Laboratory of Geo-information Science and Remote Sensing

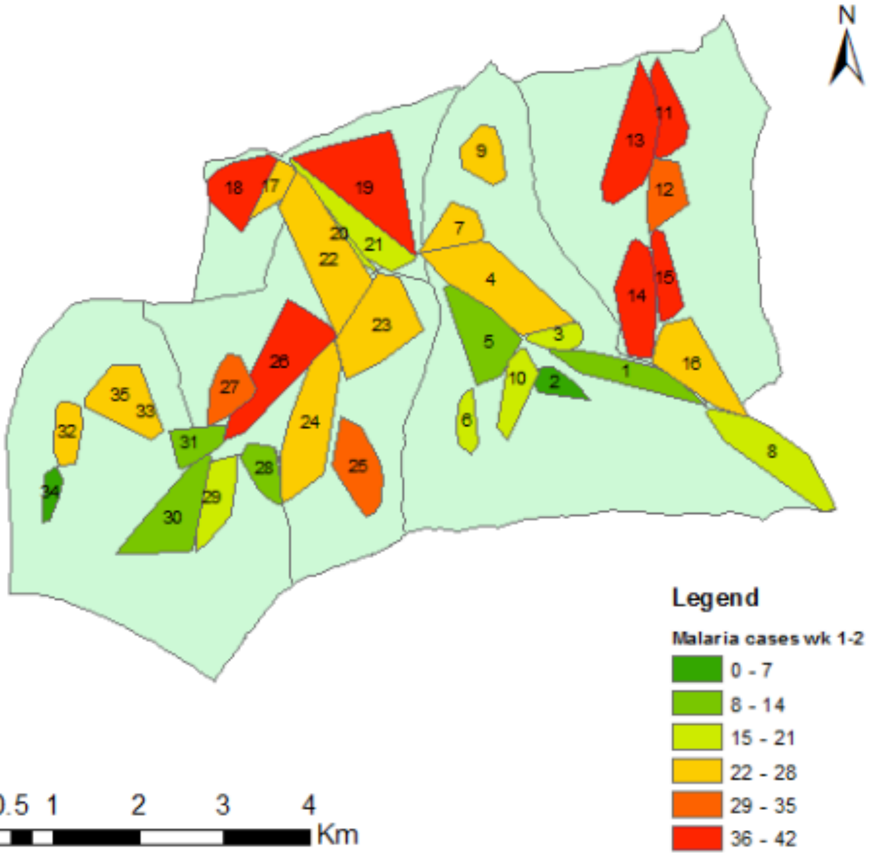
Thesis Report GIRS-2017-03

The influence of small-scale human movement on the transmission of malaria

A spatial temporal approach to a case study in Ruhuha sector in Rwanda

D. Bosch

April 20th 2017



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A spatial temporal approach to a case study in Ruhuha sector in Rwanda

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Abstract

It has been noticed in previous research that the movement of people and animals can influence the spreading of malaria by carrying the *Plasmodium* parasite or the *Anopheles* mosquito into areas previously devoid of malaria. This relationship was not quantified, and only considered on a larger scale.

This research investigates the influence of the small-scale movements of people on the spreading of malaria. The spatial movement patterns of the human population in the Ruhuha district in Rwanda was investigated using high-resolution satellite images, and the temporal movements along these patterns were estimated according to a set of assumptions. This resulted in a number of people visiting each of the villages, a number of people travelling through them, and a number of people who visit a number of villages from their own villages each day.

This information was fitted to the malaria occurrence during six months in the study area in 2013 using multiple regression models. When relating the entire population, no significant correlation was found. However, when investigating the relationship between malaria occurrence and the number of children or adults visiting a number of villages daily a significant positive relationship was found.

Keywords: Malaria; Vector-borne diseases; Network analysis; Human movement

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1 Malaria

During the last half of the previous century and with great effort malaria has been eradicated from large parts of the globe (WHO, 2016), and is no longer found in temperate regions, yet still abundant in tropical areas (Gilles and Warrell, 1993). A wide range of complex factors has caused a re-emergence of mosquito-borne diseases, such as malaria in the past few decades (Gubler, 1998; Townson et al., 2005).

1.1 The Disease

1.1.1 Manifestations of Malaria

Malaria is caused by *Plasmodium* parasites, which are spread by the bite of the infected female *Anopheles* mosquitoes. Malaria can affect both humans and several animal species including cattle, depending on the preference of the species of the vector and the species of the parasite, some may affect both (Cox, 2010). This infection can have a range of outcomes ranging from asymptotic parasitemia, clinical malaria, severe malaria, to, in the worst cases, death (Breman, 2001).

Since malaria remains endemic in large areas, mostly concentrated around the equator (figure 1), it continues to be a serious risk for human health today (Hay et al., 2004). To most patients malaria is not fatal, however for non-immune patients, immune-compromised patients, children between six and 36 months old, pregnant women, or otherwise weakened patients malaria can have lasting health effects or even result in death (WHO, 2014b; Breman et al., 2014).

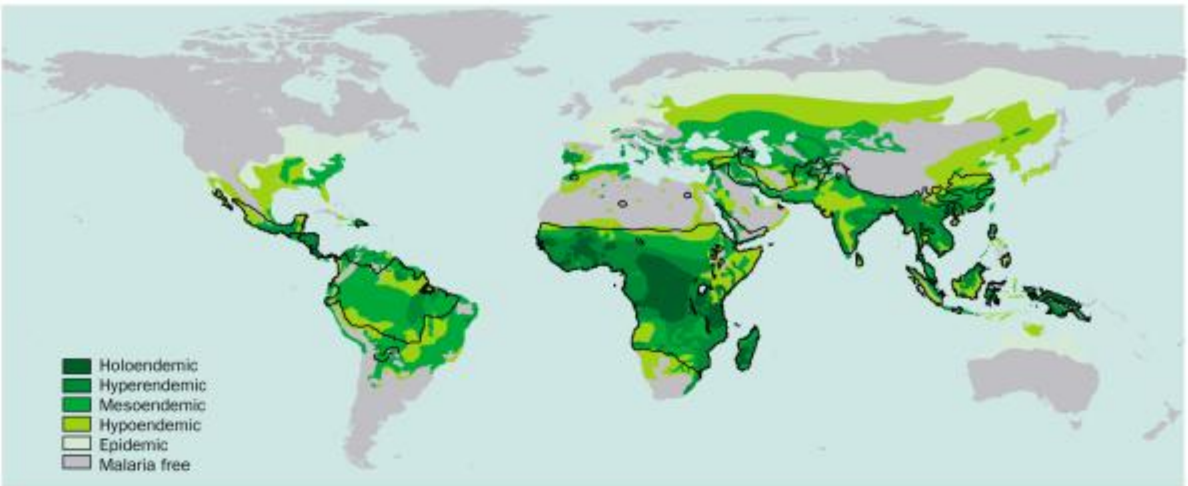

Figure 1: The global status of malaria endemicity. The black line indicates the 2002 limit of malaria risk. Taken from Hay et al. (2004).

Depending on the species of *Plasmodium*, the infected patient will start showing the first symptoms of malaria after an incubation period between twelve days and three months (Svenson et al., 1995). The symptoms of malaria may include: an increased heart rate, rapid breathing, chills, general discomfort, fatigue, sweating, headaches, coughing, anorexia, nausea, vomiting, abdominal pain, diarrhea, joint pain, and muscle pain (Svenson et al., 1995). Severe cases of malaria can cause pulmonary edema, acute renal failure, severe anemia, and/or bleeding, acidosis, hypoglycaemia, and the most common metabolic complications (WHO, 2014b).

1.1.2 History of Malaria

Malaria, autumnal fever, quartan fever, Roman fever, or one of the many other names this disease has been called during its long history, has been plaguing humanity since the first of the *Homo* genus walked planet Earth, as both the vectors and the malaria parasite evolved alongside humanity (Carter and Mendis, 2002). Even though we cannot be certain that all (written) mentions of the aforementioned fevers were what we call malaria today, the recognizable symptoms, and other characteristics, such as environmental variables, and the seasonal variation mentioned in those texts, do indicate that it was indeed widespread throughout the world until recently (Reiter, 2001).

In 1957 the decision was made to eradicate malaria disease from continental Europe (Bruce-Chwatt, 1987). With the help of new insecticides such as dichlorodiphenyltri-chloroethane, more commonly known as DDT, modern farming techniques, and changing social dynamics, this goal was achieved in 1975 when The Netherlands were the last country in Europe to be officially declared completely free of malaria (WHO, 1978). With similar strategies, countries in northern America managed to eradicate the disease as well. These days, malaria is only sporadically found in temperate regions, yet it is still abundant in tropical areas (Gilles and Warrell, 1993).

1.2 The Parasite and Vector

As mentioned in the previous chapter, malaria is caused by an infection of the *Plasmodium* parasite. This parasite is transferred between hosts by female *Anopheles* mosquitoes. When searching for a blood meal, which is necessary for the mosquito to lay her eggs, she may infect her victim with the malaria sporozoites she carries with her (Meijerink et al., 2000; Cox, 2010).

1.2.1 Life Cycle of Malaria

The infection of humans, or animals however this thesis focuses on the infection of humans, with malaria begins when *Plasmodium* sporozoites are transferred to the human by a mosquito bite. Sporozoites are the spore like life stage of *(Plasmodium)* parasites, which are capable of moving themselves within the host. For a graphic overview of the *Plasmodium* life cycle, see figure 2.

The sporozoites are released into the bloodstream of the human during the bite. (14). Once the sporozoites reach the liver of the host (1) they will fulfill a stage of asexual reproduction, the so-called exoerythrocytic schizogony (2 and 3). After this, the parasite may remain dormant for weeks up to several years depending on the species of *Plasmodium* (CDC, 2016). After the next life-stage of the parasite, called uninucleate merozoites (4), invade the host's red blood cells, and proceed with a second stage of asexual reproductions, called erythrocytic schizogony (5 through 7) (Cox, 2010). During this blood stage we see clinical manifestations of malaria (CDC, 2016).

This process is repeated several times, and the merozoites grow into male and female gametocytes (8), which are taken up from the host by another *Anopheles* mosquito when they feed. There, the gametocytes will mature into gametes (9) and reproduce again (10 through 13). The formed sporozoites will be injected with the mosquito saliva into a human when the mosquito feeds again (Cox, 2010). In summary; the vector infects the human hosts with malaria parasites, who in turn may infect more mosquitoes, which continue to spread the disease by biting more hosts.

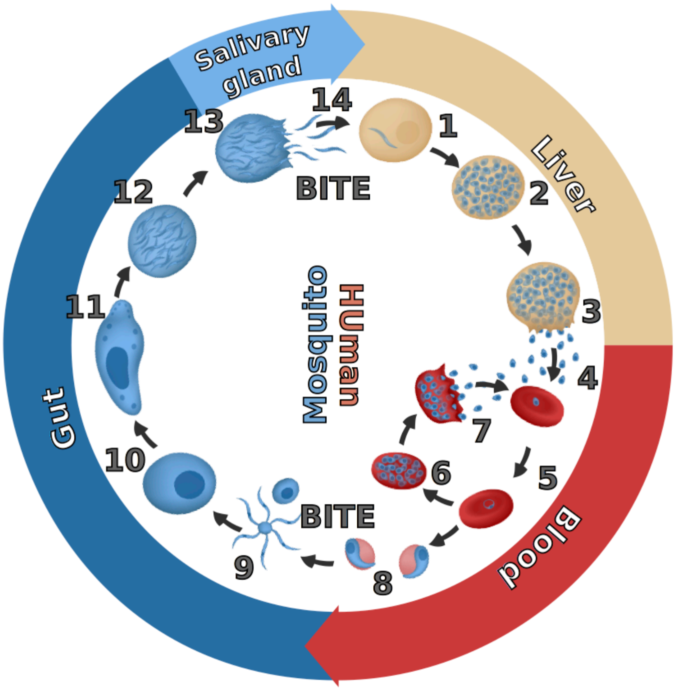

Figure 2: Complete life cycle of Plasmodium parasites. The numbers are referred to in the text above, indicating the described steps. Adapted from (nvbdcp, n.d.; CDC, 2016; yourgenome, 2016)

1.2.2 The Life of the Vector Species

While certain knowledge on the cause of the disease and the parasite is required to understand the spreading and severity of malaria, the spreading of the disease between hosts is best understood when looking at the behavior of the vector species, the *Anopheles* mosquito, and more specifically the female. While the behavior of the mosquito varies highly per sub-species, she will always lay her eggs in some form of stagnant water, or a place that will likely contain water soon shortly after having had sufficient blood meal (Macan 1961; Clements, 1963; Bentley, 1989; Beier et al., 1990). The larvae emerging from these eggs will feed on algae, bacteria, and other microorganisms in the water. It then proceeds to develop into a pupa, and subsequently into an adult mosquito, and fly out into the world to feed, reproduce and, if female, lay more eggs (Evans, 1938; Cox, 2010).

1.2.3 The Environment of the Vector Species

In order to breed, the female *Anopheles* mosquito requires a blood source within mosquito flying distance from a suitable location for laying eggs (Kaufmann and Briegel, 2004). It has been shown by Minakawa et al. (1999) that the *Anopheles* mosquito prefers to breed near houses, and thus mi2nimize the flying distance between blood meal, and the oviposition site.

Supporting the above findings, it has also been proved that the improving of housing, and separating cattle from humans by building modern stables at farms have contributed significantly to the decrease of malaria in Western countries (Reiter, 2001).

Many (sub-) tropical countries have a climate with a wet and a dry season. During the dry season, the number of mosquitoes found per time interval per area in several studies was much lower than those collected during the wet season (Mbogo et al., 1995; Minakawa et al., 2001; Bomblies and Eltahir, 2009; Loha and Lindtjørn, 2010).

