UNIVERSITY OF NAIROBI

WATER SUPPLY SECURITY IN A DROUGHT EXPOSED LANGATA SUB-COUNTY: ADOPTING A BLOCKCHAIN PROVENANCE TRACKING FOR INFORMAL WATER ALTERNATIVES

BY

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PLAGIARISM STATEMENT

I confirm that this thesis report is my own work, except quotations from published and unpublished sources, which are clearly indicated and acknowledged as such, and has not been submitted elsewhere for research, see appendix 10. I confirm that I have read and understood the Institute's and the University's regulation on plagiarism. The source of any picture, map or other illustrations is also indicated, as is the source, published or unpublished, of any material not resulting from my own experimentation, observation or specimen-collecting.

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DEDICATION

This thesis report is dedicated to my wife, Mary Akech, our adorable children (Ellen, Laura, Elvis and Kyle) and my parents, Mr. and Mrs. Joel Ochungo Abura. Thank you for your prayers, and encouragement throughout the entire study period. May God richly bless each of you.

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ABSTRACT

Today climate change induced drought risk has occasioned frequent water supply deficits thereby making many urban households to turn to informal water alternatives, especially in the poor nations. Because of their quality doubt, interest to own boreholes and the use of bottled water for drinking purposes is on the rise. The aim of this study was to identify the main socio-demographic adoption determinant for the uptake of a water quality tracking system (WQTS) running on a blockchain technology platform among the Langata sub County households in Nairobi, who currently suffer from the daily water supply deficit.

The study deployed a Participatory Action Research (PAR) method in analysing drought risk for the community and the existing water shortage coping methods. The Standardized Precipitation (SPI) was used to reconstruct the drought exposure hazard profile over Langata while Pearson moment correlation analysis was used to investigate the relationship between the drought events and the number of boreholes installed in the area. Additionally, trend analysis was used to compute the groundwater level decline rate. From the 8-geochemical parameters of the 39 sampled boreholes from records of Water Resources Authority office, a weighted arithmetic formula was applied to develop the area's geo-chemical water quality index (WQI). A water quality grading scale was also crafted following the WHO /KeBS guidelines. A graph of each year's average WQI and each year's standard precipitation index was drawn to investigate the influence of drought on the groundwater quality decline which was validated by the application of the probability of exceedance formula on the area's water quality grade. A vulnerability assessment output was used as a primer in the discrete choice experiment survey meant to solicit for the stated preference out of a bundle of four choice-options of the WQTS, which included individual, communal, a mix of the two and status quo. This led to the development of the Maji-Safi App for facilitating an online tracking of the quality of informal water from their source points.

The results showed that over half of the study period was drought years with a weak non-significant positive correlation between the groundwater level decline rate and droughts. Further, results showed that the quality of the groundwater in the study area is "good" (symbolised by grade C in this study's crafted grading scale). Additionally the results indicate that the deterioration of quality of the groundwater is probably influenced by drought events, while the area's water shortage Coping Cost Burden was found to be relatively high. The preferred choice was identified as Option 2; a communal water access method. Being of the male gender was identified as the main determinant for the adoption of WQTS.

The study concludes that, between 1957 and 2013, Langata area experienced frequent drought which led to increased investment in boreholes with a resultant drop in groundwater levels. The study further concludes that the frequent droughts influenced the quality of the groundwater. The study also concludes that the adoption of the developed prototype "Maji-Safi" App can reduce the existing computed cost burden.

The study recommends for the establishment of a groundwater protection initiative and a roll out of a groundwater quality tracking system based on a purposely formulated water access policy recognizing the role of informal water sector actors.

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ABBREVIATIONS

AR5	Assessment Report Number Five by Intergovernmental Panel on Climate Change
CBS	Central Bureau of Statistics
CDR	Carbon Dioxide Removal
CO2	Carbon Dioxide
DCE	Discrete Choice Experiment
DTM	Digital Terrain Model
ECA	Economic Commission for Africa
FAO	Food and Agriculture Organization
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GPRS	General Packet Radio Service
IBT	Increasing Block Tariff
IIWQ	International Initiative on Water Quality
IFRC	International Federation of Red Cross
IGAD	Intergovernmental Authority on Development
IPCC	Intergovernmental Panel on Climate Change
NAP	National Adaptation Plan
NCCC	National Climate Change Council
NCW&SC	Nairobi City Water and Sewerage Company
^{O}C	Degree Centigrade
R	Coefficient of Determination
SPI	Standard Precipitation Index
SQ	Status Quo

SRM	Solar Radiation Management
TAM	Technology Adoption Model
UNEP	United Nations Environment Program
UNFCCC	United Nations Framework on Climate Change Commission
USD	United States Dollar
U, T, B	Utility, Tanker and Bottled water sources
WaSReB	Water Services Regulatory Board
WRA	Water Resources Authority
WHO	World Health Organization
WQI	Water Quality Index
WQTS	Water Quality Tracking System
WTP	Willingness to Pay

CHAPTER ONE: INTRODUCTION

1 Introduction

This section presents the study's motivation, the background information on the problem of quality of the informal water alternatives, a brief narration on the global climate change exposure profile and its implications on the global water security debate. It also traces the drinking water quality surveillance and monitoring discussions from the past and compares it with the present online drinking water quality tracking systems. Further, it has outlined the research problem including the presentation of the research questions and the corresponding objectives as a guide to the study process. It ends with the presentation of the study's justification, scope and the thesis outline.

1.1 Motivation

On 21st June, 2015, the Nation newspaper published a photo of a young girl in a kneeling position as she drank her fill from a river in Laikipia County, Kenya; see figure 1 (**Onyango-Obbo, 2015**).Her action exhibited the great trust she had in the river water quality but on my part, it reminded me of the water shortage challenge in my neighborhood in Langata, Nairobi County. In Langata, households rely on the informal water alternatives peddled by vendors but whose quality they least trust. Due to the incessant mistrust in quality, most families buy bottled water for drinking purposes and for those who can afford; investment in personal boreholes has become a priority. Coping in this manner with the drought induced water shortage is counterproductive. The locals may be getting exposed to poor quality groundwater on top of other risks. The question that quickly came into my mind is; how can the quality of water from the informal market be trusted by Langata residents? The idea regarding the deployment of Blockchain Technology in the informal water market to help in the quality provenance tracking service started creeping into my mind. And that is how my study journey started off.

Figure 1: A girl drinking her fill from a river in Laikipia,Kenya (Source:Onyango-Obbo, 2015)

1.2 Background information

There is a considerable surge of research interest on the drinking water safety everywhere (**Tadesse et al., 2010**). It began with the 1978's Alma Ata declaration which listed safe water provision as a primary health care duty (**Briscoe, 1984**). Presently, the United Nations 2030 agenda for sustainable development has prioritized the universal access of safe water (**Larsen et al., 2016**), an initiative aimed at lowering the global disease burden (**Prüss-Üstünet al., 2008**;**Prüss et al., 2002**).Unsafe water means that, the physical, chemical and biological characteristics of the water have failed to meet the set drinking water quality standards. In that respect, drinking water quality can be taken singularly as the measure of the score of the concentration of each of the above properties weighed against a set standard of safety. And in other cases, drinking water quality can also be the combined measurement of the score of concentration of water properties as weighed against a quality index scale. Consequently, the quality of drinking water is expected to be managed with utmost care as it affects the wellbeing of the people (**Howard et al., 2003**).

