of 1.0 L/min for weaner pigs and 1.7 L/min for grower/finisher pigs, reducing water pressure at the drinkers if it exceeds 138 kPa for weaner pigs and 276 kPa for grower/finisher pigs, adjusting the height of drinkers as pigs gain weight, changing the type of drinker used, re-orienting drinkers and/or re-positioning them within each pen, installing side partitions on drinkers, using wet/dry feeders, providing pigs with objects to enrich their environment, improving water quality and palatability, adjusting the nutrient specifications of the diet of the pigs, reducing pen stocking density, creating large pen groups by removing partitions between adjacent pens, and reducing heat stress under hot weather conditions (Patience, 2012; APL, 2017; PIC, 2019). These alternative strategies would need to be evaluated systematically in a series of pen trials.

Other potential benefits from using water metering systems in pig buildings

Fully automated systems have been proposed to enhance pig health, welfare and productivity through the prediction and early detection of disease in pigs because, like many animals, pigs modify many of their behaviours (including drinking and feeding) as adaptive responses to disease (Matthews et al., 2016). Pen-level studies have described changes in the water use and drinking behaviour of pigs 1–7 days prior to outbreaks of diarrhoea (Krsnik et al., 1999; Madsen and Kristensen, 2005; Crabtree et al., 2008). More recently, systems based on spatial models incorporating water use data from multiple flowmeters have been developed and evaluated for early detection of diarrhoea and pen fouling in sections of a building (Dominiak et al., 2019a; 2019b). However, the development of an effective, fully automated pen-level system for early detection of disease based solely on water use and drinking behaviour is unlikely for several reasons. First, the water use and drinking behaviour of pigs may change in response to many factors other than disease. Second, between-animal and within-animal variation in daily water use and drinking behaviour is naturally large in any group of growing pigs, requiring statistical methods able to identify subtle changes in water use and drinking behaviour (Kapun et al., 2017). Third, further research is required to adequately characterise the adaptive changes in the water use and drinking behaviour of pigs that are associated with infection with specific enteric and respiratory pathogens and understand at what stage in the progression of the disease the changes occur.

Seven-day models of patterns of water used and wasted by groups of pigs in farm buildings, as we have proposed, could be useful to identify a deviation in water use and wastage patterns, triggering investigation of the possible cause(s), including disease. However, accurate fully automated early detection of disease in pigs at the pen level is likely to require quantification and analysis of changes in several behaviours (drinking, feeding, elimination, standing/lying and locomotion) using multiple sensors (Matthews et al., 2016; Jensen et al., 2017; Larsen et al., 2019; Miller et al., 2019).

Limitations of this study

This study has for the first time successfully quantified the water use and wastage patterns of a group of growing pigs utilising nipple drinkers on both daily and hourly time scales under farm conditions. However, the results obtained are specific to the group of pigs studied and cannot be extrapolated to other pigs. The study was observational. It was not designed to measure drinking behaviour parameters such as the frequency and duration of visits by pigs to drinkers. Estimation of the proportion of water used by the cohort of pigs that was wasted at any time was subject to the degree of accuracy of each of the two water metering systems used. Implementing HGAMs describing the hourly water usage and water wastage in pigs is challenging, as the data for each day are noisy and relatively limited. Aggregating data on water used and wasted per minute into smaller time periods than hours would add substantially to the computational load and make interpretation of smoothers difficult. This study should be considered to be a first step in gaining a detailed understanding of the water consumption and wastage behaviour in growing pigs. Further research is needed to evaluate the water use and wastage patterns of weaner and grower/finisher pigs and breeding pigs under a range of conditions.

Conclusion

It is feasible to quantify the water use and wastage patterns of pigs in farm buildings using a system that records and aggregates data, and analyses them using a Bayesian method. This system could support more efficacious in-water antimicrobial dosing, and better antimicrobial stewardship on pig farms, by helping to reduce the quantities of antimicrobials used and disseminated into the environment. It may also be a useful tool to identify and implement water-saving strategies on farms that may help to reduce their water footprints. The findings of this study are applicable not only to antimicrobials but also to all other additives administered in-water for which the degree of efficacy is dependent on the dose administered, and wastage is undesirable. These additives include vaccines, parasiticides, direct-fed microbials and potentially new therapeutic products such as bacteriophages. Further studies are warranted to understand what factors influence the volumes of water consumed and wasted by pigs per day, and the patterns of water used and wasted within each 24-h period.

Supplementary material

Supplementary material to this article can be found online at https://doi.org/10.1016/j.animal.2022.100586.

Ethics approval

The study was conducted with the approval of the Rivalea Animal Ethics Committee (Authority no. 19B030, approved 12 August 2019 and amended 24 March 2020) and was conducted in compliance with its conditions.

Data and model availability statement

The data presented in this study are available on request from the corresponding author. The data have not been deposited in an official repository because of the conditions of the ethics agreement. The model code is provided in Supplementary Material S1.

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Declaration of interest

The authors declare no conflict of interest.

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