The amount of *Anopheles* often increases a short time after rainfall has occurred; the specific lag-time depends on the mosquito species (Galardo et al., 2009). This increase is due to increased availability of breeding sites, and thus a rapid increase of young mosquitoes a while later after they grow from larvae to adults.

The eggs of most *Anopheles* mosquitoes are laid in stagnant water bodies, with widely varying and species-specific properties. Therefore, the availability of stagnant water is the first and foremost condition for the presence of mosquitoes, and by implication also for the presence of malaria. Most *Anopheles* mosquitoes oviposit directly into stagnant water. Some of these species do this in any available water, while others require very specific hydrological conditions (Macan, 1961). Stagnant water can be ponds, marshes, puddles, artificial containers, plant axils, or literally anything else that might contain water for a period long enough to allow the larvae to develop (Gillet, 1971; Stresman, 2010).

Human activity can both provide the mosquitoes with more food for blood meals, and with more and better oviposition sites. Especially agricultural practices and deforestation can increase the number of *Anopheles* in an area significantly (Rosenberg, 1982; Dolo et al. 2004; Diuk-Wasser et al., 2006).

The number of mosquitoes is greatest in those places that are warm, moist, and have both humans and stagnant water for feeding and breeding respectively (Patz et al., 1996; Epstein et al., 1998; Depinay et al., 2004; Galardo et al., 2009). However, the mosquito does not enjoy extremes of any of the environmental variables mentioned. Too much or too little nutrients in the water, extreme air or water temperatures, dry air, and heavy rains may decrease the number of malaria vectors (Jepson et al., 1947; Hayes and Charlwood 1979; Martens, 1997).

Since it is the mosquito that will transfer the parasite to the host, environmental variables favorable to these species are determining factors in the occurrence of malaria in an area. If the vector cannot survive in a certain area due to the environmental conditions, we will not contract malaria there either. And the other way around, in areas where the environmental conditions are very favorable, we will be more likely to be bitten by an infected mosquito, and thus contract malaria.

1.2.4 Attempts to Reduce the Transmission of Malaria

Despite a wide range of methods to control malaria, such as insecticide treated bed-nets (ITNs), indoor residual spraying (IRS), and rapid diagnostic tests (RDT) and treatment, the battle against malaria has not yet been won (Rulisa et al., 2013). In Rwanda, the effect of this was a 50% reduction in malaria mortality between 2000 and 2010 (WHO, 2011). However, in 2009, 2011 and 2013 a resurgence in malaria cases was observed (WHO, 2014a), showing that the measures taken at the moment are insufficient, and a deeper knowledge into this disease and the vector species is needed to prevent further setback.

2 Malaria Transmission by Human Movement

Not only the movement of mosquito vectors is important for the spreading of malaria, but also the movement of the human or animal hosts. While travelling from an area of high infection risk to an area with a lower risk, humans can carry both the parasite and/or the vector with them (Prothero, 1961; Shanks et al., 2005). The parasite would be carried inside the body as they have parasitaemia. The mosquitoes hitchhike on luggage, cars, cattle skin, and similar ways.

This is of special interest when considering the fact that in areas with a lower risk, less people contract malaria and thus the population immunity is lower (Prothero, 1961; Doolan et al., 2009). When malaria is brought into these areas, for example by the increased accessibility after the laying of roads or an increase in trade, this can result in severe malaria outbreaks in places where malaria was previously non-existent or rare (Spencer et al., 1956; Peters et al., 1958; Gascon et al., 1984). There are a few examples in malaria research where this has been found; often only as footnotes in scientific malaria articles, yet when put together they tell an interesting story. A summary of the limited literature on malaria spread by human movement follows in this chapter.

2.1 Malaria Transmission Due to Mass Migration

Human mass movement is a major cause of the spread of many diseases; this also is true for malaria (Teklehaimanot, 1986; Dar et al., 1993; Yukich et al., 2013). By far the largest groups travelling across significant distances are doing so because war, either armies or refugees, or mass movement due to displacement caused by civil unrest, famine, natural disasters, or other similar reasons.

2.1.1 Armies

It is common knowledge that the placement of soldiers in foreign territories may cause both them to become sick due to lack of immunity to local diseases, as well as due to an often overall lack of hygiene, food, and other hardships, which attribute to an increased vulnerability to any disease. Occasionally, soldiers bring these diseases back home. Vice versa, these armies may bring diseases into the areas through which they travel or are stationed at, thereby infecting the local population. The following examples show that this is also true for malaria.

The first recorded epidemics of malaria in the highlands of Kenya were when soldiers returned home after the World War One from Tanzania, they were infected with enough parasites to start an epidemic (Matson, 1957). A few years later, during the next world war, near Kericho in Kenya a camp of soldiers passing by prompted a large and sustained epidemic with the local tea-estate (Garnham, 1945).

2.1.2 Refugees

One of the most common causes of death among refugees is malaria when they move to malaria endemic countries (CDC, 1992; Martens and Hall, 2000; Bloland and Williams, 2002). Especially because for those who are displaced due to natural disasters, war, economic, or political reasons often lack housing and basic necessities which may prevent sickness or should improve their chances of survival.

An outbreak of malaria in a refugee camp in Tanzania with Burundian refugees caused the mortality from malaria and anemia in children younger than five year to become ten times larger, indicating the low immunity in these children (Crowe, 1997).

After 15 years of war the population of Luanda, Angola, increased exponentially in the 1980's. This caused an increase from malaria hypo-endemic to meso-endemic in only five years, and made malaria the number one cause of child death instead of the sixth (Kanji and Harpham, 1992).

In 2000 a group of 224 refugees from Tanzanian refugee camp were relocated in Quebec, Canada. Three to four weeks later an outbreak of malaria was observed in the area despite the fact that the refugees had been dispersed around the entire province (Ndao et al., 2004).

Both these examples show that when a large group travels from malaria endemic areas, to clean areas, they can introduce the parasite into the local population, which often is not immune to malaria.

2.2 Searching for Work

In the entire African continent, large-scale labour migration is of major social, economic, and demographic importance. In search for work people travel small or great distances, often crossing national boundaries. These can exhibit a seasonal pattern for agricultural labour, travelling mostly outside of the malaria season, or are completely detached of a pattern such as in mining, industrial, and commercial businesses. In both cases, the people from areas devoid of malaria can easily be infected and bring the parasite back to their home, starting an epidemic there (Prothero, 1961).

Both in Central and South America the movement of such seasonal labourers from non-endemic into endemic areas has been found to correlate with the outbreaks of local transmission of malaria upon their return home (Zucker, 1996; Malakooti et al., 1998; Shanks et al., 2000).

In Swaziland where malaria was eradicated in the 1950's, the disease was reintroduced after agricultural developments in the 1960's and 1970's, where labour from Mozambique reintroduced the *Plasmodium* parasite back into the newly cultivated sugar estates, which are favored mosquito oviposition sites (Packard, 1986).

These examples show that even small groups can disperse malaria if they move in the same direction around the same time scale. They can introduce malaria into clean areas, and often these groups searching for work are more vulnerable themselves due to their displacement or poverty.

2.3 Influence of Nomadic Habits on Transmitting Malaria

Since the political boundaries of the African continent were defined by European governments during colonization, and thereafter divided into new countries, these arbitrary boundaries now have had little meaning to many of the people living in these lands. Many, and especially nomadic peoples, move freely within pre-colonial and flexible territories, crossing the borders as they see fit (Prothero, 1961). Very little research has been published on malaria spreading by human migration and especially few papers have been published on nomadic influences, even though medical aid to these vulnerable groups seems to have improved, the overall situation is still similar.

2.3.1 Nomadic Patterns

These nomads most definitely have a unique and important factor when considering the influence of human travelling on the spreading of malaria, and should be considered separately due to their distinctive qualities. These qualities vary greatly between nomadic groups, but most have a period of residence in farming areas where they erect temporary shelters during the early wet season, and most often a large group of cattle accompany them (Prothero, 1961; Sheik-Mohamed and Velema, 1999). Some travel with their entire community and others leave those who are vulnerable, such as the elderly and children, behind in a permanent home (Sheik-Mohamed and Velema, 1999). A smaller fraction is hunters and collectors in the rainforests; they do not have cattle or farms (Sheik-Mohamed and Velema, 1999).

In addition to this, pastoral habits where part of the community moves to low-lying areas for a season to search for water for cattle or to partake in agricultural activities has been identified as a significant contribution to malaria in the highlands. After a season in malaria endemic areas, such as the low-lying wetlands, these people return to those left behind and enable infection (Longstreth and Kondrachine, 2002; Mboera et al., 2005).

2.3.2 Lack of Medicine and Control

The patterns of these nomadic tribes are often not fixed, they go wherever they can find what they need and only a small number has permanent settlements to which they return regularly. This, in combination with their reserved attitude towards strangers and conservative society, makes it difficult for humanitarian aid to find and assist them in the eradication of malaria and other diseases (Prothero, 1961; Sheik-Mohamed and Velema, 1999). Due to the trans-borders nature of their travelling. International cooperation is needed in order to create effective malaria treatment and prevention programs.

An example of this lack of international cooperation is the situation on the border of Ethiopia and Somalia. Here, nomads make use of open tanks that conserve rainwater to survive during dry seasons since there are no other dependable sources of water in the area. These tanks, located both on the Ethiopian side of the border and the Somali side, make perfect breeding grounds for mosquitoes. The nomads travel freely across and beyond these areas. In Somalia the tanks are observed, and treated to prevent mosquito breeding if necessary. However, on the Ethiopian side they are not, and thus the nomads may still be infected with malaria in Ethiopia and spread it into Somalia, despite the latters efforts to prevent mosquito breeding (Prothero, 1961).

2.3.3 Habits Enabling Survival of Vector and Parasite

Especially the large number of cattle, which can carry both the malaria parasite and the vector across great distances, are a reason nomadic tribes manage to bring malaria into previously unaffected areas (Prothero, 1961). In addition to this, their shelters, which for African tribes are often made of plant materials as opposed to the nomads in the Middle

East, are very favorable shelter to mosquitoes, and due to their limited contact with governments or health care workers are hardly ever sprayed with insecticide (Prothero, 1961). To make them even more susceptible to malaria, the African tribes most determining factor for movement is water, they follow water sources, and thus have increased chances of getting bitten by mosquitoes (Sheik-Mohamed and Velema, 1999).

While there is no substantial evidence that nomads spread malaria beyond their own societies, their habits show that their vulnerability to the disease is quite large. And the amount of travelling they do between endemic and clean areas is mentioned in the papers as a source of malaria in other peoples they visit or travel along.

2.4 Other Population Movements

Aside from the human movements mentioned in the previous paragraphs, some of which are large numbers of people, or across large distances, there are several more examples of extreme population movements. These show that it is indeed possible to reintroduce malaria into areas where it was previously non-endemic and caused an outbreak.

One of the most striking examples are the highlands of Madagascar, where between the late 1960s and the early 1980s malaria was completely suppressed. Then, once the local population had lost it's natural immunity, malaria was reintroduced and a two-year epidemic followed, costing tens of thousands of lives (Carter and Mendis, 2002). This shows that when a population is (no longer) familiar and thus immune to malaria, (re-) introduction of the parasite can have devastating results.

2.3.1 Colonization of New Land

Whenever people move to new areas that have previously not been in contact with malaria they may bring the disease with them. This effect is amplified by generally more harsh conditions such as lack of food, exhaustion, and basic housing, which weaken people, as well as enables close contact with the vectors (Martens and Hall, 2000).

An illustration of this is the Brazilian Amazon region, which was almost entirely malaria free after national malaria campaigns during the 1950's and 1960's. During the late 1960's and onwards large road construction work, as well as agricultural settlements, hydroelectric projects, and the discovery of gold, enabled large-scale migration towards the area, and subsequently a dramatic increase in malaria (Marques, 1986; Martens and Hall, 2000).

Another striking example would be the colonization of the New World. The populations of the Americas before 1492 were almost entirely devoid of any of the genetic anomalies that are connected with the long-term exposure to malaria infections; this leads the authors to the suggestion that they have not been in contact with malaria before this time (Carter and Mendis, 2000). It has been suggested that the parasite survived within the European colonizers the long sea voyages across the Atlantic and infected mosquitoes in the New World and enabled them to infect the non-immune local population (Carter and Mendis, 2000).

2.3.2 Moving from Rural to Urban Areas

As is well known, the population is shifting from rural to urban areas all over the world. In the first stages this often is accompanied with extreme poverty and the thus resulting lack of food, shelter, and health care (Longstreth and Kondrachine, 2002).

This means that the people arriving in urban areas who often have to live in the worst situations and often do not have access to health care, have an increased risk of getting ill, including from malaria. Poor sanitation, bad roads, and open water containers increase the amount of breeding sites, and the lack of shelter increases the chances of urban immigrants to be bitten by mosquitoes (Martens and Hall, 2000; Longstreth and Kondrachine, 2002). To make matters worse, the turnover rate of these immigrants is very high, they do not stay long in any location and new ones always take their place, and they are often not legal, which makes them hard to trace and keep track of in order to gain proper insight into their lives as well as their medical state, increasing both the uncertainty of their influence on spreading malaria, as well as attempts to reduce this (Prothero, 1961).

2.5 Lessons from Literature Review

From the above literature review we can conclude that malaria can travel large distances by hitchhiking with humans. These distances surpass any distance a mosquito can fly on its own. Whether these spreads are due to infected patients carrying the *Plasmodium* parasite into areas where malaria is non-endemic, or because of carrying infected mosquitoes with them is subject to speculation, and most likely a combination of the two, depending on the distance and nature of the travels.

How strong exactly this influence is remains unknown; no research has yet been done into the direct influence of human travelling patterns on the spreading of vector borne diseases. We can assume that the influence of these patterns does depend on the condition of the parasite, the mosquito, as well as the host, both for the sending and for the receiving population (Longstreth and Kondrachine, 2002).

