MODELING THE IMPACT OF LAND USE CHANGE (IRRIGATION) ON THE TRANSMISSION DYNAMICS OF WEST NILE VIRUS (WNV) IN TANA RIVER COUNTY, KENYA

By

OSOWO ODHIAMBO FREDRICK

I56/69429/2013

Centre for Biotechnology and Bioinformatics

University of Nairobi

Thesis submitted to Centre for Biotechnology and Bioinformatics in partial fulfillment for the award of **MASTER OF SCIENCE IN BIOINFORMATICS**.

27th June 2017

DECLARATION

I declare that this Thesis is my own work, and has not been presented for award of degree in any institution of learning.

Signature: _____ Date_____

RECOMMENDATION

We confirm that this thesis has our approval to be presented for examination as per the University of Nairobi regulations.

Signature: _____Date_____

Dr. Bernard Bett, PhD

International Livestock Research Institute (ILRI)

Signature: _____Date_____

Dr. George Obiero, PhD

Centre for Biotechnology and Bioinformatics

University Of Nairobi

Signature: _____Date_____

Dr. Timothy K. Kuria Kamanu, PhD

School of Mathematics

University Of Nairobi

DEDICATION

I dedicate this work to my beloved children,

Lloyd- Justin Odhiambo

And

Nicole Aluoch Odhiambo

ACKNOWLEDGEMENTS

First, I thank the almighty God for enabling me successfully complete this project. I am greatly indebted to the University of Nairobi and in particular Centre for Biotechnology and Bioinformatics for awarding me the full University Scholarship that enabled me pursue this course. In addition, this project would not have been possible without the field data, Institutional support and abled supervision. I therefore also thank International Livestock Research Institute (ILRI), through Dr. Bernard Bett for allowing me to use their data and for their collaboration in this project.

I acknowledge the immense input and guidance provided by my supervisors who sacrificed a lot of their valuable time to ensure that this work was successfully completed. I appreciate Dr. Bernard Bett for taking up with dedication the critical role of being my lead supervisor and for successfully steering this project. I thank Dr. George Obiero, the director of Centre for Biotechnology and Bioinformatics for the supervision and personal guidance he offered me. I also acknowledge the critical input offered by Dr. Timothy K.K Kamanu as my supervisor.

Special appreciation goes to Dr. Daniel Ochiel (Director, IAVI) who was the brain child behind my pursuance of this course. His technical guidance, support and personal involvement in my work contributed significantly towards this achievement. In the same breath I recognize the constant encouragement, support and personal contacts offered by Dr. Edward Okoth (ILRI) that kept me pushing on during challenging times. I also want to thank in a special way Mr. George Oudo Osowo and Mrs. Everlyne Oudo for their financial and great moral support. It would have not been possible to complete this work without their crucial and timely contribution.

I received a lot of support from my classmates in terms of exhibiting a great show of exemplary teamwork that made sailing through the course a lot more easily. I therefore recognize Faith Obange, Kelvin Mucheru, Patrick Gunga, Sharon Towett, Willington Odhiambo, Muna Abre and Maria Awuor for being such valuable comrades.

Finally, I register my gratitude to my wife, Violet Olesi and children, Lloyd-Justin Odhiambo and Nicole Odhiambo for enabling me come this far. They were very understanding and endured a long duration and many hours of my absence from home due to this time demanding project.

ABSTRACT

West Nile Virus (WNV) is an arbovirus that is transmitted by *Culex* mosquitoes. Birds are its amplifying hosts while horses, humans and other animals are dead-end hosts. WNV mainly causes fatalities in birds and horses while in humans, it mostly causes subclinical infection. However, fatal meningo-encephalitis is experienced in about 2 to 17% of those infected. Several outbreaks of WNV have been recorded in some countries like Greece, Israel, Romania, Russia and USA. There is a WNV vaccine for horses but not for humans.

The aim of this study was to develop a parsimonious epidemiological model to study how irrigation affects the transmission dynamics of West Nile virus in Tana River County in Kenya. The study also evaluated the impact of use of mosquito adulticides repellents and larvicides as WNV control interventions. We formulated a SEIR (Susceptible, Exposed, Infectious, and Recovered) model with compartments for mosquitoes, birds and humans. Parameters were originated from published literature while the meteorological data for the study site was obtained from the meteorological department. Ordinary differential equations (ODEs) generated from the model were used in R programming language to simulate the risk of WNV under various study scenarios. The simulation was driven by mosquito suitability index which is a function of irrigation and rainfall patterns.

The model outcome indicated that the irrigation increased both the amount of water and suitability of the habitat for mosquito breeding about five-fold. This resulted in about three-fold increase in vector density and risk of WNV. Irrigation therefore increased the risk of WNV transmission in Tana River by about 200%. The comparative efficacy analysis of the vector control interventions showed that use of mosquito adulticides was the most effective method followed by repellents and lastly larvicides.

The model also showed that WNV epidemics may be seasonal in nature for rainfall situations where they are likely to occur about one month after peak rainfall. However, for irrigated situations, the risk of WNV is likely to be a perennial phenomenon.

This model may be used as a framework to guide decision making on the timing and choice of WNV control intervention. However, the model needs to be developed further by incorporating more factors to improve on its accuracy.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS AND ABBREVIATION

ASALs----------Arid and Semi-Arid Lands

ODEs----------Ordinary Differential Equations

EIR----------Entomological Inoculation Rate

WNV----------West Nile virus

EM----------Electron Microscope

CDC----------Centre for Disease Control

RNA----------Ribonucleic acid

R----------R programming Language

SEIR----------Susceptible, Exposed, Infectious and Removed

CHAPTER ONE

1.0 INTRODUCTION

1.1. Overview

West Nile virus (WNV) is a mosquito-borne virus of genus *flavivirus* that affects humans, birds, horses and other mammals. West Nile virus infection in humans presents with a variety of symptoms that range from mild asymptomatic to fatal encephalitis (Sips *et al.* 2012). There is no known cure or vaccine for human WNV infection.

In the recent years, there have been several WNV outbreaks globally and its emergence in new territories. These outbreaks have been recorded in Tunisia, Morocco, Algeria and South Africa. Greece, Italy, Hungary, Spain and France among other European countries have experienced outbreaks in different years. Israel, Australia and USA have also suffered from WNV outbreak (Platonov *et al*. 2001; Sirbu et al. 2011).

The exact trigger for these outbreaks has not been established but irrigation among other factors has been proposed to be a risk factors associated with increased prevalence and WNV transmission (Gates and Boston 2009).

About 17% of the land in Kenya receives adequate rainfall to support rain-fed agriculture while the rest of the country can be categorized as arid and semi-arid lands (ASALs). Global warming is thought to have caused climate variability with its consequences ranging from unreliable rainfall patterns, occasional flooding and severe droughts observed in many parts of the country (Mariara and Fredrick K Karanja 2007). Due to persistent and increased practices that affect the climate, it is likely that effects of climate change may worsen and this may predispose the country to worse food insecurity situation in future (Mariara and Fredrick K Karanja 2007).

The government of Kenya has embarked on an expansion programme of new and existing irrigation projects in the country to mitigate the devastation of drought. A one-million-acre Galana irrigation project in Tana River and Kilifi Counties was initiated in July 2015 by the government with the aimed at increasing sustained and reliable food production in the country independent of the weather. At present, no study has been done to evaluate the impact of increasing acreage of land under irrigation on the prevalence of WNV in Kenya.

This study was done in the semi-arid area of Tana River County – Kenya where Bura irrigation scheme is located. The study seeks to determine the effects of irrigation as a risk factor for WNV infection and to compare the efficacy of control interventions.

1.2. Research Question, Hypothesis and Objectives

1.2.1. Research Question

Does flood irrigation, as a form of land use change, influence the transmission dynamics of WNV? What are the relative impacts of larvicides, adulticides and repellents on the risk of WNV in humans?

1.2.2. Hypothesis

Irrigation in semi-arid areas of Tana River County has a positive correlation to the transmission dynamics of West Nile virus. Adulticides usage is the most effective control intervention for West Nile Virus.

1.2.3. General objective

The aim of the study is to develop a parsimonious West Nile virus epidemiological model to help understand the impacts of irrigation and use of adulticides, larvicides and repellents as vector control interventions on the West Nile virus transmission patterns in Tana River County-Kenya

1.2.4. Specific objectives

Design and implement a compartmental (SEIR) epidemiological model using R programming language and thereby:

1. Simulate WNV transmission patterns in mosquitoes
2. Analyze and compare the transmission patterns of WNV under different uses of land scenarios (irrigated and non-irrigated areas); and
3. Predict the impact of use of mosquito larvicides, adulticides and repellents as interventions against WNV infection.

1.3. Justification for the Study

The widespread and unpredicted global trend in outbreaks of WNV infection implies that even though Kenya has never experienced an outbreak, there may be risk of WNV outbreak in future (Hayes *et al.* 2005). In fact, Kenya is a WNV endemic region (Lutomiah et al. 2011). The massive irrigation projects in the semi-arid areas of Tana River County may change transmission dynamics of mosquito-borne diseases in these areas. Irrigation has been associated with increased mosquito suitability indices and therefore may be a risk factor for WNV infection (Eisen *et al*. 2010).

WNV has been reported to be endemic in the Rift Valley, Nyanza, semi-arid regions of North-Eastern and coastal parts of Kenya. LaBeaud *et al* **(**2011) who collected and confirmed WNV seropositive birds in Kisumu and Marigat (LaBeaud **et al**. 2011). WNV has also been isolated from mosquitoes in the Country. *Culex univittatus, Culex quinquefasciattus* and *Culex vansomereni* mosquito species were found to harbor the virus and can be competent vectors for WNV in laboratory conditions (Lutomiah et al. 2011). WNV can also be found in ticks (Lwande *et al*. 2014).

Kenya may therefore be at a risk of WNV outbreak since there is no known trigger for the outbreaks globally. It is therefore important to monitor and simulate WNV prevalence so as to be able to predict would be WNV outbreak in the country.

There is no WNV transmission model that has been developed to study the impact of irrigation on WNV transmission dynamics in Kenya. Studies done in USA indicate a positive correlation between irrigation and increased risk for WNV infection. Gates & Boston (2009) investigated irrigation as a risk factor for WNV transmission in the USA Counties and found a 0.1% increase in area under irrigation of the total county area resulted in an increase of over 50% and 63% incidence rate of WNV in humans and animals respectively (Gates and Boston 2009)Another study was done by Cardenas *et al* (2011) to analyze the effects of using irrigation water to flood their yards in El Paso, Texas. The immediate authors found out that flooding their yards with irrigation water increased cases of WNV infection 2.5 fold (Cardenas *et al*. 2011).

Extent and proximity to irrigated agricultural farms has also been cited as a risk factor for WNV infection in DeGroote *et al.* (2008) and Eisen *et al.* (2010) in central United States of America.

Most undiagnosed human febrile conditions in malaria endemic areas of Kenya, are generally diagnosed and treated as malaria without considering any other possible causes, even in areas where WNV is known to occur at endemic proportions (Tigoi *et al.* 2015). Some of the undiagnosed febrile illnesses could be due to WNV and other arboviruses or co-infections with malaria (Tigoi *et al.* 2015). Our model could be combined with other tools to increase the level of awareness about the presence of the West Nile Virus disease as well as the processes that make it to be more prevalent.

West Nile Virus epidemiological model can be used to predict and evaluate the efficacy of various control interventions and their relative efficacy. Such a model may also be used as early warning system for WNV outbreak in addition to generating prior knowledge required for policy formulation to guide on the design of WNV intervention strategies in Kenya.

CHAPTER TWO

2.0 REVIEW OF LITERATURE

2.1. Structure of West Nile Virus

West Nile Virus (WNV) is an arthropod-borne virus (arbovirus) belonging to the family *flaviviridae* and the genus *flavivirus*. Other genera of *flaviviridae* are hepaciviruses which is composed of hepatitis B and C viruses and pestiviruses which affect hoofed mammals e.g. bovine viral diarrhea virus. There are over 70 viruses in the genus *flavivirus* which can be divided into two groups; the tick-borne and mosquito-borne viruses. The mosquito-borne viruses can further be divided into encephalitic clade (Japanese Encephalitis Antigenic complex) and non-encephalitic clade (hemorrhagic fever). About 40 of these viruses affect human beings. WNV falls under encephalitic clade together with Japanese encephalitis virus. The hemorrhagic clade is composed of dengue virus and Yellow fever virus (Kuno *et al.* 1998).

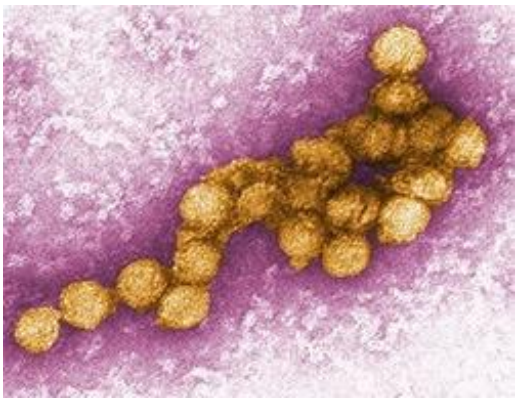

Figure 2-1: Transmission electron micrograph for West Nile Virus (Source: Centers for Disease Control and Prevention)

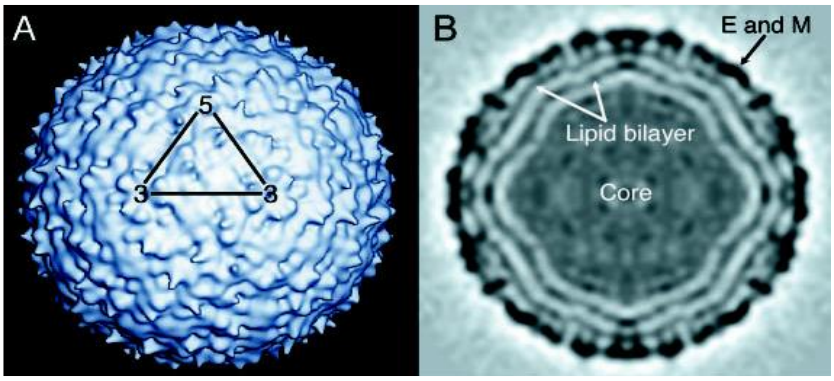

Figure 2-2: Cryo-EM visualization of West Nile virus

A shows the surface of the virion while **B** shows the central cross-section view of West Nile virus (Source: Science, 10 October 2003:248.DOI:10.1126/science.1089316)

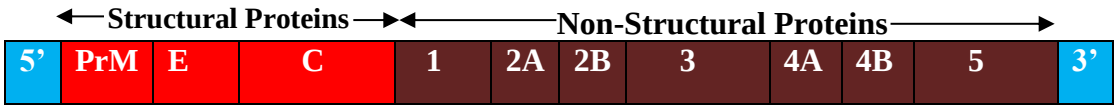

Figure 2-3: The Genome West Nile Virus

The figure shows the **three** structural proteins, **PrM, E & C** and **Seven** non-structural proteins**, 1, 2A, 2B, 3, 4A, 4B & 5**

WNV is a small icosahedral RNA virus measuring 50nm in diameter. Its structure is made up of nucleocaspid that is surrounded by lipid bilayer envelope consisting of envelope proteins. The nucleocapsid is associated with a nucleic acid core of positive, single strand RNA of about 11kb (Mukhopadhyay *et al.* 2003) **(Figure 2-3).** The whole viral genome is composed of only one open reading frame that is translated into a single polyprotein**.** Through the action of both the viral and host proteases, the polyprotein is cleaved into three structural and seven non-structural proteins. The structural proteins i.e. Envelope protein (E), Pre-membrane protein (PrM) and the Capsid (C) are found within the 5' end of the viral genome while the seven non-structural proteins i.e. NS1, NS2A, NS2B, NS3, NS4A, NS4B and NS5 are found within the 3' end of the genome (Chambers *et al.* 1990)(figures 4 and 5)

Table 2-1: Functions of West Nile Virus structural Proteins

Protein	**Function**
Capsid (C)	Forms the viral nucleocapsid of capsid protein dimmers
Envelope protein (E),	Forms the PrM-E hetero-dimers in immature virion lipid bilayer envelope and mono-dimers in mature virion
Pre-membrane protein (PrM)	Forms the PrM-E hetero-dimers in immature virion envelope

Table 2-2: Functions of West Nile Virus Non-structural Proteins

Protein	Function
NS1	Cofactor for viral RNA replication and regulation of innate immune response
NS2A	Viral replication, virions assembly and major IFN-b transcription
NS2B	Cofactor for serine protease function of NS3 and interferon antagonist
NS3	Auto cleavage of protein polyprotein (Serine protease), NTPase, RNA helicase
NS4A	Involved in replication complex and inhibits interferon a and b host responses
NS4B	Inhibits interferon a and b host responses and increase NS3 helicase activity
NS5	RNA dependent RNA polymerase

2.2. Transmission of West Nile Virus

WNV is transmitted by ornithophilic mosquitoes (*Culex* spp) which are the enzootic vectors for the transmission of the virus in nature. Other mosquito genera may also be involved in the transmission of the virus as indicated by the isolation of the virus from at least 29 more mosquito genera e.g. *Anopheles, Aedes* and *Ochlerotatus* (Campbell *et al.*2002; Goddard et al. 2002; Komar 2000)**.** Ticks may also be involved in the natural transmission of the virus. This suggestion was made after natural WNV infection of *Rhipicephallus pulchellus* ticks isolated from livestock in Kenya was encountered (Lwande et al. 2014).

Some of the major *Culex* species involved in the transmission of the virus include; *C. univittatus, C. quinquefasciatus, C. stigmatosoma, C. thriambus, C. pipiens, C. caspius, C. modestus and C. nigripalpus*. A study done in Kenya by Lutomia *et al.* (2011) found that *C. quinquefasciatus, C. univittatus, C. vansomerini* may have a role in the transmission of WNV as competent vectors. Other WNV species have also been reported to be circulating in Kenya (Lutomiah *et a*l. 2011).

The natural maintenance of WNV virus occurs in a sylvatic cycle that involves passerine birds as hosts and competent mosquitoes as vectors. Humans, equines and other mammals and reptiles can be infected by the virus but they are mainly dead end hosts. This is because viraemia in these hosts is usually too low to cause infection in mosquitoes (Dauphin *et al*. 2004).

Transmission of the West Nile virus is also known to occur through non vectoral means (Chen *et al*. 2005). The virus has been isolated from male mosquitoes which suggests the existence of vertical transmission of the virus from eggs to the male mosquitoes (Miller et al. 2000). Iatrogenic transmission (through blood transfusion and organ transplant), intrauterine and lactogenic transmission have been reported in human. Accidental transmissions in humans through laboratory and necropsy have also been suggested. Peroral transmissions through scavenging by birds of prey and fecal shedding of the virus are other suggestions that have been put forward.

2.3. Life Cycles of West Nile Virus and Mosquito Vector

In this study, we ignored other transmission vehicles and methods and focus exclusively on vectoral transmission of WNV by *Culex* mosquito. The life cycle of WNV is divided into two components, one in the host and the other in the mosquito vector. The mosquito vector on the other hand has also a life cycle that is categorized into aquatic and terrestrial components, which represents the preimaginal (immature) and adult stages respectively. A detailed description of the vector lifecycle is given below.

The life cycle of the mosquito entails the *Culex* mosquitoes searching for suitable breeding sites to lay their eggs. Their eggs are usually stuck together in ‘rafts’, which is a bunch of about 200 eggs that float on water. Under favorable conditions, the eggs hatch into larvae within 48 hours or between 1-3 days depending on temperature.

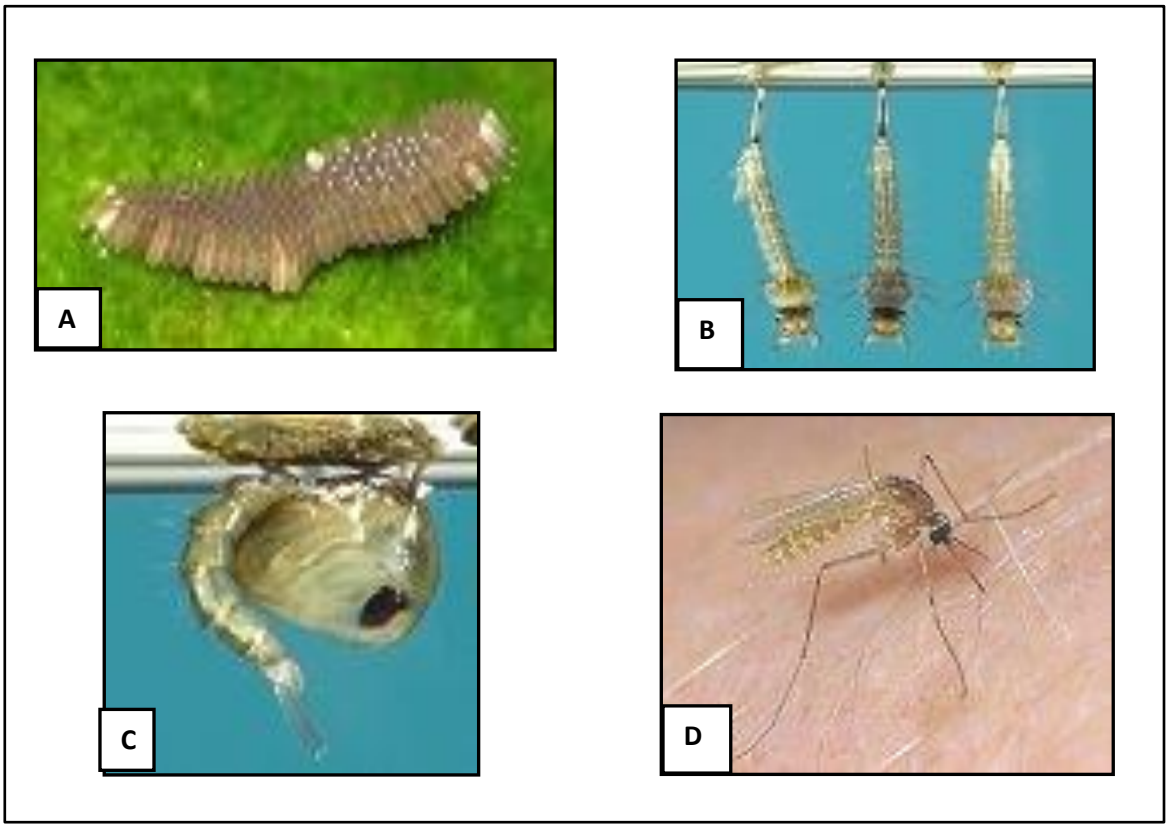

Figure 2-4: Four Developmental stages of *Culex* Mosquito

A-Eggs, **B**-Larva, **C**-Pupa, **D**-Adult

A part from the number and size of suitable breeding sites, the number of eggs laid per mosquito is also affected by the number and accessibility of suitable hosts by the mosquitoes in order to obtain blood meal. The blood meal is a necessity for the completion the gonotrophic cycle. The most preferred natural hosts are passerine birds, humans and horses. However, other mammals and reptiles are also considered by the *culicidine* mosquitoes for a blood meal. Nevertheless, given that we developed a parsimonious model, we only considered birds and humans as hosts.

Access to suitable breeding sites may be affected by mosquito's limited flight range of between 50 Meters and 50 kilometers (Verdonschot and Besse-Lototskaya 2014). High concentration of fertile female mosquitoes, leads to high larval mortality and reduced gonotrophic capabilities of the adults which subsequently affects vector density. This is attributable to competition for the limited recourses by the high number of larvae due to congestion. The competition results in development of smaller adults with reduced gonotroghic potential (Takken and Lindsay 2003).

The larval stage is the most active stage of the immature stages. They feed on micro-organisms and organic matter. They also move around in water and occasionally come to the surface to breathe through siphons by hanging upside down on the water surface. Larvae grow but since they are covered with a rigid cutin, they have to molt by shedding off the cutin for them to grow. They molt into instars, a total of 4 times, becoming bigger each time and on the fourth molt, they develop into pupae. The larval stage is critical and important for future survival of the mosquito and therefore takes a longer time. How big the larvae grows is particularly important since adult mosquitoes do not grow and usually the bigger the adult the more eggs it produces. This subsequently affects the number of mosquitoes it the next generation.

The larvae develops into a pupa which is comma shaped. Pupa is a resting, non-feeding stage that eventually develops into an adult mosquito. It is capable of moving around in water, to safer places or where there is water when water is dying out. It also breathes through a pair of trumpet shaped breathing tubes. This stage lasts only a few days and eventually the adult mosquito emerges from the pupae.

The life cycle of WNV involves the mosquito vector, birds as amplifying hosts and humans (in our case) as dead end hosts. A mosquito that is infected by WNV finds and bites a competent bird during feeding to complete its gonotrophic cycle. In the process of feeding, it injects the saliva containing the virus into the bird exposing it to WNV. The rate at which the mosquito feeds depends on the length of the gonotrophic cycle, which is in turn temperature dependent. Likewise, uninfected mosquito can also acquire WNV from infected bird during the feeding process. This is how cross infection takes place between the birds and the mosquitoes where infected mosquitoes infect uninfected birds and infected birds too infect uninfected mosquitoes.

A part from feeding on birds, infected mosquitoes can also bite humans for a blood meal exposing them to the WNV during the process. However, humans are dead end hosts.