This quality management role is a mandate of the drinking water supply entities. It begins from the drinking water treatment plants through the distribution network up to use point. Contaminants that occur in source water are supposed to be eliminated at the treatment stage (**Howard and Bartram, 2005**) as per the drinking water standards (**WHO, 2011**).The treated water quality is to be monitoring over the distribution network in order to maintain its purity (**Sanders et al., 1983**).The monitoring is expected to extend to collection and storage phases (**Han et al., 1989;Wright et al., 2004**).The process of monitoring and maintaining the purity of the treated water in the supply infrastructure is known as surveillance (**Howard, 2002**;**Whitefield, 1988**).Cities in developed nations have a robust monitoring and surveillance networks (**Ward and Loftis, 1983**) that track the violation of drinking water quality standards in the supply system (**Sanders et al., 1983**).In cities of poor nations on the other hand, we have a number of deficiencies in drinking water distribution system key one being, non-revenue water loss (**Mutikanga et al., 2011**). Other deficiencies include; poor water treatment, illegal connections, back-siphonage, biofilm development within pipes and loss of residual disinfectant which altogether contribute to the deterioration of the drinking water quality (**Lee and Schwab, 2005**).

When the drinking water supply system fails to deliver in these cities, households switch to point sources, known in this study as informal water alternatives. Sourcing water this way presents a principal risk to the public (**Quick et al., 1999**). Exacerbating this risk is the global climate change impact on water resources (**Assefa et al., 2018**). Drought, defined as a below normal rainfall in a place (**Wilhite et al., 2014**), is an important global climate change exposure indicator that is poised to slow progress towards achieving universal drinking water security (**Thomson et al., 2018**).This will affect many cities in the developing nations whose main water supply systems are already operating below optimum even as their water demands are projected to rise. In such cities, most households usually turn to ground water sources (**Freeze and Cherry, 1979**).The groundwater quality is usually affected by excess nitrate compounds (**Foster et al., 1986**), Flouride over-concentration levels (**Ortiz et al., 1998**) and other contaminants as reviewed recently in Ghana by (**Yeleliere et al., 2018**).Establishing a system that can track the quality of these informal water alternative is an important urban water security solution.

Urban water security is a multifaceted concept mired in management conundrum. In it, we have the concept of tracking of quality of drinking water within a distribution network **(Eliades and Polycarpou, 2009**).Ideally, we talk of an urban drinking water supply security when the dependent population of the system has an uninterrupted access to an adequate quantity of safe water (**UN-Water, 2013; Gleick and Palaniappan, 2010**).The topic belongs in the natural resource management genre (**Loucks and van Beek, 2017**).Previous work on urban drinking water supply security has always raised a red flag on drought exposure (**Wilhite et al., 2014**). In fact, presently, water supply crisis is rated as one of the top global threats in terms of likelihood and impact, both on quantity and quality of freshwater resources (**Guppy and Anderson, 2017**).

Conventionally, a water supply system is designed to provide continuous safe and clean water to its customers. But the impact of global climate change on the earth's hydrological system has become a big impediment to this aspiration (**Emilsson and Sang, 2017**). As a result, nearly 1.2 billion people today, face water scarcity (**UN-Water, 2018**). A part from the quantity aspect, the quality of water in the distribution system is also an important security issue. In the olden days, the quality of treated water was menially monitored through laboratory testing (**Aisopou et al., 2012**).In the developed world today, real-time water quality tracking systems are in use (**Eliades and Polycarpou, 2013**).This is so because, the infrastructure is always easy to access even by people with criminal intent or accidental faults (**Liu et al., 2017**).Such foreign matters always have the ability to exhibit decay or growth dynamics (**Hart et al., 2008**).

Arising from this propensity for in-pipe water contamination, (**Kessler et al., 1998**) pioneered a system for the detection of accidental contamination of municipal water networks. But in the early years, Horton had also developed an index system for rating water quality at the source (**Horton, 1965**). The index system, which today is universally used, is based on a composite aggregation of water quality measurement parameters (**Pesce and Wunderlin, 2000**;**WHO, 2011**).Most of the water quality indices rely on normalization or standardization by comparing individual parameter with normal and interpreting as either "good" or "bad". The parameters are weighted as per their perceived importance in the overall water quality spectrum and the final index is calculated as the weighted average of observations of interest (**Tsegaye et al., 2006**). The indexing method is known to always eclipse some parameters with potential contaminants that the expert may overlook especially if the standards of comparison are also hideous in nature (**Liou et al., 2004**).

In-pipe contaminant detection method and water quality indexing method are the two known early warning systems in the drinking water supply service landscape. Both have become foundation pillars in the drinking water quality monitoring and tracking. For example, today most utility companies are known to deploy the Supervisory Control and Data Acquisition (SCADA). Services from SCADA networks are quick and effective in the reporting of the unusual action or security breaches on water systems (**Amin et al., 2013**). SCADA network system has progressed to cover installation of on-line stations with real-time monitoring of data and algorithmic analytics capability (**Storey et al., 2011**). From 1990s, continuous quality tracking to measure the gradual deterioration of water quality and detection of accidental contamination activities for river waters began (**Zulkifli et al., 2018**). Water quality monitoring system determines the physical, chemical and biological characteristics of source water providing the basis for making sustainable management, regulatory choices and scientific conclusions (**Telci et al., 2009**).

The commercially available online water quality tracking systems are mostly designed for the formal water distribution systems. An example is the Threat Ensemble Vulnerability Assessment-Sensor Placement Optimization Tool (TEVA-SPOT) which is a readily available open source water quality tracking application (**Fahnestock et al., 2012**; **Hart and Murray, 2010**; **Hernandez-Ramirez et al., 2019**).Their trial on intermittent water systems has yielded insignificant results (**Nabira et al., 2015**). It is said that the water distribution network is the safety barrier to contaminant intrusion (**Mays, 1999**). Therefore, to guarantee the delivery of high-quality water to customers, in-network water quality stabilization is needed (**Liu et al., 2017**). The stabilization schemes include: re-suspension potential measurements (RPM, turbidity < 0.8NTU) for physical stability (**Vreeburg et al., 2008**), saturation index (SI, -0.2 to 0.3) for chemical stability (**Verberk et al., 2009**), and assimilable organic carbon limit (AOC, < 10 mg C/l for unchlorinated water) for biological stability (**Van der Kooij, 1992**). Achieving these stability standards has become another important driving force behind the upgrading of treatment processes (**Pinheiro and Wagner, 2001; Miner, 2002; Qu et al., 2012**).

In the informal water market, vendors are often blamed for supplying unsafe water (**Kjellen and McGranahan, 2006; McGranahan et al., 2017**; **Coelho et al, 2003**; **Vij et al., 2019**). But, the dependency on the informal water alternatives is poised to rise since water supply systems remain culpable to the impacts of global climate change exposure (**Rudiak-Gould, 2013**; **Liu et al., 2013b**).Because the informal water market depends on ground water sources, more issues will emerge including; groundwater over-exploitation threat (**Mumma et al., 2011**), high access tariff and most crucially, drinking water related disease burdens. This study proposes to develop an online blockchain technology-run water quality tracking system (also here known as provenance tracking system) to safeguard the welfare of the urban residents that depend on the informal water alternatives during drought times. The question is; what socio-demographic factors will influence the adoption of such a system? In answering this question, the study first presents a brief on the global climate change exposure as the main suspected instigator of drought events and how a planned adaptation using an online water quality tracking system for the informal water market can contribute to the overall water security.

1.3 Briefs on the concepts around the research problem

1.3.1 Climate change exposure phenomenon

The danger posed by exposure to the global climate change threat is a ubiquitous reality (**IPCC, 2018; Cook et al., 2013**) and is a solemn problem of our time (**Naomi, 2004**).It is attracting interest across major research disciplines (**Haied et al., 2007**).The evidence of its exposure impacts and vulnerability is overwhelming as it continues to wreak havoc on all life support systems on earth. Previous atmospheric observational studies have shown an increasing trend of both land and sea surface temperatures due to resulting warming effects (**Miranda et al., 2001**; **Ahn et al., 2012**). Actually, it is this warming effect which is the main trigger of the already being witnessed global climate and ecological changes (**Solomon et al., 2007**).