3 This Research

This thesis research aims to further investigate the above-mentioned influence of human movement on the transmission of malaria. While geographical information sciences (GIS) are more often used in understanding and aiding disease control, in vector borne diseases GIS mostly focuses on the habitat of the vector and not on the potentially otherwise spreading methods of the disease.

3.1 Problem Definition

It is common knowledge that the *Anopheles* mosquito spreads the *Plasmodium* parasite by infecting new hosts, as discussed in chapter one. But it is less commonly known that also the vector and the parasite are spread by being carried about by humans across larger distances, or what exactly the influence of this pathway is on the occurrence of the malaria disease, see chapter two. Despite the research done on the correlation between human movement and the transmission of malaria infection as mentioned in the previous chapter, no extensive research has been done on using more than basic GIS knowledge. Though some qualitative research has been done on the relationship between human movements, no in-depth quantitative analysis has been done in this field to identify the exact influence of the number of people moving and the spreading of malaria.

Whether or not human movement contributes to the spread of malaria, and perhaps also of other vector borne diseases, is still unknown. In addition to the lack of a GIS approach to these specific questions, most of the aforementioned research is done using secondary data and solely over large areas, often transcending national borders. There is a definite lack of a quantitative insight on the small-scale movements of people and the spreading of malaria.

3.2 Research Questions and Objective

The objective of this research would thus be to identify a correlation between human movement and the spreading of malaria. This would be done using existing data on the occurrence of malaria in a study area in the Ruhuha district in Rwanda and the road network as deducted from satellite imagery. To reach this goal, the following research questions are asked:

RQ 1: Along which routes do the people travel in the study area?
RQ 2: How do these travel patterns vary in time?
RQ 3: Where and when did malaria occur in the study area?
RQ 4: What relationship is there between the spatial and temporal travelling patterns in the study area and the occurrence of malaria?
RQ 5: By what approach is a relationship to be evaluated?

3.3 Research Approach and the Study Area

3.3.1 Research Approach

The answers to these questions will be investigated in the Ruhuha sector in Eastern Rwanda. As described in the following chapter, there is no road map of the study area available at the moment. Thus the first step is to create such a network and to estimate the movement of people within the area supported with some assumptions based on general knowledge about the area and its inhabitants. This information, combined with the malariometric survey data, should be able to answer each of the above mentioned research questions and fulfill the objective of the study.

3.3.2 Ruhuha Sector in Rwanda

The survey data used for this research is collected in the Ruhuha sector in the Bugasera district in the Eastern province of Rwanda, see figure 3 for the exact location of this study area. Malaria in this area has been classified as hypo-endemic (Kateera et al., 2015).

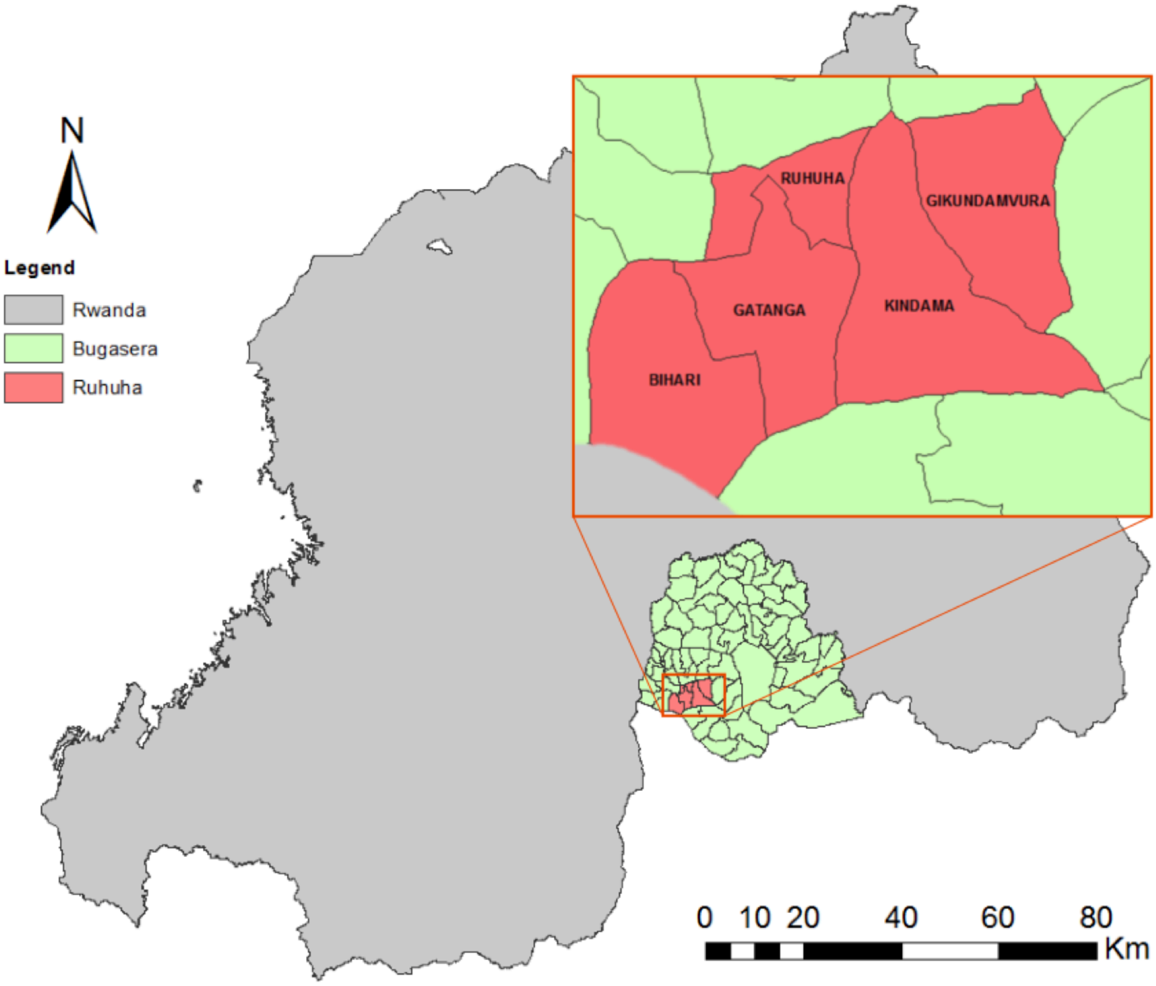

Figure 3: The location of the Ruhuha district within Bugesera in Rwanda where the malariometric survey data used for this research was collected in 2013 and the study area of this research.

The area is divided into five administrative cells, and has 35 villages of varying size on an area of roughly six by ten km. There is a health centre roughly at the centre of the sector as well as two other health clinics just outside its borders, since this is a traditionally high malaria transmission area, there is quite some data available from the health centre on the number of malaria cases. In addition to the clinics, about 140 Community Health Workers (CHW) are active in the area, 105 of which are also members of the Community Malaria

Action Teams (CMAT), which is part of the on-going Malaria Elimination Program in Ruhuha (MEPR) to combat malaria using a community-oriented approach (Kateera et al., 2015a).

This area is predominantly rural; the main income in most households is crop cultivation (76%), followed by fishing (9%) and herding (7%). Most of the houses are located around the road running from the mid-North to the Southeast of the area. The rest of the houses are spread throughout the sector in small clusters, with around 125 households per village.

In the Southwest a lake borders the sector and a few marshlands are scattered around the entire area, most of which are cultivated with rice fields. The area has a tropical climate with an average temperature of between 20°C and 30°C. There are two rainy seasons and an average annual precipitation of 1,608 mm per year (Tuyishimire, 2013).

3.3.3 Malariometric Baseline Survey

Between June and December 2013 a complete malariometric baseline survey was carried among the 4,352 households in the Ruhuha sector. After giving informed consent, the head of each household answered a number of questions regarding the demographics of the household, the living standards of the house, some questions about the perception on malaria and the health system, as well as informing to any malaria cases in the past year and the way this was dealt with. Some of this data was used for this thesis, for the used variables see table 1 below.

Table 1: Variables extracted from the 2013 baseline survey on households in the Ruhuha district.

Data	Variables	Unit
Administrative data	Unique identifier	-
	Household number	-
	Village	ID/ name
	Location	Lat/ Long
Household statistics	Household size	Number of people
	Source income	Crops/ livestock/ fishing/ other
	Religion	Catholic/ Protestant/ Muslim/ etc.
House characteristics	Toilet	Flush/ pit latrine/ VIP latrine/ none/ other
	Water source	Pipe/ public well/ borehole/ rain/ surface/ public tap/ bottled/ other
	IRS	Yes/ no/ unknown
Transport to health clinic	Difficulty due to distance	Yes/ no/ unknown
	Estimated transport time	< 1 hrs/ 1-2 hrs/ > 2 hrs/ unknown
	Transport method	Car/ bike/ public transport/ walking/ other
Malaria cases	Last fever	1-2 wks/ 3-4 wks/ 2-3 mths/ >3 mnths/ none
	Medical care	Hospital/ pharmacy/ CHW/ health centre/ none
	Treatment	Yes/ no

The complete study involved 12,965 individuals, of which 652 (5%) were found to have malaria parasitaemia, which means that the *Plasmodium* parasite was present in their blood. A high risk of malaria was associated with being child, adolescent, male, or living in a household with multiple occupants. The parasitaemia cases were found in 518 households (13%). The risk of malaria increased when these houses were closer to the marshlands and water, and when they had floors and walls made of natural materials such as mud, earth, wood, or straw (Kateera et al., 2015b).

3.3.4 The EVOCA Project

This study will be conducted within the framework of the Environmental Virtual Observatories for Connective Action project (EVOCA project) in crop, water, livestock and disease management. This project aims to increase the understanding of local environmental system dynamics in order to enable action for tackling developmental challenges (Leeuwis, 2016). Part of the EVOCA project is specifically aimed at understanding malaria and its spread throughout the study area by using digital media and citizen science (Leeuwis, 2016). The research proposed here would support the health aspect of the EVOCA project by allowing human movement to be taken into account when researching malaria and the spreading of mosquitoes.

4 Methodology

In order to answer the research questions, a method has been developed based on the available data. These will be described in the following chapter according to the research questions. A schematic overview of these methods is shown in figure 4 below.

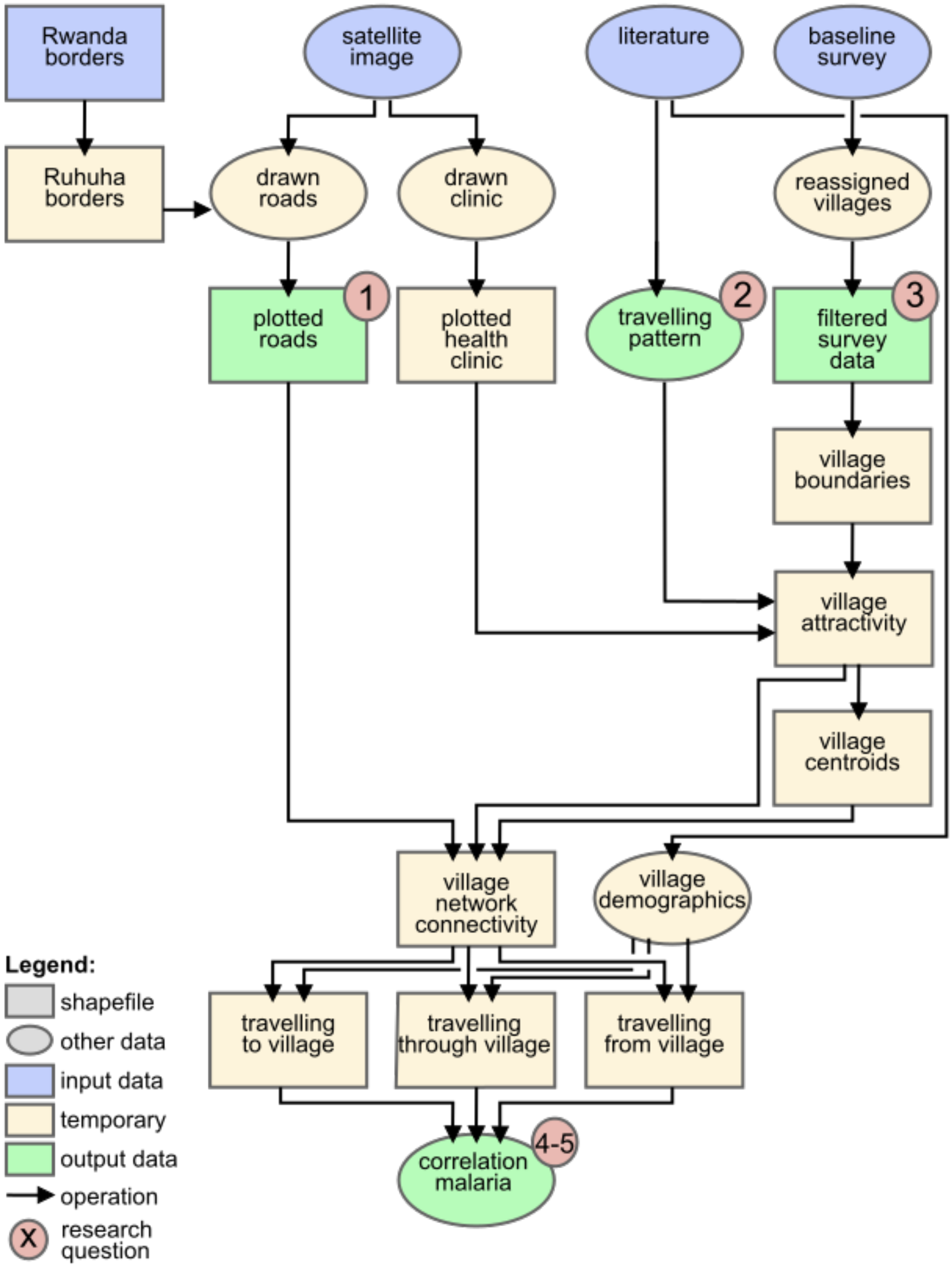

Figure 4: Flowchart of the methodology of this research.

