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DEPARTMENT OF BIOLOGICAL AND ENVIRONMENTAL SCIENCES

PATTERNS OF WATER USE AMONG AFRICAN SAVANNAH ELEPHANTS (*LOXODONTA AFRICANA*)

Movements toward a water source

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Frontpage image taken by camera trap set up by Elephants for Africa

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Abstract

The African savannah elephant requires a large amount of water to sustain itself and regularly travels to water sources, typically along traditional ‘elephant highways’ and frequently through or in close proximity to human settlements or farmland, with negative interactions and consequences for both humans and elephants. To help mitigate these problems, a better understanding is needed of spatial and temporal patterns of elephant movements to and from water sources. This study of elephants in Makgadikgadi Pans National Park, Botswana, used camera trap images to analyse when and why elephants travel towards their main water source, the Boteti River. Camera trap images taken along an elephant highway, leading down to the water, between 2014 and 2017 were used within the framework of a general additive model (GAM) to predict elephant movement across 24-hour cycles. Different factors including herd size, temperature, presence of juveniles and 30-day mean rainfall, were allowed to interact with time of day to check for their effects on the probability of elephants traveling to the water. The results showed strong interactions between time of day and herd size, as well as between time of day and temperature in changing the probability of when the elephants sought out the water source. Larger groups showed less of a diurnal pattern, which could indicate a greater sense of security or showcase the influence of between group variation in terms of ecological strategies. Higher temperatures resulted in a greater drop in probability in the afternoons, likely related to heat avoidance by the elephants.

1. Introduction

1.1 General ecology

The African savannah elephant, *Loxodonta africana* (henceforward referred to as elephant) is the largest land mammal on earth, and requires a substantial amount of water to sustain itself (Fritz, 2017; Mukomberanwa et al., 2024). Elephants, for instance, regularly need to drink water with an adult usually having to drink every one to three days, with a daily water intake of about 150-200 litres (Kingdon, 2013; Wato et al., 2018). In addition to their metabolic need of water, elephants heavily rely on it for thermoregulatory purposes (Dunkin et al., 2013; Lillywhite & Stein, 1987). Due to the lack of sweat glands, elephants are dependent on external sources of water for heat evaporation by spraying and trapping water in the crevices of their epidermis (Lillywhite & Stein, 1987). However, the relative importance of access to surface water for thermoregulatory use is indicated to be strongly dependent on regional climatic conditions (Dunkin et al., 2013). Elephants may also store water in their pharyngeal pouch, an anatomical structure in their throats, and use this water for immediate thermoregulation when no external water sources are available (Shoshani & Tassy, 2005) Therefore, warmer and drier conditions will infer higher water demands for elephants.

Elephant distribution, and movement patterns are thus strongly dependent on the location and availability of water (Wato et al., 2018). As these factors seldom remain constant on a temporal and spatial scale, they will ultimately have a direct or indirect impact on the activity patterns of elephants in terms of when and how they engage in certain behaviours such as feeding and drinking (Mramba et al., 2019). These activity patterns and strategies, particularly in more arid conditions, have been found to vary on both individual and group levels, potentially highlighting the intricate social lives and cognitive abilities of elephants (Chui et al., 2024; Fritz, 2017). Additionally, evidence of elephants being capable of recollecting and storing information on water distribution (Wato et al., 2018), combined with observations of high within-population variation in ecological strategies (Chui et al., 2024), adds further complexity to their patterns of resource use.

The distances elephants travel and their core home range size have also been shown to differ across wet and dry seasons with additional differences in ecological strategies noted between males and females (Makati et al., 2025). Such differences will inevitably impact which bodies of water elephants have immediate access to. During periods of higher ambient temperatures, for example, female elephant travel distance has been observed to be constrained, as well as concentrated to occur at night between bodies of water and foraging areas (Rozen-Rechels et al., 2020). The pronounced sexual size dimorphism (males ca twice as heavy) results in partly different nutritional and water requirements, and hence different ecological strategies (Makati et al., 2025; Woolley et al., 2009). Such differences in strategies can be manifested through the spatial segregation of males and females, including the prevalence of female groups to remain in closer proximity to water compared to adult males who might not need to frequent water sources as often as lactating females (Shannon et al., 2006; Stokke & Du Toit, 2002).

Elephants hence inhabit areas that vary in terms of their climate, environmental conditions and population composition, while still requiring regular water intake. Site-specific long-term

monitoring of the elephant's ecological strategies and resource use could thus give new insights and increase knowledge on local elephant ecology. This could ultimately assist communities in reducing negative interactions when sharing resources, such as water, with elephants through spatio-temporal avoidance for example.

1.2 Social organisation and dynamics

1.2.2 Male social composition and dynamics

Male elephants usually leave their natal family units in their adolescence to become independent (Goldenberg et al., 2014; Moss, 1988)**.** Association patterns among males have furthermore proven to be more complex and dynamic than originally assumed, particularly among younger newly independent males who frequently associate with other young males (Chiyo et al., 2011; Evans & Harris, 2008; Goldenberg et al., 2014). These patterns continue to evolve and change as the males grow older at which point they stabilize and consolidate their social networks with other males (Chiyo et al., 2011; Murphy et al., 2019). Nevertheless, younger males are less likely to be found alone and have been observed to seek out the company of older males, potentially acquiring vital social and ecological knowledge and security (Allen et al., 2020; Evans & Harris, 2008). The presence of older males could therefore shape the movement patterns and ecological strategies among these younger males (Evans & Harris, 2012).