The documented climate and ecological changes by scientists are normally packaged by the media (**Boykoff et al., 2007**) for the public information (**Wilson, 1995**).It is however important to note that the earth's climate is a solar powered system (**Schaub and Turek, 2011**). And so therefore, the stability of the global climatic system is dependent on the heat balance between the solar and the earth systems. But activities such as biomass and fossil fuel burnings, both related to mankind's consumption demands (**Allen et al., 2018**) are the ones which do emit greenhouse gases including the long-lived carbon dioxide(CO_2). These greenhouse gases end up accumulating in the upper part of the troposphere and within stratosphere (**Diallo et al., 2017**; **Bodansky, 1993**). When this happens, a greenhouse effect gets forms on the earth's surface with its accompanying warming effect (**Markandya, 2017**).

The warming effect causes the alteration of the processes of the hydrological cycle (**Vörösmarty et al., 2010; Lvovich, 1979**).This ongoing uncertain state of flux must be reduced (**Perry et al., 2007**) because it is the cause of weather changes and variability in different regions of the world (**Manabe and Wetherald, 1967**). The average of these weather changes lasting for at least three decades or more is what is known as a climate change phenomenon. The average of these regional changes constitutes the global climate change (**Solomon et al., 2007**). The concern on the earth's climatic system's stability in the face of the increasing growth trajectory was first raised by the system dynamics simulator; Jay W. Forrester in the early 1970s (**Forrester, 1971a**).

He was later joined by his system's management student Dennis L. Meadows, with whom he co-authored the book "the limits to growth" (**Meadows et al., 1972**) which subsequently shaped the initial debate on the state of earth's environmental deterioration then. The legacy of their prediction is still being witnessed to date in the ongoing rapid rate of global climatic changes (**Crutzen, 2002**), which mostly affect the freshwater availability in a number of regions of the world (**Hinrichsen et al., 1999**).A scholar like Mike Hulme, has argued that the search for culpability on adverse weather events has always been on a blame narrative in most societies (**Hulme, 2014**). But today, a universal / or pan-human implication has been accepted, mainly due to high fossil fuel-based energy use by man and over-exploitation of natural resources (**Rudiak-Gould, 2014**).

The current levels of human consumption of natural resources in the words of (**Swim et al., 2011**) at a rate that out-competes self-regeneration is out-rightly counterproductive in the observation of many scientists (**Rockstrom et al., 2010; Swart et al., 2004; Jerneck et al., 2011**).Suffice to say, this intransigent behavior by man may be construed, with hindsight, to mean his intentional plan for self-annihilation (**Kilker, 2008**). But such a ludicrous plan is obviously a fictional thought (**Rull, 2009**) since man is a key member of the earth's biosphere (**Pinn, 2008**).In sum, continuing the current rate of greenhouse gas emissions is expected to yield a great variety of undesirable consequences that would increase over time (**IPCC, 2007**).

A growing population and the corresponding expected increase in consumption demand are major contributors to the impact of humans on the environment and on the rising CO_2 concentration levels in the atmosphere in particular. These negative contributions may trigger the sixth mass extinction of species (**Ceballos and Ehrlich, 2018**) especially now that some of the planetary boundary thresholds have been surpassed (**Jonas et al., 2014; Mace et al., 2014**).Mankind's consumptive appetite should have been tamed in the early 1980s (**Wackernagel et al., 2002**) by adopting sustainability traits (**Sato and Lindenmayer,2017;Bland et al.,2017a**).Environmentalists began this appeal in the 1970s but an effective response delayed to take off (**Kolbert, 2006**).

In the late 1980s however, the global community got a conviction of sorts on the impending danger of inaction. And so, several plans of actions were pipelined to contain the increasing global warming threat (**McNamara, 2014**). To start off, a research forum, Intergovernmental Panel on Climate Change (IPCC) was established 1988 which has to date compiled a number of scientific synthesis reports to aid decision making. In 1994, the United Nations Framework Convention on Climate Change (UNFCCC) international environmental treaty entered into force. The treaty was mandated to stabilize the greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system using mitigation strategies (**Kyuper et al., 2018**).

Despite this great initiative, there are still embers of haggling and arguments on who carries the blame on the cause of global warming. In other words, consensus on the burden of responsibility between poor and developed nations is yet to be reached. Poor nations feel that their contribution to the damages is insignificant yet they suffer most from the impacts (**Rudiak-Gould, 2014**). This has come about because the treaty is based on the polluter pays principle as reinforced by a common but differentiated responsibility and respective capabilities (**Zahar, 2017**). The Warsaw International Mechanism for Loss and Damages was formed to pacify the hostility in the debate. This it does by enhancing action and support, including finance, technology and capacity-building, to address loss and damage associated with the adverse effects of climate. It usually classifies losses based on extreme and slow onset events (**Escoz-Roldan et al., 2019; Simlinger and Mayer, 2018**).

A show of serious commitment by the world community to stem the global warming menace has been seen in the recent ratification of the Paris Agreement in 2015 .This latest climate agreement set up an ambitious plan to limit the land and sea surface temperature rise well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius. To this end, everyone acknowledges that the fruits from these mitigation efforts will take some time, and so the world community also adopted initiatives on adaptation to deal with the residual damages from the past GHGs emission (**Henderson et al.,2018**) as a complimentary measure to mitigation (**Fankhauser, 2017;DeNicola et al., 2015**).

Adaptation is defined as an adjustment by human and natural systems to cope with changes wrought by the anthropogenic global warming (**McCarthy et al., 2001;IPCC WGII, 2007**).Contextually and as per the Paris Agreement, adaptation strategies should be undertaken under the Sendai Framework; the successor instrument to the Hyogo Framework for Action (**Lockley et al., 2019;Aitsi-Selmi et al., 2015**).Sendai Framework is meant to help in building the resilience of nations and communities in coping with disasters (**Barnese et al., 2019**),most of which are associated with the legacies of anthropogenic global warming (**Muller and Hepburn, 2006**).

Next to the two traditional climate change management approaches, a new method of dealing with climate change using geo-engineering technology schemes has entered the scene, although it is still in embryonic stage of technological development. Geo-Engineering ideas like Earth

Radiation Management aims to modify the terrestrial albedo or to reflect the incoming shortwave solar radiation back to space (**Lockley et al, 2019**).Other techniques include; Carbon Dioxide Removal, earth cooling through artificial pumping of aerosols into the space and use of emission trading market mechanisms (**Ming et al., 2014**). But experts like (**Abas et al., 2015**), are of the view that, to decelerate climate change and develop sustainable energy resources, the world community must support the grand energy transition from fossil fuels to renewable and alternative energy resources. Efforts like this are already being tried in water treatment works (**Zerrenner, 2020**).

Without the energy transition effort as suggested above, experts have warned that the climate exposure disaster indicators like; temperature rise, heavy rainfall, drought, and sea level rise will continue to affect life on earth (**Adger, 2006**). This is so because, it has been found that, disaster events can predispose unprepared communities to shocks and stresses and for the ones with a low adaptive capacity, the effects can be adversarial (**ditto**).This is the reason as to why it has always been stated that communities from poor nations are disproportionately at risk from climate change exposure (**Christensen et al., 2013**).