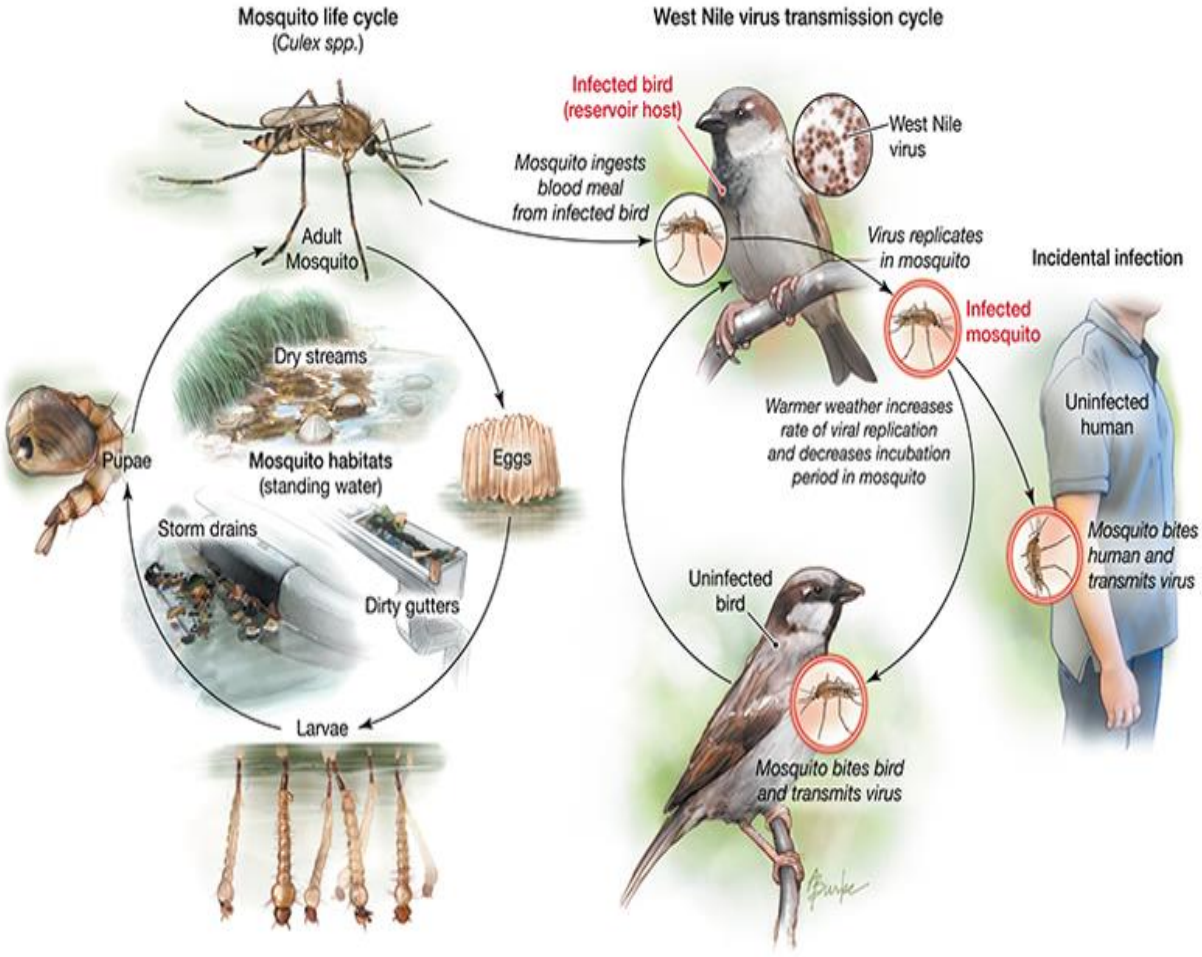

Figure 2-5: Relationship between the life cycles of the West Nile Virus and *Culex* mosquito.
(Source: JAMA.2012:308(18):1846 - 1848)

While adult female mosquitoes need a blood meal to complete the development of their eggs, males on the other hand feed entirely on plants. Males only live for about one week during which they mate the females. After just one mating, the females store sperms in a special organ known as spermatotheca which it utilizes to fertilize subsequent eggs to be laid. Females generally live longer compared to males and can live for months.

The immature mosquito stages are entirely aquatic and therefore their survival is dependent on fluctuations in weather conditions. They are also affected by other factors like competition for

limited recourses, predators, cannibalism, parasites and pathogens (Koenraadt *et al.* 2006; Munga *et al*. 2006).

The average duration of development from the eggs to adult mosquito is about 12 days and approximately only 10% of preimaginal population successfully reaches maturity. These rates are based on a study done in Kenya and Mali (Mwangangi *et al*. 2006). However, as earlier stated the development rate is dependent on temperature.

2.4. Epidemiology of West Nile Virus

The first case on record of WNV infection was in West Nile District, Uganda in1937 (Smithburn et al. 1940). Since then the virus has been known to circulate Uganda in an endemic cycle. From this focus, WNV has since spread globally to Europe, Middle East, North America, West Asia and Australia where it has caused several outbreaks of varying severities.

WNV was initially phylogenetically divided into two lineages, namely I and II. However, recently, variants of the virus have since been identified and added to the initial two lineages making the total number of lineages to five, named as lineages I, II, III, IV and V. Lineage I has a worldwide distribution and is composed of clades Ia and clade Ib. Clade Ia is mostly found in North America, Europe, Middle East and Northern Africa. The lineage I clade Ib is composed of the Kunjin virus which is the Australian strain of WNV. Lineage II of the virus has a limited distribution and has majorly been confined to Southern Sahara and Madagascar except for the recent exception where it has been detected in Hungary (Bakonyi *et al.* 2005), Italy (Savini *et al*. 2012), Austria and Greece (Papa 2013)

Lineage III which is composed of the WNV isolate from Czech Republic known as Rabenburg virus (Bakonyi *et al*. 2006). Lineage IV is composed the Russian isolate from Caucasus. (Lvov et al. 2000) and lineage V is composed of the India Lineage (Bondre *et al.* 2007).

Several outbreaks of WNV have been recorded in various countries including Greece (2010), Israel 1950s, late 1970s, 1988 and 2000, France 2000, Mediterranean region including Algeria, Tunisia and Morocco between 1994 ,1997 and 2012, Romania, Russia 1999, Portugal (2004), Spain (2004,2010), Italy (2008-2013), Hungary (2003–2013) , South Africa (2009),

Australia (2011) and USA (1999-2010) *(Del Giudice et al. 2004; Platonov et al. 2001; Sirbu et al*. 2011; Weinberger *et al*. 2001).

The unpredictable nature of these WNV infection outbreaks has made it difficult for scientists to precisely explain the epidemiology of the virus. To try and explain the nature of these outbreaks, several authors have come up with various theories. One of such theories is that there are possibilities that maintenance and transmission of the virus across distant locations and continents could be due to more diverse mosquito vectors other than the ones documented so far (Komar 2000). The role of ticks in the transmission of the virus also needs to be explored since it has been documented that they can act as vectors and reservoirs of WNV (Laperriere *et al*. 2011). Though establishment of WNV in Europe and Middle East has been attributed to migratory birds (passerines) like crows and jays, its spread to USA is still not clear (Artsob et al. 2009).

In Kenya, although no WNV outbreaks have been reported so far, a study by Lwande *et al.* (2013) indicates that the WNV in *Culex* mosquito vector is endemic in Kenya (Lwande *et al*. 2013). A survey conducted by Nyamwaya *et al*.(2016) in Tana River and Garissa Counties in Kenya to detect WNV in wild birds found out that 18% of the wild birds tested positive for WNV thereby confirming circulation of WNV in wild birds (Nyamwaya *et al.* 2016). Desirre *et al*.(2011) also established the prevalence of WNV in Kenyan mosquito population which suggested that the virus is naturally endemic in the country (LaBeaud *et al*. 2011). However, the actual disease incidence in the country has not been mapped out. Earlier on in 2009 during a surveillance programme for avian influenza, WNV antibodies were detected in birds from different parts of the country which further fortified the assertion that the virus is active in the country (Lutomiah *et al*. 2011). A study conducted on characterization of arboviruses from mosquitoes in Ijaara District in Kenya also found out that 22% of the samples screened were positive for WNV (Thomas and Urena 2001). Earlier in 1968, again in Kenya, WNV antibodies were detected in Marsabit and Garissa (Henderson *et al.* 1970) and Ijaara in 2010 (Lwande *et al.* 2013)**.**

2.5. Pathology of West Nile Virus

In humans, about 30% of people exposed to WNV get WNV infections manifesting in wide range of degree of severity from mild flu-like infection to fatal meningo-encephalitis in 2% to

17% of the cases. The severe form of infection is common in the elderly and immune-compromised population as witnessed in the Israel outbreak of 1957 (Campbell *et al.* 2002) and USA in 1999 (Guarner et al. 2004).

Majority of VNW infections goes unnoticed with about 80% of the infections being asymptomatic. Of the symptomatic cases, a greater number present with mild self-limiting symptoms in form of West Nile fever which manifests as acute systemic febrile illness with symptoms like headache, tiredness, body aches and swollen lymph nodes (Campbell *et al.* 2002; Petersen and Marfin 2002).

In about 1% cases of human WNV infections, the virus directly invades the central nervous system leading to a lethal encephalitis in form of West Nile Virus Neuroinvasive Disease (WNND) which results in cognitive dysfunction and flaccid paralysis (Petersen and Marfin 2002; Sejvar 2014). The neuro-invasive disease affects the central nervous system structures leading to West Nile virus meningitis, West Nile virus encephalitis or West Nile virus poliomyelitis (Campbell *et al*. 2002)**.** Symptoms commonly observed in neurological disease include stiffness of the neck, stupor, tremors muscle weakness, convulsions and paralysis. There is still no vaccine for human WNV infection.

Like in humans, most horses infected with WNV do not show any clinical signs with only about 10% presenting with neurological symptoms (Bunning *et al.* 2002). In the year 2000, in Southern France there was a WNV outbreak in horses with a mortality rate of 57.1% in the clinically affected horses (Murgue *et al* 2002). In the USA outbreak in 2000, the outbreak had a mortality rate of 38% while in Italy in 1998, the mortality was 42% (Cantile *et al*. 2001; Ostlund et al. 2001).

Most of the clinical signs presented by horses infected by WNV are almost entirely due to nervous system pathology particularly on the spinal cord with the cerebral cortex often less affected (Cantile *et al*. 2001). Some of the clinical manifestations observed in such cases include paresis (weakness) and paralysis of the limbs, ataxia, muscle tremors, muscle rigidity and recumbency. Transient fever may also be observed though not in all cases like the case in Italy outbreak in 1998 (Cantile *et al*. 2001). The case fatality rate for horses is 33% (CDC. 2009). However there is a vaccine for WNV in horses.

Wild Birds are the principal amplifying host of WMV in nature. Some birds, especially those of the family Corvidae which includes crows, jays and magpies are highly susceptible to the virus resulting in severe illness with high mortality rates. Other bird species are less susceptible to WNV exhibiting only transient vireamia then subsequently develop life-long immunity (Petersen LR, 2001).

Domestic birds are also infected by WNV but do not show any clinical signs. Serological tests however have revealed WNV antibodies in domestic birds as shown by one study conducted in Madagascar (Maquart *et al.* 2016). The birds evaluated included, chicken, guinea fowl goose, duck and turkey.

Domestic animals like dogs, cat, sheep, cattle and pigs do not show any symptoms of WNV infection. However antibodies can be detected in them.

2.6. Effects of Climate Change on the Transmission of West Nile Virus

WNV exhibits a complex epidemiology due to involvement of other factors in addition to the virus transmission and distribution. These factors affect the dynamics and interactions between the virus, vector, host and also the environment. One such factor is the climate. The environment is influenced by weather conditions which consequently directly or indirectly affects the vector population dynamics, vector competence and the virus extrinsic incubation rate (Kilpatrick 2011; Paz 2015).

The climatic variables that affect the epidemiology of WNV includes; precipitation, temperature, relative humidity and wind. Climate change has in the recent years sometimes brought extreme above normal variations in the above climatic factors resulting in devastating health impacts. For instance it has been documented that in the past 50 years, the average temperature and precipitation has increased across USA with precipitation rising by an average of about 5%. There has been also an increase in both frequency and intensity of some extreme weather conditions like heat, cold, precipitation and droughts. (Denman *et al.* 2007, IPCC 2007 Working Group II: US Environmental Protection Agency. 2012)

It has been proposed that above normal rainfall might generally lead to increases in the abundance of vectors with subsequent increased potential for WNV disease outbreak (Nasci *et*

al. 2001). In fact a positive correlation has been demonstrated between WNV disease outbreak and months before above normal rainfall. However, different studies have revealed a complex impact of rainfall on WNV epidemiology. For instance, heavy rainfall might create pools of water required for mosquito breeding. Heavy rainfall at the same time can also have a negative effect on the larval breeding by diluting and flushing away the breeding sites (Shaman *et al*. 2002).

Depending on the land ecology and topology, drought may increase or reduce potential for WNV disease outbreak. Drought generally causes drying up of mosquito breeding sites which in turn lead to a reduction of vector population. Some mosquito species may however thrive well in semi-permanent wetlands during drought because these areas form stagnant water pools which become rich in organic matter. Such pools may also have fewer competitors and predators which enhances their suitability for mosquito breeding (Letters 2003; Paz and Semenza 2013). A case in hand is the Texas WNV outbreak in the summer of 2012 which was partly attributed to drought that resulted in formation of stagnant pools of water (Roehr 2012).

Drought may also enhance WNV transmission rates by encouraging close contacts between hosts (birds) and vectors because of sharing the few remaining water sources. This can lead to an outbreak due to the rapid amplification of the virus within the population (Shaman *et al.* 2005).

Variations in ambient temperatures brought about by climate change can have a great impact on WNV transmission and replication rates. High ambient temperatures positively correlate with vector population growth, viral transmission efficiency and evolution rates (Kilpatrick 2011; Paz and Semenza 2013). On the other hand, a negative correlation exists between gonotroghic cycle, extrinsic incubation rates and high ambient temperatures (Ruiz *et al.* 2010).

There is limited research on the effect of relative humidity on the transmission WNV. However, some studies have suggested positive correlation between WNV infections and relative humidity. One such study was conducted in Tel Aviv where hospital admissions correlated with relative humidity (Paz 2006). Relative humidity may also positively correlate with vector population dynamics (Walsh 2012). Therefore climate change which involves alterations of the relative humidity is likely to affect the WNV transmission in the population.

One of the effects of climate change may be deviation from the normal pattern, direction and intensity of wind. Wind pattern has been associated with the transmission of WNV through its effect on dispersal of wind-blown vectors (Cantile et al. 2001; Paz 2015). This may therefore introduce vectors to new territories with the subsequent transmission of WNV to those populations. A case in hand is one where *Culex tritaeniorhynchus* was introduced in China (Ji-Guang M 1996).

2.7. The Tana River County Irrigation Project

The conversion of rangelands into crop lands through irrigation in Tana River County is expected to increase the suitability of these areas for mosquito breeding and high prevalence of vector-borne diseases including WNV. This is because studies have shown that WNV is endemic in habitats where competent vectors (*Culex* mosquitoes) and suitable hosts are prevalent. Irrigation results in availability of stagnant water in the irrigated areas and in drainage canals and which offers condusive habitat for mosquito breeding. Vectors also find plenty of feed including pollen from some of the crops grown in the irrigated farms (Ye-Ebivo *et al.* 2003). Birds and small animals visit the cultivated fields for food and water, enabling mosquitoes to access multiple sources of blood meal.

However, no studies have been done to determine processes that influence WNV transmission in irrigated areas. Therefore this study will attempt to give key insights into the WNV transmission dynamics in irrigated and non-irrigated regions in Tana delta.

2.8. Use of Epidemiological Model in Disease Transmission Analysis

Epidemiological model is a mathematical representation and simplification of epidemiology and its associated disease transmission processes. Models are important tool that can be used by policy makers during the planning stages to decide on the most cost effective method for disease intervention. Disease model can be used to simulate reality. It can also be used as a predictive and risk assessment tool when planning for contingency to counter potential WNV disease epidemics.

Models integrate the effects and interactions of multiple factors including ecological data, host and virus actors. Some models are based on differential equations (ODEs). The ODEs have parameters values based on the data to simulate the various ‘what if’ situations under study.

This enables determination of how different parameters under study affect the transmission dynamics of system.

A deterministic SEIR Model was used in this study .The SEIR model is based on the classical S-I-R *m*odel representing the Susceptible, Infected and Recovered classes but modified to SEIR (Susceptible, Exposed, Infectious, and Removed) model. Our Parsimonious model comprises of six mosquito compartments.

The epidemiological model developed here can be used to study WNV epidemiology subject to climatic variability and land use changes (irrigation). The model can also facilitate the evaluation of efficacy of various mosquito control measures such as use mosquito larvicides, adulticides and repellents.

We considered SEIR Model in this study given that similar models have previously been successfully used in investigating vector-borne diseases and some infectious diseases like malaria, influenza and measles (Hethcote *et al.* 2002)**.** In 1908, Ronald Ross developed the first epidemic model for vector-borne diseases known as Ross–Macdonald malaria model (Ross *et al.* 1911; Macdonald *et al*. 1957**)**. Based on this model, several models have been developed for vector-borne diseases including; African horse sickness (Lord, Woolhouse, and Heesterbeek 1996), bluetongue disease (Gubbins *et al.* 2008) and Usutu virus epidemics (Rubel et al. 2008).

Thomas & Urena (2001) presented the first WNV model in 2001. The authors sought to explain the effectiveness of pesticide sprays in reducing mosquito density after the outbreak of WNV in New Yolk city in 1999. More WNV models were later developed that involved use of basic reproductive numbers (R_O) (Cruz-Pacheco et al. 2005; Marjorie *et al.* 2004). Additional WNV models developed so far include the ones by Bowman *et al*.(2005), (M J Wonham and Lewis 2008) and Durand et al.(2010). The limitation of the above models is that they were developed with constant parameters and are therefore not able to simulate seasonal variability encountered in WNV prone regions.

The USUTU model by Rubel *et al.* (2008) and the WNV simulation model by (Laperriere, Brugger, and Rubel 2011) sought to improve on the existing models by using temperature-dependent mosquito parameters. It is however known that mosquito densities are not driven by a multitude of other ecological and non-ecological factors. Therefore to make a model

more realistic, as many variables as possible should be used. Unfortunately this makes the model to be more complex to develop and evaluate. It therefore calls for a trade-off between complexity and reality in developing a practical model.

Our model is simulated using precipitation-driven mosquito population densities. Additionally, mosquito suitability indices data variability is incorporated in the system. The variability in suitability indices are driven by amount of rainfall and irrigation.

CHAPTER THREE

3.0 METHODOLOGY AND MATERIALS

3.1. Study Area

Tana River delta region is the largest freshwater wetland system in Kenya. It is located in Tana River County which is located at 1^0 30'S 40^0 0^0E in the coastal region of Kenya. The delta covers an area of more than 130,000 ha of which 69,000 ha that is prone to flooding (Odhengo *et al*. 2012). The area is semi-arid with annual rainfall of about 400-700mm and 30 - 33^0C being the average annual temperatures. The county has low population density compared to the rest of the country which makes it ideal for both pastoralists' activities and development of irrigation projects. The main economic activities of the county revolves are pastoralism and farming. The main produce is maize, bananas, green and grams.

The landscape of the region can be classified into three: irrigated, pastoral and riverine areas. The region is composed of a unique ecological diversity composed of forests, woodlands, floodplain grasslands, various wetland types and a riverine forest that grow along the smaller rivers. There are many shallow lakes and wetlands scattered within the area. The region is home to more than 22 species of birds and a variety of migratory water birds which breed in the area (Bennun and Njoroge, *1999*).

3.2. Data Collection:

The data used in this work is described in Nyamwaya *et al.* (2016). The authors sought to detect West Nile virus in wild birds in Tana River County, Kenya.

Apart from the experimental data obtained from these studies, our study also incorporated meteorological data which was obtained from the Bura Irrigation scheme. The data included daily rainfall and average temperatures for Tana River County collected for 554 days beginning from 20th June 2013 to 22nd January 2015.

Find the attached data sheet in Appendix VI

In the study by Nyamwaya *et al*. (2016) to detect West Nile virus in birds in the study area, 361 birds were randomly trapped and blood samples obtained from them. Real time

Polymerase chain reaction test was performed to screen the samples for West Nile virus. The viral envelope protein was targeted for screening by developing gene specific primers for a portion of E genome region. The result showed that out of the 361 samples, 65 tested positive for WNV. This translates to WNV prevalence in birds of about 18% (Nyamwaya *et al*. 2016).

We used the WNV prevalence rate in mosquitoes of 18% obtained from literature in a study that was conducted in Northeastern Kenya. The study was on Arbovirus prevalence in Kenya (LaBeaud *et al*. 2011). This was the best estimate for prevalence we could get since no study on WNV prevalence in mosquitoes has been done in Tana River County specifically.

3.3 Formulation of the Model

The following assumptions were made during the model formulation,

- The model system is closed
- There is homogeneous mixing of individuals in the population
- Mosquitoes have an equal chance to access and feed on the hosts and they draw the same amount blood.
- One time step denotes a day.
- There is no transovarial transmission.
- Transmission of WNV involves *Culex* mosquitoes and a pool of birds which contribute equally in the transmission and are also equally susceptibility to WNV.

3.2.1. Model Design

Our model design is based on adoption and modification of the following models: the Usutu virus (USUV) model in Rubel *et al.* (2008) on Usutu virus epidemic in Vienna, Australia and the WNV epidemic in Minneapolis in Laperriere *et al.* (2011). The Fuzzy model in Ermert *et al.* (2011) was also incorporated. Modifications were made to ensure that the model fits our specific local conditions. The Usutu virus model was chosen on account that it is closely related to WNV by virtue of their similar characteristics including sharing the same vector (*Culex* mosquitoes) and also involving birds as hosts (Weissenb 2009). We adopted the Fuzzy model for malaria in this study it since we don't have one specifically for WNV to determine mosquito (*Culex)* suitability index.

The model is designed as closed system where new hosts are not allowed to exit or enter the system. This model was chosen given that the main focus of the work is to study local population and disease dynamics as well as the impacts of various WNV intervention strategies. An open system would be more applicable for studying how the virus gets disseminated in a spatial environment.

Data used in our model was obtained from a pool of different WNV competent bird species and average values considered to cater for the differences in susceptibly between the species. This is because even though WNV has been recovered in about 326 bird species, they all exhibit different clinical outcomes due to variability in susceptibility to WNV infection (Marka *et al.* 2013).

Our model exhibits the cross infection of WNV between mosquitoes and birds which portrays the natural transmission of the virus. The cross infection occurs when susceptible birds get infected when bitten by an infectious mosquito and also susceptible mosquitoes become infected when they bite an infectious bird. Humans get infected when they are bitten by infectious mosquitoes but they are dead-end hosts. Mosquitoes do not die from WNV infection but undergo natural death. Humans and birds can get fatal WNV infection but we did not have any data for the death rates of the two in this particular study. We therefore did not include disease-death rates for humans, birds and mosquitoes.

3.2.2. Conceptual model design

The model is a deterministic, non-spatial compartmental SEIR model that utilizes both constant and time-continuous parameters. The model has six mosquito compartments comprising the population sub-module and infection sub module. The population sub module is made up by Eggs, Larvae, Pupae and Adults (Susceptible) and the infection sub-module comprises Susceptible, Exposed and Infected mosquitoes.

In the mosquito population sub model, the adult mosquitoes lay eggs depicted in the eggs compartment. The eggs develop into larvae and move to larvae compartment or die. The larvae exit the larvae compartment when they develop into pupa and move into pupa compartment or when they die naturally or through larvicides. Some pupa develops into adult mosquito and move to adult compartment while others die.

In the mosquito infection sub model, the adult mosquito is in the susceptible compartment because they are susceptible to WNV. When these mosquitoes bite competent birds that are infected by WNV, they become infected and enter the exposed compartment. Some susceptible mosquitoes die naturally or killed by adulticides. After the incubation period, the exposed mosquitoes become infectious and move to the infectious compartment. Some exposed mosquito die naturally or due to use or adulticides. The infectious mosquito can bite and infect birds, humans or other animals and expose them to WNV.

We assumed a density-dependent (logistic) population growth and concidered the carrying capacities of mosquito's eggs to make our simulation more realistic.

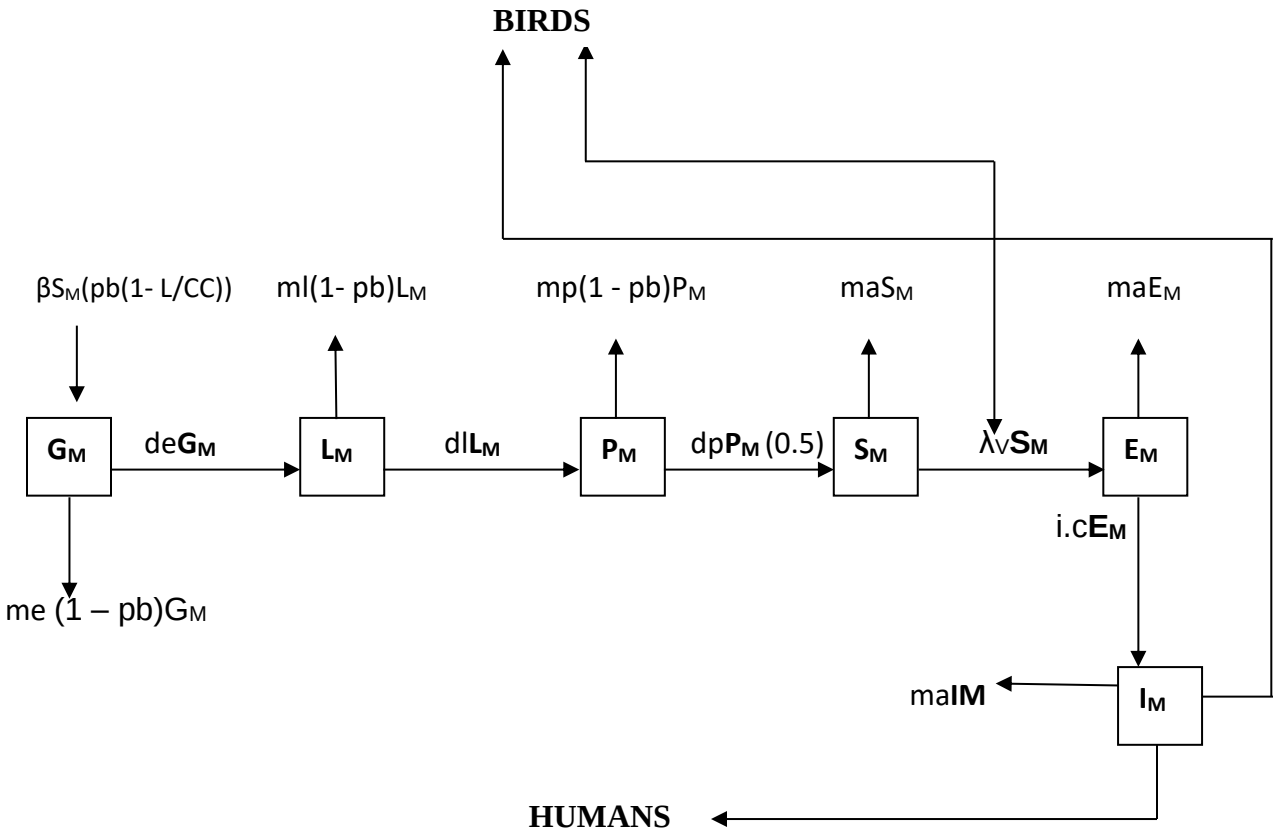

Figure 3-1: Conceptual model of the transmission of West Nile virus in mosquitoes.