Activity patterns and social associations among older males might further be altered by the onset of musth, a condition characterized by elevated levels of testosterone, during which the males become sexually active and seek out females (Poole, 1987; Poole & Moss, 1981). Since males usually do not start entering periods of musth until their mid 20s (Poole, 1989), these seasonal patterns of socio-ecological change mainly apply to the older, mature males. When associating with females, males have been observed to forage less frequently while allocating more time for reproductive purposes (Du Plessis et al., 2021). The seasonal and environmental changes might thus impact the demographic composition of males at specific water locations.

1.2.1 Female social composition and dynamics

Female elephants are highly social animals that live in complex matriarchal groups, composed mainly of related adults and their immature offspring (Archie et al., 2006; Douglas-Hamilton, 1972). Female elephants consequently tend to travel together in search of food and water. The degree of association and the size of the groups are, however, dependent on the ecological and social context, in which groups can combine and split apart in a fission-fusion manner (Wittemyer et al., 2005). The smallest, and usually most stable, social unit across ecological conditions is that of an adult female and her immature offspring (Moss, 1988). In more favourable conditions, elephants tend to congregate and travel in larger numbers, when water and food are more abundant. These wider associations typically reflect the level of relatedness among the females (Archie et al., 2006; Vance et al., 2009).

Resource competition, both between and within female family units, is more pronounced when resources are clumped, like water holes, and tend to follow a transitive linear

hierarchical system, dependent on the age and size of the females (Archie et al., 2006; Wittemyer & Getz, 2007). Although females cooperate to raise their offspring and show low levels of aggression (Lee, 1987), older and larger individuals possess a higher social ranking in the context of resource competition (Archie et al., 2006). Within families, it is usually the oldest female, the matriarch, that leads the group and her age and experience strongly influence the social status and success for the entire family (McComb et al., 2001; Wittemyer & Getz, 2007). During between-group competition, the matriarch's age and size has proven to better predict the outcomes of such competitions, rather than the size of the group itself (Wittemyer & Getz, 2007).

The dynamic fluctuations in group size reflecting the environmental conditions, coupled with the influential role of age in determining female elephant dominance, could impact their patterns of resource use in accordance with resource availability (Wittemyer et al., 2007). Different social constellations might therefore be anticipated at different times at a spatially clumped resource such as water. Investigating such socio-ecological interactions at a local scale might reveal additional characteristics of the elephants frequenting a specific area.

1.3 Anthropogenic pressures

In recent history, elephant populations across large parts of Africa, with certain exceptions being the southern parts of the continent, have declined due to the illegal killing for their ivory tusks (Douglas-Hamilton, 1987). Current figures state that up to 70% of all elephants can be found in southern Africa, with Botswana holding the single largest population of around 130 000 individuals (Chase et al., 2016; Thouless et al., 2016). In contrast to the elephant population trend, the human population in Africa has been growing and is projected to more than triple in size by the end of the century (Gerland et al., 2014). Human population growth has additionally proven to be higher near protected areas among rural communities (Wittemyer et al., 2008). Due to the expansion of human settlements, causing habitat loss and fragmentation, elephants and humans are increasingly coming into conflict over space and resources (Shaffer et al., 2019; Thouless et al., 2016). Living in closer proximity to humans, elephants might for example engage in crop raiding (Graham et al., 2010).

Although elephants might partly be able to adapt to a more human dominated landscape through altering their daily activities and movement patterns (Graham et al., 2009), coexistence and resource sharing with humans becomes increasingly difficult with ever higher human densities (Hoare & Du Toit, 1999). To mitigate negative interactions between humans and elephants, obtaining more robust knowledge on how local elephant populations utilise resources could be an important component in promoting human-elephant coexistence. The possible patterns that are found on how the elephants use a specific water source could give insights into how human use of it can be adapted, to reduce potential conflicts with the elephants.

2. Aims

The aim of this study was to investigate the temporal patterns of elephant movement toward their primary water source, the Boteti River, in northern Botswana and to explore potential factors affecting these patterns. This was to be done by answering the following questions:

(1) Are there any differences in the time of day that groups with or without juveniles are most likely to travel toward the water source?

(2) Is there a correlation between herd size and the time of day they are most likely to move toward the water source?

(3) Is temperature a determining factor influencing when elephants travel to the water?

(4) Are there any differences, or variations between dry and wet seasons in trends of temporal water use?

3. Method

3.1 Study area

All data used in this study were collected from the Makgadikgadi Pans national park in northern Botswana, by the NGO Elephants for Africa. The national park covers roughly 4900 km^2 and is bordered to the north by Nxai Pan National Park and the Boteti River to the west, whose water resurged in the area in 2009 following an absence of 19 years (Chase et al., 2018; Evans, 2019) and was present throughout the data collection period of 2014 until 2017. The area has a mean annual rainfall of 450 mm of which most occurs during the wet season spanning from November to April during which the rains can be quite sporadic (Thomas & Shaw, 1991). The climate is semi-arid and can experience temperature peaks of over 40 C^o during the warmer periods of the wet season while plummeting to below freezing levels during the cooler nights of the dry season (Kgathi & Kalikawe, 1993; Thomas & Shaw, 1991).

The elephant population increased when the water returned to the Boteti River and has been observed to mainly consist of males (Chase, 2011; Evans, 2019). Across the park, there exists a network of trails called elephant highways that have been created by the elephants, connecting different resource patches with each other (Allen et al., 2020). These trails tend to be used by elephants as they travel to and from these fixed locations.