4.1 Spatial Travelling Patterns

The first research question is: along which routes do the people travel in the study area? This question was investigated by clipping the study area from a satellite image, on which then the routes were drawn.

4.1.1 Ruhuha Sector

Like mentioned in the previous chapter, the study area is the Ruhuha sector in Eastern Rwanda. To define the boundaries of this area, a vector shapefile of the cell boundaries of Rwanda were downloaded from the Rwanda geoportal, which was last updated in 2012 (rnra, 2015). The cells that were located in Ruhuha sector were filtered out, and so the boundaries of the study area were obtained.

4.1.2 Road Network from Satellite Image

From Google Earth version 7.1.7.2602 the true-color satellite images from CNES Astrium photographed on the 29th of June 2016 are freely available for non-commercial use. After displaying the study area boundaries on top of satellite image as provided by the program, the roads were digitally drawn manually on top of this. The roads were visually identified and with the *Add Path* function of Google Earth drawn on top of the image. In addition to this, the approximate health centre was estimated on the map and marked as a point. These were saved in a *My Places* folder, which was subsequently saved as a Keyhole Markup Language file (KLM).

These two datasets, one consisting of 443 lines with Feature IDentification numbers (FID), and the second with a single point, were imported into ArcGIS, version 10.1, and projected as WGS 84 when transformed into shapefiles.

4.1.3 Creating Network Structure

The shapefile with the spatial road pattern as created as described above was converted to a network dataset in ArcGIS with edges with a value describing the distance and road class, and nodes at their intersections. This later allows for calculating the exact distance and cost for travelling according to these roads.

4.1.4 Plotting the Villages

This research is based on a baseline survey conducted in the study area in 2013, and was part of the earlier mentioned MERP project. This project was a collaboration between the Ministry of Health, Rwanda, and the Amsterdam Medical Center, with Wageningen University as partner in the project. The data were combined with the road network constructed from satellite images obtained from Google Earth to show the spread of the households in the study area. Each household in the dataset has a unique number, as well as a number of the village they belong to.

To obtain the borders of the above-mentioned villages, their boundaries were calculated using these assigned village identification numbers. Drawing a convex hull minimum bounding area around those houses that are allocated to each village number creates the boundaries of the villages.

When plotting these data, it became clear that some of the households were allocated to villages that were in reality far away. This was likely due to wrongly recording in the field, perhaps confusion or misinformed population. The first pre-processing step was thus identifying those houses and assigning them to the villages they should belong to, based on a visual inspection of the dataset. For the 61 households with a changed village allocation see table 2 in appendix B. See figure 5 below for the difference between the resulting villages when no outliers have been filtered out. In figure 5A there are several of such points visible, which are reassigned in figure 5B. The convex hull boundaries in with these outliers in figure 5C clearly are overlapping and have some extreme protrusions that only include a single point, occasionally up to a kilometer away from the nearest household within “the same village”. These protrusions and overlapping borders are gone in figure 5D when these outliers have been reallocated.

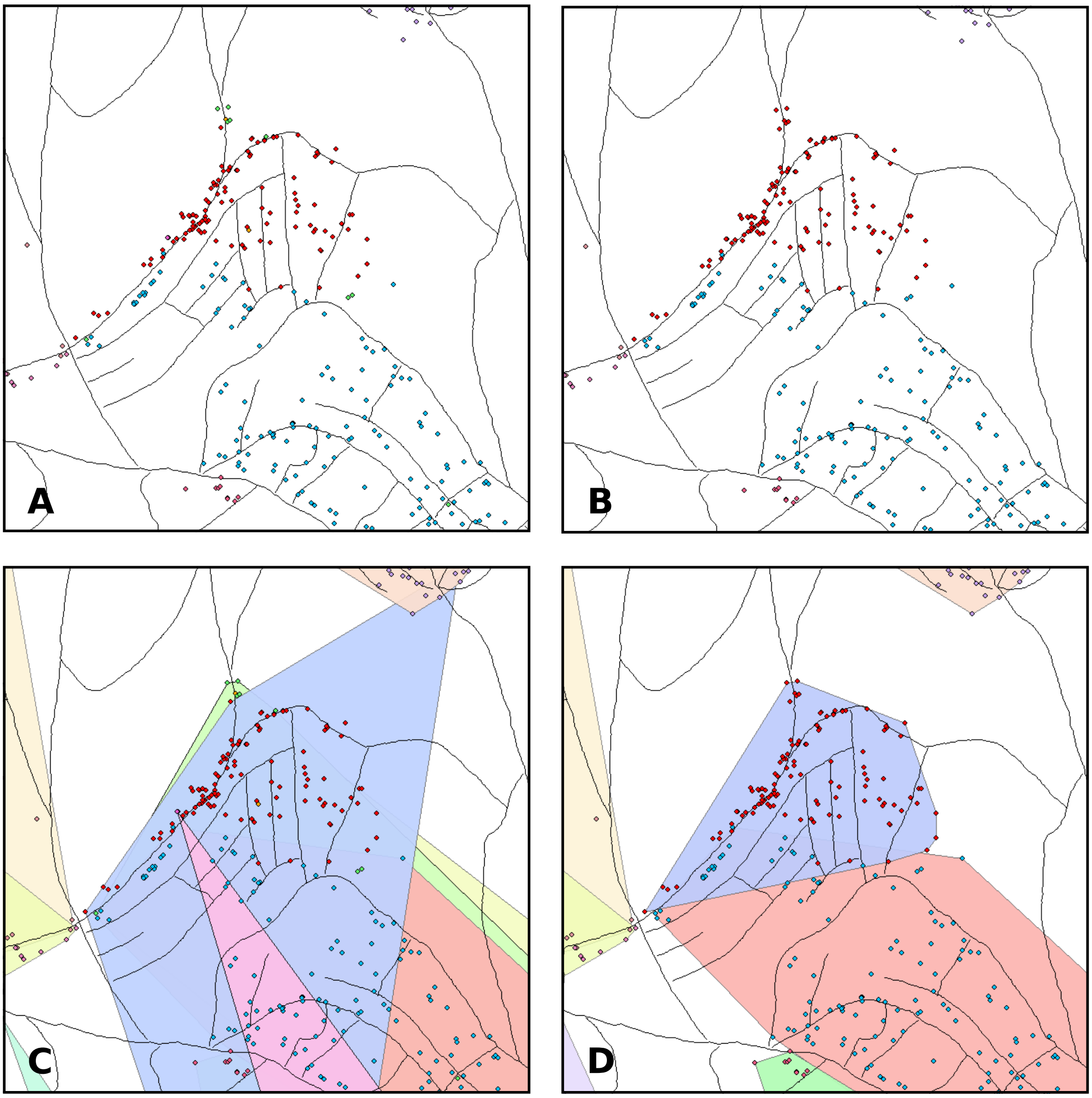

Figure 5: Before and after redefining the villages, as shown here where A and C are respectively the households and the villages before reassignment of the outliers, where Kamweru (pink) has a single outlier in the Gatare (blue) village. And the Gatare village has several extreme outliers beyond the borders of these images, as well as some other villages with which distort the image. The B and D image have these outliers reassigned, showing the difference is shape and size of especially the Gatare village.

Before proceeding to the calculations, the useful data was extracted from the entire dataset and the six empty fields were filtered out of the datasets, for unknown reasons these were not sampled. The Comma Separated File (CSV) of the survey data was converted to two shapefiles, one with a point for each household, and another one polygon for each village and projected in WGS 84.

The centroid with the average of the survey data can be calculated from the polygon shapefiles of the villages. This centroid is a centre of gravity, and in addition to the survey data of the village it also contains an attractivity factor for the surrounding population as estimated with the assumptions in paragraph 4.2.1 and the connectivity to other villages as seen using the travelling network constructed. The result of this is both a connectivity graph and an adjacency matrix of the villages according to the road network.

4.1.5 Up-Scaling the Spatial Travelling Pattern to Village Scale

In between obtaining a blood meal mosquitoes must fly from one human or animal to the next, or even from one household or village to the next. They visit their oviposition site before and after this blood meal, meaning that they must fly a substantial distance. *Anopheles* mosquitoes, which carry the malaria parasite between hosts, can fly an average distance between 0.4 and 3.9 km, over a mean time between 0.7 and 3.7 hours (Kaufmann and Briegel, 2004). These values have a significantly wide range and are strongly dependent on factors such as temperature, humidity, and nourishment (Kaufmann and Briegel, 2004; Jawara et al., 2008; Stresman, 2010).

The malariometric dataset contains 4,352 points with the survey data, each of which represents a household. Since the individual homes are clustered close together within villages, less than the average mosquito flying distance, the distance in between the households is negligible for these calculations and the data is aggregated to village level by creating a centroid for each village with the average survey data.

After this, the connections between the villages were calculated both for the distance between the centroids and for the nearest distance between the two outer boundaries of the villages and added to an adjacency matrix. This was then plotted into a new and simplified spatial travelling network for the study area.

4.2 Temporal Travelling Patterns

The second research question was: how do these travel patterns vary in time? This question was answered based on a number of assumptions, supported by data from several sources as described below.

4.2.1 Assumptions on Temporal Patterns

While we know for certain where the roads lie, for they are visible on the satellite image, we cannot see on a photograph which road is travelled at what moment in time or for what purpose. Therefore, several assumptions have to be made concerning the temporal travelling patterns since there was no time available to perform another survey to investigate the travelling habits of the local population.

Instead, using the malariometric baseline survey, the assumptions were made based on travelling for work, education, or religious reasons. Other assumptions for travelling frequencies and radius were made using additional sources on the facilities available in the study area. These temporal travelling patterns were divided into daily and weekly patterns of travelling between villages.

4.2.2 Combining with Spatial Patterns

As the attraction and the number of inhabitants for each village are known, these are added to the village level network as mentioned before. Then this information is translated into fractions of persons travelling along each connection on average every week. The information will later be used for calculating the relationship between travelling patterns and malaria occurrence.

4.2.3 Travellers Visiting in, from, or Travelling Trough Villages

The first indicator of the number of people travelling in the area is the amount of people visiting any village. This is calculated by the attractivity, and the number of people that are attracted to this factor based on the demographics. For example, there are two primary schools in the study area; each should serve about half the amount of kids in the age range for primary schools, who will visit these two villages daily. A total number of people visiting each village are then calculated based on all of the separate groups travelling there. This shows the number of people that can carry mosquitoes into each village as well as infect local mosquitoes with malaria parasites.

The next indicator is the amount of people travelling through each village on their way to their goals. These are added for all directions and each of attractivity factors. This shows the number of people that can carry mosquitoes into each village as well as infect local mosquitoes with malaria parasites.

The final indicator is the amount of villages visited from each of the villages. This is taken into consideration since it indicates the number of people each of the travellers comes into contact with, and the opportunity for being bitten by an infected mosquito, or a mosquito hitching a ride to their own village to bite others there later. People living in villages on the edges of the study area generally have to travel through more villages. The amount of villages visited is also multiplied by the total inhabitants of the village, since the population has quite a wide range.

4.3 Malaria Occurrence in the Study Area

The third research question is: where and when did malaria occur in the study area? The answer of this question came from the before mentioned malariometric survey. This dataset has a parameter indicating the last malaria case if there has been one in the past six months for each household, see table 1. These data are then plotted both for each household, and for values within each village. The latter is done for the number of malaria cases in each time class.

4.4 Relationship Between the Travelling Patterns and the Occurrence of Malaria

The fourth research question is: what relationship is there between the spatial and temporal travelling patterns in the study area and the occurrence of malaria? In order to determine the presence of a correlation between the malaria occurrence and the human travelling patterns linear and multiple regression analyses of the travelling patterns and the malaria occurrence have been performed.

4.5 Evaluation of Validity

The final research question was: by what approach is a relationship to be evaluated? In order to gain insight into the validity of the above-described research methods, leaving out certain categories of data tested the sensitivity of the data and the assumptions.

First this was done with a regression analysis with only the school children as a dependable variable, and another with all people travelling but the children. This was done because the amount of school children was a factor ten higher than the rest of the people travelling around in the study area.

Another sensitivity analysis was done using the malaria data only from the first time class, and from the first and the second in the assumption that these are closer to reality at the moment of the survey data.

5 Results

5.1 Spatial Travelling Patterns

The following answers have been found to the first research question regarding the spatial travelling patterns of the population within the study area.

5.1.1 Complete Road Pattern

In figure 6 the road pattern is shown as obtained when tracing the roads as seen on the satellite image like described in paragraph 4.1.2. The households have been plotted into the map to show the location of the roads compared to the locations of the houses. The results were 443 roads, assigned to three different classes as based on width and visual appearance to indicate and approximate their importance and average travelling speed. This speed is assigned to it based on the assumption that most people walk. This assumption is supported by the malariometric survey, which states that the majority of the inhabitants of the study area travel around the Ruhuha sector by foot when going to find medical help. If they walk when sick, or when a family member is sick, it should be safe to assume they walk in general. The study area is approximately 43.4 km^2 so when walking the local population can travel within the entire Ruhuha sector in a day.