The model shows the eggs ($\mathbf{G_M}$), larvae ($\mathbf{L_M}$), pupa ($\mathbf{P_M}$), susceptible ($\mathbf{S_M}$), exposed ($\mathbf{E_M}$) and infectious ($\mathbf{I_M}$) mosquito compartments. The de, dl, dp, λv and i.c are transition rates from the eggs. larva, pupa, susceptible and exposed compartments respectively. me, ml, mp and ma represents the mortality rates for the eggs, larva, pupa and adult compartments respectively.

Susceptible mosquitoes denote the number of mosquitoes that can become infected after taking a blood meal from an infectious host.

Exposed mosquitoes represent the proportion that even though are infected with the virus, cannot transmit the virus to a susceptible host until the incubation period has elapsed.

Infectious mosquitoes on the other hand can transmit the virus to a susceptible host. Infectious mosquitoes remain infectious for life.

We considered the dynamics in mosquito compartments in this project. The birds and human are shown to illustrate how transmission takes between the vector and the two hosts.

3.2.3. Derivation of Ordinary Differential Equations (ODEs)

(A) ODEs for Mosquitoes' Population Dynamics (Non-irrigated areas)

$$\frac{dE_M}{dt} = \beta A_M pb\left(1 - \frac{L_M}{CC}\right) - (deE_M - me(1 - pb)E_M) \quad \textbf{(1)}$$

$$\frac{dL_M}{dt} = deE_M - dlL_M - ml(1 - pb)L_M \quad \textbf{(2)}$$

$$\frac{dP_M}{dt} = dlL_M - dpP_M - mp(1 - pb)P_M \quad \textbf{(3)}$$

$$\frac{dA_M}{dt} = dpP_M(0.5) - maA_M \quad \textbf{(4)}$$

(B) ODEs for Mosquitoes' Population Dynamics (Irrigated areas)

$$\frac{dE_{MW}}{dt} = \beta A_{MW} pb.adj\left(1 - \frac{L_{MW}}{CC}\right) - deE_{MW} - me(1 - pb.adj)E_{MW} \quad \textbf{(5)}$$

$$\frac{dL_{MW}}{dt} = deE_{MW} - dlL_{MW} - ml(1 - pb.adj)L_{MW} \quad \textbf{(6)}$$

$$\frac{dP_{MW}}{dt} = dlL_{MW} - dpP_{MW} - mp(1 - pb.adj)P_{MW} \quad \textbf{(7)}$$

$$\frac{dA_{MW}}{dt} = dpP_{MW}(0.5) - maA_{MW} \quad \textbf{(8)}$$

(C) ODEs for Mosquitoes' Disease Dynamics (Non- irrigated areas)

$$\frac{dS_C}{dt} = dpP_M(0.5) - \lambda_V S_C - maS_C \quad \textbf{(9)}$$

$$\frac{dE_C}{dt} = \lambda_V S_C - incub.c\ E_C - maE_C \quad \textbf{(10)}$$

$$\frac{dI_C}{dt} = incub.c\ E_C - maI_C \quad \textbf{(11)}$$

(D) ODEs for Mosquitoes' Disease Dynamics (Irrigated areas)

$$\frac{dS_{CW}}{dt} = dpP_{MW}(0.5) - \lambda_{VW} S_{CW} - maS_{CW} \quad \textbf{(12)}$$

$$\frac{dE_{CW}}{dt} = \lambda_{VW} S_{CW} - incub.cE_{CW} - maE_{CW} \quad \textbf{(13)}$$

$$\frac{dI_{CW}}{dt} = incub.cE_{CW} - maI_{CW} \quad \textbf{(14)}$$

3.2.4. Parameter Estimation

Table 3-1 contains a summary of the parameters that we used in this model. The parameters are presented as per capita, per day. Most of the parameters are derived from literature published by different authors as indicated in the table. The parameters fall into two groups: constant and variable ones. The variable parameters are driven by temperature and suitability index (precipitation)

Table 3-1: Parameters used in the West Nile Virus model.

	Parameter	**Symbol**	**Value**	**Source**
	Culex average per capita egg laying rate	β	40	Wong *et al*. (2011)
	Culex eggs hatching rate	de	**0.33**	Clements *et al.(*1992)
	Culex larva daily per capita mortality rate	ml	**0.1**	Unavailable
	Culex larva development rate	dl	**0.1**	Clements *et al.*(1992)
	Culex pupa development rate	dp	**0.2**	Gokhale *et al.* (2013)
	Culex pupa daily mortality rate	mp	**0.1**	Unavailable
	Culex adult daily mortality rate	ma	**0.1(.01666)**	Christy *et al.*(2013)
	Culex lifespan	De	**3 - 60**	Gaff *et al.*(2007)
	Transmission probability by infectious mosquitoes.(Mosquito to bird)	p_{MB}	**0.88**	Turell *et al.* (2001)
	Culex per capita biting rate on birds (Gonotrophic interval)	k (gono.c)	**0.2 – 1 (0.33)**	Cruz-Pacheco *et al.* (2005)
	Culex per capita transition rate, exposed to infected	γ_M	**0.106**	Sardelis *et al.*(2001)

Suitability Function

Parameter	**function**
β	f(pb) = 40(pb)
me	f(pb) = 1 – (0.825(pb))
ml	f(pb) = 1 – (0.825(pb))
mp	f(pb) = 1 – (0.825(pb))

Source: Ermert *et al.* (2011)

We only considered precipitation (suitability index) in OUR model.

The average per capita egg laying rate (β) was estimated at 40 according to (Wong et al. 2011). We considered two functions as drivers for the eggs laying rate i.e. gonotrophic cycle and suitability (pb) index which is a function of precipitation. It is described as;

f(pb) =(pb) 40

This is based on the study on Anopheles mosquito Ermert *et al*.(2011)

The mortality rates **me, ml** and **mp** of the preimaginal stages of the mosquitoes are driven by Suitability index as follows;

1 – (0.825(pb) Ermert *et al*.(2011)

The value of 0.825 is used to cater for other factors that also contribute to the mortality of these preimaginal stages other than suitability index. Some of these factors include parasites, predators, competition for resources, crowding stress and destruction by physical features.

Temperature also an important driver of these mortality rates according to Bailey and Gieke (1968) but this was not captured in our model

The development rate of immature mosquitoes was estimated at 0.1 (Reisen *et al.*1995) and are also driven by the suitability index by Ermert *et al.* (2011) as follows;

f(pb) = β (pb)

f(pb) = dl(pd)

f(pb) = dp(pd)

The Culex mosquito biting rate **k** is adopted as 0.2 – 1(Cruz-Pacheco *et al.* 2005). However, this rate is variable and is driven by temperature by the following function:

$$f(T) = 0.344/[1 + 1.231 \exp(-0.184(T-20))]$$

The biting rate is determined by the gonotroghic cycle which in turn is driven by temperature (Reisen *et al.* 2006).

In this study, this biting rate is also varied by the interventions against WNV i.e. use repellents.

The transmission probability by infectious mosquito (from mosquito to birds) (P_{MB}) was adapted at 0.88 (Turell *et al*. 2001). This is a measure of vector infectivity. We also used the same value as an estimate of same parameter for transmission from mosquitoes to humans (P_{MH})

3.2.5. Model Description: Vector module

The Vector module comprises (i) mosquito population dynamics sub-model which can explain densities of eggs, larvae, pupae and adult stages of mosquitoes at each time step, and (ii) infection dynamics sub-model which simulate the rate of infection and development of infection in the vector population through susceptible, exposed and infectious compartment.

Vector population is determined by density dynamics of the immature mosquitos' stages. The hatching, development and mortality rates of these preimaginal stages are assumed to be driven by the suitability of the environment for mosquito breeding.

To determine the mosquito suitability index (referred to in this study as **pb**) of the irrigated and non-irrigated sites, we adopted the Fuzzy Distribution Model that was used by (Ermert *et al.* 2011)**.** Mosquito vector population dynamics is driven by environmental and climatic variables that include water, precipitation and temperature.

Even though the amount of rainfall is directly correlated to the number of suitable breeding sites, this relationship is not linear (Shaman *et al*. 2005). This is because the number of created breeding sites proportionately increases with the amount of rainfall up to some optimum amount. Beyond this point there are no more suitable breeding sites created and hence no corresponding increases in the vector densities. Strong rains on the other hand wash away the suitable mosquito breeding sites and therefore reduce larval densities by flushing and killing them (Gimnig *et al*. 2001).

Fuzzy distribution model is based on the fuzzy logic which uses qualitative arguments of whether the site is suitable or rendered unsuitable for mosquito breeding as determined by amounts of rainfall. We used this method to determine the mosquito oviposition rate and the immature mosquito survival rates.

The principle behind the Fuzzy model is founded on the basis of the following three scenarios; that there is only minimal or no oviposition without water (rainfall), excess rainfall destroys breeding sites and optimal rainfall leads to more eggs being oviposited. Based on the above, the fuzzy model categorizes regions as dry unsuitable condition threshold (**U_1**), unsuitable condition threshold due to excess rainfall (**U_2**) and the most suitable condition, (**S**).

The model uses the 10-day accumulated rainfall (**R_{10d}**) values as daily rainfall input values and outputs fractions of values between **0** for most unsuitable conditions(**U_1** and (**U_2**) and **1** for the most suitable condition**(S)** as fuzzy suitability index. The results of the fuzzy model are derived from the sigmoid curve below;

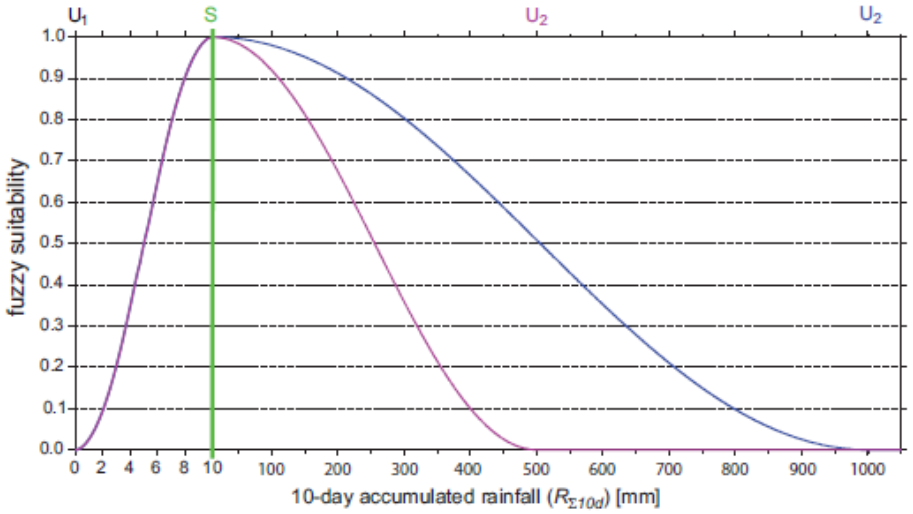

Figure 3-2 : The Fuzzy Suitability Distribution Model

Source :(Ermert *et al*. 2011)

The fuzzy model is driven by the 10-day accumulated rainfall fuzzy function ($f(R_{10d})$) .This function incorporates three conditions as follows;

(i) If $\mathbf{R_{10d}}$ is between $\mathbf{U_1}$ and **S,** then ,

$$f(R_{10d}) = 1 - \cos^2\left(\frac{\mathbf{R_{10d}} - \mathbf{U_1}}{\mathbf{S} - \mathbf{U_1}} \cdot \frac{\boldsymbol{\pi}}{\mathbf{2}}\right)$$

(ii) If $\mathbf{R_{10d}}$ is between **S** and $\mathbf{U_2}$, then ,

$$f(R_{10d}) = \cos^2\left(\frac{\mathbf{R_{10d}} - \mathbf{S}}{\mathbf{U_2} - \mathbf{S}} \cdot \frac{\boldsymbol{\pi}}{\mathbf{2}}\right)$$

(iii) Else,

$$f(R_{10d}) = 0$$

Oviposition rate can be determined by the number of ovipositing mosquitoes and the number of suitable breeding sites which is driven by the 10-day accumulated rainfall. We used the fuzzy distribution model used by (Ermert *et al*. 2011) to determine the suitabilities of breeding sites. The Fuzzy model uses 10-day accumulated rainfall to categorize suitability into two unsuitable conditions (U_1 and U_2) and one suitable (S) condition.

Dry conditions and excess rainfall provide unsuitable environment while moist conditions are suitable. The model outputs fractions from **0** for unsuitable to **1** for the most suitable through computing the 10 day-rainfall as input. This computation is done through the sigmoidal fuzzy membership curve. (See figure 3-2)

The suitability index (pb values) obtained by this model is used to drive the densities of the eggs, larvae and pupae which eventually determines the mosquito densities for various scenarios.

3.2.6. Formulation of the Population models

The population density of mature mosquitoes depends on its probability of survival which is a factor of both intrinsic and extrinsic mosquito characteristics. These include the species, age of mosquito, parasites, predators, environmental factors and control interventions. The probability of survival directly correlates to the mosquito reproduction rate (Samarawickrema WA *et al*. 1967).

We used a use the density-depended population model for the mosquito because the mosquito population growth can inhibited in the long-run by competition for limited resources like water, nutrition and space. The population model is formulated as ordinary differential equations (ODE), which is denoted by the difference between the birth rates and the mortality rates i.e.

$r = b – m,$

Where r is the reproduction rate, b is the birthrate and m, the mortality rate.

The ODE for both the aquatic and the terrestrial groups of mosquitoes can be given as expressions as;

$$dE_M/dt = \beta A_M pb\ (1 - L_M/CC) - (deE_M) – me(1-pb)E_M$$

$$dL_M/dt = deE_M - dlL_M - ml(1-pb)L_M$$

$$dP_M/dt = dlL_M - dpP_M - mp(1-pb)P_M$$

Where;

CC is the carrying capacity of mosquito larvae

pb is the suitability index

The mosquito population dynamics is influenced by temperature and precipitation (rainfall and irrigation) which in turn affect the birth and mortality rates of both adult mosquitoes and the preimaginal stages.

The birth rates include;

β which is the egg deposition rate

$dpP_M(0.5)$ which is the adult mosquito birth rate (Only females considered)

The death rates include;

$me(1-pb)E_M$ - Egg mortality rate

$ml(1-pb)L_M$ - Larvae mortality rate

$mp(1-pb)P_M$ - Pupa mortality rate

maA_M - Adult mortality rate.

3.2.7. Infection models

In the mosquito module, the infection model demonstrates the infection dynamics in the Susceptible, Exposed, and Infectious mosquito compartments. The transitions are driven by the following transmission parameters; adult maturity rate denoted by **dp**, the force of infection denoted by **λ**, incubation rates denoted by **incub.c** and mortality rates denoted by **ma.**

The ODEs for the mosquito infection model are as follows;

$$dS_C/dt = dpP_M(0.5) - \lambda_V S_C - maS_C$$

$$dE_C/dt = \lambda_V S_C - incub.c\ E_C - maE_C$$

$$dI_C/dt = incub.c\ E_C - maI_C$$

3.2.8. Transmission models for West Nile virus

(A) From Mosquito to Birds

The rate of transmission of WNV (the force of infection) from an infectious mosquito to a susceptible bird is denoted by a composite variable, λ_{MB}. It is made up of the following variables;

(i) Mosquito biting rate (**k**)

This is estimated as the inverse of the mosquito gonotrophic cycle and it is a temperature dependent variable.

(ii) Mosquito transmission probability (p_{MB})

This is the probability that a bite from an infected mosquito will result into an infection in a susceptible bird.

(iii) Mosquito to Bird ratio.(Φ_B)

This is obtained by dividing the density of mosquitoes by that of birds. This implies that each bird receives k ΦB bites from mosquitoes per unit time.

(iv) Mosquito blood meal index (bld)

This measures the proportion of blood meals a mosquito obtains from a bird.

(v) WNV prevalence in the mosquito (I_M/K_M)

This is important because the force of infection depends on the proportion of the infectious group with respect to the carrying capacity. It is a therefore a frequency dependent process as described by Macdonald (1952)

The mosquito specific force of infection is thereby obtained by;

$$\lambda_{MB} = k * p_{MB} * \Phi_B * bldmeal * I_M/K_M$$

As for this model, to calculate our mosquito force of infection to birds (λ_{MB}), we considered the gonotrophic cycle (Biting rate), probability of infection, mosquito blood meal index and mosquito disease prevalence. The mosquito to bird ratio was ignored.

Therefore our mosquito specific force of infection is;

$$\lambda_{MB} = k * p_{MB} * bldmeal * I_M/K_M$$

(B) Transmission of WNV from Mosquito to Humans

Derivation of mosquito specific force of infection to humans follows the same pattern as the one illustrated above for the bird. However, the probability of infection and the ratio have to be adjusted specifically for humans thus;

(i) Mosquito biting rate (**k**)

This is estimated as the inverse of the mosquito gonotrophic cycle and it is a temperature dependent variable.

(ii) Mosquito transmission probability (p_{MH})

This is the probability that a bite from an infected mosquito will result into an infection in a susceptible human.

(iii) Mosquito to Human ratio.(Φ_H)

This is obtained by dividing the density of mosquitoes by that of humans. This implies that each person receives k ΦH bites from mosquitoes per unit time.

(iv) Mosquito blood meal index (bld)

This measures the proportion of blood meals a mosquito obtains from a person.

(v) WNV prevalence in the mosquito (I_M/K_M)

The force of infection depends on the proportion of the infectious group with respect to the carrying capacity.

Therefore;

$$\lambda_{MH}. = k * p_{MH} * \Phi_H * bldmeal * I_M/KM$$

This model however, did not consider the Human: mosquitos' ratio and therefore adjusted the formula to;

$$\lambda_{MH}. = k * p_{MH} * bldmeal * I_M/KM$$

3.3. R Code Generation

R version 3.1.2 (2014-10-31) was used. The following R libraries were also was used in the analysis;

- Stats, Graghics and Gr graphics -R Core Team (2014)).
- Lubridate -Garrett Grolemund, Hadley Wickham (2011)
- MESS -Claus Ekstrom (2014).)

Our model was driven by meteorological data which we imported to R studio from the original excel sheet (The data having been converted to comma separated format (CSV).The data was then cleaned by removing redundancies (dates). The amount of water used for irrigation was then converted to same units as used for measuring rainfall i.e. mm^3 /mm^2 for easier comparison.

Cumulative 10-day rainfall and irrigation water was then calculated from the daily rainfall data. A data set with ordered number of days, dates, rainfall, temperature and cumulative 10-rainfall was then generation after which the all the initial and transition parameters were inputted including Fuzzy model

The code was then implemented through thre various ODEs under study and obtaining numerical and graphical outputs.

3.4. Analysis of the Model

3.4.1. Sensitivity analysis

Sensitivity analysis was done to determine how our model output was sensitive to changes in the parameters used. The analysis was done by holding other parameters values constant and only varying the parameter under study. The value of each parameter to be evaluated was in turn adjusted by 50%± of the baseline value and noting the corresponding percentage effect on the model output. The parameters that were analyzed included adult mosquito mortality rate, larval mortality rate, biting rate and probability to getting infection from an infectious bite.

The sensitivity was also done for the initial number of adult mosquitoes, eggs, larvae and the carrying capacity.

3.4.2. Model Outputs

Using the plot function, various plots were generated to analyze the different aspects and situations under study. The following situations analyzed as follows;

(a) Comparative rainfall and all water pattern over time

(b) Comparative cumulative 10-day rainfall and all water over time

(c) Comparative suitability indices for water and all water over time

(d) Comparative effects of rainfall and all water on vector density over time

(e) Comparative Entomological Inoculation Rates (EIRs) for rainfall and all water.

3.4.3. Scenario analyses

The model was used to analyze and determine how irrigation impacts on risk of WNV infection in humans. Other scenarios analyzed by the model were the effects of the various WNV control measures on its level of risk. The interventions analyzed included the use of mosquito repellents, Larvicides and Adulticides.

3.4.4. The impact of irrigation on the risk of West Nile Virus infection.

In this study, we used the Entomological Inoculation Rate (EIR) as a measure of risk of transmission of WNV. EIR was chosen because it measures the infectious bite per unit time per person which is a direct reflection of the intensity of WNV transmission by vectors and vector control interventions. This method has previously been used to determine the impact of vector control measures for malaria (McDermott and Coleman 2001; Shaukat, Breman, and McKenzie 2010).

EIR is derived from the following formula;

EIR = A/human pop*pinfec.h *prev WNV in culex*k.

Where;

- A is the total number of *Culex* from the population dynamics model.

- Human population is 10000,

- **pinfect.h** is the probability that human gets infected with WNV from an infectious mosquito bite

- **prev WNV** is the prevalence of WNV in Culex –18% (LaBeaud et al. 2011).

- **k** is the biting rate i.e. 1/3

The impact of irrigation is determined through finding the difference between EIR for rainfall alone and that for rainfall plus irrigation (All water). This simulation is mainly driven by respective suitability indexes of the two scenarios i.e**. pb** and $\mathbf{pb_{adj}}$ for rainfall and all water respectively. These suitability indices are derived from the Fuzzy distribution modeling using 10-day accumulated rainfall and irrigation water (All water).

These suitability indexes ultimately affect the vector population (A), which is used as an input in determining the EIR.

The quantify the difference in the risk of WNV under irrigated and non-irrigated situations, the Area under the curve (AUC) package in R was used to calculate the EIR values for the respective situations.

The percentage increase in WNV risk attributable to irrigation was obtained by the following formulae;

$$\frac{EIRw - EIR}{EIR} * 100$$

Where EIRw and EIR represents EIR for all water and rainfall respectively

3.4.5. Analysis of the impact of WNV control measures

The analysis was done by determining the impact of each control measure individually on the respective EIR values. The following assumptions were made during these analyses:

The analyses were done and compared for both rainfall situation alone and for both rainfall and irrigation.

3.4.6. Impact of repellents

Repellents act by reducing the contact rates between mosquitoes and humans which affects the biting rate (**k**). Therefore to test the effects of repellents on the model, we adjusted the transmission parameter, **k**. This corresponds to the gonotrophic cycle (gono.c),

For this analysis, the gonotrophic cycle (gono.c), was adjusted from the baseline value of 0.333 denoted as 0% repellent usage. At this 0% repellent usage (0.333) the WNV risk corresponds the EIR obtained for rainfall and all water without any interventions. The gono.c rate was then adjusted gradually from 0% usage (baseline rate of 0.333) to 100% (1) to simulate increasing levels of repellent usage from minimum to maximum.

EIR = A/human pop*pinfec.h *prev WNV in culex* gono.c (Adjusted values).

These adjusted values of gono.c were in turn inputted in the model and outputted the corresponding new EIR values. These EIR values and the corresponding % repellent usages were then used plot a graph showing the impact various levels of repellents usage on the risk of WNV (EIR).

This computation was performed by our R model

3.4.7. Impact of Larvicides

Larvicides affects the immature mosquitoes i.e. larva and pupae. In our model, the larvicides affect **L** and **P** compartments in the mosquito population model by altering the larval mortality rate (**ml**). This eventually feeds into the adult mosquito (**A)** compartment in the mosquito population model.

It has been demonstrated that different larvicides have varying levels of efficacy. For instance, Chih-Yuan Wang *et al* demonstrated that pyripoxifen (insect growth regulator), had 100% efficacy against larvae but only 1.5 to 7.8% efficacy against pupae. They also found out that polydimethylsiloxane (monomolecular film), was 100% efficacious against pupae compared to about 38% against larvae. Larvicidal oil was found to have an efficacy of between 93.3 to 100% on both larvae and pupae (Wang *et al*. 2013).

We however ignored these varying levels of larvicides efficacy and assumed a constant efficacy. We also assumed that the larvicides only affect the larvae but not the pupa.

For analysis of larvicides the larva mortality rate (ml), was adjusted from the baseline value of 0.1 representing 0% larvicide usage up to 100% usage and obtaining the corresponding EIR values

At 0% usage (0.1) the WNV risk corresponds the EIR obtained for rainfall condition without any interventions. The ml rate was then adjusted sequentially from 0% up to 100% from the baseline value of 0.1.

These adjusted ml values were in turn inputted in the model and obtained the corresponding number of adult mosquitos **(A).**

$$\mathbf{dL_M/dt = deE_M - dlL_M - ml(1\text{-}pb)L_M}$$

The different output levels of A (Adults mosquitoes) obtained by the variation of ml in the above calculations are fed into the disease model for obtaining the corresponding EIR values.

EIR = A (Adjusted values***)/human pop*pinfec.h *prev WNV in culex* gono.c***

Ultimately, the varying levels of ml (larvicide usage) resulted into different corresponding EIR values. The EIR values and corresponding % larvicide usage was used to plot a graph showing how various levels of larvicide usage impacts on the risk of WNV. This is done to compare the rainfall and all water situations.