Figure 1.Shows an illustration of the study area, created in Biorender, including the relative positions of the camera traps (denoted as EfA02 and EfA06) along elephant highways used to gather image data. The shaded green area represents a section of the Makgadikgadi Pans national park separated from the unprotected community area (light green) by the Boteti river.

3.2 Camera trap footage data

Images of elephants, taken between August 2014 and March 2017, were obtained from two camera traps set up by Elephants for Africa along two different elephant pathways leading down to the Boteti river (Figure 1). The first camera trap was named EfA02 with the coordinates, written in the degrees, minutes, second format (DMS), 20°18'59.4"S, 24°17'22.2"E and the second camera was named EfA06 with the coordinates 20°23'56.5"S, 24°31'16.2"E. Both cameras were motion-triggered and of the brand Reconyx HC600 Hyperfire after April 2016 with EfA06 having previously been of the brand Bushnell 119435C. Collection of camera trap data for EfA06 occurred between August 2014 and April 2016 followed by a pause and then resumed between July 2016 and March 2017. EfA02 was deployed between November 2014 and March 2016.

The images derived from the cameras were stored as URL-links in Excel spreadsheets together with information on each image such as the date and time it was taken, the name of the species captured, the number of individuals observed, behaviours performed, age classes and presence of young. Due to uncertainties in the number of elephants observed in some images, there existed three separate columns in the data sheet termed ‘question__count_min’, question__count_max’ and ‘question__count_median’, of which the the first two columns specified the minimum and maximum number of elephants, respectively, that had been counted in each image. The median was then the midpoint value between these.

The identification of species, their behaviours and potential presence of young were made by citizen scientists through Snapshot Safaris (SnapshotSafari). Based on the percentage of participants who agreed on the categorization of these attributes, a probability consensus score was calculated and presented within the data. These scores could range from 0-1 with 1 signifying a 100% agreement among the participants that analysed an image on observing a particular feature.

3.3 Data filtering and processing

All data processing was made in R (version 4.5.2; R Core Team, 2026). Additional assistance, through the acquisition of suggested lines of code, was provided by ChatGPT from OpenAI. The data was filtered using the dplyr package (version 1.2.1; Wickham et al., 2026). The images were additionally filtered so that only elephants engaged in moving were retained. The selection of images was based on the consensus probability scores with a threshold value of $p>0.8$ used (see section 3.2). For information on herd size, the column that included the maximum counted number (see section 3.2) was used as it was deemed more likely to represent the minimum total count of the true number of elephants present.

Further filtering was done to only incorporate images taken at least one minute apart to reduce the risk of multiple consecutive images of lingering individuals being included. This required combining the date and time that each image was taken and arranging these in chronological order, which was done using the lubridate package (version 1.9.4; Grolemund & Wickham, 2011). To additionally make sure that there existed a continuous range in time differences, and justify the one minute threshold, a histogram of the time differences in minutes between consecutive images was created using the ggplot2 package (version 4.0.0; Wickham, 2016). Of the images that were taken less than one minute apart, one was arbitrarily omitted from the data.

From each photo, the direction that the elephants moved relative to the camera, was manually extracted. These were termed L (left), R (right) or O (unclear) with the last one describing cases of elephants either moving directly towards or away from the camera. The direction variable was compiled in a separate Excel spreadsheet that was then loaded into R and merged with the preexisting data. Based on the positions of the cameras relative to the water source, elephants moving to the left were categorized as moving towards the water, while elephants moving to the right were moving away from it. From the direction notations, a new binary variable, termed ‘move_L’ was then created that answered the question of whether the elephant was moving towards the water (denoted as 1) or not (denoted as 0).

In order to differentiate between male and female groups, a second binary variable was created based on the consensus probability score of juveniles (0-9 years) being present. If $p>0.5$ it would be classified as young present and hence the binary outcome would be 1. Such an outcome would then be used to differentiate between observations of male and female elephant groups as the presence of juveniles would most likely infer the presence of females.

A separate data set containing data on temperature and precipitation, acquired from measurements made by Elephants for Africa at their research camp, was then loaded,

cleaned and merged with the preexisting data to include these additional variables as predictors. The temperature data had been collected so that it included the maximum and minimum values measured for each day. The midpoint values of these max and min measurements were therefore extracted and used as an approximation for the average daily temperature. Due to an absence of measured temperature values during certain days, a linear interpolation function was created and tested based on present midpoint temperature values for evaluation purposes. This function was then applied to fill in the missing midpoint temperature values in the data set.

To account for seasonal fluctuations and current habitat quality, the mean rainfall during the preceding 30 days was included as a predictor, using the zoo-package in R (version 1.8.15; Zeileis et al., 2004). This was argued to better reflect the lagged effects of precipitation on vegetation growth and composition rather than the amount of rainfall per day.

3.4 Modelling and statistical analysis

For the purposes of testing the interactive effect between time of day and the remaining predictors (juveniles, rainfall, herd size and temperature), a built-in scaling function was applied to scale these. This was done to make the different interactions more comparable with each other. The time-variable, represented by the extracted hour-term from each observation, was also sine-transformed in order to treat time as a circular variable which would, for example, mean that the time points 23:00 and 01:00, that are numerically far apart, are interpreted as close in time.