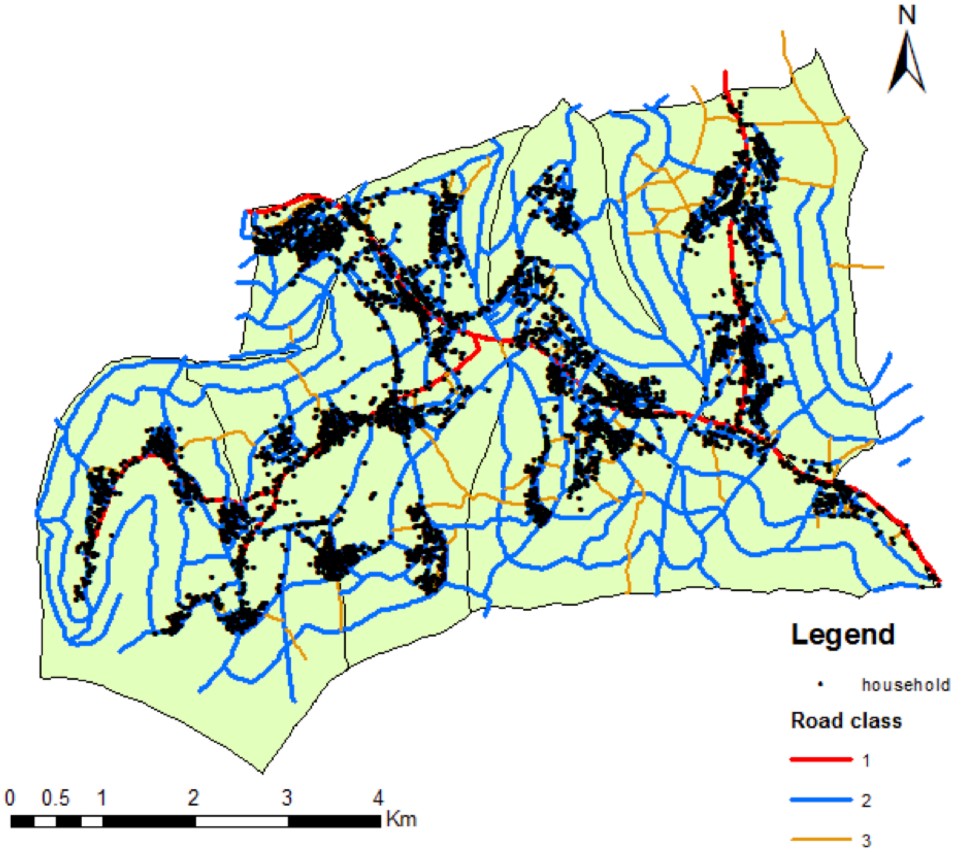

Figure 6: The complete road network and households in the study area based on satellite imagery and according to the malariometric survey.

The network clearly connects the different villages and the roads are the densest around the houses. Though the intensity of use of each road is unknown, we can see that some might be more frequently used because they are wider or more clearly visible on satellite images. In the Southwest of the study area some roads have dead ends. This is where the lake starts and the road ends at its shore. On all other borders the roads cross into the surrounding sectors. These ends have been left purposefully dangling, to indicate the fact that this is not a closed system.

From this the network was calculated, so that later the distances between the houses and villages can be calculated. The occasional gaps between two roads at crossroads caused by the manual drawing were closed.

5.1.2 Villages

As mentioned in paragraph 4.1.4, there were several villages that had extreme outliers. Thus before calculating the centroids these were re-assigned according to table 2 in appendix B. The original villages are shown in figure 7, and the corrected ones in figure 8.

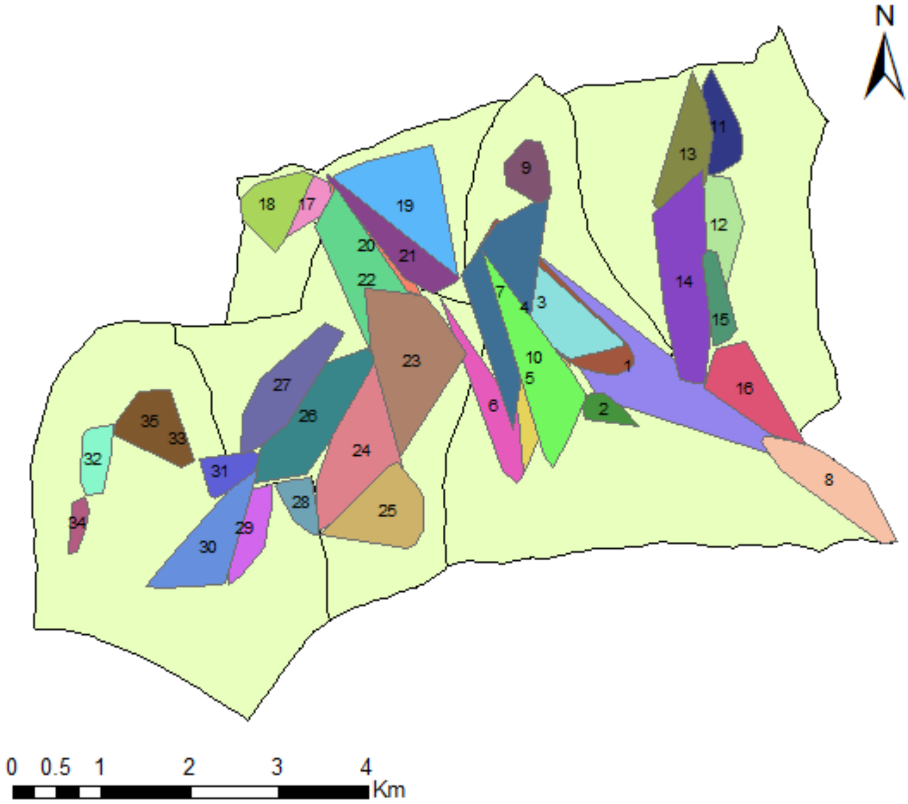

Figure 7: Village locations and centroids (number) before removing the outliers.

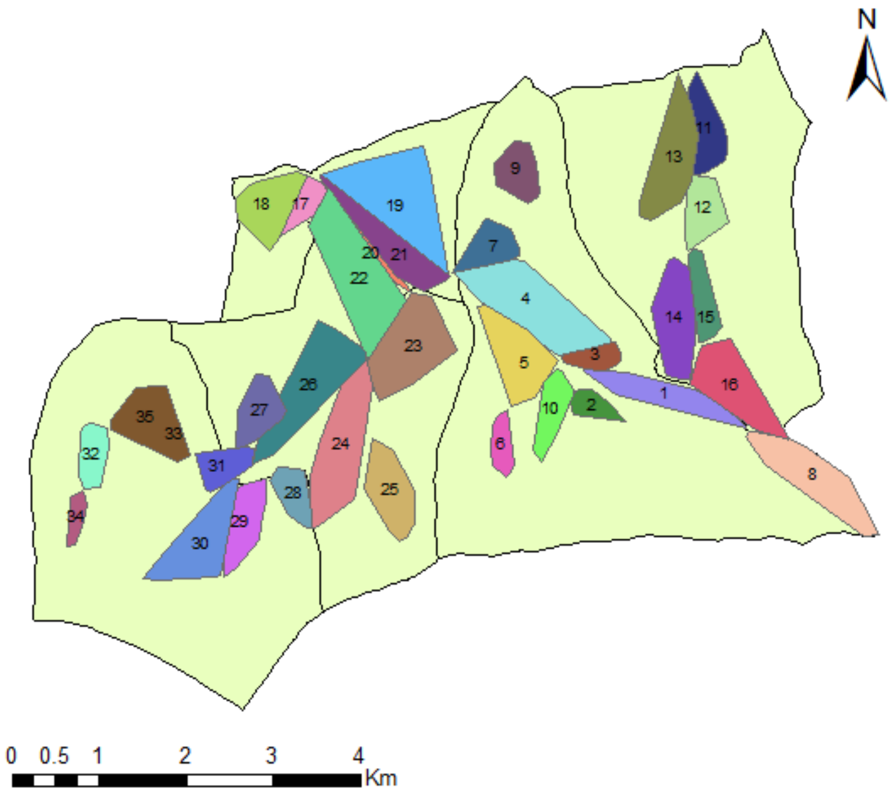

Figure 8: Village locations with centroids (numbers) after removing outliers.

It can be seen that some of the villages change shape and size significantly. Since the outliers are located very obviously in other villages, it is still assumed that the corrected villages are more accurate. In table 2 in appendix B the distance between the original and the corrected centroids of the villages are calculated. This resulted in a mean difference of 163.67 m (STD = 238.38). It should be noted that there are 15 villages that did not have any outliers removed or assigned to them, and their centroids thus remained in the same position. The largest differences were for Kindama (1), Kagasera (3), and Saruduha (10).

5.1.3 Village Scale Spatial Network

The above-obtained centroids are then used to create a simplified map of the villages and their connections. This results in the simplified abstract map in figure 9, where the connections between the villages can be seen, where the estimated distances between the village centroids are shown.

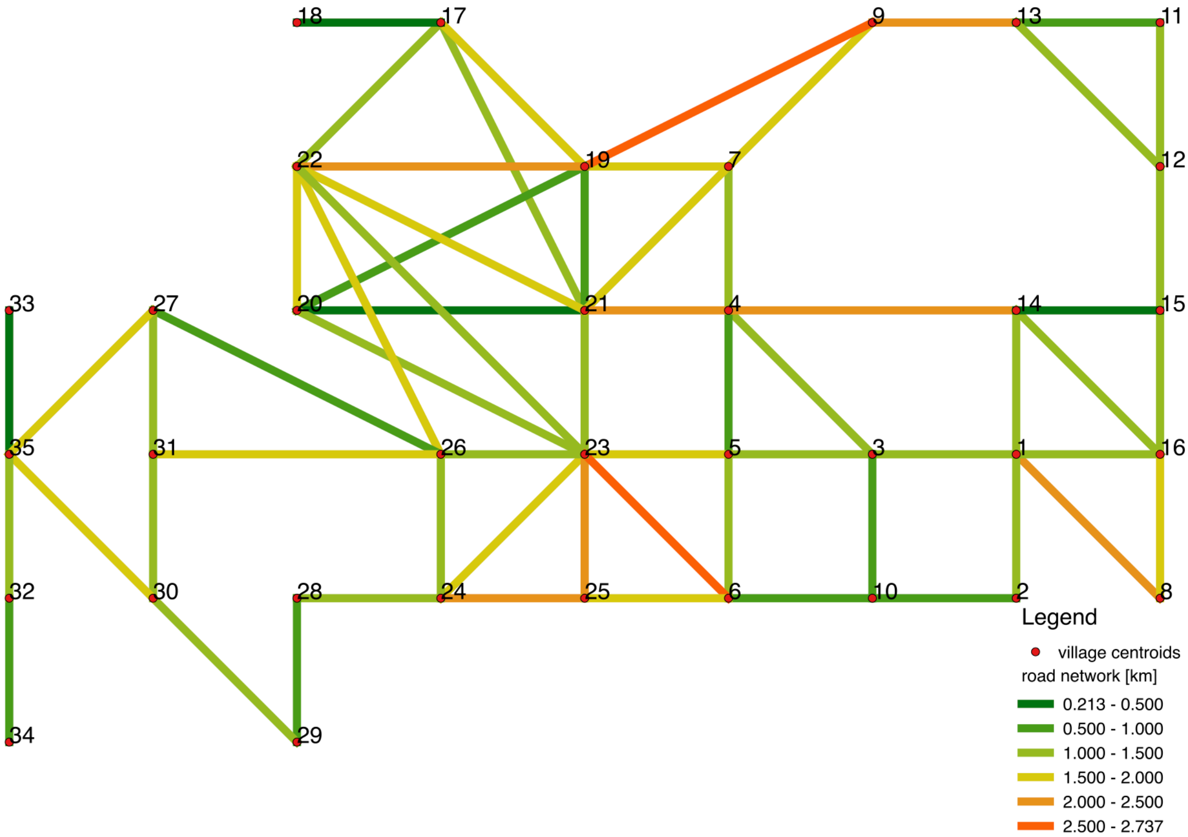

Figure 9: Simplified map of the travelling connections between the different villages in the study area.

The connections in figure 9 are simplified; they do not show the true direction, and the colors, not the length of the edges, show the distance between the villages. This network shows the study area as a closed system, however it should be kept in mind that there are road connections to the rest of the world. These are not taking into consideration due to complexity. The dangling ends of Masenga 2 (33) and Busasamana (34) are where the study area borders to water and there is no possibility to travel further, only back to the previous villages.

5.2 Temporal Travelling Patterns

5.2.1 Daily Travelling Patterns

From the malariometric survey, we know that the main source income for most of the households is crops cultivated on private property. From this information, we may assume that most people do not travel often and/or far outside of their village and the immediate land surrounding it, for their work is close to home and demands their constant attention. Even the people who earn their income by fishing, herding or cattle breeding also work close to home in the direct surroundings of their villages. According to the malariometric survey, the other 8% of the population has incomes predominantly coming from local businesses, and as such their travel is not frequent and has no large outreach from their home. We assume that daily commute for working purposes does not go beyond one village away. Of course these assumptions are not entirely correct, a 10 % number of people travelling towards different working opportunities give an indication of those people traveling for work purposes around the study area.

From a report by the Rwandese ministry of education we find that nearly all children aged between 7 and 12 attend primary education (95.9%). Before this age the percentage of students attending pre-primary education is much lower (10.1%), and after primary education between the ages of 13 and 18 the amount of children attending secondary school is considerably less as well (25.7%) (MinEdu Rwanda, 2012). Two secondary schools are located in Ruhuha, one in Ruramba (5), and another in Nyabaranga (19) (Glopoi, n.d.). In addition to this two primary schools are found, one in Kagasera (3), and one in Kindama (1) (Glopoi, n.d.). It may assumed that a significant number of children travel to and from these schools daily from their homes. Other (older) students may travel further, or be located at boarding schools outside of the study area. Either way, there will be significant daily travelling to and from the above-mentioned villages.

5.2.2 Weekly Travelling Patterns

In addition to this, a post office as well as a community centre is found in Kindama (1) (Glopoi, n.d.), these could be reasons for travelling. A market is found in Nyabaranga (19) (Glopoi, n.d.), but what seem to be shops are found along the entire main road in the centre of the study area when looking at the satellite image. It is assumed that most shopping, and market activities are centered in this area, and thus these villages are assumed to be a large attractor of people and result in much travelling.

Another reason for travelling within the area might be religious worship. Three official churches are located in the Ruhuha sector; two in Kindama (1) and one in Saruduha (10) (Glopoi, n.d.). However, there might be more churches, mosques, or other places of worship not registered in the area. Either way, we can assume that there is a significant semi-weekly travelling pattern towards these villages.