In Africa for example, research has shown that rainfall patterns have become very variable (**Girvetz et al., 2019;Conway et al., 2009; ECA, 2000**).And this is particularly very noticeable in the Sub Saharan Africa region which has been characterized as being extremely susceptible to weather risk pool since most of her people are poor (**De la Fuente, 2008**).These people often suffer a double tragedy as the aid they receive to lift them out of disaster stress is also sometimes misappropriated (**Awondo, 2019**).The most common form of these disasters are as a result of hydrological hazards. In fact, statistical record has shown that up to 90% of all disasters are water-related (**Morrison et al., 2009**). East African region in particular has been found to suffer most from drought risk (**Seckler et al., 1998**).

To shore up resident communities' readiness to resiliently cope with shocks from climate exposure, efforts towards the deployment of early warning systems are being encouraged, like the case of the Horn of Africa region (**Li et al., 2016; Marigi, 2017;Okello et al., 2015;Opiyo et al.,2015 ;Ferrer et al., 2016**).The Kenya government for example, has the Kenya Meteorological Department doing a stellar service in this line by sensitizing the communities regarding the projected adverse weather events (**Shilenje and Ogwang, 2015; Abura et al., 201**7). In addition, Kenya has shown commitments to most of the international environmental treaties (**Dalla Longa and van der Zwana, 2017**) and has even mainstreamed their provisions in statute laws and development plans (**Mutimba and Wanyoike, 2013**).Regarding mitigation efforts, Kenya submitted to the UNFCCC her nationally determined contributions in 2017 (**Dalla Longa and van der Zwana, 2017**).

In terms of disaster events, Kenya has lately witnessed recurring extreme weather actions mostly in the form of droughts and floods in alternate patterns. The world community has always extended their support towards Kenyan community's recovery and reconstruction efforts from disaster loss and damages through the Green Climate Fund. It is worthy to note that, Kenya's climatic system is controlled by trade winds and other seasonal dynamic processes making it an absolute necessity to prepare communities to adapt (**Koech, 2015; Saji et al., 1999**). Because of these dynamic processes, Kenya has witnessed weather disasters whose damages are unforgettable, like the case of 1977 drought that resulted in wildlife deaths in the Nairobi National Park (**Hillman and Hillman, 1977**). Generally, Kenya's situation is a bit fragile given the fact that only 20% of her land mass is arable. Consequently, the frequent drought events often cause serious water stress to many communities (**Thomas et al., 2019**).

To build resilience of these communities to cope with the emerging climatic exposure events, forging of a collaborative partnership between science and practice is required (**Hueting, 1987**).The easiest way is to deploy a participatory action research (PAR) that creates room for the input of every stakeholder using a bottom-up approach (**Maguire, 1987**).This is especially necessary considering that developing a water resource management framework is a complex issue that requires a dynamic and iterative action sequencing processes that is able to recognize every stakeholder. In order to navigate a solution, this study proposed the adoption of a blockchain technology platform (**Sultan, 2018**) for the informal water market's quality provenance tracking.

1.3.2 Blockchain technology

Blockchain is an innovative technology, offering functionalities and attributes that enhance the transparency of communication between actors in a system, and addresses some of the barriers experienced in previous attempts to regulate actions (**Rocha and Ducasse, 2018; Gramoli, 2017**).Technically, a blockchain is a digital list of records in which transactions are recorded in 'blocks' and linked using coded passwords known in information and communication parlance as cryptography. When the blocks are filled with data, they are 'sealed' and added to the blockchain chronologically in a manner that is verifiable and cannot be altered without the consensus of a majority of participants (**Cartier et al., 2018**).To retrieve information on each chain of blocks, as **Zyskind et al. (2015**) explains in Figure 2 below, the actor's crypto-key (personal password) must be used.

Therefore, as a rule, the constituent members share out the special keys among themselves thereby granting access to respective individual data stored behind one's chain of time-stamped footprints, oops! blocks. This controlled action over the network promotes transparency in the information exchange which establishes trust within the network. Historically, blockchain technology originated in the Bitcoin crypto currency buzzing back in 2008 (**Nakamoto, 2008**; **Pilkington, 2016**). Today however, blockchain technology has since been recommended for use in many areas. In the climate change arena, article 6.2 of Paris Agreement on carbon market mechanism is expected to tap the transparency potential of blockchain technology (**Franke et al., 2020**).

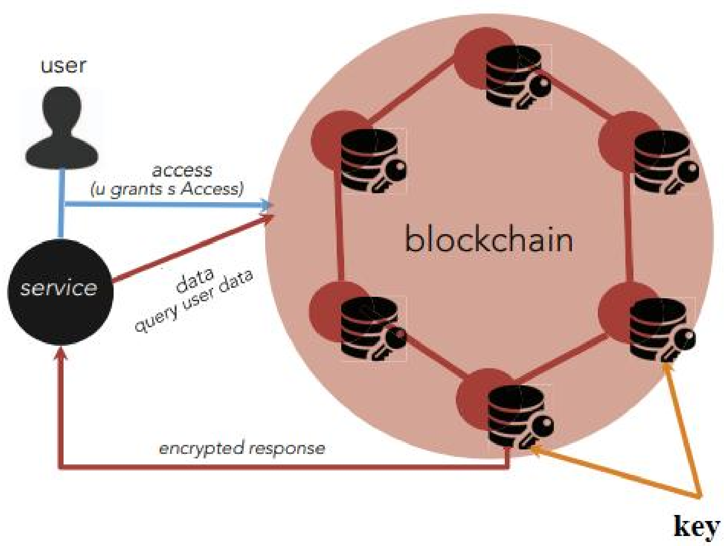


Figure 2:Overview of decentralized blockchain platform **(**Source,Zyskind et al., 2015)

Blockchain Technology has become useful in many other sectors as well (**Sikorski et al., 2017**), especially in areas where smart contracts can be effectively utilized (**Leible et al., 2019**).All these are possible because it runs on the internet technology which today is the harbinger of cyberculture allowing communities that are dispersed or virtual to freely share information (**Clarke, 1999**).Blockchain technology experts are of the view that by placing trust and authority in a decentralized network, rather than in a powerful central institution, it could reconfigure how we assign, protect and transfer many assets and services, including in the natural environment (**Pisa, 2018**).Since there is quality information asymmetry in the informal water market, Blockchain technology's transparency will make open the quality information signal exchange between the vendors and the vendees through a quality provenance tracking system. The proposed system is being equated to a quality information signaling tool in this study.

1.3.3 Product quality signaling

Quality information signaling is a very important concept in all consumer goods' market. This study sought to understand its evolution. The debate on product quality information signaling began with the characterizing of quality information sharing as a form of a "signaling act" that is meant to shape and condition the consumer purchasing decisions (**Nelson, 1970**).To a sales person, the quality information attributes must always be packaged to convince the buyer. But most of the time however, it is the sales person who asymmetrically knows the "actual" quality information of his products. This phenomenon of product quality information signaling asymmetry was first witnessed in the second hand vehicle markets in America in the early 1970s, a market which George Akerlof named as a "lemon market" (**Akerlof, 1970**).

In most instances in our everyday life, the quality information is used as a tool (**Vantamay, 2007**) to drive up sales' volumes (**Aaker and Jacobsen, 1994**).Actually, the problem is often the lack of trust which can be equated to the Byzantines general's problem (**Lamport et al., 1982**).Traders sometimes can falsify a product's quality information (**Shelley, 2012**) just to boost sales' volume. It has been stated that having in place a traceability system can help establish trust as Alphonse Bertillon did when he created a Bertillon system as a searchable database of inmates in France in the 19^{th} century from the measurement of 11 key dimensions of their bodies (**Farebrother and Champkin, 2014; Raymond, 2016**) .The system solved the prisoner escape and re-arrest problem (**Hoobler and Hoobler, 2009**).