As the data had been gathered from two different sites (see section 3.2), with one site (EfA06) accounting for close to 90% of the observations, the smaller site (EfA02) was not included in the final analysis rather than including sites as a random effect.

Each scaled predictor was allowed to interact with the scaled sine-transformed hour-variable within the framework of a logistic regression model using the *glm()*-function. To allow for better fits within each interaction, and not constrain these to one sole sine curve with fixed peaks, different combinations of hourly time shifts were tested when sine-transforming the hour-variable. This involved creating a matrix containing all possible combinations of time shifts among the four interaction terms in the model where each of four the sine-curves were allowed to be shifted between 0-12 hours. In total this generated 13^4 = 28 561 unique combinations. From these, a function was created to extract the combination of the four sine-curves with the lowest AIC-value, representing the best fit.

However, so as not to confine the model to predetermined sine-curves, which might not capture some of the more dynamic temporal variations, a generalized additive model (GAM) was also created to allow for more flexibility. This was done using the *gam()*-function within the mgcv-package (version 1.9.3; Wood, 2017). The hour-variable was not sine-transformed, instead the GAM-function was set to use circular splines, accounting for time being circular. In addition to the interaction terms, the hour-variable was also included separately as a baseline trend for the model when doing the interactions.

4. Results

Overview

A total of 2056 observations were analysed in the model, all derived from the site termed as EfA06 between August 2014 and March 2017. Time of day on its own was a significant predictor in determining the probability of elephants moving towards the water source (Table 1). Of the interaction terms tested, the number of counted elephants and temperature had a significant effect on affecting the probability of movement towards water (Table 1). Since neither the presence of young nor rainfall had a significant effect in altering the daily movement patterns, their effects have not been included in any graphs.

Table 1. Summarises the output from the GAM-model, including the smooth terms and their statistical significance. The effective degrees of freedom (Edf) describe the complexity of each term regarding its deviance from linearity with higher values signalling more complex, non-linear relationships. The reference degrees of freedom (Ref.df) represent the number of degrees of freedom used to calculate the statistical significance of each term. The smooth terms include the interactions tested between the smoothed hour-variable and the additional four scaled predictors, herd size, juveniles, temperature and rainfall. The R^2-value indicates the proportion of the variation in the data explained by the model.

Terms	***Edf***	***Ref.df***	***Chi square***	***P-value***
s(hour)	7.089	8.000	117.154	< 0.001***
s(hour): herd size	1.002	1.005	12.648	<0.001***
s(hour): juveniles	3.277	4.014	6.629	0.161
s(hour): temperature	4.443	5.416	40.953	<0.001***
s(hour): rainfall	2.762	3.436	8.515	0.0585 .

R^2 = 0.11

Time of day

The probability of seeking out the water was significantly influenced by time of day (X^2 = 117.154, p<0.001, Table 1). Around midnight, the probability of moving towards the water was around 50% which was followed by a pronounced increase in probability with a peak of over 80% slightly before 12:00 (Figure 2). The probability then dropped and reached its lowest point in the afternoon at around 16:00 when the probability fell below 40% after which it increased again toward the evening (Figure 2).

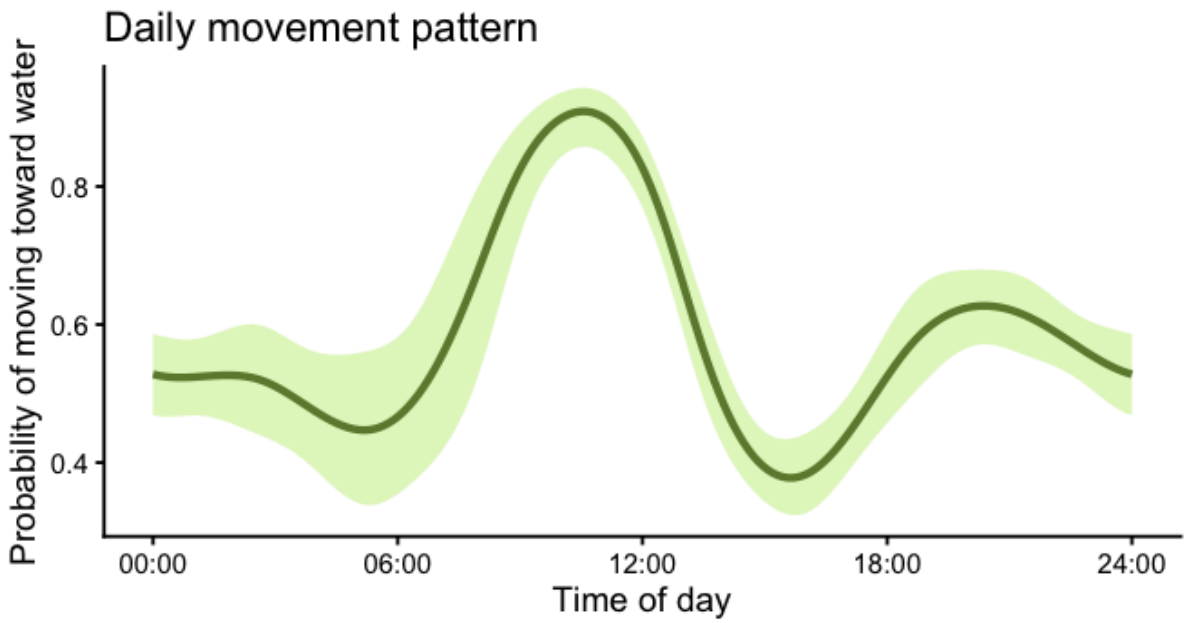

Figure 2. Illustrates the probability of African savannah elephants moving toward the water source across a 24 hour time cycle. The bold line represents the fitted probability values derived from the GAM-model while the shaded area represents the 95% confidence interval.