3.4.8. Impact of mosquito Adulticides

In the mosquito population model, the mosquito adulticides affects the densities of the adult mosquitoes compartment (**A**) directly by altering is the adult mosquito mortality rate (**ma**).

For analysis of adulticides the adult mosquito death rate (**ma**), was adjusted from the baseline value of 0.0167. To simulate the impact of use of mosquito adulticides on the population model, we adjusted **ma** as we did for Repellents and larvicides. The resulting **A** values are then fed into the disease model to obtain the corresponding EIRs as follows;

EIR = **A** (Adjusted)/human pop*pinfec.h *prev WNV in culex* k

All computations were done in R version 3.3.2 (2016-10-31)

CHAPTER FOUR

4.0 RESULTS

4.1. Irrigation and Rain Pattern over Time.

The graphical output for the rainfall and irrigation pattern shows that Tana River area received low rainfall with most days recording no rainfall. The rains were mostly below 5mm and patchy in nature. However, high rainfall showed a seasonal pattern mainly experienced between around day 50 and day 150, between around day 240 to day 300 and finally between day 460 and 500. The longest dry spell with no rainfall at all was between days 152 to day 238.

Using the R, area under the curve (AUC) function, we calculated and compared the amount of rainfall and irrigation water. The total amount of rainfall was 403.8mm. This represents the cumulative amount of rain received in the area over the study period.

```
> sum(x3$rain)        [1] 403.8
```

Irrigation water on the other hand was pumped throughout the entire period except between day 260 to day 290. Most water was pumped between day 140 and 250 when there was completely no rainfall. There was sufficient rainfall during the short period when no water was pumped. The total amount of water pumped was 2197.616mm

```
> totalmm_pump        [1] 2197.616
```

The total amount of water from rainfall and irrigation combined was 2601.316mm

```
> totalmm_irrig       [1] 2601.316
```

The percentage increase in water using rainfall as baseline that is attributable to irrigation was 544.3686 %

```
> totalmm_rain        [1] 403.7
> totalmm_irrig       [1] 2601.316
> change_mm           [1] 544.3686
```

The graphs below show the outputs for the rainfall and irrigation pattern over time.

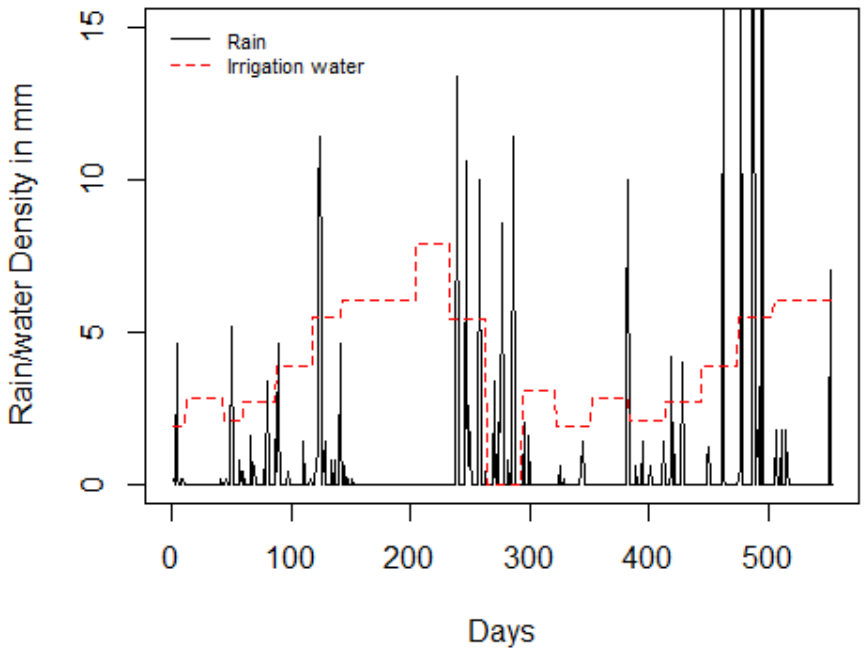

Figure 4-1: Rainfall and Irrigation Pattern over time

4.2. Cumulative 10-day Rainfall and Irrigation Patterns

We obtained the cumulative 10-day rainfall and irrigation under the following perspectives:

- Cumulative 10-day rainfall pattern
- Comparative cumulative 10-day rainfall pattern and rainfall pattern
- Cumulative 10-day all-water pattern
- Comparative cumulative 10-day all-water pattern and irrigation pattern
- Comparative cumulative 10-day all-water pattern and cumulative 10-day rainfall pattern

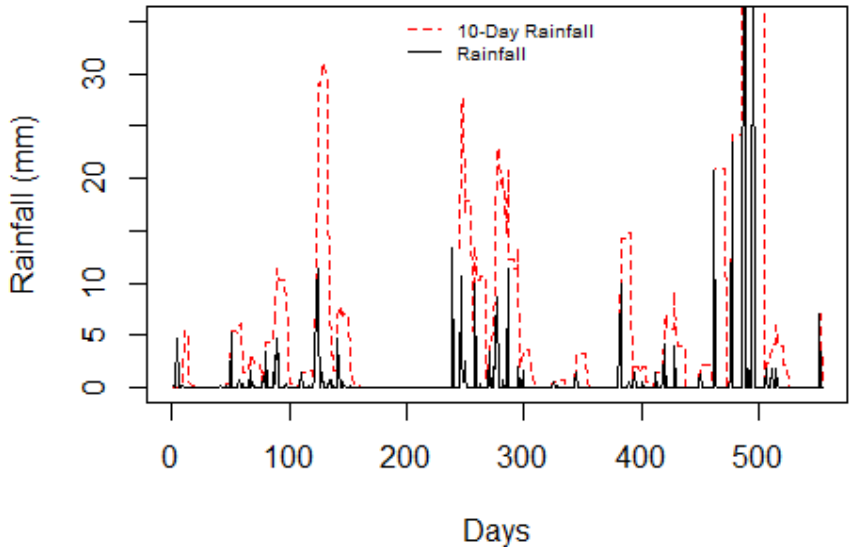

Figure 4-2: Comparison of cumulative 10-day-rainfall and rainfall

The cumulative 10- day rainfall increased the amount of 'rainfall' and also extended the number of days the 'rains' were experienced. This resulted in creation of approximately three peaks of rainfall above 20mm. Several days which had no actual rainfall were considered as having rain in this scenario.

In overall, the cumulative 10-day rainfall increased the amount of 'rainfall' from 403.8mm to 3950.8mm.This translates to an apparent 878% increase in 'rainfall'.

For the irrigation scenario, the cumulative 10-day all-water increased the amount of 'water' from 2601.316mm to 25,550.67mm which is an increase of 882.22%.

```
> sum (water)
[1] 25550.67
```

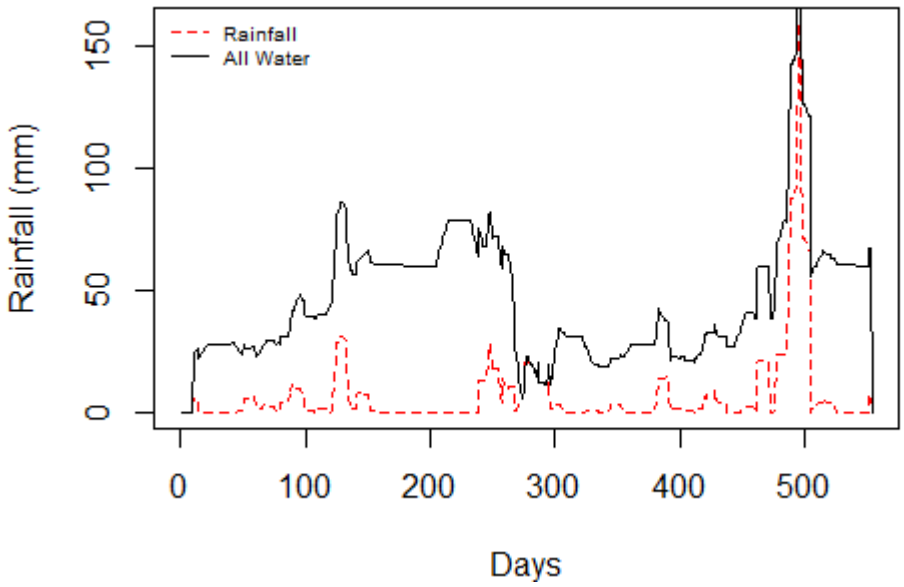

Figure 4-3: Comparative cumulative 10-day-rainfall and irrigation

The result shows an increase in both the amount of rainfall and number of days that received r ainfall due to changes attributable to the 10-day accumulated rainfall and irrigation water. This is compared to actual rainfall and all water recorded.

In the rainfall situation, the total amount of rainfall was 403.7 mm while the 10-Day accumula ted rainfall was 3950.8mm. This is an increase of 544.3686 % attributed to 10-Day accumulate d rainfall.

On the other hand in the irrigation situation, the total amount of water pumped for the period was 3950.8mm while the 10-Day accumulated water was 25550.67mm, an increase by 546.72 13 %.

```
> totalmm_rain        [1] 403.7       # Total rainfall
> totalmm_irrig       [1] 2601.316    # Total All Water
> change_mm           [1] 544.3686    # % Increase in due to Irrigation
```

```
> total10mm_rain      [1] 3950.8     # Total 10-Day rainfall
> total10mm_irrig     [1] 25550.67   # Total 10-Day All water
> change_10mm         [1] 546.7214   # % Increase in 10-Day water
```

Table 4-1 : Summary of Rainfall, All water and Cumulative Water amounts

	Amount (mm)	Cumulative 10-Day(mm)	% Change
Rainfall	403.7	3,950.8	878.65
All Water	2601.316	25,550.67	882.22
% Change	544.3686	546.72	

4.3. Evaluation of Suitability Index

The Fuzzy logistical model was used to derive the relevant suitability indices in R for irrigated and non- irrigated scenarios. These suitability indices were used to drive the vector density model that ultimately determined the disease risk. The suitability index was evaluated under the following scenarios;

- Suitability index for rainfall only
- Suitability for all water
- Comparative suitability for both rainfall and all water

The results showed that the total suitability for rainfall alone was **45.2475** while that of all water was **310.1399**. Therefore irrigation increased the suitability of the area for mosquito breeding by **585.4298 %**

```
> total_suitab_rain        [1] 45.2475
> total_suitab irrig       [1] 310.1399
> change_suit              [1] 585.4298
```

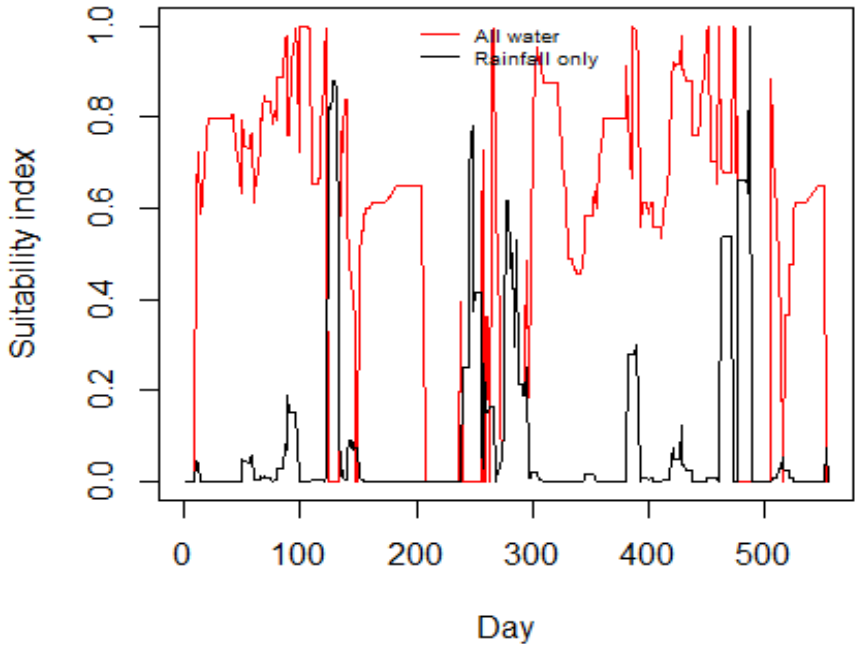

Figure 4-4: Comparative suitability index for irrigation and rainfall

4.4. Evaluation of Vector Densities

In order to understand how irrigation affects the vector densities, we used the R AUC function to evaluated the vector densities in respect to;

- Effect of rainfall alone on vector population
- Effect of all water on vector density
- Comparative effects of both rainfall and all water effects on vector density

In the rainfall scenario, the vector density had three main peaks corresponding to the peaks of the rainfall pattern. The highest peak was the third one occurring after day 500 which corresponds to the period with the highest rainfall.

In the all water scenario the highest mosquito density was recorded before day 500. The total number of adult mosquitoes recorded was 2,161,072,547 and 6,738,736,699 for rainfall and irrigation situations respectively. This translates to 211.8237% increase in mosquito density that is attributable to irrigation.

```
> Atotal;
                                  # Total number of mosquitoes for rainfall
[1] 2161072547
> Awtotal;
                                  # Total number of mosquitoes in all water
[1] 6738736699
> Aadj = (((Awtotal-Atotal)/Atotal)*100);
                                  # % change in vector density due irrigation
> Aadj;
                                  # % change in vector density due irrigation
[1] 211.8237
```

The graph that correlates the suitability index and vector density in rainfall situation, shows three peaks of suitability index with corresponding positive correlation between vector density and suitability index. However, the peak vector densities appeared as a lag of about one month after the peak suitability index. The peak suitability in turn corresponds to the peak rainfall patterns

On the other hand in the irrigation scenario, there was no clear direct correlation between peak all water, suitability index and vector density

;

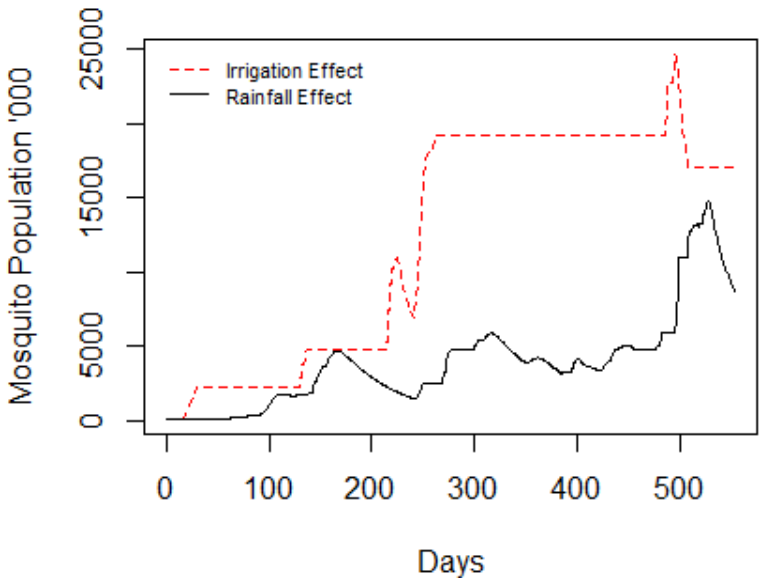

Figure 4-5: Comparative effect of irrigation and rainfall on the vector density

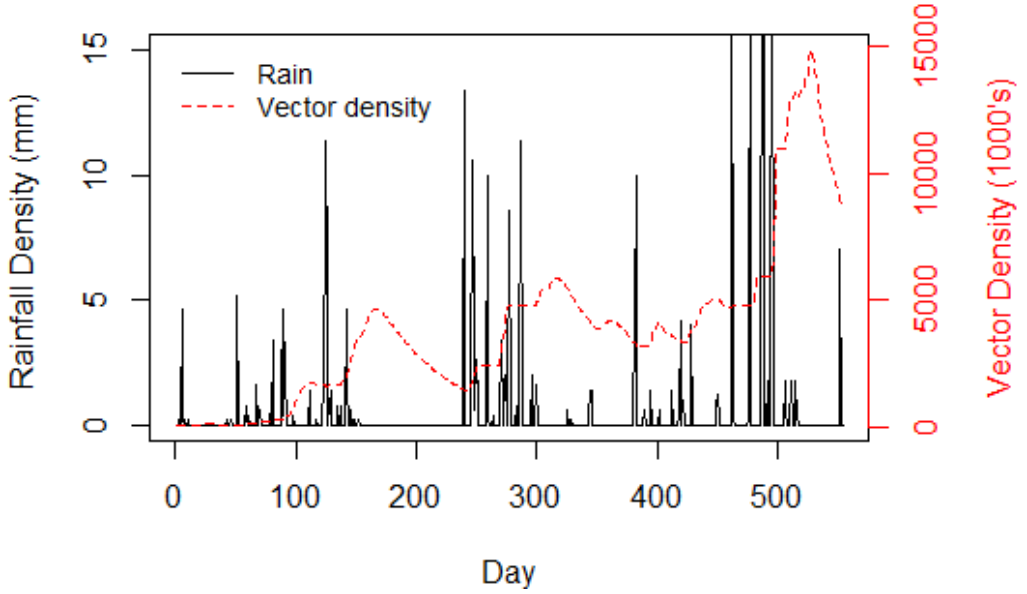

Figure 4-6: Correlation between rainfall pattern and vector density

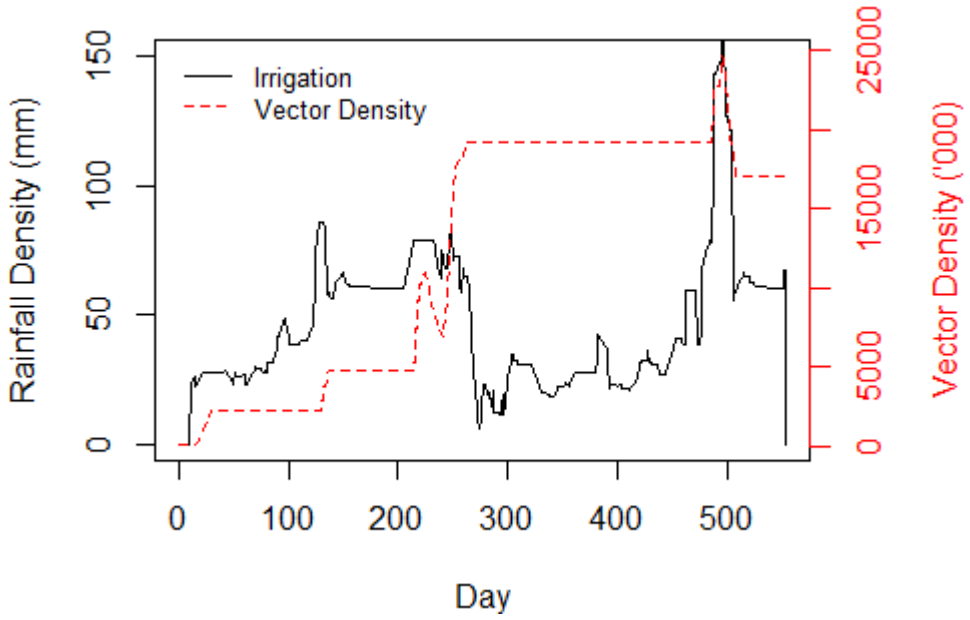

Figure 4-7: Correlation between irrigation pattern and vector density

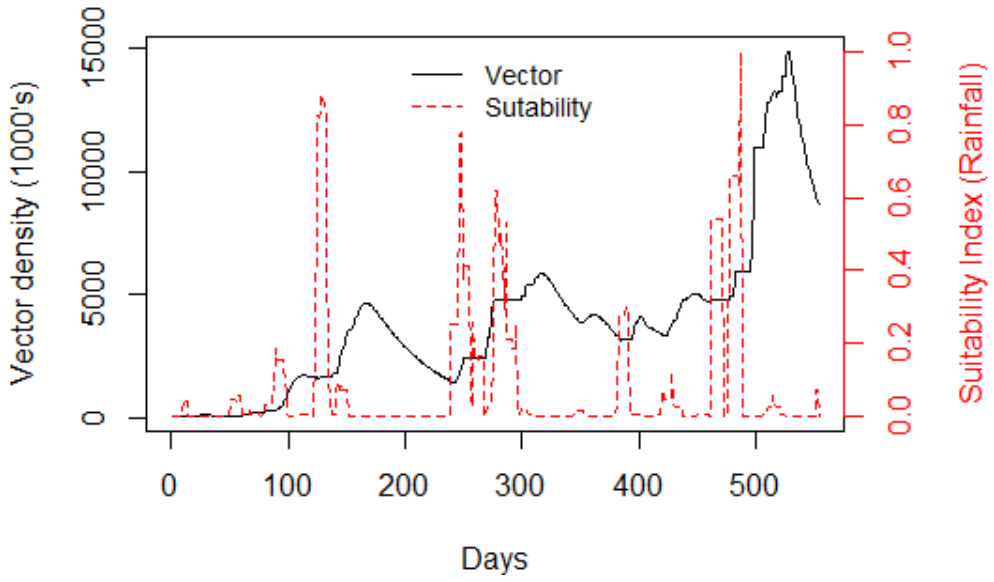

Figure 4-8: Correlation between suitability index (Rain) and vector density

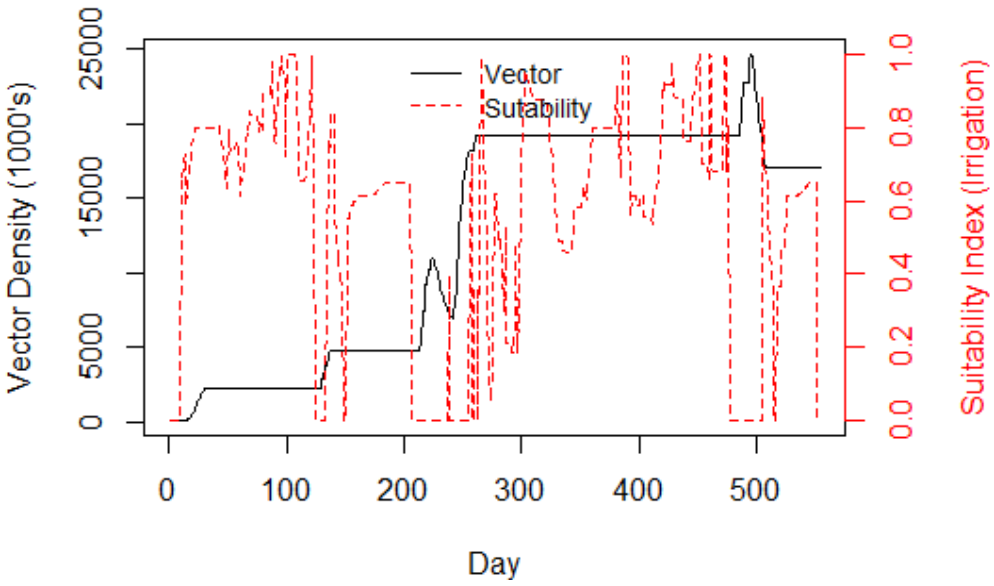

Figure 4-9: Correlation between suitability index (Irrigation) and vector density

4.5. Evaluation of Disease Risk of West Nile Virus (Entomological Inoculation Rates)

Entomological inoculation rates (EIR) measures the number of per capita infectious mosquito bites per day. It can therefore be used as a measure of risk of WNV. To determine the comparative risk in our study situations, we obtained the EIR value for both the rainfall and all water and compared the difference.

The graphical presentation of all the plots for the EIR showed a similar pattern as those of the mosquito densities discussed above. Using the *AUC* function in R, we calculated the daily EI R values of 10.25685 and 32.03134 for rainfall and all water respectively. This was 212.2922 **%** increase in EIR value due to irrigation.