Drawing from the foregoing elucidation, it is a matter of a necessity therefore; that even the informal water market should have a traceability system in place as part of the urban water security solution. A lot of times, water vendors are considered to be the ones holding the true quality information of the water they sell. This has brewed mistrust in the informal water market. Establishing trust in this market will allow the services of the water vendors to be formerly integrated in the urban water security solution bracket. To do this, we need to understand how the debate on water security has progressed from inception. It is rather stunning that this topic of water security has everyone's attention. Actually, everyone has an idea or two about how to improve water security (**Gleick and Palaniappan, 2010**).

1.3.4 Water security debate

From our dinner tables to the round tables of international conferences, discussions on this topic is ongoing (**Hoekstra et al., 2018**).At the onset, the supply side commanded the debate (**Vörösmarty et al., 2010**), but as urbanization trend set off on a piquing trajectory, demand management ideas started trickling in (**Sharma, 2003**).In the ensuing exchanges on the topic, it has been recognized that poor nations are ill prepared to cope with water disasters given their low adaptive capacity (**McGuigan et al., 2002**) especially as regards being vulnerable to climate change exposure impacts (**O'Connell, 2017**).It is partly for this reality that, the United Nations took up the lead role in the campaign towards the universal water access even as the current world population of 7.7 Billion is projected to hit 9.4 Billion by 2050 (**Boretti and Rosa, 2019**).

The universal water access campaign was started by the United Nations way back in 1977, when it organized the first global water conference in Mal del Plata, Argentina (**Garrick and Hall, 2014**).Stemming from the resolutions of this first meeting, the period 1981-1990 was declared as the drinking water supply and sanitation decade using the integrated water resource management approaches (**Mason and Calo, 2012**).New ideas on sustainable resource use cropped in after the publication of the Brundtland report .In the water security sector, sustainable water resource management took over as the guiding rod (**Brundtland, 1987**).In between, other scholars stressed on the urgency of investing in new water infrastructure to boost supplies (**Wutich, 2014**).

In the early 1990s, the issue of climate change emerged which demanded for a shift to dynamism and so the adaptive water resource management paradigm was crafted which also incorporated soft path approaches (**Pahl-Wostl, 2007**).In 2000, the United Nations again organized the second global water conference in the Hague, Switzerland, which came up with a raft of measures, part of which was that water was recognized as a “good” (**GWP, 2000**).From the universal discussion on water security, other scholars started off on a new urban water security knowledge domain. Here, it was recognized that the pursuit for an urban water supply security is a unique endeavor (**Salman, 2004**).This arose because, everyone appreciated that urban systems are absolute consumers (**Aboelnga et al., 2019**) and mostly rely on the hinterland ecosystem flows to survive, a dependency which can cause community conflicts (**van Ginkel et al., 2018**).For that reason, other scholars proposed the urban water supply security discussion to follow the perspective approach (**Cook and Bakker, 2012**).

The disciplinary based solutions from engineers, hydrologists and geologists have always contributed great innovations (**ditto**) backed up with problem approach solutions (**Padowski et al., 2016**).Goal oriented systems ,like the 2030 Agenda are also part of the urban water security initiatives (**Larsen et al., 2016**).There are also others like; integrated approaches (**Savacool and Savacool, 2006**),policy driven methods (**Bakker and Morriville, 2013**),dynamic planning method (**Brown et al., 2009**) and indices methods (**Arcadis, 2016**).These approaches continue to offer solutions for the elusive urban water security. It was realized that the above approaches were generally focused on the global city-wide water supply. Another clique of scholars therefore was motivated to start the debate on water quality tracking within the distribution network through the detection of accidental contaminations.

1.3.5 Drinking water quality tracking

The detection of accidental contaminations in municipal water networks using chlorine concentration was pioneered by (**Kessler et al., 1998**).The use of chlorine as a tracer in detecting contamination was found to be very novelic.Later, in the year 2000, (**Pesce and Wunderlin, 2000**) used indices method to track the quality of the Suquía River in Argentina using measured concentrations of different parameters. This Suquía River study reported that the minimal index was well correlated to the objective index, and that both water quality indices were generally correlated to the measured concentrations of different parameters. In a study similar to the

Argentinean one, (**Stambuk-Giljanovik, 2003**) compared the performance of several water quality indices for Croatian waters. The study found that modified arithmetic indices were best suited for discriminating sites according to water quality condition (good versus poor).

In Taiwan, (**Liou et al., 2004**) developed an index of river water quality to help track the scores on parameters such as; temperature, pH, toxic substances, organics (dissolved oxygen, BOD, ammonia), particulate (suspended solids, turbidity), and microorganisms (fecal coliforms) based on predetermined rating curves. A score of 100 indicates excellent water quality and a score of 0 indicates poor water quality. A part from the indices approach, other scholars in the water quality tracking genre have suggested on-line approaches. For monitoring of contaminants in-pipe water (**van der Gaag and Volz, 2008**) developed a protocol to track chlorine concentration using an online programme. In 2008, (**Hart et al., 2008**) deployed a TEVA-SPOT toolkit to track contaminants in drinking water using an early warning system design. These online tracking systems are now part of the Supervisory Control and Data Acquisition (SCADA) due to the latter's ability to quickly and effectively report unusual action or security breaches on water systems (**Amin et al., 2013**).Today water quality tracking has become basically focused on contaminants provenance to help enforce environmental regulations (**Hernandez-Ramirez et al., 2019**).

1.3.6 Existing water supply situation in Nairobi and Kenya in general

This present study down-scaled the issue of urban water supply security and focused attention on Nairobi, the capital city of the Republic of Kenya. Nairobi shares a common fate with other cities within the developing nations when it comes to water supply security since it has a daily supply gap of 200,000m^3 (**Njoroge, 2011**).As such the utility water company uses rationing program (**Mungai and Owuor, 2011**).When residents fail to receive enough water during their quota, about 25% of the households turn to groundwater sources(**Mumma et al., 2011**), mostly supplied by water vendors (**Chakava et al., 2014**).From a national perspective, Kenya's groundwater endowment is a mere 1.3% of the whole of Africa (**MacDonald et al., 2012**).And further, knowledge on Kenya's groundwater characteristics is yet to be fully developed (**Olago, 2019**), bringing into doubt if this source can be a reliable alternative .

Other scholars have also raised concern on Kenya's general water security considering the fact that, her demand for water is growing in the face of a growing climate variability threat (**Ashton and Turton, 2009; Omondi et al., 2012; Nyaoro, nd**).In 2010, the World Bank had projected that by 2050, Kenya's population would hit the 85 million mark (**Fengler, 2010**).Most of her people are youthful with a high water use needs (**Ondigo et al., 2018**). In 2017, Food and Agriculture Organization posted on its AQUASTAT online global information system on water that, per capita water availability for Kenya was only 416m^3 (**FAO, 2017**).Overall, a country with a per capita water availability which is less than 500m^3 is characterized as having an absolute water scarcity (**Falkenmark and Widstrand, 1992**).Despite these glaring risks, Kenya as a country is yet to develop enough water storage facilities as a cushion to drought risk (**Siderius et al., 2018**).

This risk is more serious in Nairobi city which depends on the Aberdare ecosystem's water for up to 95% of its water needs (**Ark, 2011**). Aberdare falls within the Upper Tana River basin which often suffers from frequent meteorological droughts (**Nyandega and Khroda, 2019**). Additionally, Ndakaini dam which stores up to 85% of Nairobi's water needs also suffers from the same drought effects (**Maseno, 2017**).In terms of pipe connections, Nairobi prides itself in posting 98% progress (**Majuru et al., 2016**), but the taps are mostly running dry (**Cudjoe and Okonski, 2006**) bringing into question the novelty of measuring and reporting the safe water access progress for a city using households' pipe connections data (**Chikozho et al., 2019**).Mostly ,the quality aspect is not considered (**Godfrey et al., 2010**).This is the reason as to why this study is proposing a rethink on water development for Nairobi city (**Hansen et al., 2012**).