5.2.3 Negligible Travelling Patterns and Complete Pattern

Travelling for water and/or bathrooms was considered as well. According to the malariometric survey most households do not have a private water source, but instead use a public tap point (52%) or a public well (34%). However, it is assumed that these water sources are within the village boundaries and thus do not require travelling far. The same assumptions are made for the toilets, which are mainly shared pit latrines (93%). These are assumed to be relatively close to the households and thus do not require a lot of travelling over large distances.

In conclusion, most travelling will be done to and from the central villages: Kindama (1), Kagasera (3), Rebero (4), Ruramba (5), Kimikamba (17), Mubano (18), Nyabaranga (19), Ruhuha 1 (20), Ruhuha 2 (21), Nyakagarama (22), and Rwanika (23), near the main road from the surrounding smaller villages. This is done daily by primary and secondary school students, and semi-weekly for other purposes such as shopping, religious worship etc. Work is done mostly near the homes.

5.2.4 Attraction of Villages and Number of People Travelling

In order to obtain exact numbers of people, the above-mentioned assumptions were applied to the demographic composition of Rwanda. The result of this was a table with the average number of men and women in each village, the amount of children for each rough school age group as based on general census data from all of Rwanda (Petroze et al., 2012;

Rwanda census, 2012). The resulting composition of each of the villages is shown in table 3 in appendix C. There is no differentiation between the villages, the composition of them is the same for all and based on the rural population of all of Rwanda. The only differences stem from the total number of people living in each village.

The number of school attending children is calculated for each village for each school level. Based on a few assumptions, the amount of people travelling for work, shopping, religion, and other reasons are calculated.

Based on the assumed reasons for traveling, the attractivity of each village was set to a relative number for each traveling reason. The resulting number of people traveling to visit each village is shown in figure 10.

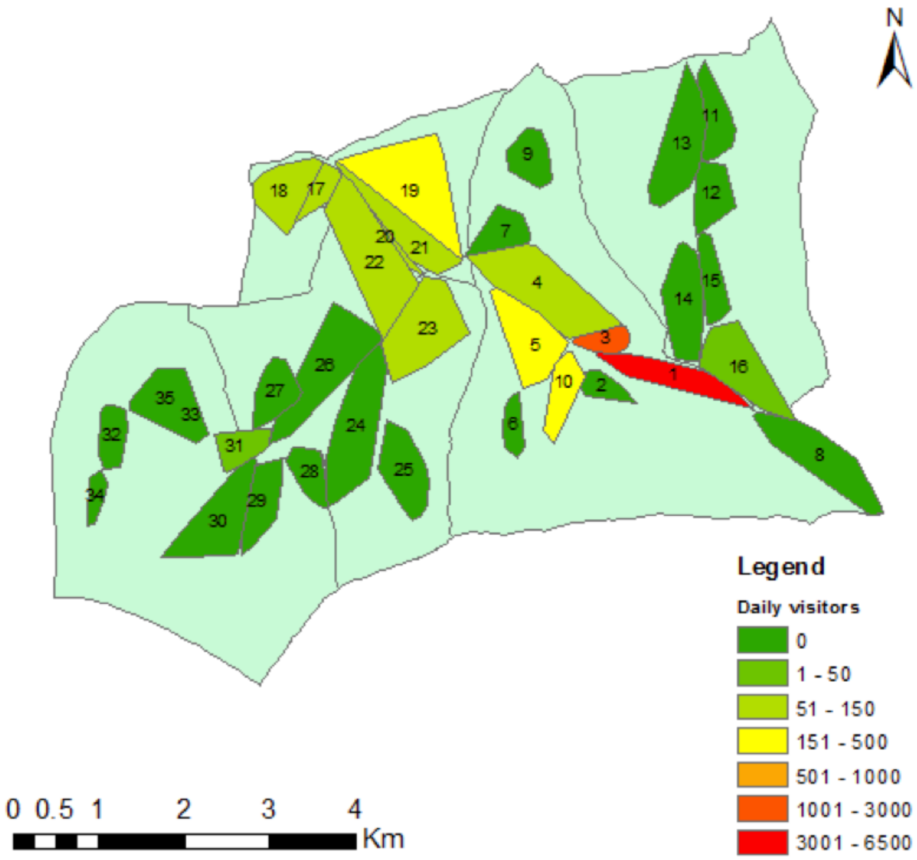

Figure 10: The estimated number of people traveling to each village every day.

The amount of visitors is extremely high in Kindama (1) and Kagasera (3). This is because nearly all children between the ages of 5 and 14 are assumed to attend school in these two villages every day. Aside from those children, the amount of adults traveling is significantly lower, because as mentioned in paragraph 5.2.1, they mostly work from home, only 8% travel towards work. Reasons for traveling such as shopping, religion, and others are not considered to be daily, thus their influence is relatively small compared to the number of people travelling to schools daily.

If we do not only consider the final destination of the trips, but the number of people travelling through villages on their way to their goal, we get an entirely different pattern. See figure 11 for the number of people travelling through each village every day.

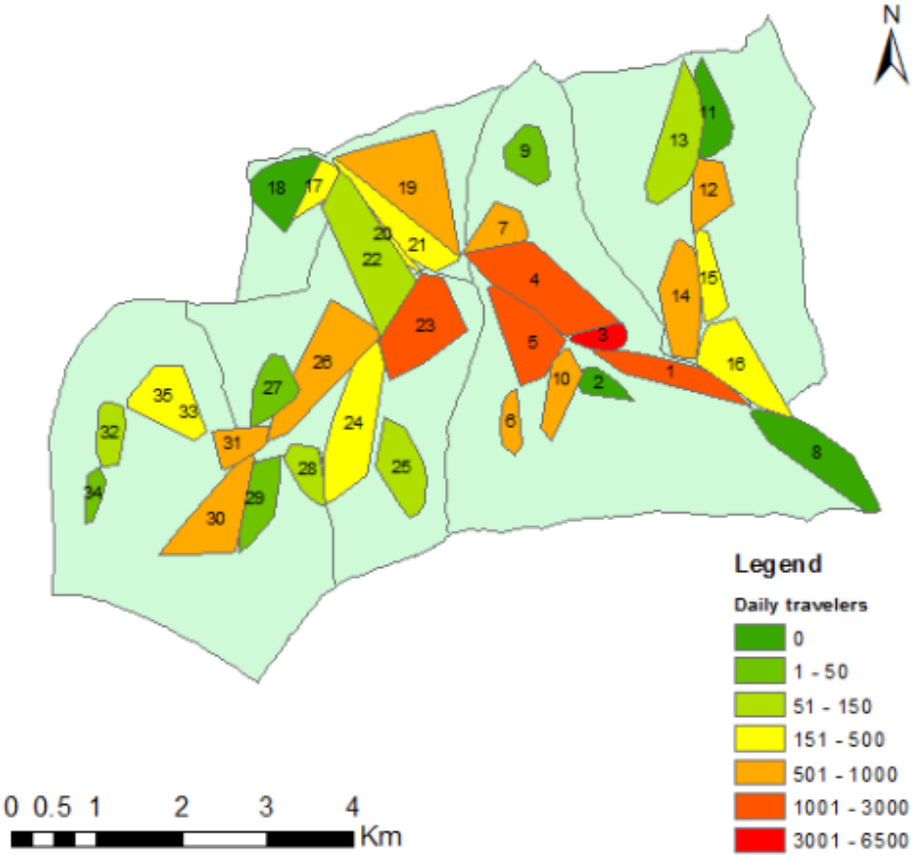

Figure 11: The estimated number of people passing through each village as they travel around the study area daily.

Figure 11 is based on the network in figure 9, and from this it is obvious that most people travel through the most central villages. Those villages at the ends of the roads are not interesting for people to travel trough on their way to their goal, and thus these villages see a much smaller amount of outsiders passing through than the ones around the centre of the study area. Some of the villages like Kayigi (26), Nyagafunzo (30), and Bihari (31)

Since not only the amount of people from outside visiting each village is important, but also the number of people visiting villages returning to their own village, this is also investigated. See figure 12 for the number of villages visited from each villages.

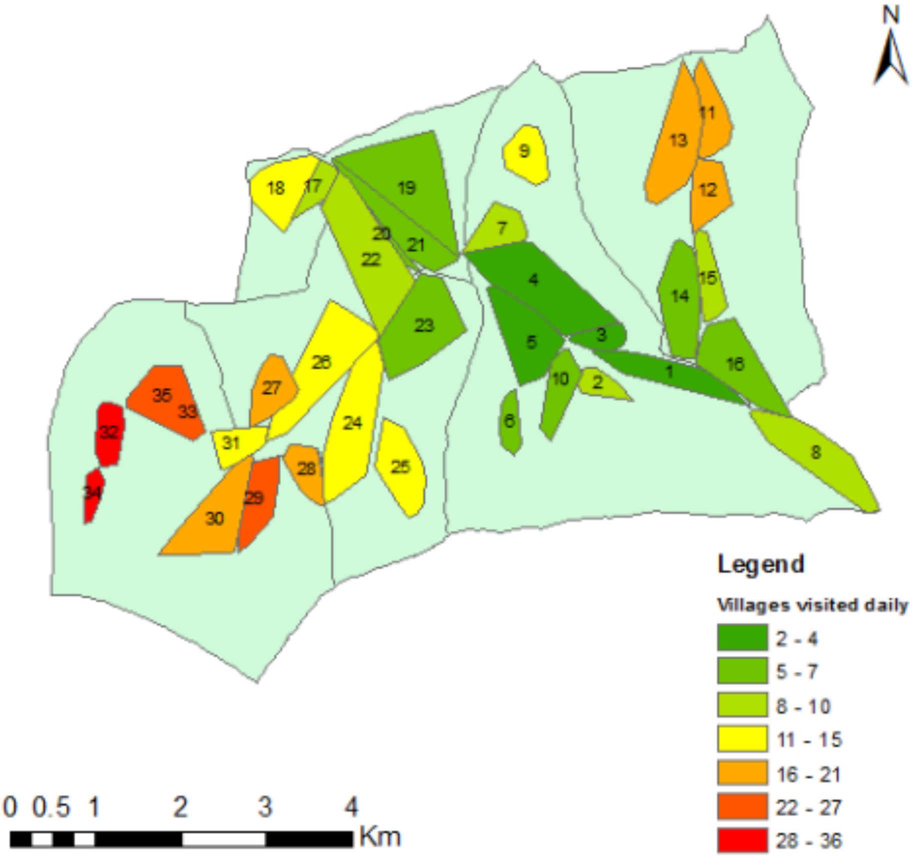

Figure 12: The estimated number of villages visited daily from each village.

It is obvious that the people from those villages, which lie on the outskirts of the study area, such as Gikundamvura (11), Rusenyi (12), and Kanombe (13), and Mukoma (29), Masenga 1 (32), Busasamana (34), and Rwanzunga (35), have to travel through most villages every single day. It should however be noted again that the study area is not a closed system, and from several villages in the North, Northeast, and South it is possible and likely that people travel in and out of the study area every day. This is not taken into consideration because of lack of information on these numbers.

See table 5 in appendix D for the exact number of estimated people traveling to, through, from each village.

5.3 Malaria Occurrence in the Study Area

For the percentage and exact amount of households per village that have had a malaria case in the past six months, see table 6 in appendix E. An overall average of 54.89% of the households in the study area have had at least one member who has suffered malaria in these six months. The malariometric survey does not show the number of inhabitants per household who suffered malaria, only if there has been at least one case.

See figure 13 for all of the households that have had a malaria case in the time period covered by the malariometric study area, and figure 14 for the number of malaria cases per village for each time period.

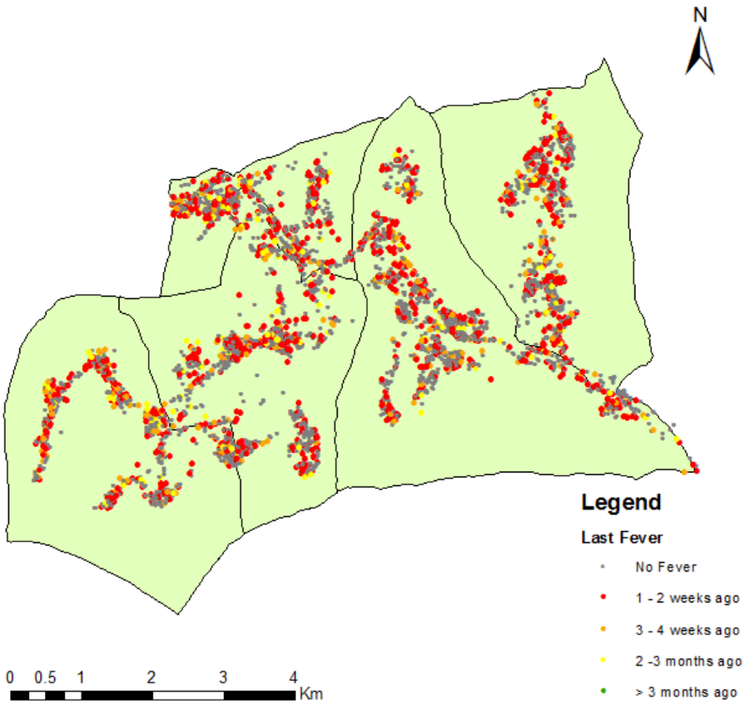

Figure 13: The households in which malaria occurred in the past six months, and those who had no malaria in the time previous to the malariometric survey.