Time of day x Herd size

There was a significant interaction between herd size and time of day in determining the probability of moving towards the water source (X^2 = 12.648, p<0.001, Table 1). The diurnal pattern illustrated in Figure 2 became less pronounced with an increasing herd size, exhibited by the less wiggly curvature of the daily probability trend (Figure 3).

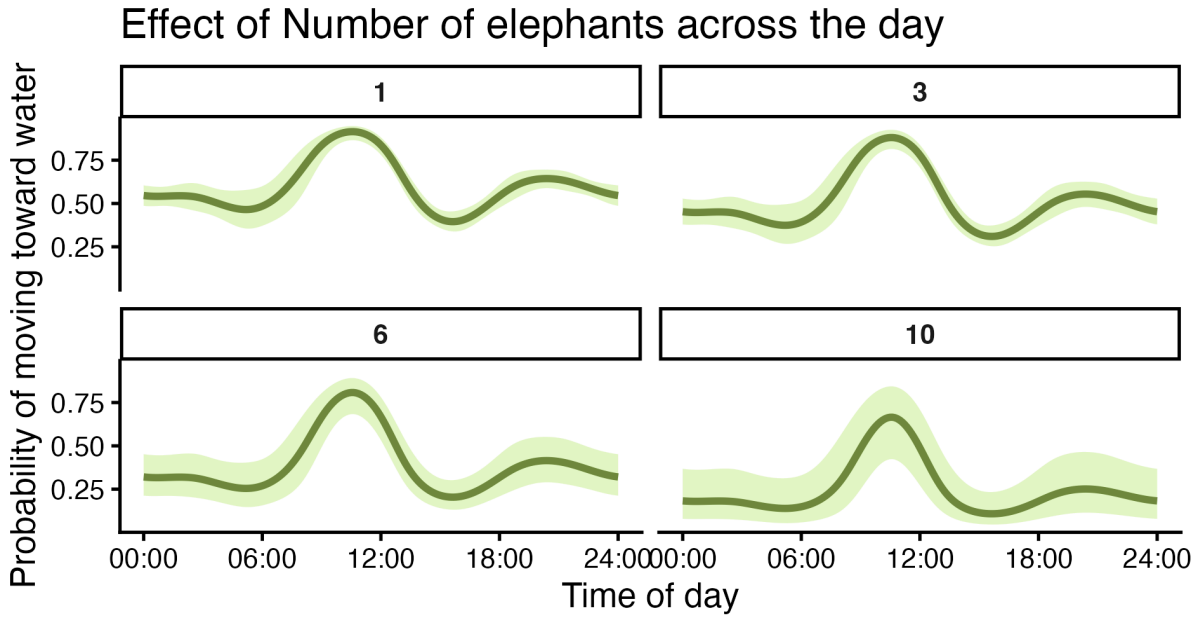

Figure 3. Shows the effect of African elephant herd size on the probability of moving toward the water source. Each facet includes the fitted probability values of moving toward the water predicted from the GAM-model under the condition of either 1,3,6 or 10 elephants being present. The shaded area represents the 95% confidence interval.

Time of day x Temperature

The mean daily temperature showed a strong interaction with time of day in predicting the probability of elephants moving toward the water (X^2 = 40.953, p<0.001, Table 1). For temperatures between 30-40 C°, a stronger dip in probability of moving toward water occurred in the afternoon, while the probability of moving tended to be the highest during the later part of the morning at around 10-11:00 among all temperature conditions (Figure 4).