Since Kenya promulgated the 2010 constitution (**Lecert et al., 2016**), the new water act 2016 has devolved the water service to county governments as stipulated (**Chepyegon and Kamiya, 2018; Khaunya et al., 2015**).As such Nairobi City County through the water company is mandated to provide water to her residents (**Ledant, 2013**).The efficiency of this service has been questioned given the intermittent flow of water to households (**Mungai and Owuor, 2011**).Nairobi City County has 17 sub regions. Out of these, Langata sub County region is the most disproportionately affected in water supply service. The residents of Langata are instead left to depend on informal water alternatives with questionable quality. These informal water alternatives are from groundwater sources. Generally, previous investigations on the potability of groundwater in Kenya have established that some zones' groundwater can sometimes be of poor quality, a clear pointer that Langata's could also be problematic.

For example, (**Olonga et al., 2015**) did an assessment of seasonal variation in physicochemical and microbiological quality of groundwater in Ruiru, Kiambu County to highlight the quality of water in the informal market. A total of 109 well water samples, 51 boreholes and 58 shallow wells were assessed during 2 different seasons, viz. dry and wet season by measuring a parameter score and comparing with both World Health Organization and Kenya Bureau of Standards. Significant difference between seasons was observed in all parameters studied except, for sodium and magnesium. In 2016, a study was conducted in Ongata Rongai town in Kajiado County to assess the seasonal variations of borehole water quality. The findings from this study showed that water quality is affected by the distance between septic tank and borehole location. The study observed that the contamination problem of borehole water in Ongata Rongai is growing and must urgently be managed to safeguard the human health and the environment (**Hinga, 2016**). A similar study was done in Tharaka Nithi County which reported that dry spell periods contribute substantially to the deterioration of ground water quality in the area (**Mbura, 2018**).

The Ruiru, Ongata Rongai and the Tharaka Nithi studies on borehole water quality serve as a representative of the situation within Langata Sub County's setting. The studies used the on-site measurement approach to report on the water quality stati. The present study however proposes to use a combination of water quality index approach and the on-line tracking system. Water Quality Indices (WQIs) are aggregate indicators of water quality that bring together otherwise complex water quality data into a unit-less value that can be quickly and easily communicated to its intended audience without getting mired in a technical lingo. These indices have been used to provide comparisons of water quality stati for different locations and at different times, which is helpful in prioritizing management efforts. These WQIs can also be used as tools to predict potentially harmful conditions especially of a contaminant intrusion into a water system (**Achieng et al., 2019**). They are also potentially useful in assessing and communicating overall impacts of existing, planned, or proposed water quality interventions and management decisions (**Gitau et al., 2016**).

On the other hand, the on-line water quality tracking system is a comprehensively developed drinking water contamination warning system under a water security initiative. As is known, water security is an increasing concern for utility managers, and protecting the water distribution system from contamination remains a top priority concern (**Sela and Ostfeld, 2013**). The water contamination warning system includes the installation of an Online Water Quality Monitoring (OWQM) reporting system to detect contaminant intrusion concerns. The first step involves the creation of an analytical model to define a design basis threat (contaminant, location of contamination, time of contamination, contaminant properties, size of affected population, sensor set size, and optimization objective) that would be used in the simulations (**Bartrand et al., 2010**).

It should be noted that this study is limited to the software development and its public adoption only. The development of the hardware part may follow the low-cost prototype by (**Lambrou et al., 2014**) in a separate study. Finally, the system will admit users of low-cost phones. The self-operating capability of the system through use of backend programmed language, makes the real-time quality tracking more advantageous over other available products that have been created for water distribution systems or large water bodies to monitor contamination attempts (**Kumpel et al., 2015**).The system is accurate, reliable and has a short processing time.

It has been argued that a blockchain operated system like the one proposed in this study could enable a step-change in the optimization of distributed water management. Real-time transparent data on water quality and quantity can inform conservation, dynamic pricing and trading, and spot illegal extraction or water quality tampering (**Le Sève et al., 2018**).In order to gain from the foregoing inspiration , the study will seek for the adoption of the developed water quality tracking system from among Langata Sub County households. The study intends to deploy a non-market tool; a discrete choice experiment survey model to assess the choice preferences of the stakeholders from a bundle of choice options (**He et al., 2014**).

1.4 Problem statement

From the foregoing, it is evident that the existing studies on Nairobi city's water supply security have mostly deployed a problem-perspective approach. The resulting solutions have however not facilitated the tracking of the quality of the informal water alternatives peddled by vendors, more especially in Langata sub County. And this lack of a system for quality traceability exists even though there is a growing dependence on the informal water alternatives by households in most neighbourhoods within most cities of the developing nations. As currently set up, the quality information in the informal water markets is only asymmetrically known by the vendors. This means that the customers have no other way to verify the quality beforehand except to believe in the verbal assurances. This biased quality information signalling has created a condition of mistrust in the market, but whose implications transcend both human and natural environment systems. To help establish trust, this study proposes a Blockchain Technology-run water quality provenance tracking system for public adoption.

1.5 Research questions

The global climate change exposure impact has brought an unprecedented vulnerability on the households of Langata Sub County due to recurrent drought induced water shortage problems. As a result, they are forced to rely on the informal water alternatives whose quality they cannot independently verify. This study intends to fill this gap of lack of quality traceability by answering the following research questions.

i) What is the share of drought years over Langata during the period1957-2013?

ii) What is the implication of drought on groundwater levels in Langata within the same period?

iii) What is the influence of drought events on ground water quality in Langata?

iv) Are there greater costs to borehole-sourced water alternatives than to solving the drought or rather the below normal rainfall induced water shortage problem in terms of;

(a) the computed water quality index (WQI) value and

(b) the affordability rating?

v) Can an android based water quality tracking system (WQTS) running on a blockchain technology platform establish trust in the informal water market of Langata? And secondly, what key factors can determine the adoption of the system by residents of Langata?

1.6 Objectives

The overall objective of the study is to develop a blockchain provenance-based water quality tracking system and determine the main socio-demographic factor for its adoption.

1.6.1 Specific objectives

i) To determine the distribution of drought years over Langata sub County for the period 1957 and 2013.

ii) To assess drought influence on the suspected: groundwater depletion threat and the groundwater quality decline.

iii) To assess the households' water access cost as read from the computed geo-chemical WQI grade for the area and the computed vendor water access cost burden.

iv) To develop a prototype of a water quality tracking system using an android technology software development kit.

v) To identify and document the main socio-demographic factor that determine the public adoption of a blockchain provenance-based water quality tracking system

1.7 Justification and significance of the study

The discourse on the race towards the global universal water access is today on its fifth decade if we begin our count from the first global water conference that was convened by the United Nations in Mar del Plata, Argentina, between 14th -25th March,1977 (**Stein, 1977**). Despite the crafting of numerous successive plans of action from several follow up meetings by leaders across the social spectrum over the same issue, many people, world over, continue to suffer from lack of access to safe and adequate water (**Pereira et al., 2002**). Their suffering is worsened by the affront on the finite freshwater resource base by the reducing and mostly erratic rainfall patterns. The increasing challenge of drought induced water shortage in many regions of the world is today a major a contributor to the growing water crisis in the world.