This therefore implied that irrigation may increase the risk of WNV in Tana River County by about 200**%.**

```
> EIR_daily_av;                    # EIR for rainfall
[1] 2.05965

> EIRw_daily_av;                   # EIR for All water
[1] 6.422478

> EIR_risk     = (((EIRw_daily_av-EIR_daily_av)/EIR_daily_av)*100);

                # % increase in EIR due to irrigation

> EIR_risk;                                  # % increase in EIR due to irrigation
[1] 212.2922
```

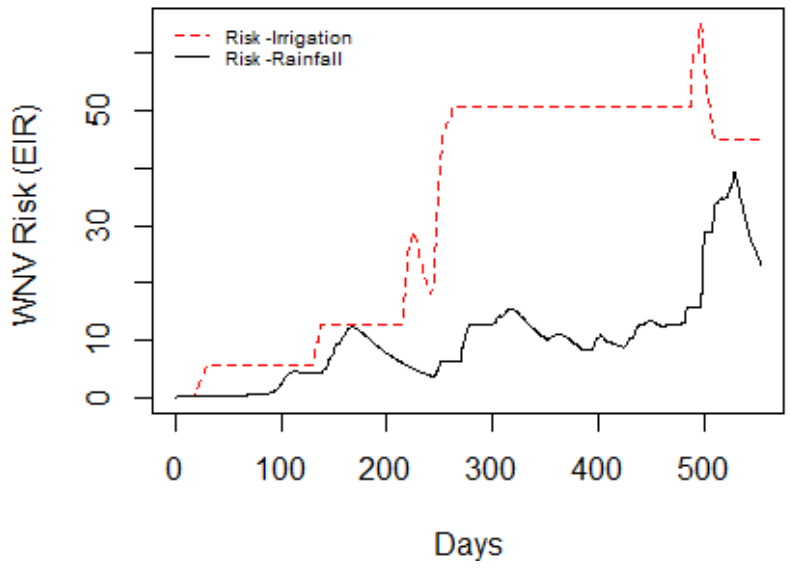

Figure 4-10: Comparison of risk of West Nile Virus due to Rainfall and Irrigation

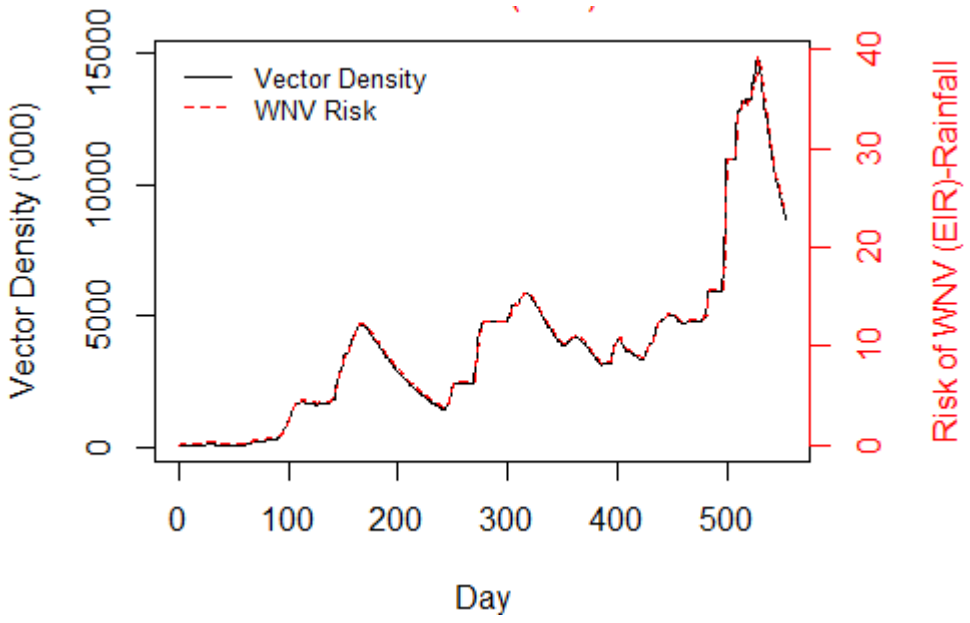

Figure 4-11: Correlation between vector density (rainfall) and risk of West Nile Virus

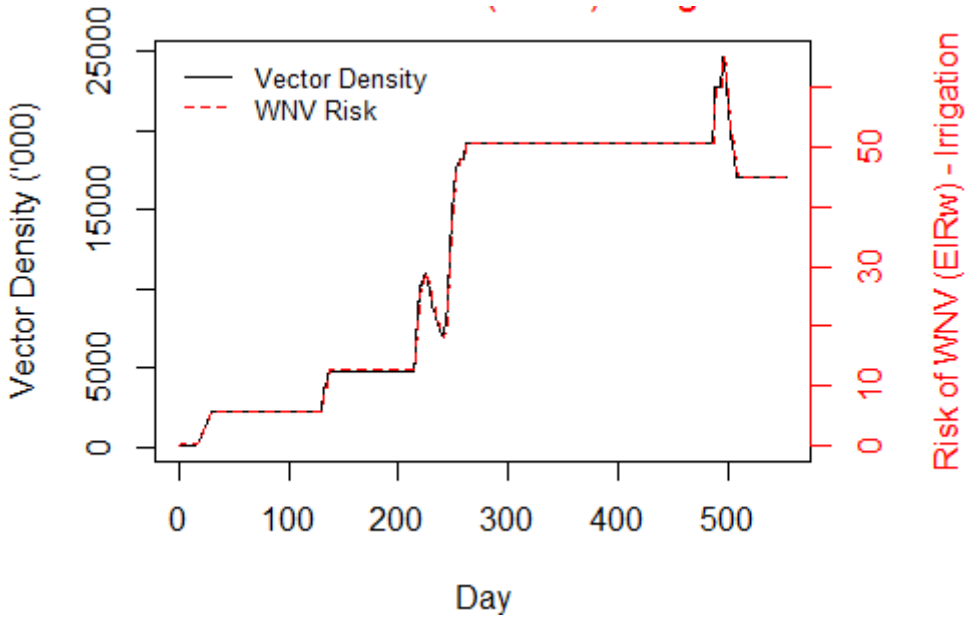

Figure 4-12: Correlation between vector density (irrigation) and risk of West Nile Virus

Table 4-2: Effect of Irrigation on risk WNV

	Rain	**Irrigation**	**Increase (%)**
Total Water(mm)	403.8	2601.316	544.3686
Cumulative 10-Day Water (mm)	3950.8	25,550.67	546.72
Total Suitability Index	45.2475	310.1399	585.4298
Total Vector Density	2,161,072,547	6,738,736,699	211.8237
WNV Risk (EIR)	2.05137	6.406268	**212.2922**

4.6. Analysis of the Impact of Control Measures West Nile Virus

4.6.1. Results of Comparative Effect of the Three Interventions

Larvicides had the greatest rate of change in reducing the disease risk followed by repellents and lastly larvicides.

This implies that adulticides are the best control intervention compared to larvicides and repellents.

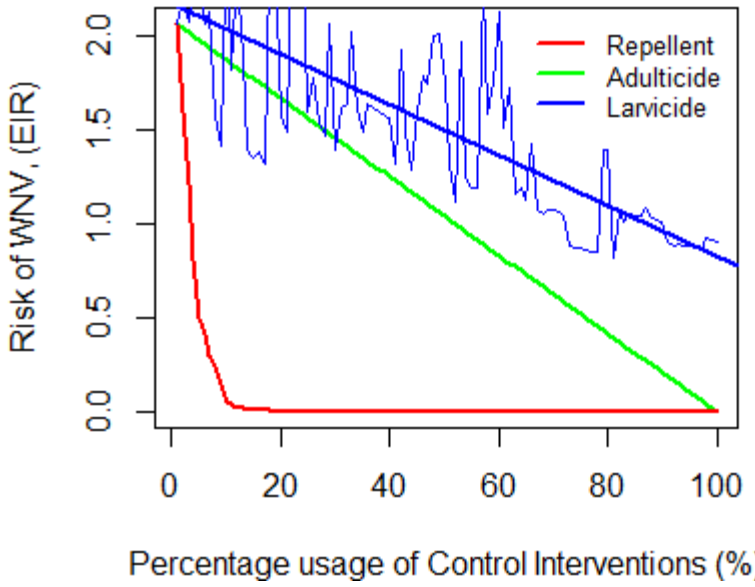

Figure 4-13: Comparison of efficacy of Larvicides, Repellents and Adulticides on the risk of West Nile Virus

4.7. Sensitivity Analysis

The results for the sensitivity analysis were generally grouped into two;

- Adult mosquitoes, carrying capacity, probability of infection and biting rate were all sensitive to any changes in the initial values
- The eggs and larvae were not sensitive to varying the initial values

Below are the graphical presentations of the sensitivity analysis as generated by our model;

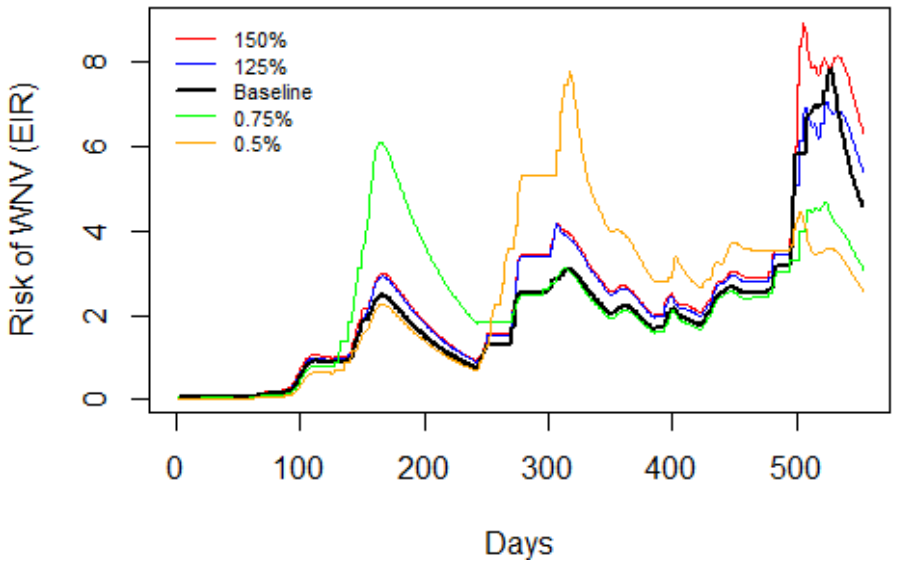

Figure 4-14: Sensitivity analysis of the initial number of adult mosquitoes

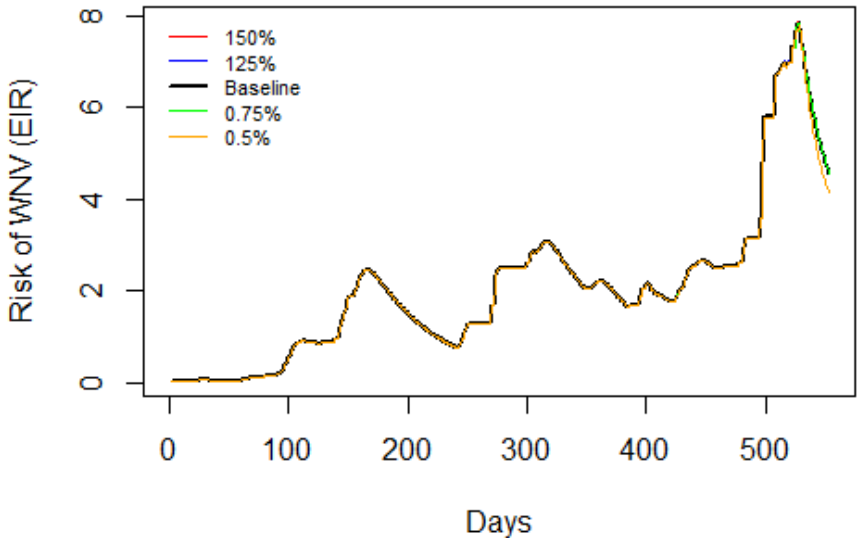

Figure 4-15: Sensitivity analysis of the initial number of Larvae

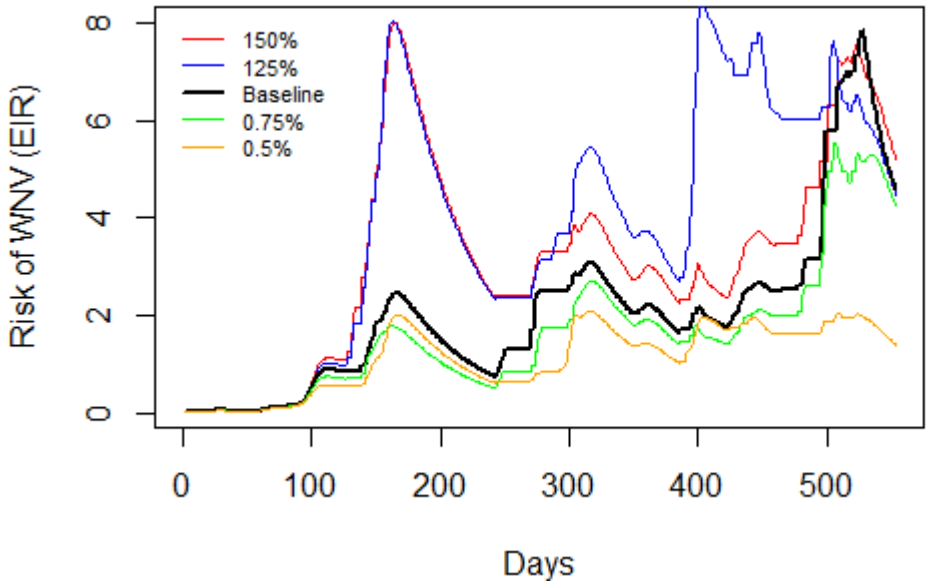

Figure 4-16: Sensitivity analysis of the Carrying Capacity

CHAPTER FIVE

5.0 DISCUSSION, CONCLUTIONS AND RECOMMENDATIONS

5.1. Discussion

Kenya has a rapid population growth that mostly depends on rain-fed agriculture for food production, but only a small fraction of the country constitutes arable land. This has exerted pressure of food production and the situation calls for alternative means to be sought to realize food security. Irrigation has therefore been identified as an alternative method to enhance food production to supplement the current farming practice that is entirely depended on rainfall-fed agriculture.

However this practice comes with its own challenges, top of which is the possible increase in resultant water-borne diseases. In addition to malaria and other vector-borne diseases, West Nile virus outbreak has also been mapped out as a possible potential threat in areas that have been transformed into irrigation zones. This has created a situation where a tradeoff between food production and risk of disease burden has to be carefully considered. It then calls for mechanisms to be put in place to mitigate on any public health challenges associated with irrigation that may arise while rolling out the irrigation projects. One such mechanism is to map out and gain in insight into all public health risks associated with irrigation.

Use of epidemiological models is one the methods that can be employed to analyze such risks through studying the diseases transmission dynamics in a population. They are able to give insight into factors that affect the epidemiology of such diseases and the effects of interaction of such factors. Models can therefore be used in decision making process to guide on the most rational strategy to control diseases. They offer the flexibility needed to explore the various "what if" situations that may be considered before deciding on an intervention strategy.

The advantages of Models are that they simplify more complex systems or situations under investigation and also shrink time and space. This allows for various possible manipulations to be performed on the model to do the course-effect analysis for each manipulation. They therefore enable otherwise impossible, expensive and time consuming 'experiments' to be performed conveniently, faster and cheaply.

To gain insight into the potential risk of WNV in Tana River County that is attributed to irrigation, we developed a West Nile Virus epidemiological model that can aid in policy making for WNV surveillance.

The model that we developed is a deterministic, compartmental WNV epidemiological model that uses rainfall data, vector and disease transmission parameters as inputs. The model is able to simulate and evaluate different situations driven by amounts of rainfall. It can also evaluate the various 'what if' situations concerning the risk of WNV by manipulating the vector and disease transmission parameters. The manipulations of the parameters can be done by increasing or decreasing specific of combination of parameters and recording the corresponding effect of the risk of WNV. Through this, the model can be useful in understanding the resultant effects of extreme of unusual environmental conditions of the risk of WNV.

Our model simulated and compared the dynamics of vector density and risk of WNV infection under rainfall and irrigation situations. The model also compared the efficacy of repellents, larvicides and adulticides as interventions for WNV disease.

In rainfall situation, our model simulated vector density that corresponds to the respective suitability index that was driven by cumulative 10-day rainfall pattern. The model outputs corresponding suitability indices for different amounts of rainfall over time. This explains why most days were not suitable for vector breeding since mosquitoes cannot oviposit without water. This signifies that mosquito transmission in these areas was seasonal.

In the irrigation scenario, higher suitability indices, vector densities and entomological inoculation rates (EIR) throughout the irrigation period was recorded compared to rainfall situations.

Our model shows that the study area received low, scattered rainfall most of the study duration. Relatively higher rainfall was seasonal. The models also indicate that the days that received higher total water (Irrigation and rainfall) exhibited corresponding higher incidences of WNV.

Irrigation increases the amount of water available on the land and can increase the number and suitability of vector breeding sites resulting in higher vector densities. This is why higher vector densities were recorded in the irrigation scenario compared to rainfall situation. Our model is a parsimonious one that is only driven by vector density to determine the risk of WNV. However, risk of WNV if influenced by many factor including biotic and abiotic factors including density of hosts.

This demonstrates that irrigation creates more suitable habitat for vector breeding and

consequently enhances risk of WNV among other mosquito-borne diseases. (Eisen *et al.* 2010) Irrigation is therefore likely to increase the risk of WNV in Tana River County three fold. This result is consistent a study done in El Paso, Texas to determine the risk of WNV which was attributable to using irrigation water to flood the yards. The study also sought to find out how proximity to irrigation canals impacted on the risk of WNV. The study found out that irrigation increased cases of WNV infection 2.5 fold (Cardenas *et al*. 2011).

In a study done in United States of America to investigate hoe biotic and abiotic factors determine the spatial and temporal distribution of WNV, irrigation in the rural areas was found to increase the incidence of WNV (De Groote *et al.* 2008). Irrigation was also associated with higher risk of WNV in humans and veterinary animals in the United States of America. The study found out that an increase in irrigation of 0.1% of the total land resulted in 50% increase in incidence of WNV(Gates and Boston 2009). A study by in Iowa and Eisen *et al.* (2010) in Larimer-Boulder-Weld area of North- Central Colorado also found that irrigation increased the risk of WNV.

The results show that the percentage increase in water, cumulative 10-day rainfall and suitability index does not correspond proportionately with level of increase in vector density and risk of WNV. This is probably because the vector density and hence the risk of WNV is also determined by other factors in addition to suitability index e. g the maximum number of eggs a mosquito can lay per day and the constant transition rates between larvae, pupa to adults stages. For instance however much rain is received the mosquito egg laying rate is limited to 40. Therefore further increase in rain may not necessarily result in corresponding increase in the number of eggs and mosquito density.

In this model, the patterns of EIR and vector densities were similar for both rainfall and irrigation situations. This is because in our formulae for calculating the EIR, only the vector density (**A**) was considered as a variable.

EIR = A/human pop*pinfec.h *prev WNV in culex* gono.c.

All other parameters were held constant. Therefore higher mosquito densities resulted in corresponding increase in risk of WNV.

This might not be the case in reality because the prevalence of WNV in the mosquitoes varies

depending on the WNV infection dynamics. This was not considered in this model because we used a constant WNV prevalent rate of 18%. In reality this rate varies depending on the number of competent infected birds and the extent of interaction between these birds and mosquitoes. We did not also factor in the ratio of mosquitoes to humans which also influences the EIR according to the above formula.

While evaluating the effects of rainfall pattern on the suitability index, vector density pattern and risk of WNV, three peaks corresponding to rainfall pattern were realized. Rainfall created conducive environment to lay eggs and development of the preimaginal mosquitoes. This led to corresponding rise in mosquito density and subsequent increase in risk of WNV. Therefore the risk of WNV under rainfall condition is likely to be seasonal. On average, the risk of WNV under rainfall was relatively low at about two infectious mosquito bites per person per day.

The peaks of vector density and risk of WNV were seen after about a month after the corresponding peaks of rainfall and suitability indices. This implied that it took about one month for the mosquitoes to develop through the preimaginal stages before emerging as adults. This contrasts an earlier study done in Kenya and Mali that found the average duration for maturation of mosquitoes to be 12 days (Mwangangi *et al*. 2006). This information can be utilized to determine the timing for instituting vector control interventions.

On the other hand, in the irrigation scenario, the pattern of suitability index, vector density and risk of WNV did not correlate with the irrigation water. However in general, the result of irrigation was a five- fold increased the suitability of the area for mosquito breeding. This ultimately resulted in a WNV risk of about six per capita daily infectious mosquito bites, which was three-fold the rate of the rainfall situation. The risk was perennial compared to the rainfall situation where it was seasonal. Therefore irrigation would transform the area from seasonal risk patter of WNV infection to perennial.

Sensitivity analysis for models is critical when trying to identify the parameters that have the greatest impact on the model output. The most sensitive parameters cause the greatest changes to the model outcome and are therefore the right candidates to target for control interventions. Our model was most sensitive to adulticides where just 10% usage in rainfall situations was enough to reduce the risk of West Nile Virus by over 90% compared to repellents which has a linear effect where 50% usage is required to produce 50% effect. Larvicides are the least effective method to control West Nile Virus according to this model. The results show that

even at maximum usage (100%), the risk of West Nile Virus could only be reduced by half and not zero.

5.2. Conclusions

Epidemiological models can be used to study WNV transmission dynamics and derive useful information that can be used to gain more insight into the transmission processes under different and use scenarios. In this study, the outcome indicates that irrigation is likely to increase the vector density and risk of WNV in Tana River County three fold. There was also a direct correlation between the vector density pattern and the risk of WNV disease pattern.

In the rainfall scenario, the highest risk of WNV disease corresponded to the pattern of peak rainfall making the risk a seasonal phenomenon. However, the peak of WNV disease risk comes about one month after the peak rainfall. This information can be utilized in the designing the policy for timings of the application of the control interventions. On the other hand, in the irrigated situations, the risk of WNV disease was spread throughout the entire period making it a Perennial risk

.Use of mosquito Adulticides was the most efficacious WNV control method compared to use of larvicides and repellents. Larvicides are the least effective method while repellents had a linear effect.

5.3. Future Work

To improve the accuracy of this model, more data need to be collected to model the bird and humans compartments e.g. the population of birds, people and vector density, carrying capacity, prevalence of WNV in mosquitoes and humans. The parameters used in the model also need to be studied so that they are specific for this region.

To make the model even more realistic, as many factors as possible that affect the disease transmission dynamics need to be incorporated in the model. Some of these factors include; temperature, humidity, wind speeds, soil type, land cover type, land topology, host immunity levels, types of birds, movement of people and migration patterns of birds among others

Finally it could be more useful to convert the model into stochastic and spatial model to cater for the uncertainties in the variable and the geographical spread of the disease.

REFERENCES

Artsob, H. et al. 2009. "West Nile Virus in the New World: Trends in the Spread and Proliferation of West Nile Virus in the Western Hemisphere." *Zoonoses and Public Health* 56(6–7): 357–69.

Bakonyi, Tamás et al. 2006. "Lineage 1 and 2 Strains of Encephalitic West Nile Virus, Central Europe." *Emerging Infectious Diseases* 12(4): 618–23.

Bakonyi, Tamás, Zdenek Hubálek, Ivo Rudolf, and Norbert Nowotny. 2005. "Novel Flavivirus or New Lineage of West Nile Virus, Central Europe." *Emerging Infectious Diseases* 11(2): 225–31.

Bondre, Vijay P. et al. 2007. "West Nile Virus Isolates from India: Evidence for a Distinct Genetic Lineage." *Journal of General Virology* 88(3): 875–84.

Bowman, C. et al. 2005. "A Mathematical Model for Assessing Control Strategies against West Nile Virus." *Bulletin of Mathematical Biology* 67(5): 1107–33.

Bunning, M L et al. 2002. "Experimental Infection of Horses with West Nile Virus." *Emerging infectious diseases* 8(4): 380–86.

Campbell, Grant L et al. 2002. "Reviews West Nile Virus." *The Lancet* 2(September): 519–29. http://www.sciencedirect.com/science/article/pii/s1473309902003687.

Campbell G.L., Marfin A.A., Lanciotti R.S., Gubler D.J. 2002. "West Nile Virus." *Lancet Infect. Dis.* 2(2): 519–29.

Cantile, C., F. Del Piero, G. Di Guardo, and M. Arispici. 2001. "Pathologic and Immunohistochemical Findings in Naturally Occurring West Nile Virus Infection in Horses." *Veterinary Pathology* 38(4): 414–31.

Cardenas, Victor M. et al. 2011. "Yard Flooding by Irrigation Canals Increased the Risk of West Nile Disease in El Paso, Texas." *Annals of Epidemiology* 21(12): 922–29. http://dx.doi.org/10.1016/j.annepidem.2011.08.001.

Chambers, Thomas J, Chang S Hahn, Ricardo Galler, and Charles M Rice. 1990. "AND REPLICATION ORGJ \ NIZATION , EXPRESSION , L."

Christy E. Jones, L.Phillip Lounibos, Peter P. Marra and A.Marm Kilpatrick. 2013. "Rainfall Influences Survival of Culex pipiens(Diptera:Culicidae) in a Residential Neighbourhooh in the Mid-Atlantic USA." *J Med Entomol* 49(3): 467–73.

Cornel, Anton J, Peter G Jupp, and Nigel K Blackburn. "Environmental Temperature on the

Vector Competence of Culex Univittatus (Diptera : Culicidae) for West Nile Virus." : 1993.

Cruz-Pacheco, Gustavo, Lourdes Esteva, Juan Antonio Montaño-Hirose, and Cristobal Vargas. 2005. "Modelling the Dynamics of West Nile Virus." *Bulletin of Mathematical Biology* 67(6): 1157–72.

Dauphin, Gwena??lle, St??phan Zientara, Herv?? Zeller, and Bernadette Murgue. 2004. "West Nile: Worldwide Current Situation in Animals and Humans." *Comparative Immunology, Microbiology and Infectious Diseases* 27(5): 343–55.

Durand, Benoit, Gilles Balança, Thierry Baldet, and Véronique Chevalier. 2010. "A Metapopulation Model to Simulate West Nile Virus Circulation in Western Africa, Southern Europe and the Mediterranean Basin." *Veterinary research* 41(3): 32.

Eisen, Lars et al. 2010. "Irrigated Agriculture Is an Important Risk Factor for West Nile Virus Disease in the Hyperendemic Larimer-Boulder-Weld Area of North Central Colorado." *Journal of medical entomology* 47(5): 939–51. http://www.ncbi.nlm.nih.gov/pubmed/20939393.

Ermert, Volker, Andreas H Fink, Anne E Jones, and Andrew P Morse. 2011. "Development of a New Version of the Liverpool Malaria Model . I . Refining the Parameter Settings and Mathematical Formulation of Basic Processes Based on a Literature Review." : 1–17.

Gaff, Holly D, David M Hartley, and Nicole P Leahy. 2007. "An Epidemiological Model of Rift Valley Fever." 2007(115): 1–12.

Gates, Maureen C., and Raymond C. Boston. 2009. "Irrigation Linked to a Greater Incidence of Human and Veterinary West Nile Virus Cases in the United States from 2004 to 2006." *Preventive Veterinary Medicine* 89(1–2): 134–37.

Gimnig, John E, Maurice Ombok, Luna Kamau, and William A Hawley. 2001. "Characteristics of Larval Anopheline (Diptera : Culicidae) Habitats in Western Kenya." (March).

Del Giudice, Pascal et al. 2004. "Human West Nile Virus, France." *Emerging infectious diseases* 10(10): 1885–86.

Goddard, Laura B et al. 2002. "Vector Competence of California Mosquitoes for." *Emerging Infectious Diseases* 8(12): 1385–91.

Gokhale, Mangesh D., Mandar S. Paingankar, and Sachin D. Dhaigude. 2013. "Comparison of

Biological Attributes of Culex Quinquefasciatus (Diptera: Culicidae) Populations from India." *ISRN Entomology* 2013: 1–9. http://www.hindawi.com/isrn/entomology/2013/451592/.