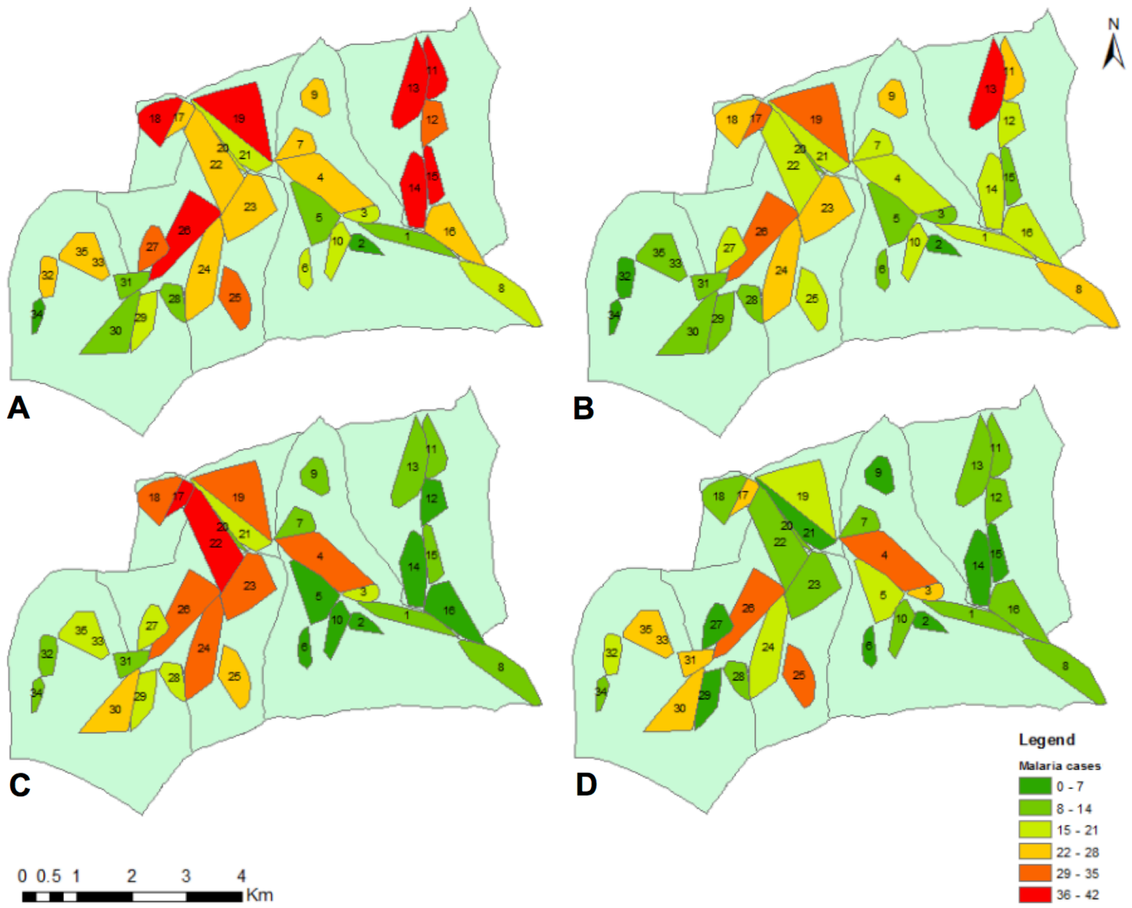

Figure 14: The number of households per village where at least one case of malaria occurred in the weeks 1-2 (A), weeks 3-4 (B), months 2-3 (C), or more than 3 months (D) before the survey.

On a household scale, there is no visible pattern distinguishable. It seems as if malaria is dispersed equally throughout the study area. No spread in time is visible in on this scale; this is why it was up scaled and separated for the villages and time steps.

In the image above, the spatial spread of malaria in the study area is quite obvious in time. The number of cases starts out relatively low and dispersed throughout the entire study area (figure 14D), and then intensifies during the next two months in the mid-West of the study area (figure 14C). Then it disperses a little again (figure 14B), before moving to be especially high in the Northeast of the study area (figure 14A).

This does show that malaria appears to move around the study area, and some of the villages consistently have a higher number of malaria cases, such as Rebero (4), and Nyabaranga (19). These are both villages that are along the main road, and close to most of the facilities in the study area. Some other villages always seem to have a lower number of malaria cases. For example Gatovu (2), Rugarama (28), and Busasamana (34). Some of these are located in the more remote and less travelled areas of Ruhuha, and some are in the middle of the crowded area.

5.4 Relationship Between the Travelling Patterns and the Occurrence of Malaria

Each of the variables mentioned in the 5.2.4 were fitted into a linear regression model to investigate their relationship with the occurrence of malaria in each village. See table 7 for the results of the regression models.

Table 7: The results of (multiple) regression models fitting the potentially explanatory variables to malaria occurrence in the study area.

Explanatory variable	Intercept	Parameter			Adj. R^2
Visitors	71.65	-0.005			-0.016
Travellers	70.00	0.001			-0.029
Visitors + Travellers	69.33	-0.009	0.006		-0.029
Visited villages	79.94	-0.718			0.024
People visiting other villages	52.80	0.008			0.142
Visitors + Travellers + People visiting other villages	43.66	-0.005	0.011	0.010	0.153

Judging by the adjusted R^2 values of the regression models, none of the investigated variables have a significant correlation with the occurrence of malaria in the study area. It appears that according to these calculations the number of people visiting other villages seem to have a slight correlation with the occurrence of malaria in the study area, but this is not of significant value. Thus this does not prove the hypothesis that there is a correlation with the occurrence of malaria and the number of people travelling in and out of an area.

5.6 Evaluation of Validity

In order to evaluate the validity of the outcome of the final research question, the data was split into sub-sets, which investigate the influence of each of the groups onto the outcome of the study.

5.6.1 The Influence of the Time Scale

First the influence of the malariometric data, which has a variable indicating the occurrence of malaria in each of the households divided into four time periods. In order to see if there is a significant difference when only investigating a single time period, the malaria cases in the past two weeks are filtered out and a regression function with the same explanatory variables is fitted to these malaria cases. For the results, see table 8.

Table 8: The results of (multiple) regression models fitting the potentially explanatory variables to malaria occurrence in the first week only.

Explanatory variable	Intercept	Parameter			Adj. R^2
Visitors	23.54	-0.003			0.013
Travellers	23.76	-0.002			-0.015
Visitors + Travellers	23.53	-0.004	0.035 E^{-3}		-0.018
Visited villages	25.79	-0.224			0.009
People visiting other villages	17.54	0.002			0.083
Visitors + Travellers + People visiting other villages	17.50	-0.002	0.001	0.002	0.037

Overall, it seems that the correlation between the occurrence of malaria and the people travelling to, through, or from villages decreases.

5.6.2 The Influence of School-Attending Children

Since there are only four schools in the area in four different villages, and a large number of children, their daily travels towards these schools are of a very significant influence onto the number of people travelling around the study area. Therefore the correlation is repeated both for only the amount of children, and only the amount of adults travelling around the study area. See table 9 for the regression analysis using only school-attending children, and table 10 for the results when using only the adults.

Table 9: The results of (multiple) regression models fitting the potentially explanatory variables to malaria occurrence using only the school-attending children.

Explanatory variable	Intercept	Parameter			Adj. R^2
Visitors	1390	-0.339			0.090
Travellers	1464	-0.294			0.118
Visitors + Travellers	1453	-0.157	-0.211		0.105
Visited villages	887.2	82.70			0.170
People visiting other villages	228.5	1.094			0.972
Visitors + Travellers + People visiting other villages	165.0	-0.017	0.068	1.131	0.976

Table 10: The results of (multiple) regression models fitting the potentially explanatory variables to malaria occurrence using only the adult population.

Explanatory variable	Intercept	Parameter			Adj. R^2
Visitors	1390	-0.830			0.032
Travellers	1447	-0.130			0.059
Visitors + Travellers	1457	-0.518	-0.103		0.051
Visited villages	1095	32.37			0.093
People visiting other villages	362.9	3.781			0.310
Visitors + Travellers + People visiting other villages	459.8	-0.531	-0.118	3.917	0.408

It appears that when both when using only school-attending children or adults the correlation improves. However, only when using children do we obtain a significant correlation between the number of travellers that have visited other villages and the malaria occurrence in the study area. This correlation improves slightly more when we take all variables into consideration.

6 Conclusions

It is clear from the network constructed using satellite images that there is a vast structure of roads covering almost the entire Ruhuha sector. There should be plenty of (foot) traffic in the study area, and it is thus assumed that the people travel around between the villages roughly according to figure 9. This map answers the first research question; along which routes do the people travel in the study area?

The variation in time was a little more difficult to identify, but with a few assumptions the figures 10, 11, and 12 respectively show the numbers of people travelling towards, through on from each village. This shows that indeed the villages at the central road of the study area are most travelled towards, and that the inhabitants of those villages at the edges of the study area travel visit the largest number of other villages.

The occurrence of malaria seems to be well spread throughout the study area, see figure 13. When splitting the malariometric data into the different time classes, it appears that there is some temporal pattern in malaria cases, see figure 14.

However, when a regression model is applied to the malaria data and the travelling patterns, no significant correlation was found for any of the reasons for travelling. The highest correlation with malaria seems to be the number of villages visited, and not the number of people travelling through, or towards any village.

If we only look at one timeframe closest to when the malariometric study was conducted, the significance of the correlation decreases to even lesser values. However, when we conduct a regression for only children or adults, we see that the correlation improves drastically. We can even assume that the number of villages the children travel through every day can be used as a way of estimating the number of malaria cases in their home village. Overall, regardless of the adjusted R^2, the same pattern is found with the correlation between malaria and the different explanatory variables; an often negative relationship with the visitors and travellers, or these combined, and a much more strong relationship with the number of villages visited, especially when taking the population number of the village of origin into account.

7 Discussion

7.1 The Spatial Travelling Patterns

The first dataset required for this study was the spatial network between the villages. Since this was constructed using a high-resolution satellite image, the overall network was quite complete, and as exact as possible without field surveys.

The satellite image was taken in 2016, while the malariometric data was collected in 2013. Some roads might have developed between those three years, or even have disappeared or moved, especially considering that most of the roads in the study area appear to be small and sandy paths or tracks in the field, or unpaved larger roads. While the basic and main roads most likely haven’t changed location or importance, this is a small and unknown error.

7.1.1 Constructing the Village Boundaries

The spatial locations of the houses according to the malariometric survey are accurate enough for the purposes of this study. The several outliers were filtered out, and thus the locations of the villages are assumed to be correct.

However, these villages vary greatly in both area and the number of inhabitants. Grouping houses to similar sizes, both for population and for area or number of households was considered. The fact that people travel more within their villages for water and sanitation, as well as their general community would roughly be within these borders, thus their travelling pattern within these villages would be so intense that it cannot be modeled without tracking actual people. In combination with the large area size differences for less densely populated areas when dividing by population, or the high number of people when dividing by area, a straightforward administrative village boundary division was used.

7.1.2 Taking the Route Less Travelled

Even though the roads and paths are visible on the satellite imagery, we do not know how many people travel which routes. The simplified routes are taken based on the assumption that people take the shortest routes. Of course this is not true in reality, but tracking the routes of all people in the study area for a longer period is not possible, thus there will be a slight error in both the amount of people visiting each village, as well as the fact that the influences from outside the area are completely neglected.

7.1.3 Travelling Beyond Boundaries

Since no information was available on the area outside of the study area, it was assumed for the sake of this study that all traveling was solely within the area. Of course the study area is not a closed boundary system; people travel freely across the administrative border as they please.

From the satellite imagery it is clear that Kimikamba (17) and Mubano (18) are a group of houses dispersed completely across the border of the Ruhuha sector and the bordering sectors Mareba and Nyanugenge. Not only will these people travel daily into these other sectors, but people from those sectors will travel into Ruhuha as well. This is also an issue in the East and South border of the study area and the bordering Ngeruka sector. There are less homes close to the border, so the number of people travelling daily in and out of the might be smaller.

These roads in and out of the study area are of course used. They were not considered into this study because of lack of malaria data, as well as demographic information on the population and the number of people travelling in and out of the study area. Assuming a closed system will have significantly influenced the amount of people travelling in, through, and out of the villages and the study area.

7.2 The Temporal Travelling Patterns

7.2.1 Assumed Travelling Reasons and Directions

As mentioned in paragraph 4.2.1, the original plan for this research involved surveying the travelling patterns of the people within the study area. Since this was not possible due to logistical reasons, the temporal pattern of movement is solely based on assumptions.

Of course these assumptions are slightly off. However, the demographic composition of the area is based on the official census data of Rwanda and the malariometric data. Thus the amount of people and the age distribution is quite close to truth, and the number of schoolchildren will be roughly the same as reality. However, it is not known how many children from which village go to which school in the Ruhuha sector, or even outside of the study area.

The other reasons for travelling and attractivity are based on even larger assumptions. The percentage of people travelling for reasons such as work, markets, religion, or other is a rough estimation. The number and the destinations might be significantly far from the true situation. However, by far the largest group of travellers is school children, thus the rest of the people travelling around is almost negligible.

7.2.2 Transportation Methods

Since the study area is only 43.4 km^2, the majority of the population travels around the immediate area by walking, and occasionally biking. Even when the entire population uses walking as a primary way of getting around the Ruhuha sector, they can cover the distance between the East and West of the area in a few hours, this means that it does not matter which transportation they use within the study area since a smaller temporal scale than a day is irrelevant to malaria dispersion.

7.3 The Malariometric Survey Data

7.3.1 The Temporal Scale

The malariometric survey data was collected with the intention of gaining insight into the general population of the Ruhuha sector, their perception of malaria, any factors which might influence malaria and the amount of malaria cases they might suffer. This is a snapshot collected over seven months, and does not show the spread of malaria across time aside from a simple question regarding the last fever case in the area. Not only does fever not always indicate malaria, some households also might have suffered multiple cases of fever or malaria, which is not shown in this dataset.

At the moment the temporal scale is two weeks for the first month, and then moves upwards to several months for the later time period. Ideally, in order to gain proper insight into the spreading and temporal movement of malaria in the study area, a repeat study every few weeks should be conducted.