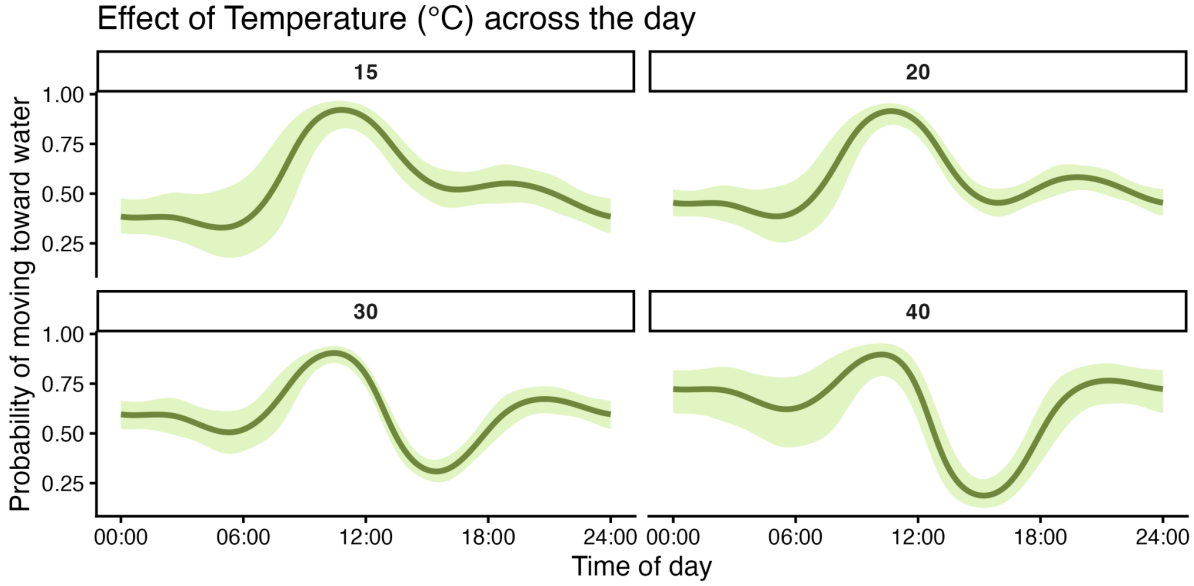

Figure 4. Shows the effect of daily mean temperature on the probability of African savannah elephants moving toward the water source. Each facet includes the fitted probability values of moving toward the water predicted from the GAM-model under different temperature conditions (15°C, 20°C, 30°C and 40°C respectively). The shaded area represents the 95% confidence interval.

Time of day x Presence of juveniles

The social composition, determined based on the presence or absence of juvenile individuals (0-9 years old) within groups, did not have a significant effect on changing the timely patterns of seeking out the water (Table 1).

Time of day x 30 day mean rainfall

There existed weak, but non-significant, evidence of the 30 day mean rainfall having an effect on the elephants' propensity to seek out the water at different times across the day (Table 1).

5. Discussion

5.1 Main findings

This study aimed at investigating patterns of how elephants travel to a water source by using camera trap images to create a model predicting the probability of traveling toward the water across the day and how it is influenced by different factors. The study found high evidence for a general daily pattern in elephant movement toward the water, with both herd size and ambient temperature influencing these patterns by altering the probability trends across the day. While neither the presence of juveniles nor rainfall had any significant effects, they might nevertheless highlight some of the specific attributes that characterized the study area in terms of its elephant population and climate.

5.2 Herd size

The size of the herds traveling toward the water interacted with time of day such that larger herds exhibited a weaker diurnal pattern and instead had a more even probability distribution across a 24 hour cycle with a less wiggly profile. These trends could partly reflect the individual and group variations that exist in terms of ecological strategies among elephants (Chui et al., 2024; Fritz, 2017)**.** Larger groups of elephants might adhere to the choices and strategies made by different individuals at different times. This might furthermore become more prominent if the groups change composition as might be more prevalent among males (Chiyo et al., 2011; Evans & Harris, 2008; Goldenberg et al., 2014). As the study population was mainly composed of male elephants (Chase, 2011; Evans, 2019), further highlighted by the fact that 2009 of the 2072 observations were of males, it could entail more dynamic social association patterns with particularly younger males following the lead of older male role models (Allen et al., 2020; Evans & Harris, 2012). All these factors combined, might then boost the variation of when larger groups are most likely to frequent the water.

The effect of herd size might also reflect a response to human presence and activity. Given the close proximity to human settlements and the shared use of water, elephants traveling alone might show a higher propensity to adapt their movement patterns to a perceived anthropogenic threat. Previous studies have shown that elephants avoid moving through areas that experience higher human activities during certain times of the day (Graham et al., 2009). However, those studies primarily looked at agricultural areas that were subjected to crop raiding from elephants and found a higher tendency for nocturnal activities, when human presence was lower, while in this study elephants were more likely to be traveling late in the morning with less timely preferences with larger groups. Considering that these cases involved different resources, it might reflect both differences between how humans and elephants share and utilise these resources and the potential higher level of security elephants feel when accompanied by conspecifics.

5.3 Effect of temperature

Temperature affected the tendency of the elephants to seek out the water by making it less likely for them to head there in the afternoons during warmer days. While water is a key component in thermoregulation for elephants (Dunkin et al., 2013; Lillywhite & Stein, 1987), which could imply higher water requirements during warmer periods, there might exist a trade-off in avoiding traveling when it is the warmest. Previous studies have for example demonstrated that female groups concentrate their movements to water at night to avoid the warmer daytime temperatures (Rozen-Rechels et al., 2020). Additional studies have showcased that the likelihood of elephants remaining in shaded areas increases with higher temperatures (Mole et al., 2016). It was also noted that temperature fluctuations did not influence the tendency of drinking during the day, although it did influence the likelihood of using the water for thermoregulatory purposes (Mole et al., 2016). Similarly, the elephants in the study area may have remained in shaded areas more exclusively in the afternoons during the warmer days while traveling to the sun-exposed body of water before and after the warmest parts of the day to cool off. This may act as an example of the elephants' flexibility in terms of responding to environmental variability (Mramba et al., 2019).

5.4 Presence of juveniles and rainfall

While the presence or absence of juveniles did not significantly change or affect the probability of seeking out the water across the day, it could be a reflection of the low number of observations with juveniles rather than an absence of an effect. Of the 2072 observations included in the model, only 63 were classified as having juveniles. This relatively low sample size could be linked to the area primarily being inhabited by male elephants at the time of the study. Given that the area only relatively recently has seen larger number of elephants following the resurgence of the Boteti river (Chase et al., 2018; Evans, 2019), the domination of males in the population may reflect their differing ecological strategies from that of females (Makati et al., 2025; Woolley et al., 2009). While males might be more prone to seek out new areas in search of food and water, females with young might not take the same risks and hence take longer time to re-colonize new areas. Previous studies have for example highlighted that elephant population expansion is density-dependent but that males will often expand their range to areas with more human activity and thus take higher risks (Fortin et al., 2022).