Guarner, Jeannette et al. 2004. "Clinicopathologic Study and Laboratory Diagnosis of 23 Cases with West Nile Virus Encephalomyelitis." *Human pathology* 35(8): 983–90.

Gubbins, Simon et al. 2008. "Assessing the Risk of Bluetongue to UK Livestock : Uncertainty and Sensitivity Analyses of a Temperature-Dependent Model for the Basic Reproduction Number." (May 2007): 363–71.

Henderson, B. E., D. Metselaar, G. B. Kirya, and G. L. Timms. 1970. "Investigations into Yellow Fever Virus and Other Arboviruses in the Northern Regions of Kenya." *Bulletin of the World Health Organization* 42(5): 787–95.

Hethcote, Herbert. 2002. "Effects of Quarantine in Six Endemic Models for Infectious Diseases for Infectious Diseases." (May 2016).

Ji-Guang M, Mei X. 1996. "1996 Progress in Studies on the Overwintering of the Mosquito Culex Tritaeniorhynchus. Southeast Asian J. Trop. Med. Public Health 27 , 810 – 817." : 1996.

Kilpatrick, A Marm. 2011. "Globalization, Land Use, and the Invasion of West Nile Virus." *Science (New York, N.Y.)* 334(6054): 323–27. files/955/hurtley2012_WN.pdf%5Cnhttp://www.ncbi.nlm.nih.gov/pubmed/22021850.

Koenraadt, C. J M et al. 2006. "Low Larval Vector Survival Explains Unstable Malaria in the Western Kenya Highlands." *Tropical Medicine and International Health* 11(8): 1195–1205.

Komar, N. 2000. "West Nile Viral Encephalitis." *Revue scientifique et technique (International Office of Epizootics)* 19(1): 166–76.

Kuno, Goro et al. 1998. "Phylogeny of the Genus Flavivirus." 72(1): 73–83.

LaBeaud, A. Desiree et al. 2011. "Arbovirus Prevalence in Mosquitoes, Kenya." *Emerging Infectious Diseases* 17(2): 233–41.

Laperriere, Vincent, Katharina Brugger, and Franz Rubel. 2011. "Simulation of the Seasonal Cycles of Bird, Equine and Human West Nile Virus Cases." *Preventive Veterinary Medicine* 98(2–3): 99–110. http://dx.doi.org/10.1016/j.prevetmed.2010.10.013.

Letters, Ecology. 2003. "Drought-Induced Mosquito Outbreaks in Wetlands." : 1017–24.

Lord, C C, M E J Woolhouse, and J A P Heesterbeek. 1996. “Vector-Borne Diseases and the Basic Reproduction Number : A Case Study of African Horse Sickness.”

Lutomiah, J L et al. 2011. “Ability of Selected Kenyan Mosquito (Diptera: Culicidae) Species to Transmit West Nile Virus under Laboratory Conditions.” *J Med Entomol* 48(6): 1197–1201.

Lvov, D. K. et al. 2000. “Isolation of Two Strains of West Nile Virus during an Outbreak in Southern Russia, 1999.” *Emerging Infectious Diseases* 6(4): 373–76.

Lwande, Olivia et al. 2014. “Whole Genome Phylogenetic Investigation of a West Nile Virus Strain Isolated from a Tick Sampled from Livestock in North Eastern Kenya.” *Parasites & Vectors* 7(1): 542. http://www.parasitesandvectors.com/content/7/1/542.

Lwande, Olivia Wesula et al. 2013. “Isolation of Tick and Mosquito-Borne Arboviruses from Ticks Sampled from Livestock and Wild Animal Hosts in Ijara District, Kenya.” *Vector borne and zoonotic diseases (Larchmont, N.Y.)* 13(9): 637–42. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3777299&tool=pmcentrez&rendertype=abstract.

———. 2014. “Whole Genome Phylogenetic Investigation of a West Nile Virus Strain Isolated from a Tick Sampled from Livestock in North Eastern Kenya.” *Parasites & vectors* 7(1): 542. http://www.parasitesandvectors.com/content/7/1/542.

Maquart, Marianne et al. 2016. “High Prevalence of West Nile Virus in Domestic Birds and Detection in 2 New Mosquito Species in Madagascar.” *Plos One* 11(1): e0147589. http://dx.plos.org/10.1371/journal.pone.0147589.

Mariara, Jane Kabubo, and Fredrick K Karanja. 2007. “The Economic Impact of Climate Change on Kenyan Crop Agriculture: A Ricardian Approach. World Bank Policy Research Working Paper, (4334).” (4334): 1–40. http://ideas.repec.org/p/pra/mprapa/68188.html.

Marka, Andriani et al. 2013. “West Nile Virus State of the Art Report of MALWEST Project.” *International journal of environmental research and public health* 10(12): 6534–6610. http://www.mdpi.com/1660-4601/10/12/6534/htm (January 27, 2016).

McDermott, J J, and P G Coleman. 2001. “Comparing Apples and Oranges--Model-Based Assessment of Different Tsetse-Transmitted Trypanosomosis Control Strategies.” *International journal for parasitology* 31(5–6): 603–9.

http://www.ncbi.nlm.nih.gov/pubmed/11334949.

Miller, Barry R. et al. 2000. “First Field Evidence for Natural Vertical Transmission of West Nile Virus in Culex Univittatus Complex Mosquitoes from Rift Valley Province, Kenya.” *American Journal of Tropical Medicine and Hygiene* 62(2): 240–46.

Mukhopadhyay, Suchetana et al. 2003. “Structure of West Nile Virus.” 302(October): 2003.

Munga, Stephen et al. 2006. “Effects of Larval Competitors and Predators on Oviposition Site Selection of Anopheles Gambiae Sensu Stricto Effects of Larval Competitors and Predators on Oviposition Site Selection of Anopheles Gambiae Sensu Stricto.” 43(2): 221–24.

Murgue, B, H Zeller, and V Deubel. 2002. “The Ecology and Epidemiology of West Nile Virus in Africa, Europe and Asia.” *Japanese Encephalitis and West Nile Viruses* 267: 195–221. //243.68.170.42.

Mwangangi, Joseph M et al. 2006. “Survival of Immature Anopheles Arabiensis (Diptera: Culicidae) in Aquatic Habitats in Mwea Rice Irrigation Scheme, Central Kenya.” *Malaria journal* 5: 114. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=1698490&tool=pmcentrez&rendertype=abstract.

Nasci, Roger S. et al. 2001. “West Nile Virus in Overwintering Culex Mosquitoes, New York City, 2000.” *Emerging Infectious Diseases* 7(4): 742–44.

Nyamwaya, Doris et al. 2016. “Detection of West Nile Virus in Wild Birds in Tana River and Garissa Counties, Kenya.” *BMC Infectious Diseases* 16(1): 696. http://bmcinfectdis.biomedcentral.com/articles/10.1186/s12879-016-2019-8.

Odhengo, Peter et al. 2012. “Tana River Delta Land Use Plan Framework 2012.”

Ostlund, Eileen N. et al. 2001. “Equine West Nile Encephalitis, United States.” *Emerging Infectious Diseases* 7(4): 665–69.

Papa, Anna. 2013. “West Nile Virus Infections in Humans-Focus on Greece.” *Journal of Clinical Virology* 58(2): 351–53.

Paz, Shlomit. 2006. “The West Nile Virus Outbreak in Israel (2000) from a New Perspective: The Regional Impact of Climate Change.” *International journal of environmental health research* 16(1): 1–13.

———. 2015. “Climate Change Impacts on West Nile Virus Transmission in a Global

Context."

Paz, Shlomit, and Jan C Semenza. 2013. "Environmental Drivers of West Nile Fever Epidemiology in Europe and Western Asia--a Review." *International journal of environmental research and public health* 10(8): 3543–62. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3774453&tool=pmcentrez&rendertype=abstract.

Petersen, Lyle R, and Anthony a Marfin. 2002. "Review West Nile Virus : A Primer for the Clinician." *Annals of Internal Medicine* 137(3): 173–79.

Platonov, Alexander E. et al. 2001. "Outbreak of West Nile Virus Infection, Volgograd Region, Russia, 1999." *Emerging Infectious Diseases* 7(1): 128–32.

Reisen, William K, Ying Fang, and Vincent M Martinez. 2006. "Effects of Temperature on the Transmission of West Nile Virus by Culex Tarsalis (Diptera : Culicidae)." : 309–17.

Roehr, Bob. 2012. "US Hit by Massive West Nile Virus Outbreak Centred around Texas." *BMJ (Clinical research ed.)* 345(August): e5633. http://www.ncbi.nlm.nih.gov/pubmed/22915691.

Rubel, Franz et al. 2008. "Explaining Usutu Virus Dynamics in Austria: Model Development and Calibration." *Preventive Veterinary Medicine* 85(3–4): 166–86.

Ruiz, Marilyn et al. 2010. "Local Impact of Temperature and Precipitation on West Nile Virus Infection in Culex Species Mosquitoes in Northeast Illinois, USA." *Parasites & Vectors* 3(1): 1–16. http://www.springerlink.com/content/y5182982120333g5/abstract/%5Cnfiles/1800/Ruiz et al. - 2010 - Local impact of temperature and precipitation on W.pdf%5Cnfiles/1532/abstract.html.

Sardelis, Michael R., Michael J. Turell, David J. Dohm, and Monica L. O'Guinn. 2001. "Vector Competence of Selected North American Culex and Coquillettidia Mosquitoes for West Nile Virus." *Emerging Infectious Diseases* 7(6): 1018–22.

Savini, G. et al. 2012. "Evidence of West Nile Virus Lineage 2 Circulation in Northern Italy." *Veterinary Microbiology* 158(3–4): 267–73.

Sejvar, James J. 2014. "Clinical Manifestations and Outcomes of West Nile Virus Infection." *Viruses* 6(2): 606–23.

Shaman, Jeffrey et al. 2002. "Using a Dynamic Hydrology Model to Predict Mosquito

Abundances in Flood and Swamp Water." *Emerging Infectious Diseases* 8(1): 6–13.

———. 2005. "Ournal of Medical Entomology."

Shaukat, Ayesha M, Joel G Breman, and F Ellis McKenzie. 2010. "Using the Entomological Inoculation Rate to Assess the Impact of Vector Control on Malaria Parasite Transmission and Elimination." *Malaria journal* 9: 122.

Sips, Gregorius J., Jan Wilschut, and Jolanda M. Smit. 2012. "Neuroinvasive Flavivirus Infections." *Reviews in Medical Virology* 22(2): 69–87.

Sirbu, a et al. 2011. "Outbreak of West Nile Virus Infection in Humans, Romania, July to October 2010." *Euro surveillance : bulletin Européen sur les maladies transmissibles = European communicable disease bulletin* 16(2): 19762.

Smithburn, K. C., Hughes, T. P., Burke, A. W., and Paul, J. H. 1940. "Aneurotropic Virus Isolated from the Blood of a Native of Uganda.,." *Am. J.Trop. Med.* 20: 471 – 492.

Takken, Willem, and Steve W Lindsay. 2003. "7. Factors Affecting the Vectorial Competence of Scale." : 75–90.

Thomas, M, and B Urena. 2001. "A Model Describing the Evolution of West Nile-Like Encephalitis in New York City." 7177(1).

Tigoi, Caroline et al. 2015. "Seroepidemiology of Selected Arboviruses in Febrile Patients Visiting Selected Health Facilities in the Lake/river Basin Areas of Lake Baringo, Lake Naivasha, and Tana River, Kenya." *Vector borne and zoonotic diseases (Larchmont, N.Y.)* 15(2): 124–32. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=4340645&tool=pmcentrez&rendertype=abstract.

Turell, Michael J, Monica L O Guinn, David J Dohm, and James W Jones. 2001. "Vector Competence of North American Mosquitoes (Diptera : Culicidae) for West Nile Virus." (March): 2585.

Verdonschot, Piet F M, and Anna A. Besse-Lototskaya. 2014. "Flight Distance of Mosquitoes (Culicidae): A Metadata Analysis to Support the Management of Barrier Zones around Rewetted and Newly Constructed Wetlands." *Limnologica* 45(January 2013): 69–79.

Walsh, Michael G. 2012. "The Role of Hydrogeography and Climate in the Landscape Epidemiology of West Nile Virus in New York State from 2000 to 2010." 7(2).

Wang, Chih Yuan et al. 2013. "Efficacy of Various Larvicides against Aedes Aegypti

Immatures in the Laboratory." *Japanese Journal of Infectious Diseases* 66(4): 341–44.

Weinberger, Miriam et al. 2001. "West Nile Fever Outbreak, Israel, 2000: Epidemiologic Aspects." *Emerging Infectious Diseases* 7(4): 686–91.

Weissenb, Herbert. 2009. "Usutu Virus in Wild Birds in Northern Italy." *Veterinary Medicine, Veterinary Microbiology,* (May 2016).

Wong, Jacklyn et al. 2011. "Oviposition Site Selection by the Dengue Vector Aedes Aegypti and Its Implications for Dengue Control." 5(4).

Wonham, M J, and M a Lewis. 2008. "A Comparative Analysis of Models for West Nile Virus." *Mathematical Epidemiology*: 365–90.

Wonham, Marjorie J, Tomás de-Camino-Beck, and Mark a Lewis. 2004. "An Epidemiological Model for West Nile Virus: Invasion Analysis and Control Applications." *Proceedings. Biological sciences / The Royal Society* 271(1538): 501–7.