7.3.2 The Temporal Distribution of Malaria

When looking at the temporal distribution of malaria in the study area according to the malariometric survey data, see table 6 in appendix E, it is clear that most of the malaria cases have occurred in the first two weeks before the survey was taken. A third occurred in the last two weeks, and 82% of the cases in the last half of the time studied, see table 11.

Table 11: The number of malaria cases over time, corrected per week, and the estimated amount of malaria cases assuming an even spread of malaria in the study area.

Time	Mean number of malaria cases/ village	Percentage of total mean cases/ village	Mean number of malaria cases/ village/ week	Calculated mean number of malaria cases/ village
1-2 weeks	22.89	0.33	11.44	5.89
3-4 weeks	17.26	0.25	8.63	5.89
2-3 months	16.83	0.24	2.10	23.54
> 3 months	13.66	0.19	1.14	35.31

When corrected for the amount of time, it is much more evident that the number of malaria cases per week are significantly higher for the final two weeks of the study. The last column shows the number of malaria cases per village in each time class if we assume that the number of cases is evenly spread over time, notice the significant difference between column two and five.

Between October and November there is a low peak in the rainfall in Rwanda, this often causes an increase in mosquitoes and thus also in malaria cases (Mbogo et al., 1995; Minakawa et al., 2001; Bomblies and Eltahir, 2009; Galardo et al., 2009; Loha and Lindtjørn, 2010). Since the survey was taken between June and December, the rainy season might have influenced the data and a larger number of people might have had malaria in the last weeks before they were questioned.

7.3.3 Population Bias

However, a population bias always occurs when conducting such a survey. Especially for the last few weeks before a questioning the memory of those asked will be clearer, thus they will be able to indicate the exact moment of the malaria case better, as well as it's specifications such as medications taken. Any malaria cases further back in time might have already been forgotten or considered not important. Thus we must assume that the amount of malaria cases especially during the first few months of the time observed was in reality significantly higher.

As this was a baseline survey, every single household in the study area was inspected and the head of the household questioned. A few homes were found to be empty, and the interviewers returned at a later date. Thus the number of non-response is negligible, and the survey can be considered representative for the entire Ruhuha sector.

7.4 Correlation

As seen in paragraph 5.4, the correlation between malaria and the number of people visiting a village is insignificant. However, this might be both explained by the lack of exact data as described in the first part of this chapter.

In addition to this, the incubation period is also not considered in this research. The incubation period for malaria is between 12 and 35 days, depending on the *Plasmodium* species (Breman et al., 2014). This period is significantly longer than the smallest time scale on which the malariometric survey was conducted, which was 14 days, and the amount of travelling done in those 18 days causes further dispersion of malaria and thus distortion of the data as obtained.

Like mentioned in the introduction, malaria is especially harsh on children and otherwise vulnerable people. This means that the number of children can indeed have a larger influence on the distribution of malaria, since they get sick easier and thus if they visit other locations and are bitten there they may bring it back home. Their vulnerability, in combination with their frequent travelling is thus of a major influence as seen in paragraph 5.6.2 in table 9.

Another reason for why the number of villages visited might have a more significant influence on the occurrence of malaria in a village, and not the number of people visiting it or travelling through it during a day might be because most malaria vectors take a blood meal in the evening or at night (Harris et al., 2006). This could mean that the mosquito lifts on the inhabitants as they travel through the area, and then proceed to bite them or others as they start actively searching for blood after the sun has set in the traveller's home, or houses surrounding it.

8 Recommendation

The major challenges with this research stemmed from a lack of malaria data and a lack of temporal travel pattern data. Therefore a different approach is recommended for a future study into the same research questions.

First and foremost, the travel pattern must be improved in order to correctly determine any possible correlation. While obtaining the spatial pattern was no issue for this study area, the number of people visiting is a very rough estimation. Thus a study where over a longer period of time, for example a year, people are tracked in their movement to see where they go, how long it takes them. This data would be on a day scale, and the locations to which they travel would preferably have some indication as to the risk whether the person could have picked up malaria parasites or mosquitoes in this area.

This should be combined with another malaria survey that preferably uses blood tests to determine parasitaemia in the population in order to truly see the number of malaria cases in the study area. Taking incubation and general feasibility into account, such tests would preferably be conducted once a month in order to be able to see a temporal pattern in the occurrence of malaria in such a study area.

In order to properly see the influence of the travelling into villages, through them, or towards them and returning home, a set of three different villages of similar sizes would be preferred. The first group of villages would be those who have a high attractivity, such as schools, markets, factories, or similar incentives to go there. The malaria occurrence here would indicate the influence of people travelling towards the village on the malaria occurrence. Preferably this would be coupled with a survey to indicate the number of people travelling into the city each day for a number of days during the study to be able to estimate the total number of visitors. The second group would be located along roads frequently travelled in order to estimate the influence of these on the occurrence of malaria. Again, a survey regarding the number of people travelling into and out of the villages for a number of days would give a better estimation of this number of people. The last group of villages would have to be very isolated villages, preferably on the dead end of a road, so that the only way malaria could be carried into these places would be by the inhabitants themselves. Each of these villages should not be located anywhere near mosquito breeding habitat in order to reduce the chance that these mosquitoes fly into the villages themselves.

Of course such a study would be time consuming and intensive. Yet the tailored data would not only show the temporal spread of malaria in an area within a year, but it might also give a more definite answer to the questions posed in this research paper.

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Appendix A: Contents DVD

Table of Content of the DVD that accompanies the thesis report:

- Report (DOCX, PDF)
- Midterm presentation (PPTX)
- Final presentation (PPTX)
- Malariometric dataset and key (XLSX)
- Malariometric survey questionnaire (DOCX)
- Used dataset (XLSX)
- Figures (PNG)
- Maps (SHP)
- Tables (XLSX)
- Literature (PDF)

Appendix B: Outliers Villages

Table 2: The households which are after a visual inspection assumed to have been wrongly allocated to a village during the field survey, the villages to which they are now allocated, and the distance between the centroids before and after re-allocation.

Village ID	Village name	FID	New village ID	Distance between old and new centroids [m]
1	Kindama	864	3	679.90
		1104	7	
		1739	7	
		2522	8	
		4147	7	
2	Gatovu	No outliers		0.00
3	Kagasera	335	4	926.77
		844	7	
		1016	4	
		1938	4	
		2622	7	
		2877	4	
		3231	7	
		3419	7	
		3735	7	
		3951	7	
4	Rebero	No outliers		0.00
5	Ruramba	1672	6	228.72
		1850	6	
		2446	6	
		2776	6	
		2832	6	
		3695	6	
		3909	6	
6	Kibaza	1783	23	536,46
7	Gatare	1598	9	513.62
		3830	6	
8	Kamweru	No outliers		0.00
9	Rutare	No outliers		0.00
10	Saruduha	1806	7	545.32
11	Gikundamvura	No outliers		0.00
12	Rusenyi	652	15	187.35
13	Kanombe	No outliers		12.49
14	Kazabagarura	130	13	508.79
		739	13	
		1946	13	
		3113	13	
15	Rukurazo	No outliers		0.00
16	Kiyovu	No outliers		0.00
17	Kimikamba	No outliers		0.00
18	Mubano	No outliers		0.00
19	Nyabaranga	No outliers		14.02

Village ID	Village name	FID	New village ID	Distance between old and new centroids [m]
20	Ruhuha 1	417	19	191.48
		485	19	
		1988	19	
		1989	19	
		3838	22	
21	Ruhuha 2	No outliers		0.00
22	Nyakagarma	No outliers		0.00
23	Rwanika	1312	22	175.58
		2487	25	
		3658	22	
		4048	22	
		4062	25	
24	Butereri	2903	25	94.82
25	Kibaza	823	24	237.65
		859	24	
		899	24	
		2804	24	
		3785	24	
26	Kayigi	400	28	324.59
		790	31	
		1156	31	
		1190	28	
		1704	28	
		2681	30	
		2760	31	
		3347	24	
		3493	31	
27	Nyaburiba	576	26	404.70
		708	26	
		2488	26	
28	Rugarama	No outliers		35.86
29	Mukoma	No outliers		0.00
30	Nyagafunzo	403	36	74.27
31	Bihari	No outliers		10.75
32	Masenga 1	1350	35	25.86
33	Masenga 2	No outliers		0.00
34	Busasamana	No outliers		0.00
35	Rwanzunga	No outliers		0.00

Appendix C: Demographics

Table 4: Demographic spread of the population among the villages in Ruhuha as calculated based on general population census data for Rwanda.

Village ID	Households	Population	Male	Female	Children 0-4 years	Children 5-14 years	Children 15-19 years	Adults
1	109	461	217	244	69	124	51	217
2	59	249	117	132	37	67	27	117
3	138	606	285	321	91	164	67	285
4	205	862	405	457	129	233	95	405
5	105	459	216	243	69	124	50	216
6	84	354	166	188	53	96	39	166
7	118	448	211	237	67	121	49	211
8	117	472	222	250	71	127	52	222
9	95	401	188	213	60	108	44	188
10	125	525	247	278	79	142	58	247
11	134	543	255	288	81	147	60	255
12	102	403	189	214	60	109	44	189
13	176	753	354	399	113	203	83	354
14	118	489	230	259	73	132	54	230
15	133	532	250	282	80	144	59	250
16	113	486	228	258	73	131	53	228
17	184	854	401	453	128	231	94	401
18	179	748	352	396	112	202	82	352
19	208	930	437	493	140	251	102	437
20	107	525	247	278	79	142	58	247
21	130	602	283	319	90	163	66	283
22	165	738	347	391	111	199	81	347
23	136	610	287	323	92	165	67	287
24	149	661	311	350	99	178	73	311
25	159	664	312	352	100	179	73	312
26	198	852	400	452	128	230	94	400
27	96	397	187	210	60	107	44	187
28	111	474	223	251	71	128	52	223
29	87	338	159	179	51	91	37	159
30	120	535	251	284	80	144	59	251
31	94	439	206	233	66	119	48	206
32	95	411	193	218	62	111	45	193
33	30	105	49	56	16	28	12	49
34	53	212	100	112	32	57	23	100
35	120	517	243	274	78	140	57	243
Mean	*124.34*	*533.00*	*250.51*	*282.49*	*79.95*	*143.91*	*58.63*	*250.51*

Appendix D: Visitors and Travellers

Table 5: Estimated number of people travelling to, through, and from each village every day.

Village ID	Number of people visiting	Number of people travelling through	Number of people travelling through and visiting	Number of villages visited	Number of people visiting a number of villages	Total number of people traveling to or from
1	3,347	1,419	4765	2	101	4,867
2	0	0	0	8	617	617
3	2,444	3,793	6237	2	352	6,589
4	58	1,113	1171	4	1,138	2,308
5	322	2,169	2491	3	556	3,047
6	0	727	727	7	894	1,621
7	0	682	682	9	1,557	2,239
8	0	0	0	8	1,171	1,171
9	0	37	37	13	1,901	1,938
10	371	981	1352	6	998	2,350
11	0	0	0	20	4,081	4,081
12	0	592	592	16	2,205	2,796
13	0	119	119	19	5,581	5,700
14	0	870	870	7	1,160	2,029
15	0	211	211	10	1,713	1,924
16	29	260	289	5	520	809
17	98	264	363	9	2,620	2,983
18	78	0	78	12	2,934	3,013
19	366	594	960	7	2,501	3,461
20	135	208	343	7	1,224	1,567
21	135	168	303	6	1,240	1,544
22	62	66	129	8	1,919	2,048
23	60	2,208	2269	7	1,545	3,813
24	0	317	317	13	3,169	3,486
25	0	99	99	12	2,868	2,967
26	0	976	976	11	3,278	4,254
27	0	1	1	16	2,243	2,244
28	0	126	126	19	3,344	3,470
29	0	3	3	25	3,149	3,152
30	0	517	517	21	3,970	4,487
31	40	733	773	15	2,267	3,040
32	0	89	89	31	4,686	4,775
33	0	3	3	33	1,248	1,251
34	0	4	4	36	2,849	2,853
35	0	298	298	27	5,113	5,411
Mean	*216*	*561*	*777*	*13*	*2,192*	*2,969*

Appendix E: Malaria cases per Village

Table 6: Amount of malaria cases in each village and the moment in the past 6 months they occurred according to the malariometric survey in 2013.

Village ID	Number of houses	Amount of houses with malaria [%]	Malaria in past 1-2 weeks	Malaria in 3-4 weeks ago	Malaria 2-3 months ago	Malaria 3-5 months ago
1	109	45.87	14	15	11	10
2	59	37.29	6	7	5	4
3	138	45.65	15	10	16	22
4	205	50.73	25	16	31	32
5	105	43.81	13	12	6	15
6	84	50.00	20	12	5	5
7	118	47.46	23	17	8	8
8	117	52.14	19	26	8	8
9	95	64.21	25	24	8	4
10	125	42.40	18	17	6	12
11	134	59.70	37	24	10	9
12	102	61.76	29	20	3	11
13	176	56.82	39	41	12	8
14	118	55.08	38	18	3	6
15	133	49.62	38	10	11	7
16	113	46.90	27	20	5	11
17	184	24.00	24	34	38	24
18	179	59.22	42	22	30	12
19	208	57.21	36	30	35	18
20	107	52.34	21	10	13	12
21	130	47.69	18	21	16	7
22	165	55.76	22	18	39	13
23	136	69.12	25	22	35	12
24	149	64.43	23	22	34	17
25	159	66.04	29	19	28	29
26	198	68.18	38	30	34	33
27	96	69.79	29	15	18	5
28	111	47.75	11	10	18	14
29	87	57.47	15	8	21	6
30	120	63.33	14	14	25	23
31	94	60.64	10	9	10	28
32	95	68.42	26	7	13	19
33	30	63.33	3	6	6	4
34	53	52.83	7	5	8	8
35	120	64.17	22	13	20	22
Mean	*124.34*	*54.89*	*22.89*	*17.26*	*16.83*	*13.66*