The weak but non-significant evidence of monthly mean rainfall, representing wet and dry seasons, altering the elephants's patterns in seeking out the water could partly be a result of the nature of the region's precipitation patterns. The study area's sporadic and patchy rainfall patterns (Thomas & Shaw, 1991) might not be of such a magnitude to significantly alter the relative importance of the permanent water sources. Nevertheless, wet and dry seasons might still influence the ranging and movement patterns of elephants as has already been documented (Wato et al., 2018) with elephants moving greater distances when resources are more plentiful. Even so, the elephants might still adhere to certain preferred time slots when accessing the water source during different seasons. As the study question was formulated to investigate the influence of the seasons a 30 day rolling mean of rainfall was used as the predictor to incorporate subsequent vegetation change. However, it is possible that rainfall might have had more short-term effects by creating temporary water sources that reduced the need for the elephants to use the permanent sources on a regular basis.

5.5 Limitations and improvements for future studies

The population composition in the area has since the observations were made changed and now include a larger number of females (Evans, pers. comm., 2026). This could motivate additional follow-up studies investigating how this may be manifested by answering the same research questions. Consequently, the results presented in this study may not as accurately describe the current state of the study area. A higher proportion of females could imply a higher frequency of larger groups given that females are found in stable family units that frequently associate with each other (Archie et al., 2006; Vance et al., 2009). The presence of more female groups could possibly also alter the behaviour of the males in the area by the increase in reproductive opportunities. Other studies have for instance shown that males allocate more time for reproductive purposes when associating with females (Du Plessis et al., 2021) which could infer changes in their daily activity patterns, such as when they seek out water. Such an effect could be argued to primarily involve the older males, as they compete most successfully for mating opportunities (Poole, 1989).

Since only a single camera trap was used to gather data for the study, it most likely resulted in an underestimation of the true number of elephants that moved to and from the water at that particular location, resulting in weaker statistical power. Although the camera trap was set along an elephant highway used by the elephants when walking between resource patches (Allen et al., 2020), when approaching the river bed the elephants could divert from the pathways and spread out more. As a result, individuals or parts of a larger group might not get detected by the camera by moving behind it for example. Including more camera traps at different locations along the river, as well as putting up multiple cameras at the same location to better capture the surroundings would be some suggestions of improvement if similar studies were to be undertaken.

Moreover, the temperature values used in this study were derived from measurements of maximum and minimum daily ambient temperatures, by calculating their corresponding midpoint values and thus do not represent the actual temperature from each observation. In order to capture more fine-tuned variation related to temperature, measurements of it could be taken at the time of each elephant observation. That might reveal possible threshold values beyond which elephants more readily adapt their movements to temperature, as other studies have shown (Rozen-Rechels et al., 2020). Additional parameters could potentially also be tested for, such as solar intensity, humidity and wind in order to capture various other metrological aspects that might influence the elephants' propensity to access the water.

Collecting more extensive data on age classes and individual ID-recognitions of the elephants observed could have added further depth to the study and allowed for detections of patterns on an individual level. When analysing the images it was noted that some individuals appeared multiple times throughout the study period. While not possible within this study, attempting to identify individual elephants as well as estimating their ages could provide valuable information on individual strategies and even identifying which individual elephants or age groups are more at risk of coming into conflict with humans.

6. Conclusion

In conclusion, the factors that affected the probability of elephants moving toward the water source was the size of the groups and the surrounding average temperature. The different seasons and social constellations, in terms of the presence or absence of juveniles, did not significantly influence the probability. The effect of temperature is likely related to elephants avoiding traveling and exposing themselves to the higher temperatures, showcased by the drop in probability observed in the afternoons during warmer days as predicted by the GAM-model. When larger groups travelled toward the water, they showed less of a diurnal pattern compared to elephants traveling alone. Such a trend could indicate a greater sense of security in larger numbers, whereby the elephants do not get as constrained in when they visit the water source. A second possibility is that larger groups also exhibit greater variation in ecological strategies as the group compositions might change, particularly among males, resulting in more dynamic patterns. As the population composition has changed since the data was collected, coupled with the inability to accurately assess age and individual identification, these might be some motivational points for conducting additional studies on the elephants and their patterns of resource use in the area.

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Appendix 1: Bar plot over number of observations per month during time of the study