APPENDICES

Appendix I: Main R Code, WNV_CODE

```
## WNV CODE
rm(list=ls());
gc();

setwd("E:/fred_project/codes/Submit/")

# LOAD REQUIRED LIBRARIES
library(stats);
library(graphics);
library(grDevices);
library(lubridate);
library(MESS);

# LOAD REQUIRED SELF-DEFINED PROGRAMS/FUNCTIONS/SUBROUTINES
source("Load_Data.R");
source("Cummulative_Rainfall.R");



# PATHS & DIRECTORIES
Dpath = "E:/fred_project/data/metereology_data.csv";

# LOAD DATASET
x3 = Load_Data(Dpath);
source("Population_Dynamics.R");

MDAY0 = length(x3$date);        # Maximum number of day
MDAY1 = length(x3$date)-1;      # Maximum number of iterations


# DETERMINE CUMMULATIVE RAINFALL OVER TEN DAY PERIODS & CALCULATION  OF MOSQUITO SUITABILITIES (pb)
RAINPB   = Cummulative_Rainfall(x3);
Rainfall = RAINPB[[1]];
water    = RAINPB[[2]];
pb       = RAINPB[[3]];
pb.adj   = RAINPB[[4]];

source("Initialize_Parameters.r");

total10mm_rain    = auc(1:MDAY0,Rainfall);                                    # total 10-day rainfall in mm3/mm2
total10mm_irrig   = auc(1:MDAY0,water);                                       # total 10-day irrigation water in mm3/mm2
change_10mm       = ((total10mm_irrig - total10mm_rain) /total10mm_rain)*100;  # % increase in mm due to irrigation
total_suitab_all  = auc(1:MDAY0,pb.adj);                                      # toatal suitability index for all water
total_suitab_rain = auc(1:MDAY0,pb);                                          # total suitability index for rainfall only
change_suitab     = ((total_suitab_all-total_suitab_rain)/total_suitab_rain)*100;  # % increase in suitability due to irrigation
cat ("The Percentage Increase in water due to Irrigation = ",change_10mm);
cat ("The Percentage Increase in Suitability due to Irrigation = ",change_suitab);
```

```
# PLOTS
#Rainfall and Irrigation Pattern Over time-1
plot   (1:MDAY0, x3$rain, type="l", col="black",lwd=1,xlab="Day", ylab="Rain/water density in mm");
title  (main = list("Rainfall and Irrigation Pattern over Time-1", font=1, cex=1.2, col="red"));
lines  (1:MDAY0, x3$ir.water, type="l", col="red", lty=2,lwd=1);
legend ("topleft", legend=c("Rain", "Irrigation water"), bty="n", inset=0.01, cex=.7,
       lty=c(1,2),lwd=c(1,1),
       col=c("black", "red"));

#Rainfall and Irrigation Pattern Over time-2  # different scale for visibility
plot   (1:MDAY0, x3$rain, type="l", col="black",lwd=1, ylim=c(0,15), xlim=c(0,554),xlab="Day", ylab="Rain/water density in mm");
title  (main = list("Rainfall and Irrigation Pattern over Time-2", font=1, cex=1.2, col="red"));
lines  (1:MDAY0, x3$ir.water, type="l", col="red", lty=2,lwd=1);
legend ("topleft", legend=c("Rain", "Irrigation water"), bty="n", inset=0.01, cex=.7,
       lty=c(1,2),lwd=c(1,1),
       col=c("black", "red"));

# Analysing increase in water due to irrigation
totalmm_rain  = auc(1:MDAY0, x3$rain);                                          # total rainfall in mm3/mm2
totalmm_irrig = auc(1:MDAY0, x3$all.water);                                     # total irrigation water in mm3/mm2
change_mm     = (totalmm_irrig/totalmm_rain)*100;                               # % increase in mm due to irrigation
cat("Total Amount of Rainfall =",totalmm_rain);
cat("Total Amount of Irrigation and rainfall Water =",totalmm_irrig);
cat("The Percentage increase in water attributable to Irrigation =",change_mm);


# Amount of Water pumped
totalmm_pump  = auc(1:MDAY0, x3$ir.water);                                      # total water pumped
cat("Total Amount of water pumped = ",totalmm_pump);

# Cummulative 10-Day Rainfall
plot   (1:MDAY0, Rainfall, type="l", ylab="Rainfall [mm]", xlab="Day", pch=20,lwd=1);
title  (main=list("Cummulative 10-Day Rainfall", font=1,cex=1.2,col="red"));


# Comparative 10-Day Rainfall and Rainfall                                      # different scale for visibility

plot   (1:MDAY0, Rainfall, type="l", ylab="Rainfall [mm]",lty=2, ylim=c(0,35), xlab="Day", pch=20, col="red",lwd=1);
lines  (1:MDAY0, x3$rain, type="l", col="black",lwd=1);
title  (main=list("Cumulative 10-Day Rainfall and Rainfall", font=1,cex=1.2,col="red"));
legend ("top", legend=c("10-Day Rainfall","Rainfall"),inset=0.001, col=c("red","black"),lty = c(2,1), lwd=1, bty="n",cex=0.6);


# Comparative 10-Day all water and irrigation water
plot   (1:MDAY0, water, type="l", ylab="Water [mm]", xlab="Day",ylim = c(0,100), pch=20, col="black",lwd=1);
lines  (1:MDAY0, x3$ir.water, type="l", col="red", lty=2,lwd=1);
title  (main=list("Comparative 10-Day All water and irrigation",font=1,cex=1.2,col="red"));
legend ("topleft", legend=c("10-Day All Water","Irrigation"),inset=0.001,col=c("black","red"),lty = c(1,2), lwd=1,bty = "n", cex=0.6);
```

```
# Comparative 10-Day all water and irrigation water
plot   (1:MDAY0, water, type="l", ylab="Water [mm]", xlab="Day",ylim = c(0,100), pch=20, col="black",lwd=1);
lines  (1:MDAY0, x3$ir.water, type="l", col="red", lty=2,lwd=1);
title  (main=list("Comparative 10-Day All water and irrigation",font=1,cex=1.2,col="red"));
legend ("topleft", legend=c("10-Day All Water","Irrigation"),inset=0.001,col=c("black","red"),lty = c(1,2), lwd=1,bty = "n", cex=0.6);

# All water Vs Rainfall
plot   (1:MDAY0, Rainfall, type="l", ylab="Rainfall [mm]", xlab="Day", pch=20, col="red",lty=2,lwd=1);
title  (main=list("Cummulative 10-Day Rainfall Vs All Water", font=1,cex=1.2,col="red"))
lines  (1:MDAY0, water, type="l",col="black",lty=1);
legend ("topleft", legend=c("Rainfall","All Water"), inset=0.001, col=c("red", "black"), lwd=c(1, 1),lty = c(2,1), cex=0.6,bty = "n");

# total 10-Day Rainfall and Irrigation
total10mm_rain  = auc(1:MDAY0,Rainfall[1:554]);                                    # total 10-day rainfall in mm3/mm2
total10mm_irrig = auc(1:MDAY0,water[1:554]);                                       # total 10-day irrigation water in mm3/mm2
change_10mm     = ((total10mm_irrig - total10mm_rain)/total10mm_rain)*100;         # % increase in mm due to irrigation
cat("Total Amount of 10-Day Rainfall =",total10mm_rain);
cat("Total Amount of 10-Day Irrigation and Rainfall Water =",total10mm_irrig);
cat("The Percentage increase in 10-Day water/rainfall attributable to Irrigation =", change_10mm);

#Suitability -- rainfall only
plot    (1:MDAY0, pb, type="l",ylim = range(0:1), ylab="Suitability index", xlab="Day", pch=20, lwd=1,col="black");
title   (main=list("Suitability Index, Rainfall only", font=1,cex=1.2,col="red"));


#Suitability -- All water
plot   (1:MDAY0, pb.adj, type="l",ylab="Suitability index", xlab="Day", pch=20, lwd=1,col="red");
title  (main=list("Suitability Index, All water", font=1,cex=1.2,col="red"));


#Suitability All water Vs Rainfall
plot   (1:MDAY0, pb.adj, type="l",ylab="Suitability index", xlab="Day", pch=20, lwd=1,col="red");
title  (main=list("Suitability Index, All water Vs Rainfall", font=1,cex=1.2,col="red"));
lines  (1:MDAY0, pb, type="l",ylim = range(0:1), ylab="Suitability index", xlab="Day", pch=20, lwd=1,col="black");
legend ("topleft", legend=c("All water","Rainfall only"),inset=0.01, col=c("red","black"), lwd=2, cex=0.6,bty = "n");

total_suitab_all  = auc(1:MDAY0,pb.adj[1:554]);                                    # toatal suitability index for all water
cat("Total Suitability Index due to irrigation =",total_suitab_all,"\n");

total_suitab_rain = auc(1:MDAY0,pb[1:554]);                                        # total suitability index for rainfall only
cat("Total Suitability Index due to rainfall = ",total_suitab_rain,"\n");

change_suitab     = ((total_suitab_all-total_suitab_rain)/total_suitab_rain)*100;  # % increase in suitability due to irrigation
cat("Percentage increase in suitability due to irrigation =",change_suitab,"\n");  # for checking

# Population_Dynamics_Gen- Function for analysis of population dynamics

RES1    = Population_Dynamics(E,L,P,A,Beta,pb,De,dl,dp,me,ml,mp,ma,NM,NMmin,CC);
Eggs    = RES1[[1]];
```

```
Larva   = RES1[[2]];
Pupa    = RES1[[3]];
Adults  = RES1[[4]];


RES2    = Population_Dynamics(E,L,P,A,Beta,pb.adj,De,dl,dp,me,ml,mp,ma,NM,NMmin,CC);
Eggs_w  = RES2[[1]];
Larva_w = RES2[[2]];
Pupa_w  = RES2[[3]];
Adults_w = RES2[[4]];

EIR   = ((Adults/SH)*pinfec.h*prev.c*gono.c);
EIR_w = ((Adults_w/SH)*pinfec.h*prev.c*gono.c);

#stop();
##=====================================================================

# Rainfall effects on vector densities
plot   (1:MDAY0, Adults/1000, type="l",lwd=1,col="black",ylab=c("Mosquito Population '000"), xlab=c("Days"));
title  (main=list("Rainfall Effect on Vector Population" ,font=1,col="red",cex=1.2 ));

#Irrigation effects on vector densities
plot   (1:MDAY0, Adults_w/1000, type="l",lwd=1,lty=2,col="red",ylab=c("Mosquito Population '000"), xlab=c("Days"));
title  (main=list(" Effect of Irrigation on Vector Population" ,font=1,col="red",cex=1.2 ));

# Comparing effect of Irrigation and rainfall on vector densities
plot   (1:MDAY0, Adults_w/1000, type ='l',lty=2,lwd=1,col="red",ylab=c("Mosquito Population '000"), xlab=c("Days"));
title  (main=list("Effects of Irrigation Vs Rainfall on Vector Population" ,font=1,col="red",cex=1.2 ));
lines  (1:MDAY0, Adults/1000, lty=1, lwd=1,col="black");
legend ("topleft", c("Irrigation Effect","Rainfall Effect"),inset=0.01,lwd = c(1,1), col=c("red","black"),lty=c(2,1),cex=0.7, bty="n");

# Risk Pattern-Rainfall
plot   (1:MDAY0,EIR, type="l", xlab="Days",col="black", ylab="WNV Risk (EIR)");
title  (main=list("WNV Risk (EIR) for Rainfall Only" ,font=1,col="red",cex=1.2 ));

# Risk Pattern-Irrigation
plot   (1:MDAY0,EIR_w, type="l", xlab="Days",col="red",lty=2, ylab="WNV Risk (EIRw) ");
title  (main=list("WNV Risk (EIR) for All Water" ,font=1,col="red",cex=1.2 ));

# Comparing effect of Irrigation and rainfall on risk of WNV
plot   (1:MDAY0,EIR_w, type="l",lty=2, xlab="Days",col="red", ylab="Risk of WNV (EIR)");
title  (main=list("Comparing Risk of WNV in Rainfall and
Irrigation situations" ,font=1,col="red",cex=1.2 ));
lines  (1:MDAY0,EIR, lty=1, col="black");
legend ("topleft", c("Risk-Irrigation","Risk-Rainfall"),inset=0.01,lty=c(2,1), col=c("red","black"),bty = 'n', cex=0.6);

# Analysing effects of Irrigation on Vector Density and Risk of WNV
Atotal  = auc(1:MDAY0,Adults);                                    # Total number of mosquitoes for rainfall
Awtotal = auc(1:MDAY0,Adults_w);                                  # Total number of mosquitoes in all water
```

```
Atotal;                                                                    # Total number of mosquitoes for rainfall
Awtotal;                                                                   # Total number of mosquitoes in all water
Aadj = (((Awtotal-Atotal)/Atotal)*100);                                    # % change in vector density due irrigation
Aadj;                                                                      # % change in vector density due irrigation

EIR_daily_av  = auc(1:MDAY0,EIR)/554;                                      # EIR for rainfall
EIRw_daily_av = auc(1:MDAY0,EIR_w)/554;                                    # EIR for All water
EIR_daily_av;                                                              # EIR for rainfall
EIRw_daily_av;                                                             # EIR for All water
EIR_risk     = (((EIRw_daily_av-EIR_daily_av)/EIR_daily_av)*100);          # % increase in EIR due to irrigation
EIR_risk;                                                                  # % increase in EIR due to irrigation


#two axes-Rainfall and vector density
par(mar=c(4,4,4,5))
plot(1:MDAY0, x3$rain, type="l", axes=FALSE,col="black",lwd=1, ylim=c(0,15), xlim=c(0,554),xlab="Day", ylab="Rainfall density in mm")
title(main = list("Correlation between Rainfall and Vector Density", font=1, cex=1.2, col="red"))
axis(2,ylim=c(0,15))
box()
par(new=TRUE)
plot(1:MDAY0, Adults, type="l", col="red", ylab="",xlab="",lty=2,lwd=1,axes = FALSE)
axis(4,ylim=c(0,370),col="red",xlim=c(0,554),col.axis="red")
mtext("Vector Density",side = 4,line = 3,col = "red")
axis(1,xlim=c(0,554))
legend("topleft", legend=c("Rain", "Vector density"),
       bty="n", inset=0.01, cex=.9,
       lty=c(1,2),lwd=c(1,1),
       col=c("black", "red"))


par(mar=c(4,4,4,5))
plot(1:MDAY0, water, type="l", axes=FALSE,col="black",lwd=1, ylim=c(0,150), xlim=c(0,554),xlab="Days", ylab="Rainfall density in mm")
title(main = list("Correlation between Rainfall and Vector Density", font=1, cex=1.2, col="red"))
axis(2,ylim=c(0,150))
box()
par(new=TRUE)
plot(1:MDAY0, Adults_w, type="l", col="red", ylab="",xlab="",lty=2,lwd=1,axes = FALSE)
axis(4,ylim=c(0,370),col="red",xlim=c(0,554),col.axis="red")
 mtext("Vector Density",side = 4,line = 3,col = "red")
axis(1,xlim=c(0,554))
legend("topleft", legend=c("Rain", "Vector density"),
       bty="n", inset=0.01, cex=.9,
       lty=c(1,2),lwd=c(1,1),
       col=c("black", "red"))
```

```
#2 axis suitability vs vector density-rainfall

#two axes
par(mar=c(4,4,4,5))
plot(1:MDAY0,Adults/1000, type="l", axes=FALSE,col="black",lwd=1,xlab="Day", ylab="Vector density (1000's)")
title(main = list("Correlation between Suitability(Rain) and Vector Density", font=1, cex=1.2, col="red"))
axis(2,ylim=c(0,370))
box()
par(new=TRUE)
plot(1:MDAY0, pb, type="l", col="red", ylab="",xlab="",lty=2,lwd=1,axes = FALSE)
axis(4,ylim=c(0,1),col="red",xlim=c(0,554),col.axis="red")
mtext("Suitability Index (Rainfall)",side = 4,line = 3,col = "red")
axis(1,xlim=c(0,554))
legend("top", legend=c("Vector", "Sutability"),
       bty="n", inset=0.01, cex=.9,
       lty=c(1,2),lwd=c(1,1),
       col=c("black", "red"))


#Sensitivity Analysis

#1. SENSITIVITY ANALYSIS FOR ADULTS
VAR_A =  c(0.01,0.1,seq(0.25,1.5,by=0.25));
ANS_A    = matrix(0,nrow=MDAY0,ncol=length(VAR_A));


for(i in 1:length(VAR_A)){
  SenA = Population_Dynamics(E,L,P,VAR_A[i],Beta,pb,De,dl,dp,me,ml,mp,ma,NM,NMmin,CC);
  ANS_A[,i] = (SenA[[4]]/SH)*pinfec.h*prev.c*gono.c;                                    #EIR
#  ((Adults/SH)*pinfec.h*prev.c*gono.c);

}
ANS_A = data.frame(ANS_A);
names(ANS_A) = as.character(VAR_A); # Naming the columns

#1. SENSITIVITY ANALYSIS FOR ADULTS
VAR_A     = seq(0.25,1.5,by=0.25);
EIRsen_A  = matrix(0,nrow=MDAY0,ncol=length(VAR_A));


for(i in 1:length(VAR_A)){
    Sen_A        = Population_Dynamics(E,L,P,A*(VAR_A[i]),Beta,pb,De,dl,dp,me,ml,mp,ma,NM,NMmin,CC);
     EIRsen_A[,i] = (Sen_A[[4]]/SH)*pinfec.h*prev.c*gono.c;                                  #EIR
 }
EIRsen_A = data.frame(EIRsen_A);
names(EIRsen_A) = as.character(VAR_A); # Naming the columns
```

```
#plot for sensitivity Analysis= Adults
plot   (1:MDAY0,EIRsen_A[,6], type="l",lty=1, xlab="Days",col="red", ylab="Risk of WNV (EIR)");
title  (main=list("Sensitivity Analysis for Initial Number
of Adult Mosquitoes" ,font=1,col="red",cex=1.2 ));
lines  (1:MDAY0,EIRsen_A[,5], lty=1, col="blue");
lines  (1:MDAY0,EIRsen_A[,4], lty=1, lwd=2, col="black");
lines  (1:MDAY0,EIRsen_A[,3], lty=1,col="green");
lines  (1:MDAY0,EIRsen_A[,2], lty=1, col="orange");
legend ("topleft", c("150%","125%","Baseline","0.75%","0.5%"),inset=0.01,lwd= c(1,1,2,1,1),lty=c(1,1,1,1,1),
        col=c("red","blue","black","green","orange"),bty = 'n', cex=0.7);


#2. SENSITIVITY ANALYSIS FOR LARVAE
VAR_L     = seq(0.25,1.5,by=0.25);
EIRsen_L  = matrix(0,nrow=MDAY0,ncol=length(VAR_L));

for(i in 1:length(VAR_L)){
    Sen_L        = Population_Dynamics(E,L*(VAR_L[i]),P,A,Beta,pb,De,dl,dp,me,ml,mp,ma,NM,NMmin,CC);
    EIRsen_L[,i] = (Sen_L[[4]]/SH)*pinfec.h*prev.c*gono.c;                                    #EIR
}
EIRsen_L = data.frame(EIRsen_L);
names(EIRsen_L) = as.character(VAR_L);                                                  # Naming the columns

#plot for sensitivity Analysis= Larvae
plot   (1:MDAY0,EIRsen_L[,6], type="l",lty=1, xlab="Days",col="red", ylab="Risk of WNV (EIR)");
title  (main=list("Sensitivity Analysis for Initial Number
of Larvae" ,font=1,col="red",cex=1.2 ));
lines  (1:MDAY0,EIRsen_L[,5], lty=1, col="blue");
lines  (1:MDAY0,EIRsen_L[,4], lty=1, lwd=2, col="black");
lines  (1:MDAY0,EIRsen_L[,3], lty=1,col="green");
lines  (1:MDAY0,EIRsen_L[,2], lty=1, col="orange");
legend ("topleft", c("150%","125%","Baseline","0.75%","0.5%"),inset=0.01,lwd=c(1,1,2,1,1),lty=c(1,1,1,1,1),
        col=c("red","blue","black","green","orange"),bty = 'n', cex=0.7);


#3. SENSITIVITY ANALYSIS FOR CARRING CAPACITY (CC)
VAR_CC     =  seq(0.25,1.5,by=0.25);
EIRsen_CC  =  matrix(0,nrow=MDAY0,ncol=length(VAR_CC));

for(i in 1:length(VAR_CC)){
  Sen_CC        = Population_Dynamics(E,L,P,A,Beta,pb,De,dl,dp,me,ml,mp,ma,NM,NMmin,CC*(VAR_CC[i]));
  EIRsen_CC[,i] = (Sen_CC[[4]]/SH)*pinfec.h*prev.c*gono.c;                                  #EIR

}
EIRsen_CC        = data.frame(EIRsen_CC);
names(EIRsen_CC) = as.character(VAR_CC);
```

```
#plot for sensitivity Analysis= Carrying Capacity
plot   (1:MDAY0,EIRsen_CC[,6], type="l",lty=1, xlab="Days",col="red", ylab="Risk of WNV (EIR)");
title  (main=list("Sensitivity Analysis for the Carrying Capacity" ,font=1,col="red",cex=1.2 ));
lines  (1:MDAY0,EIRsen_CC[,5], lty=1, col="blue");
lines  (1:MDAY0,EIRsen_CC[,4], lty=1, lwd=2, col="black");
lines  (1:MDAY0,EIRsen_CC[,3], lty=1,col="green");
lines  (1:MDAY0,EIRsen_CC[,2], lty=1, col="orange");
legend ("topleft", c("150%","125%","Baseline","0.75%","0.5%"),inset=0.01,lwd=c(1,1,2,1,1),lty=c(1,1,1,1,1),
        col=c("red","blue","black","green","orange"),bty = 'n', cex=0.7);


#4. SENSITIVITY ANALYSIS FOR BITING RATE (gono.c)
VAR_gono     =  seq(0.25,1.5,by=0.25);
EIRsen_gono  =  matrix(0,nrow=MDAY0,ncol=length(VAR_gono));

for(i in 1:length(VAR_gono)){
  Sen_gono        = Population_Dynamics(E,L,P,A,Beta,pb,De,dl,dp,me,ml,mp,ma,NM,NMmin,CC);
  EIRsen_gono[,i] = (Sen_gono[[4]]/SH)*pinfec.h*prev.c*gono.c*(VAR_gono[i]);                          #EIR

}
EIRsen_gono        = data.frame(EIRsen_gono);
names(EIRsen_gono) = as.character(VAR_gono);

#plot for sensitivity Analysis= Biting Rate
plot   (1:MDAY0,EIRsen_gono[,6], type="l",lty=1, xlab="Days",col="red", ylab="Risk of WNV (EIR)");
title  (main=list("Sensitivity Analysis for the Mosquitoe Biting Rate" ,font=1,col="red",cex=1.2 ));
lines  (1:MDAY0,EIRsen_gono[,5], lty=1, col="blue");
lines  (1:MDAY0,EIRsen_gono[,4], lty=1, lwd=2, col="black");
lines  (1:MDAY0,EIRsen_gono[,3], lty=1,col="green");
lines  (1:MDAY0,EIRsen_gono[,2], lty=1, col="orange");
legend ("topleft", c("150%","125%","Baseline","0.75%","0.5%"),inset=0.01,lwd=c(1,1,2,1,1),lty=c(1,1,1,1,1),
        col=c("red","blue","black","green","orange"),bty = 'n', cex=0.7);

#5. SENSITIVITY ANALYSIS FOR PROBABILITY OF INFECTION (pinfec.h)
VAR_pinfec     =  seq(0.25,1.5,by=0.25);
EIRsen_pinfec  =  matrix(0,nrow=MDAY0,ncol=length(VAR_gono));

for(i in 1:length(VAR_pinfec)){
    Sen_pinfec        = Population_Dynamics(E,L,P,A,Beta,pb,De,dl,dp,me,ml,mp,ma,NM,NMmin,CC);
    EIRsen_pinfec[,i] = (Sen_pinfec[[4]]/SH)*pinfec.h*(VAR_pinfec[i])*prev.c*gono.c;                  #EIR
 }
EIRsen_pinfec        = data.frame(EIRsen_pinfec);
names(EIRsen_pinfec) = as.character(VAR_pinfec);
```

```
#plot for sensitivity Analysis= Probability of Infection
plot   (1:MDAY0,EIRsen_pinfec[,6], type="l",lty=1, xlab="Days",col="red", ylab="Risk of WNV (EIR)");
title  (main=list("Sensitivity Analysis for the Probability
of Infection in Humans" ,font=1,col="red",cex=1.2 ));
lines  (1:MDAY0,EIRsen_pinfec[,5], lty=1, col="blue");
lines  (1:MDAY0,EIRsen_pinfec[,4], lty=1, lwd=2, col="black");
lines  (1:MDAY0,EIRsen_pinfec[,3], lty=1,col="green");
lines  (1:MDAY0,EIRsen_pinfec[,2], lty=1, col="orange");
legend ("topleft", c("150%","125%","Baseline","0.75%","0.5%"),inset=0.01,lwd=c(1,1,2,1,1),lty=c(1,1,1,1,1),
        col=c("red","blue","black","green","orange"),bty = 'n', cex=0.7);


#*************************************************************************************************

#*************************************************************************************************
#########   ANALYSIS OF EFFICASY OF CONTROL INTERVENTIONS   ################

# 1. ANALYSIS OF EFFICASY OF ADULTICIDES

VAR_ma     = seq(0.016667,1,length.out = 100);
EIR_ma     = matrix(0,nrow=MDAY0,ncol=length(VAR_ma));
EIR_2  = rep(0,length(VAR_ma));
for(i in 1:length(VAR_ma)){
  EIR_maD        = Population_Dynamics(E,L,P,A,Beta,pb,De,dl,dp,me,ml,mp,VAR_ma[i],NM,NMmin,CC);
  EIR_ma [ ,i]  = ((EIR_maD[[4]]/SH)*pinfec.h*prev.c*gono.c); #EIR


  EIR_2[i] = auc(1:554,(EIR_ma [ ,i])/554);

}
head(EIR_2);


plot(EIR_2,type = "l",lty=1,col="red",lwd=2,ylab = "Risk of West Nile Virus (EIR)",xlab = " Percentage Adulticide Usage (%)")
title(main =list("Efficacy of Adulticides in Controlling WNV",col="red",font=1,cex=1.2))



# 2. ANALYSIS OF EFFICASY OF LARVICIDES

VAR_ml     = seq(0.1,1,length.out = 100);
EIR_ml     = matrix(0,nrow=MDAY0,ncol=length(VAR_ml));
EIR_3      = rep(0,length(VAR_ml));

for(i in 1:length(VAR_ml)){
  EIR_mlD       = Population_Dynamics(E,L,P,A,Beta,pb,De,dl,dp,me,VAR_ml[i],mp,ma,NM,NMmin,CC);
  EIR_ml [ ,i]  = ((EIR_mlD[[4]]/SH)*pinfec.h*prev.c*gono.c); #EIR
```

```
  EIR_3[i] = auc(1:554,(EIR_ml [ ,i])/554);

}
head(EIR_3);

plot(EIR_3,type = "l",col="blue",xlab = "Percentage Larvicidal Usage",ylab = "Risk of West Nile Virus (EIR)")
title(main=list("Efficacy of Larvicides on Risk of WNV",col="red",font=1,cex=1.2))
aa = lm(EIR_3~ c(1:100));
abline(aa,col="blue",lwd=2);

# 3. ANALYSIS OF EFFICASY OF REPELLENTS

VAR_gono     = seq(0.33333,0,length.out = 100);
EIR_gono     = matrix(0,nrow=MDAY0,ncol=length(VAR_gono));
EIR_4  = rep(0,length(VAR_gono));

for(i in 1:length(VAR_gono)){

  EIR_gono [ ,i]  = ((Adults/SH)*pinfec.h*prev.c*VAR_gono[i]); #EIR


  EIR_4[i] = auc(1:554,(EIR_gono [,i])/554);

}

head(EIR_4);


plot(EIR_4, type="l", xlab=" Percentage Repellent usage (%)",col="red", lwd=2,ylab="Risk of WNV, (EIR)");
title(main=list("Efficacy of Repellent on Risk of WNV" ,font=1,col="red",cex=1.2 ));



# Comparing the efficasy of control interventions
plot(EIR_4, type="l", xlab="Percentage usage of Control Interventions (%)",lwd=2,col="green",ylab="Risk of WNV, (EIR)");
title(main=list("Comparative Efficacy of  Control Interventions
                in Rainfall Situation" ,font=1,col="red",cex=1.2 ));
lines(EIR_2, lty=1,lwd=2, col="red")
lines(EIR_3, lty=1, col="blue")
aa = lm(EIR_3~ c(1:100));                              #Linear Model function to create a Regressin Model
abline(aa,col="blue",lwd=2);                                 # Drawing a regression line
legend("topright", c("Repellent","Adulticide","Larvicide"),inset=0.01, lwd=c(2,2,2),
       col=c("red","green","blue"), lty=c(1,1,1),bty = 'n', cex=0.8);
```

Appendix II: R Function: Load_Data

```
Load_Data = function(Dpath){

    #Volume of irrigation water
    #>> generating months

    #CONSTANTS-DEFINATION WRT - IRRIGATION WATER
    mon       = seq(1,12);
    no.days   = c(31,28,31,30,31,30,31,31,30,31,30,31);            # Number days in a month
    acreage   = 6520;                                              # Acreage under irrigation in Bura
    sqmm_acre = 4046856422.40;                                     # sq mm in 1 acre for conversion
    m3_mm3    = 1000000000;                                        # Convert m3 to mm3
    loss      = 1;                                                 # Amount of water lost after pumping
    discharge = 2.7;                                               # c(2.7,2.7,2.7,2.7,2.7,2.7,2.7,2.7,2.7,2.7,2.7,2.7)#M3/s
    hrs_ran   = c(506,598,459,0,260,154,237,176,220,325,448,511);  # number of hrs on operation
    vol_m3    = discharge*hrs_ran*3600;
    vol_mm3   = vol_m3*m3_mm3*loss;
    water.land= vol_mm3/(acreage*sqmm_acre);


    x1 = read.csv(Dpath,header=TRUE);
    x2 = x1[match(as.vector(unique(x1$date)),x1$date),];            # get only unique days of the year without redundancy
    x3= cbind(day=1:dim(x2)[1],x2);

    # UPDATE DATA W.r.t MONTHS OF THE YEAR
    date2 = mdy(x3$date);
    month = month(date2);
    x3    = cbind(x3,month);
    print(x3[1:5,]);

    # IRRIGATION WATER AND ALL WATER STATISICS
    ir.water  = water.land/no.days;
    irrig     = as.data.frame(cbind(mon,ir.water));
    x3        = merge(x3,irrig, by.x="month", by.y="mon");         ##
    x3        = x3[order(x3$day),];

    all.water = as.vector(x3$rain) + as.vector(x3$ir.water);

    #cat("\n I AM HERE",length(ir.water),"\n\n");
    x3<-cbind(x3,all.water);

    head(x3);              # Print to screen

    return(x3);
}
```

Appendix III: R Code: Initialize_Parameters

```
#Initialize_Parameters = function(){
 #initialisation of vector states

MDAY0     = max(x3$day)
MDAY1     = MDAY0-1
#max(x3$day)= 554;
adult.init = 100000;
E   = Ew   =  rep(50,MDAY0);            # Initial number of eggs
L   = Lw   =  rep(250,MDAY0);           # Initial number of Larvae
P   = Pw   =  rep(50,MDAY0);            # Initial number of pupae
A   = Aw   =  rep(adult.init,MDAY0);
EIR = EIRw =  rep(0,MDAY0);



NM         = L + P + A;
NMmin      = 50;

# parameters -- culex mosquito population dynamics
Beta      =   40;                         # number of eggs laid by mosquito per day
De        =   0.33;                    # egg hatching rate
me         =   0.1;                    # per capita daily mortality rate of eggs
dl         =   0.1;                    # development rate of larva
ml         =   0.1;                    # per capita daily mortality rate of larvae
dp         =   0.2;                    # pupa development rate
mp         =   0.1;                    # per capita daily mortality rate of pupae
ma         =   1/60;                     # adult mortality rate
CC         =   5000000;                # larvae carying capacity
gono.c     =   1/3;              # culex feeding interval
pinfec.h   =   0.88;             # probability of an infection in humans following infectious bite
pinfec.b   =   0.88;             # probability of infection in birds following infectious bite
pculex.h   =   0.125;            # probability of infection in culex following bite on infectious human
pculex.b   =   0.125;            # probability of infection in culex following bite on infectious bird
incub.c    =   1/3;              # incubation rate in culex
i.h        =   1/3;              # incubation rate in humans
r.h        =   1/14;             # recorvery rate in humans
g.h        =   1/60;             # rate of loss of immunity in humans
i.b        =   1/14;             # incubation rate in birds
r.b        =   1/30;             # recorvery rate in birds
g.b        =   1/90;             # rate of loss of immunity in birds
gono.c     =   1/3;                   # culex feeding interval
prev.c     =   0.18                 # prevalence of WNV in moaquitoes
SH         =   100000;

#}
```

Appendix IV: R Function: Population_dynamics

```
Population_Dynamics = function(E,L,P,A,Beta,pb,De,dl,dp,me,ml,mp,ma,NM,NMmin,CC){

  for (i in 1:MDAY1){

    E[i+1] = E[i] + (Beta*A[i]*pb[i]*(1-(L[i]/CC))) - (De*E[i]) - (me*(1-pb[i])*E[i]);
    L[i+1] = L[i] + (De*E[i]) - (dl*L[i]) - (ml*(1-pb[i])*L[i]);
    P[i+1] = P[i] + (dl*L[i]) - (dp*P[i]) - (mp*(1-pb[i])*P[i]);
    A[i+1] = A[i] + (dp*P[i]*0.5)- (ma*A[i]);

    NM[i+1]=L[i+1]+P[i+1]+A[i+1];

    if (NM[i+1]<NMmin){
      L[i+1]=L[i];
      P[i+1]=P[i];
      A[i+1]=A[i];
    }
  }

  POPDYNA = list(E,L,P,A,ml,ma,CC);

  return(POPDYNA);
}
```

Appendix V: Cumulative_Rainfall

```
Cummulative_Rainfall = function(x3){

  #Fuzzy distribution model rainfall
  u1     <- 0;                                  # lower threshold of unsuitable rainfall conditions (fuzzy distribution model)
  s      <- 40;                                 # most suitable rainfall conditions (fuzzy distribution model)
  u2     <- 65;                                 # upper threshold of unsuitable rainfall conditions (fuzzy distribution model)
  pb     <- 0;
  pb.adj <- 0;
  MDAY0  = dim(x3)[1];

  Index = 9;
  Rainfall = rep(0,dim(x3)[1]);                          # Initialization
  for (i in (Index+1):(length(Rainfall)-1)){
    Rainfall[i] = sum(as.vector(x3$rain)[(i-Index):i]);      # Assignment
  }
  cat(paste("\n\nTotal length of the rainfall vector\t - \t",length(Rainfall),"\n\n"));

  for (i in 1:MDAY0){
    if( u1<Rainfall[i] & Rainfall[i]<s ){                          #fuzzy distribution to determine suitability index(pb)
      pb[i] <- (1-(cos(((Rainfall[i])/(s-u1))*(3.14/2))^2))
    } else if( (s <= Rainfall[i]) & (Rainfall[i]<= u2) ) {
      pb[i] <- cos(((Rainfall[i])/(u2-s))*(3.14/2))^2;
    } else {
      pb[i] <- 0;
    }
  }

  water = rep(0,dim(x3)[1]);                           # Initialization
  for (i in (Index+1):(length(x3$all.water)-1)){
      water[i] = sum(as.vector(x3$all.water)[(i-Index):i]);      # Assignment
  }
  #Fuzzy model for combined irrigation water and rainfall

  for (i in 1:MDAY0){
      if( u1<water[i] & water[i]<s ){                            #fuzzy distribution to determine suitability index(pb)
          pb.adj[i] <- (1-(cos(((water[i])/(s-u1))*(3.14/2))^2))
      } else if( (s < water[i]) & (water[i]<u2) ) {
          pb.adj[i] <- cos(((water[i])/(u2-s))*(3.14/2))^2;
      } else {
          pb.adj[i] <- 0;
      }
  }
  RPBR = list(Rainfall,water,pb,pb.adj);
  return(RPBR);
}
```

Appendix VI: Meteorology Data. Source: Bura Irrigation scheme

date	out_temp	rain
6/20/2013	26.22	0.2
6/21/2013	26.325	0
6/22/2013	26.325	0
6/23/2013	23.375	4.6
6/24/2013	24.875	0.2
6/25/2013	24.9917	0
6/26/2013	27.0889	0.2
6/27/2013	26.3	0
6/28/2013	26.1667	0.2
6/29/2013	25.8917	0
6/30/2013	25.75	0
7/1/2013	25.8333	0
7/2/2013	26.375	0
7/3/2013	25.975	0
7/4/2013	26.225	0
7/5/2013	25.175	0
7/6/2013	25.6917	0
7/7/2013	25.6333	0
7/8/2013	25.5083	0
7/9/2013	25.4917	0
7/10/2013	24.9083	0
7/11/2013	24.5667	0
7/12/2013	24.8833	0
7/13/2013	24.7833	0
7/14/2013	25.05	0
7/15/2013	25.6583	0
7/16/2013	25.75	0
7/17/2013	26.0833	0
7/18/2013	25.8917	0
7/19/2013	25.4417	0
7/20/2013	24.975	0
7/21/2013	25.275	0
7/22/2013	25.5167	0
7/23/2013	26.075	0
7/24/2013	25.8417	0
7/25/2013	25.0818	0
7/26/2013	25.15	0
7/27/2013	24.6333	0
7/28/2013	25.9583	0
7/29/2013	26.3083	0
7/30/2013	25.7167	0.2
7/31/2013	25.375	0
8/1/2013	25.7917	0
8/2/2013	24.375	0
8/3/2013	24.4917	0.2
8/4/2013	24.8636	0
8/5/2013	22.72	0
8/20/2013	29.7429	0
8/21/2013	26.5833	0
8/22/2013	25.1333	5.2
8/23/2013	26.025	0
8/24/2013	26.15	0
8/25/2013	26.1083	0
8/26/2013	26.3417	0
8/27/2013	25.7667	0
8/28/2013	25.1667	0
8/29/2013	25.4083	0.8
8/30/2013	25.7167	0.2
8/31/2013	26.6455	0
9/1/2013	28.5714	0.4
9/2/2013	26.275	0
9/3/2013	26.1583	0
9/4/2013	26.3667	0
9/5/2013	26.075	0
9/6/2013	26.65	0
9/7/2013	25.8833	1.6
9/8/2013	26.0417	0
9/9/2013	26.575	0.2
9/10/2013	26.3417	0.6
9/11/2013	25.8125	0
9/12/2013	26.3364	0
9/16/2013	29.3286	0
9/17/2013	27.71	0
9/18/2013	26.1917	0
9/19/2013	26.225	0
9/20/2013	26.6167	0
9/21/2013	26.9333	0
9/22/2013	27.1	1
9/23/2013	26.9083	0
9/24/2013	26.45	3.4
9/25/2013	26.825	0
9/26/2013	27.525	0
9/26/2013	27.525	0