The Horn of Africa region, where Kenya is situated, is particularly notorious in this respect. It is this notoriety, which has caused the residents of Nairobi, the capital city of Kenya, to endure with a water shortage of an estimated 200,000m3 per day (**Njoroge, 2011**). Langata sub County neighborhood, in particular, is disproportionately affected by the persistent dry taps in their homes. To survive, these households rely on the supplication from the informal water alternatives. This informal water alternative supply service exists either as an uncoordinated self-supply from personal boreholes or as vendor delivered water from commercial boreholes, but whose quality information is currently asymmetric, that is, only known by sellers.

Previous studies by **Chakava et al., 2014**) found that borehole-sourced drinking water represents an expensive but ‘least bad’ coping strategy with a mix of outcomes. According to this study, on the one hand, borehole water delivers reliability and accessibility to all consumers, while on the other hand, the same consumers are forced to live with high prices imposed on them, adverse environmental impacts arising from the groundwater level decline and some form of biophysical to geo-chemical quality concerns. Some other pioneer studies in water supply security for Nairobi city have focused on increasing the supply regimes either as a dedicated pro-poor water supply distribution, similar to the one explained by (**Boakye-Ansah et al., 2019**) or as a general water supply infrastructure network expansion (**Ledant, 2013**).

Currently, the adopted 1 billion USD Greater Nairobi City County Water Master Plan covering a 24-year expansion blueprint (2011 - 2035) is a crucial hope carrier for the city residents. It plans to inject an additional 750,000m^3 of water per day by the completion date, beginning with the Northern Collector Tunnel Phase 1 project. This plan will obviously bridge the ever-widening city’s water supply-demand gap. Unfortunately, it appears to be based on a stationary rainfall replenishing pattern. The reality of climate variability over the water source catchment basin may hamper the realization of the plan. This means that the dependence on informal water alternatives by the starved households will continue (**Hailu et al., 2011**). The only way is to improve the operational framework of the informal water market by making it possible to track and trace the quality of the informal water alternatives. This is the focus of this study.

In Langata, the present study area, water vendors serve both ends of the social divide, from the low-income groups to others in the higher earning scales. Both sets of consumers, however, face the same challenges as identified in the study by **Chakava et al., 2014**). It is therefore important to formulate a strategy to make informal water market quality tracing and tracking a possibility. This is an important feature in the drinking water distribution landscape, but one which is yet to be recognized in the informal water market’s space. The study assumes that, once the informal water alternatives quality is made traceable, then the crucial issue of groundwater environmental protection will have been sorted by the same stroke. In many cities of the developing nations, the efficiency of the water supply distribution system is often poor. This is just a pointer that quality monitoring and tracking is still a remote endeavor even for the formal water market. The findings of this study will therefore present a very important stepping stone to completing the circuit of the search for urban water supply security.

This will happen because, one, the online quality tracking system will help to detect in-pipe contaminants so long as the system algorithms embedded in sensor nodes are set to analyze and post the same. Two, since this study has launched itself from the informal water market, the online tracking of water quality will establish trust thereby giving the customers a chance not to invest in further water quality improvements or purchase of bottled water. This will contribute to sorting the water access affordability problem. Finally, but most importantly, the present study findings will allow for the integration of informal water alternatives as part of the overall urban water supply security solution. The results of this study will enable the informal water alternative users to be aware of the levels of geo-chemical property of the groundwater from each source point. This will lower their exposure to the hazards associated with over-concentrations. Additionally, the results will be useful to Nairobi City County for sensitization on ground water quality for every user to adhere to the standards (**KeBS, 2010**). This will promote safe water access in Nairobi.

1.8 Scope and limitations

This study is limited to developing an online quality tracking system for the informal water alternatives and presenting the same for public adoption. The hardware part of the water quality tracking system may be developed in a separate study using the low-cost prototype developed by (**Lambrou et al., 2014**). The primary data collection is from the Langata sub County households. And the water quality index (WQI) grading matrix for the area is developed from the 8 geo-chemical parameters extracted from borehole files for the area provided by Water Resources Authority office.

1.9 Thesis organization

This thesis report is split into five chapters.Chapter 1presents the study's motivation, the contextual quality problem of the informal water alternatives, the brief on the global climate change exposure and its implications on the global water security debate. It has traced the drinking water quality surveillance and monitoring genre from the past and compared it with the current online drinking water quality tracking systems. Further, it has outlined the research problem including the presentation of the research questions and the corresponding objectives as the guiding map book of the study process. It ends with the presentation of the study's justification, scope and chapter summaries.

Chapter 2presents the build-up of the theoretical construct and conceptual framework that guided the process leading to the adoption of the blockchain technology driven water quality provenance tracking system. It begins by presenting general climate change risk information priming. This is followed by the profiling of the evolution of drought detection methods. It further discusses the modes through which drought risk propagates via the assessments of groundwater depletion syndrome, groundwater potability and informal water supply service cost implications. For the value orientation, the chapter continues by highlighting climate change risk management technology, blockchain technology and its applicability in water sector. In addition, it chronicles the origin of android application development and how it has been applied in the water sector. It further explains the theory of protection motivation which anchors discrete choice experiment survey for the solicitation of the willingness to pay (WTP) for the communal water access system using quality tracking system. The section ends with the sketching of the water security debate propagation.

Chapter 3 presents the specific methods used in the deployment of the above conceptual framework to facilitate the realization of the study's; overall and specific objectives. It begins by presenting the information on the study site. Next, it outlines the analytical and participatory methods corresponding to each respective objective. The analytical approach was applied; to reconstruct the historical drought risk profile, to detect the area's groundwater resource depletion threat and to evaluate the potability of the area's groundwater resources. On the other hand, the participatory method was used to assess the cost implication of coping with the vendor water and to identify the major socio-demographic factors that influenced the adoption of the WQTS; a fact which also reciprocally indicated, the willingness to pay (WTP) for the shift to the new system of communal water access. For each objective, the specific detail on; methodology, sampling, data collection and data analysis technique is presented.

Chapter 4 presents the results and discussions on the six themes of this study. The first theme is the reconstructed drought history of Langata during the period 1957-2013 to establish the drought exposure risk. The next theme discussed is that of Langata's groundwater depletion threat. This is followed by Langata groundwater resource's potability assessment theme. This is followed by the development of the "maji-safi" app using the Android technology toolkit. The section ends with results of the household survey to establish affordability of the vendor water and the identification of the major socio-demographic factors that determined the adoption of the WQTS as a new coping method.

Chapter 5 presents the conclusions and recommendation of the study. It begins by presenting the key findings as per each specific objective and the corresponding conclusions .The section ends with the listing of some recommendations for further study on opportunities wrought by climate variability and change, especially with regards to drought exposure hazard's impact on the area's water supply security.

CHAPTER TWO: LITRATURE REVIEW

2 Introduction

This section presents the build-up of the theoretical construct and conceptual framework that guided the process leading to the adoption of the blockchain technology driven water quality provenance tracking system. It begins by presenting the general climate change risk information priming. This is followed by the profiling of the evolution of drought detection methods. It further discusses the modes through which drought risk propagates via the assessments of; groundwater depletion syndrome, groundwater potability and informal water supply service cost implications. For the value orientation, the chapter continues by highlighting on; climate change risk management technology, blockchain technology and its applicability in water sector. In addition, it chronicles the origin of android application development and how it has been applied in the water sector. It further explains the theory of protection motivation which anchors discrete choice experiment survey for the solicitation of the willingness to pay (WTP) for the communal water access system using quality tracking system. The section ends with the sketching of the water security debate propagation.