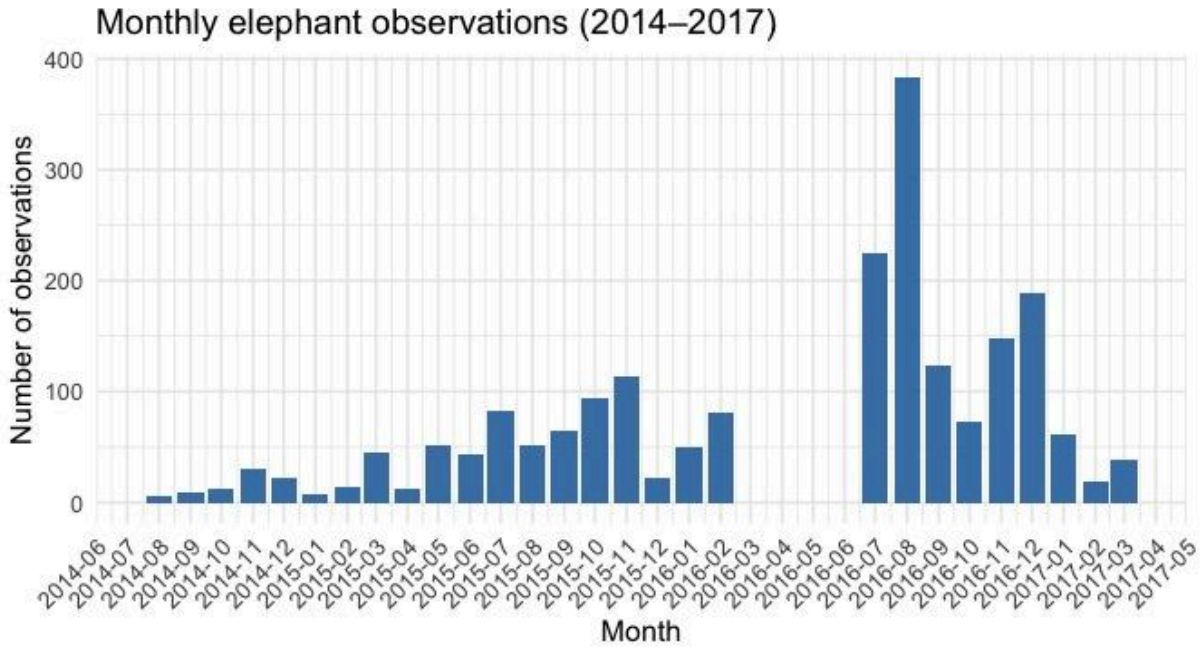

Figure A1. summaries the number of observations of elephants made each month during the study period between August 2014 and March 2017 that were included in the final model and analysis.

Appendix 2: Diagnostic plots of the GAM-model

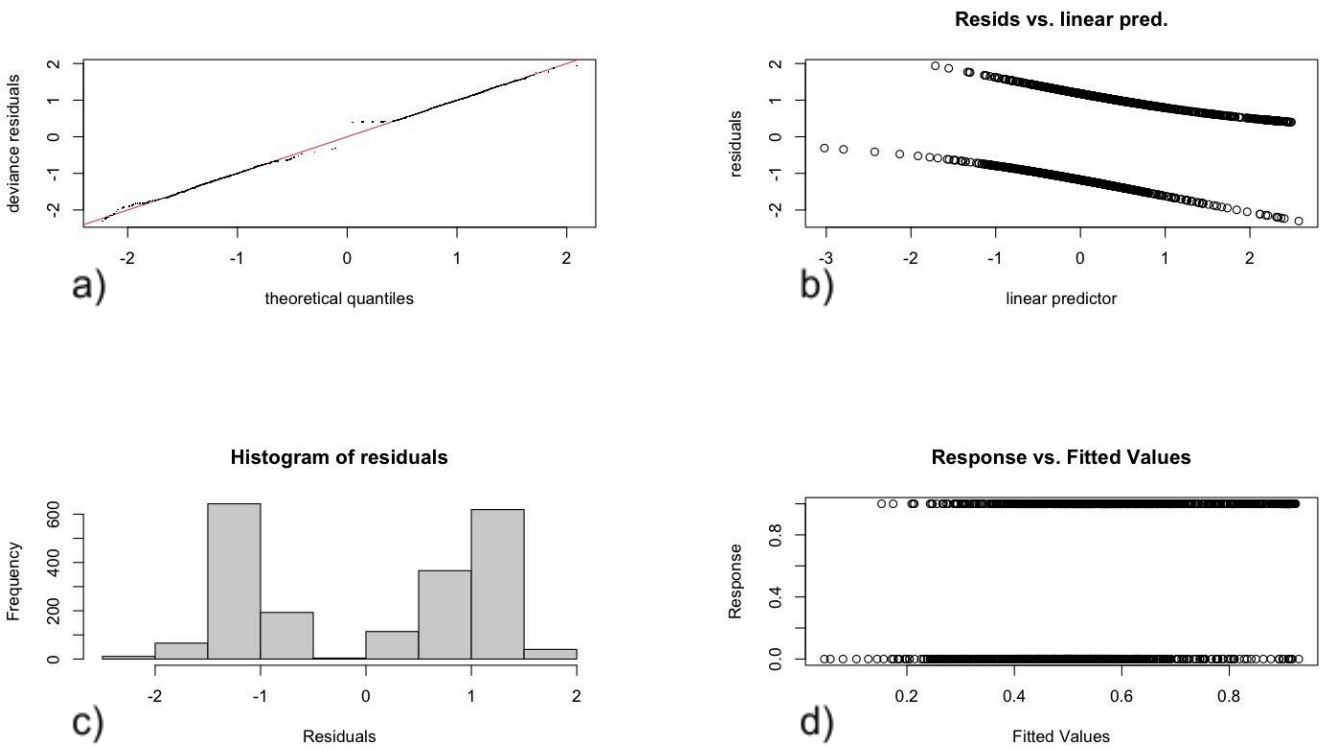

Figure A2. shows the diagnostic plots generated from the GAM-model. A2a) illustrates the QQ-plot of deviance where the residuals from the model are fitted against theoretical residuals represented by the red line to which there exists no major deviance. A2b) shows the residuals from each binary outcome, illustrated by two separate bands, plotted against their corresponding linear predictor before it has been logistically transformed. The bands show no strong and concerning curvature or clustering patterns. A2c) represents the histogram of residuals with two distinct clusters due to the response variable being binomial. A2d) shows a plot of each outcome of the response variable (either being 0 or 1) and their corresponding fitted values given by the model, representing their probabilities.