9/26/2013	27.525	0
9/26/2013	27.525	0
9/26/2013	27.525	0
9/26/2013	27.525	0
9/26/2013	27.525	0
9/26/2013	27.525	0
9/27/2013	27.2583	0
9/27/2013	27.2583	0
9/27/2013	27.2583	0
9/27/2013	27.2583	0
9/27/2013	27.2583	0
9/27/2013	27.2583	0
9/27/2013	27.2583	0
9/27/2013	27.2583	0
9/27/2013	27.2583	0
9/27/2013	27.2583	0
9/28/2013	27.075	0
9/28/2013	27.075	0
9/28/2013	27.075	0
9/28/2013	27.075	0
9/28/2013	27.075	0
9/28/2013	27.075	0
9/28/2013	27.075	0
9/28/2013	27.075	0
9/28/2013	27.075	0
9/28/2013	27.075	0
9/28/2013	27.075	0
9/28/2013	27.075	0
9/28/2013	27.075	0
9/29/2013	27.5667	0
9/29/2013	27.5667	0
9/29/2013	27.5667	0
9/29/2013	27.5667	0
9/29/2013	27.5667	0
9/29/2013	27.5667	0
9/29/2013	27.5667	0
9/29/2013	27.5667	0
9/29/2013	27.5667	0
9/29/2013	27.5667	0
9/29/2013	27.5667	0
9/30/2013	28.5083	0
9/30/2013	28.5083	0
9/30/2013	28.5083	0
9/30/2013	28.5083	0
9/30/2013	28.5083	0

9/30/2013	28.5083	0
9/30/2013	28.5083	0
10/1/2013	28.4417	3
10/1/2013	28.4417	3
10/1/2013	28.4417	3
10/1/2013	28.4417	3
10/1/2013	28.4417	3
10/1/2013	28.4417	3
10/1/2013	28.4417	3
10/1/2013	28.4417	3
10/1/2013	28.4417	3
10/1/2013	28.4417	3
10/1/2013	28.4417	3
10/2/2013	27.9167	0.4
10/2/2013	27.9167	0.4
10/2/2013	27.9167	0.4
10/2/2013	27.9167	0.4
10/2/2013	27.9167	0.4
10/2/2013	27.9167	0.4
10/2/2013	27.9167	0.4
10/2/2013	27.9167	0.4
10/2/2013	27.9167	0.4
10/2/2013	27.9167	0.4
10/2/2013	27.9167	0.4
10/2/2013	27.9167	0.4
10/2/2013	27.9167	0.4
10/2/2013	27.9167	0.4
10/3/2013	25.5667	4.6
10/4/2013	26.1333	2.2
10/5/2013	26.6083	0
10/6/2013	27.5667	0
10/7/2013	26.9417	0
10/8/2013	27.475	0
10/9/2013	28.1333	0
10/10/2013	27.875	0
10/11/2013	27.1	0.4
10/12/2013	27.9667	0
10/13/2013	28.4583	0
10/14/2013	28.5083	0
10/15/2013	28.05	0
10/16/2013	27.8417	0
10/17/2013	27.9667	0

10/18/2013	28.0917	0
10/19/2013	28.025	0
10/20/2013	27.6833	0
10/21/2013	28.2	0
10/22/2013	28.6083	0
10/23/2013	29.0333	0
10/24/2013	28.9273	1.4
10/25/2013	28.4417	0
10/26/2013	28.4167	0
10/27/2013	28.7333	0
10/28/2013	28.525	0
10/29/2013	28.4083	0
10/30/2013	28.6273	0.2
10/31/2013	28.6636	0
11/1/2013	29.45	0
11/2/2013	29.3182	0
11/3/2013	28.8273	0
11/4/2013	28.825	0.8
11/5/2013	28.9667	1
11/6/2013	27.9083	9.4
11/7/2013	26.2917	11.4
11/8/2013	27.1833	6.2
11/9/2013	28.275	0
11/10/2013	28.3833	0.8
11/11/2013	29.3182	1.4
11/12/2013	29.4167	0
11/13/2013	28.825	0
11/14/2013	29.2083	0
11/14/2013	29.2083	0
11/14/2013	29.2083	0
11/14/2013	29.2083	0
11/14/2013	29.2083	0
11/14/2013	29.2083	0
11/14/2013	29.2083	0
11/14/2013	29.2083	0
11/14/2013	29.2083	0
11/14/2013	29.2083	0
11/14/2013	29.2083	0
11/14/2013	29.2083	0
11/14/2013	29.2083	0
11/15/2013	29.1167	0
11/15/2013	29.1167	0

11/15/2013	29.1167	0
11/15/2013	29.1167	0
11/15/2013	29.1167	0
11/15/2013	29.1167	0
11/15/2013	29.1167	0
11/15/2013	29.1167	0
11/15/2013	29.1167	0
11/15/2013	29.1167	0
11/15/2013	29.1167	0
11/15/2013	29.1167	0
11/15/2013	29.1167	0
11/15/2013	29.1167	0
11/15/2013	29.1167	0
11/15/2013	29.1167	0
11/15/2013	29.1167	0
11/16/2013	30.41	0
11/16/2013	30.41	0
11/16/2013	30.41	0
11/16/2013	30.41	0
11/16/2013	30.41	0
11/16/2013	30.41	0
11/16/2013	30.41	0
11/16/2013	30.41	0
11/16/2013	30.41	0
11/16/2013	30.41	0
11/17/2013	28.8917	0.8
11/17/2013	28.8917	0.8
11/17/2013	28.8917	0.8
11/17/2013	28.8917	0.8
11/17/2013	28.8917	0.8
11/17/2013	28.8917	0.8
11/17/2013	28.8917	0.8
11/17/2013	28.8917	0.8
11/17/2013	28.8917	0.8
11/17/2013	28.8917	0.8
11/18/2013	29.675	0
11/18/2013	29.675	0
11/18/2013	29.675	0
11/18/2013	29.675	0
11/18/2013	29.675	0
11/18/2013	29.675	0
11/18/2013	29.675	0
11/18/2013	29.675	0
11/18/2013	29.675	0
11/19/2013	27.88	0.8

11/19/2013	27.88	0.8
11/19/2013	27.88	0.8
11/19/2013	27.88	0.8
11/19/2013	27.88	0.8
11/19/2013	27.88	0.8
11/19/2013	27.88	0.8
11/19/2013	27.88	0.8
11/19/2013	27.88	0.8
11/19/2013	27.88	0.8
11/20/2013	29.85	0
11/20/2013	29.85	0
11/20/2013	29.85	0
11/20/2013	29.85	0
11/20/2013	29.85	0
11/20/2013	29.85	0
11/20/2013	29.85	0
11/20/2013	29.85	0
11/20/2013	29.85	0
11/20/2013	29.85	0
11/20/2013	29.85	0
11/21/2013	29.15	0
11/22/2013	26.85	0
11/28/2013	29.2625	0
11/29/2013	27.3167	4.6
11/30/2013	27.725	1.6
12/1/2013	28.3417	0
12/2/2013	28.5333	0
12/3/2013	25.7125	0.6
12/4/2013	26.4083	0
12/5/2013	26.81	0.2
12/6/2013	27.93	0
12/7/2013	28.2333	0
12/8/2013	29.5714	0
12/9/2013	26.7	0.2
12/10/2013	28.1167	0
12/11/2013	28.1583	0
12/12/2013	28.3333	0
12/13/2013	28.2583	0
12/14/2013	28.25	0
12/15/2013	28.3333	0
12/16/2013	28.0917	0
12/17/2013	28.5417	0
12/18/2013	28.7833	0

12/19/2013	24.68	0
12/20/2013	31.8167	0
12/21/2013	28.8917	0
12/22/2013	28.5083	0
12/23/2013	29.1333	0
12/24/2013	28.7917	0
12/25/2013	29.1833	0
12/26/2013	28.775	0
12/27/2013	28.5083	0
12/28/2013	28.9167	0
12/29/2013	28.8417	0
12/30/2013	28.1083	0
12/31/2013	28.475	0
1/1/2014	28.9917	0
1/2/2014	29.3667	0
1/3/2014	29.1083	0
1/4/2014	29.5917	0
1/5/2014	29.0917	0
1/6/2014	28.9833	0
1/7/2014	29.3083	0
1/8/2014	29.3917	0
1/9/2014	29.5583	0
1/10/2014	28.7583	0
1/11/2014	28.7417	0
1/12/2014	28.5167	0
1/13/2014	29.0417	0
1/14/2014	29.5083	0
1/15/2014	28.975	0
1/16/2014	28.1	0
1/17/2014	28.85	0
1/18/2014	28.9833	0
1/19/2014	28.7333	0
1/20/2014	28.725	0
1/21/2014	28.7	0
1/22/2014	28.15	0
1/23/2014	28.7583	0
1/24/2014	27.9917	0
1/25/2014	27.925	0
1/26/2014	28.4333	0
1/27/2014	25.9625	0
1/28/2014	28.8083	0
1/29/2014	28.9833	0

1/30/2014	29.4917	0
1/31/2014	29.1167	0
2/1/2014	28.325	0
2/2/2014	29.0917	0
2/3/2014	28.7917	0
2/4/2014	29.5	0
2/5/2014	27.7091	0
2/6/2014	29.3833	0
2/7/2014	29.1083	0
2/8/2014	29.9167	0
2/9/2014	29.3417	0
2/10/2014	29.65	0
2/11/2014	30.1167	0
2/12/2014	29.5167	0
2/13/2014	29.8917	0
2/14/2014	29.9333	0
2/15/2014	29.8417	0
2/16/2014	28.8833	0
2/17/2014	27.9083	0
2/18/2014	29.2833	0
2/19/2014	30.0917	0
2/20/2014	29.3833	0
2/21/2014	29.1727	0
2/22/2014	29.65	0
2/23/2014	29.05	0
2/24/2014	29.55	0
2/25/2014	29.0909	0
2/26/2014	29.7917	0
2/27/2014	29.6083	0
2/28/2014	29.9667	0
3/1/2014	30.1818	0
3/2/2014	30.0667	0
3/3/2014	30.1667	0
3/4/2014	30.5	0
3/5/2014	30.8333	0
3/6/2014	30.3583	0
3/7/2014	29.3	13.4
3/8/2014	29.375	0
3/9/2014	29.6583	0
3/10/2014	28.3111	0
3/11/2014	30.475	0
3/12/2014	29.35	0
3/13/2014	29.8917	0
3/14/2014	28.425	10.6
3/15/2014	27.9083	3
3/16/2014	28.8273	0.6
3/17/2014	28.0583	2.6
3/18/2014	27.55	1
3/19/2014	29.2417	0
3/20/2014	29.2333	0
3/21/2014	29.8583	0
3/22/2014	30.2083	0
3/23/2014	30.925	0
3/24/2014	30.9083	0
3/25/2014	30.55	0
3/26/2014	27.3583	10
3/27/2014	27.575	0.2
3/28/2014	29.45	0
3/29/2014	29.4	0
3/30/2014	29.0923	0
3/31/2014	29.4	0.4
4/1/2014	29.2818	0
4/2/2014	31.6667	0
4/3/2014	29.7833	0
4/4/2014	31.51	0
4/5/2014	30.7	0
4/6/2014	29.6636	0
4/7/2014	27.0667	3.4
4/8/2014	28.8	0.4
4/9/2014	28.6083	0
4/10/2014	28.2	2
4/11/2014	28.4917	0
4/12/2014	28.4083	3.4
4/13/2014	27.8333	5.2
4/14/2014	27.7333	8.6
4/15/2014	28.3	0
4/16/2014	28.6417	0
4/17/2014	27.2917	0
4/18/2014	28.325	0
4/19/2014	27.2167	0.8
4/20/2014	29.325	0
4/21/2014	29.6583	0
4/22/2014	30.1167	0
4/23/2014	28.2417	11.4

4/24/2014	28.7667	0
4/25/2014	29.6667	0
4/25/2014	29.6667	0
4/25/2014	29.6667	0
4/25/2014	29.6667	0
4/25/2014	29.6667	0
4/25/2014	29.6667	0
4/25/2014	29.6667	0
4/25/2014	29.6667	0
4/26/2014	29.6583	0
4/26/2014	29.6583	0
4/26/2014	29.6583	0
4/26/2014	29.6583	0
4/26/2014	29.6583	0
4/26/2014	29.6583	0
4/26/2014	29.6583	0
4/26/2014	29.6583	0
4/26/2014	29.6583	0
4/26/2014	29.6583	0
4/26/2014	29.6583	0
4/26/2014	29.6583	0
4/26/2014	29.6583	0
4/26/2014	29.6583	0
4/26/2014	29.6583	0
4/26/2014	29.6583	0
4/26/2014	29.6583	0
4/26/2014	29.6583	0
4/26/2014	29.6583	0
4/26/2014	29.6583	0
4/26/2014	29.6583	0
4/27/2014	29.675	0
4/27/2014	29.675	0
4/27/2014	29.675	0
4/27/2014	29.675	0
4/27/2014	29.675	0
4/27/2014	29.675	0
4/28/2014	29.7	0
4/28/2014	29.7	0
4/28/2014	29.7	0
4/28/2014	29.7	0
4/28/2014	29.7	0
4/28/2014	29.7	0

4/28/2014	29.7	0
4/28/2014	29.7	0
4/28/2014	29.7	0
4/28/2014	29.7	0
4/28/2014	29.7	0
4/28/2014	29.7	0
4/28/2014	29.7	0
4/29/2014	29.8455	0
4/29/2014	29.8455	0
4/29/2014	29.8455	0
4/29/2014	29.8455	0
4/29/2014	29.8455	0
4/29/2014	29.8455	0
4/29/2014	29.8455	0
4/29/2014	29.8455	0
4/29/2014	29.8455	0
4/29/2014	29.8455	0
4/29/2014	29.8455	0
4/29/2014	29.8455	0
4/29/2014	29.8455	0
4/29/2014	29.8455	0
4/29/2014	29.8455	0
4/30/2014	30.7778	0
4/30/2014	30.7778	0
4/30/2014	30.7778	0
4/30/2014	30.7778	0
4/30/2014	30.7778	0
4/30/2014	30.7778	0
4/30/2014	30.7778	0
4/30/2014	30.7778	0
4/30/2014	30.7778	0
4/30/2014	30.7778	0
4/30/2014	30.7778	0
5/1/2014	29.45	0
5/2/2014	25.3	2
5/3/2014	28.1	0
5/4/2014	28.7917	0
5/5/2014	27.65	0
5/6/2014	25.0083	1.6
5/7/2014	27.4	0
5/8/2014	28.3083	0
5/9/2014	27.2167	0

5/10/2014	27.875	0
5/11/2014	28.725	0
5/12/2014	28.2143	0
5/13/2014	28.46	0
5/14/2014	26.8	0
5/15/2014	26.4875	0
5/16/2014	27.91	0
5/20/2014	27.94	0
5/21/2014	27.2167	0
5/22/2014	27.05	0
5/23/2014	27.55	0
5/24/2014	27.375	0
5/25/2014	26.4083	0
5/26/2014	25.775	0
5/27/2014	27.3333	0
5/28/2014	27.5083	0
5/29/2014	27.1	0
5/30/2014	27.2833	0
5/31/2014	27.3083	0
6/1/2014	27.475	0
6/2/2014	28.2167	0
6/3/2014	28.375	0
6/4/2014	25.6667	0.6
6/5/2014	26.7167	0
6/6/2014	27.35	0
6/7/2014	26.425	0.2
6/8/2014	26.7083	0
6/9/2014	27.05	0
6/10/2014	26.7417	0
6/11/2014	27.2167	0
6/12/2014	24.8	0
6/13/2014	27.9571	0
6/14/2014	26.3833	0
6/15/2014	26.85	0
6/16/2014	26.95	0
6/17/2014	27.2667	0
6/18/2014	26.75	0
6/19/2014	26.35	0
6/20/2014	26.7	0
6/21/2014	26.3583	0
6/22/2014	25.4833	0.4
6/23/2014	25.4583	1.4
6/24/2014	24.8	1.4
6/25/2014	25.8667	0
6/26/2014	26.4083	0
6/27/2014	26.7917	0
6/28/2014	27.0417	0
6/29/2014	26.05	0
6/30/2014	26.3917	0
7/1/2014	26.2083	0
7/2/2014	26.65	0
7/3/2014	26.4	0
7/4/2014	26.1083	0
7/5/2014	26.0167	0
7/6/2014	26.325	0
7/7/2014	26.7333	0
7/8/2014	26.425	0
7/9/2014	26.075	0
7/10/2014	26.3667	0
7/11/2014	25.3833	0
7/12/2014	25.9	0
7/13/2014	25.9167	0
7/14/2014	25.8083	0
7/15/2014	26.25	0
7/16/2014	25.9667	0
7/17/2014	25.8417	0
7/18/2014	25.8917	0
7/19/2014	26.7	0
7/20/2014	26.85	0
7/21/2014	26.4833	0
7/22/2014	26.6333	0
7/23/2014	26.6917	0
7/24/2014	26.575	0
7/25/2014	26.2333	0
7/26/2014	25.8583	0
7/27/2014	25.95	0
7/28/2014	26.3667	0
7/29/2014	26.6	0
7/30/2014	26.3	4.2
7/31/2014	23.5417	10
8/1/2014	25.1083	0
8/2/2014	25.9917	0
8/3/2014	25.7417	0
8/4/2014	26.25	0

8/5/2014	25.975	0
8/6/2014	25.325	0
8/7/2014	25.6583	0.6
8/8/2014	26.0667	0
8/9/2014	25.875	0
8/10/2014	26.1	0
8/11/2014	26.25	0
8/12/2014	25.7667	1.4
8/13/2014	25.8	0
8/14/2014	26.4917	0
8/15/2014	26.9889	0
8/16/2014	26.525	0
8/17/2014	25.05	0
8/18/2014	25.9583	0
8/19/2014	26.2417	0.6
8/20/2014	26.2917	0
8/21/2014	26.6583	0
8/22/2014	26.9917	0
8/23/2014	26.9167	0
8/24/2014	26.65	0
8/25/2014	26.9167	0
8/26/2014	27.0667	0
8/27/2014	27.3083	0
8/28/2014	27.375	0
8/29/2014	27.8167	0
8/30/2014	27.325	1.4
8/31/2014	26.625	0
9/1/2014	26.825	0
9/2/2014	27.0667	0
9/3/2014	26.55	0
9/4/2014	26.8667	0
9/5/2014	25.7417	0.4
9/6/2014	24.0917	4.2
9/7/2014	26.6917	0
9/8/2014	26.25	1
9/9/2014	26.75	0
9/10/2014	25.5333	0
9/11/2014	28.3111	0
9/12/2014	27.0667	0
9/13/2014	27.2333	0
9/14/2014	27.5833	0
9/15/2014	24.9667	4
9/16/2014	26.5583	0
9/17/2014	26.425	0
9/18/2014	26.5917	0
9/19/2014	26.675	0
9/20/2014	26.725	0
9/21/2014	26.9083	0
9/22/2014	26.6667	0
9/23/2014	27.0083	0
9/24/2014	26.375	0
9/25/2014	26.975	0
9/26/2014	27.1667	0
9/27/2014	27.2	0
9/28/2014	27.9083	0
9/29/2014	28.1	0
9/30/2014	27.8	0
10/1/2014	27.825	0
10/2/2014	28.5833	0
10/3/2014	28.8167	0
10/4/2014	28.6083	0
10/5/2014	27.3833	0
10/6/2014	25.9417	0.8
10/7/2014	24.7583	1.2
10/8/2014	27.2583	0.2
10/9/2014	28.525	0
10/10/2014	28.3167	0
10/11/2014	28.1833	0
10/12/2014	27.75	0
10/13/2014	28.15	0
10/14/2014	28.1333	0
10/15/2014	28.3833	0
10/16/2014	28.75	0
10/17/2014	29.3333	0
10/18/2014	29.4167	0
10/19/2014	26.7083	20.8
10/20/2014	28.2833	0.2
10/21/2014	28.3833	0
10/22/2014	28.675	0
10/23/2014	28.7833	0
10/24/2014	28.4833	0
10/25/2014	29.375	0
10/26/2014	29.0833	0
10/27/2014	28.8917	0

10/28/2014	29	0
10/29/2014	28.125	0
10/30/2014	29.0667	0
10/31/2014	29.7833	0
11/1/2014	29.175	0.2
11/2/2014	27.0833	0.6
11/3/2014	27.8417	23.4
11/4/2014	28.9333	0
11/5/2014	28.5083	0
11/6/2014	28.7083	0
11/7/2014	28.7083	0
11/8/2014	28.7333	0
11/9/2014	28.4333	0
11/10/2014	28.35	0
11/11/2014	27.325	0
11/12/2014	28.27	0
11/13/2014	28.525	49.8
11/14/2014	26.2	38
11/15/2014	24.16	0
11/16/2014	26.1	0
11/17/2014	27.5	1.8
11/18/2014	28.4	0
11/19/2014	26.4889	3.2
11/20/2014	28.27	0
11/21/2014	24.8778	66.6
11/22/2014	26.1222	0
11/23/2014	27.93	0
11/24/2014	28.05	0
11/24/2014	28.05	0
11/24/2014	28.05	0
11/24/2014	28.05	0
11/24/2014	28.05	0
11/24/2014	28.05	0
11/24/2014	28.05	0
11/24/2014	28.05	0
11/24/2014	28.05	0
11/24/2014	28.05	0
11/24/2014	28.05	0
11/24/2014	28.05	0
11/24/2014	28.05	0
11/24/2014	28.05	0
11/24/2014	28.05	0

11/25/2014	28.8091	0
11/25/2014	28.8091	0
11/25/2014	28.8091	0
11/26/2014	25.3	0
11/26/2014	25.3	0
11/26/2014	25.3	0
11/26/2014	25.3	0
11/27/2014	27.35	0
11/27/2014	27.35	0
11/27/2014	27.35	0
11/27/2014	27.35	0
11/27/2014	27.35	0
11/27/2014	27.35	0
11/27/2014	27.35	0
11/28/2014	27.94	0
11/28/2014	27.94	0
11/28/2014	27.94	0
11/28/2014	27.94	0
11/28/2014	27.94	0
11/28/2014	27.94	0
11/28/2014	27.94	0
11/28/2014	27.94	0
11/28/2014	27.94	0
11/28/2014	27.94	0
11/28/2014	27.94	0
11/28/2014	27.94	0
11/28/2014	27.94	0
11/28/2014	27.94	0
11/28/2014	27.94	0
11/28/2014	27.94	0
11/29/2014	27.75	0
11/29/2014	27.75	0
11/29/2014	27.75	0
11/29/2014	27.75	0
11/29/2014	27.75	0
11/29/2014	27.75	0
11/29/2014	27.75	0
11/29/2014	27.75	0
11/29/2014	27.75	0
11/30/2014	26.9333	0
11/30/2014	26.9333	0
11/30/2014	26.9333	0

11/30/2014	26.9333	0
11/30/2014	26.9333	0
11/30/2014	26.9333	0
11/30/2014	26.9333	0
11/30/2014	26.9333	0
12/1/2014	30.5	0
12/1/2014	30.5	0
12/1/2014	30.5	0
12/1/2014	30.5	0
12/1/2014	30.5	0
12/1/2014	30.5	0
12/1/2014	30.5	0
12/1/2014	30.5	0
12/2/2014	26.85	1.8
12/2/2014	26.85	1.8
12/2/2014	26.85	1.8
12/2/2014	26.85	1.8
12/2/2014	26.85	1.8
12/2/2014	26.85	1.8
12/2/2014	26.85	1.8
12/2/2014	26.85	1.8
12/2/2014	26.85	1.8
12/2/2014	26.85	1.8
12/3/2014	26.1	0.6
12/4/2014	23.9333	0
12/5/2014	30.1333	0
12/6/2014	26.5	0
12/7/2014	26.2222	1.8
12/8/2014	27.9	0
12/9/2014	27.4	0
12/10/2014	26.7	0
12/11/2014	26.9091	1.8
12/12/2014	27	0.4
12/13/2014	27.8286	0
12/14/2014	26.6375	0
12/15/2014	24.38	0
12/16/2014	23	0
12/17/2014	27.5	0
12/18/2014	28.75	0
12/19/2014		0
12/20/2014	29.75	0
12/21/2014		0
12/22/2014	29.95	0
12/23/2014	28.1571	0
12/24/2014	27.37	0
12/25/2014	27.84	0
12/26/2014	28.5583	0
12/27/2014	28.525	0
12/28/2014	28.6583	0
12/29/2014	27.0917	0
12/30/2014	26.82	0
12/31/2014	26.84	0
1/1/2015	26.56	0
1/2/2015	22.9333	0
1/6/2015	29.125	0
1/7/2015	27.8417	0
1/8/2015	27.8	0
1/9/2015	28.7333	0
1/10/2015	27.875	0
1/11/2015	28.0917	0
1/12/2015	29.7833	0
1/13/2015	28.6917	0
1/14/2015	28.5833	0
1/15/2015	28.2	0
1/16/2015	28.375	0
1/17/2015	28.5	0
1/18/2015	28.2583	0
1/19/2015	28.2917	0
1/20/2015	27.9	7
1/21/2015	28.0083	0
1/22/2015	24.5	0