2.1 Climate variability and change

The combined action of increased climate variability and frequency of extreme weather events is a complexity that adds onto the non-climate related drivers of modern-day vulnerability of the coupled-human-environmental systems, particularly within the African continent (**Hulme et al., 2001**). The contribution of the IPCC-lead Working Groups through their compilation of series of scientific Assessment Reports (AR5 for instance) on global warming is a good step in the risk information priming domain serving to ready the present human society on appropriate responses (**Allen et al., 2019**). The reports are the synthesis of evidences' data from; the direct measurements of rising surface air temperatures and surface ocean temperatures. And from observations such as; the increase in average global sea levels, retreating glaciers and alterations in several bio-physical systems. They (scientists) concur that, most of the global warming in recent past decades; can be attributed to human activities (**IPCC, 2001**). Freshwater ecosystems are very vulnerable to the climatic changes, especially the availability aspect, during drought years (**Woodward et al., 2010; Gleeson et al., 2019**).

Drought exposure hazard is a growing case of concern, more so in the Sub Saharan African region (**Ford et al., 2014**). For instance, in Kenya, drought management and resilience building techniques in the water sector have attracted a lot of interest, more so, the early warning and monitoring approaches (**Turman-Bryant et al., 2019**). A significant number of studies have emphasized on the need for evidence-based adaptation planning (**Kwena et al., 2014**). This approach is suited for Kenya because of her location within the Horn of Africa as the location factor, predisposes her to a perennial drought risk cycles whose footprint is full of a long list of devastating losses within households (**IFRC, 2011**). In trying to answer the often-asked question, *"what role did climate change play?"* after every extreme drought event, this thesis is a compilation of lessons drawn from the activities of working with the Langata sub County community whose focus was on; rebuilding past drought risk information. This was to help the households to jointly make decisions on how to manage future similar or more extreme risks as was earlier advised by (**Otto et al., 2018**).

2.2 Evolution of drought risk detection methods

Drought risk is basically a phenomenon characterized by below normal rainfall in a place. Consensus on the actual meaning of drought is yet to be found, but pioneer investigators agree that drought events differ in character, which therefore, necessitates the estimation of hazard and vulnerability, to inform risk management decisions (**Wilhite et al., 2014**). In the water sector, we must credit it to the Massachusetts 1962-1966 drought impact study on the municipal water supply which laid the foundation pillars in this area (**Russell et al., 1970**). In terms of the overall global drought risk spectrum for the period 1900-2013, the continent of Africa's share was reported to be a whole 45% of the 642 recorded events (**Masih et al., 2014**).

Most recently, a study which covered the period 2006 to 2015 by (**Masinde et al.,2018**), found that, the Sub Saharan African region's drought risk share was about 50% of the world drought episodes. And shockingly, the Horn of Africa is classified as being drought prone, particularly the East African region where recent records have shown a reducing trend in rainfall patterns causing frequent prolonged water shortage challenges (**Wandiga, 2015**). Kenya is acutely exposed to drought risk according to (**Uhe et al., 2017**), with the frequency becoming a norm for every year in the words of (**Nkedianye et al., 2011**) and others. In the last few years, the government of Kenya has been declaring drought emergency as national disasters, especially to heighten disaster risk response appeals to local and international partners. This happens because, 80% of Kenya's land mass falls under arid and semi-arid zone.

Drought management, it is claimed, requires evidence-based decisions (**Balint et al., 2013**). And so, for a long time, two methods that traditionally have been used to develop the evidence are; the indices based on water balance and the statistical indices based on time series. The water balance approach is known to require application of a number of climatic and physical variables at a given time and space to ascertain water deficit of the crop; Palmer Drought Severity Index (PDSI),Palmer Hydrological Drought Index (PHDI),Palmer Z-index (PZI),Crop Moisture Index (CMI),Surface Water Supply Index (SWSI) and the Reclamation Drought Index (RDI).On the other hand the statistical indices are based on one or two parameters; mostly rainfall and a few times , the temperature. In this category the most common indices are; Percent Normal Drought Index (PNDI), Standardized Precipitation Index (SPI), the Precipitation Decile Index (PDI) and the Weighted Anomaly Standardized Precipitation (WASP).

For data scarce regions like the Horn of Africa, some scholars have developed Combined Drought Index method which is adaptable to various drought monitoring regimes. The disadvantages of the standalone methods are a barrier to their effectiveness, for instance, the water balance methods are known to be far too complex and require many data sets, which mostly are not available. Secondly, the statistical approaches are mostly dependent on one or two parameters hence leaving out numerous droughts contributing factors. In addition, they do ignore elements like; the persistence of the stress periods. They also depend on data observed continuously for a long period, a situation which has been found many times to be lacking. Because of these weaknesses, scholars like (**Bayissa, 2018**) strongly recommended the use of the Combined Drought Index computation that takes care of the six drought creating parameters; rainfall deficits, persistence of dryness, temperature excesses, persistence of high temperatures, soil moisture deficit and persistence of dry soil condition.

Combined Drought Index (CDI) can be based on low data as 10-day observations, monthly records, seasonal, annual to longer period's data records. It is also applicable in data scarce situations in addition to being flexible in adjustments of outputs. Calculating CDI simply begins with the computation of Precipitation Drought Index (PDI).Then the computation of Temperature Drought Index (TDI) followed by Vegetation Drought Index (VDI) as a substitute for Soil Moisture Drought Index.Finally,the combination of the three gives the indices range of >1.0 (no drought) to < 0.4 (extreme drought) by assigning weights for each index subjectively. For example, rainfall may receive the largest weight at 50% using PDI.The remaining 50% can be assigned equally between TDI and VDI according to (**Balint et al., 2013**) as proposed for Kenya's drought monitoring.

In this study however, the data available was only the meteorological information. Consequently, and in order to develop the evidence for decision making on drought hazard management, the index method was used for the quantification of drought character in the study site (**Zargar et al., 2011**). An index formula is a programmed continuous mathematical function that is able to analyze rainfall variables (**Giddings et al., 2005**).More specifically, Standard Precipitation Index (SPI) proposed by (**McKee et al., 1993**) which has had widespread deployment in many similar studies was chosen in this study. This SPI formula was adopted by the World Meteorological Organization in 2009. And it later received global endorsement in 2011 (**Hayes et al., 2011**). In terms of application, SPI has been used in many places to classify drought types; meteorological, hydrological, agricultural and groundwater (**Hussain et al., 2018**).

Drought period reconstruction in time steps and spatial expanse is known to visualize the picture of vulnerability in water resources management (**Komoscu, 1999**). This helps to measure the; duration, intensity and frequency in time scales. While the spatial extent on the other hand, is inferred from the rainfall data collections' areal coverage. This study followed the examples of related studies on coping with drought in Kenya and India as reported by (**Nguimalet, 2018** and **Raghupathi, 2003**). Drought induced water shortage has always attracted the use of groundwater; a resource which remains vulnerable to climate change dynamics. Due to groundwater resource's vulnerability to over-use, assessment of the same, becomes an immediate necessity.

2.3 Assessment of groundwater-grab "syndrome"

Groundwater is a very important natural resource. It is a source of water for sectors such as; industrial, domestic, agricultural and the natural environment. But the uncoordinated exploitation of groundwater aquifers by human driven developmental demands remains the greatest depletion threat (**Konikow and Kendy, 2005**). The impact of climate change exacerbates this depletion threat further in many places (**Kumar, 2012**). This threat has attracted the attention of world leaders with the major concern being; the resulting implications on the healthiness of groundwater environment at a given aquifer's spatial expanse. At the start of the 19th century, debate on sustainable use of groundwater resource began and piqued in the 1970s with a focus on the cost of pumping. The transboundary aquifers, arid and semi-arid regions' aquifers have prominently featured in most of the discussions. But the hydro-myth in each society has always added some confusion on how to responsibly control the use of this resource.

The confusion has centered on the lack of consensus on what constitutes "groundwater resource over-exploitation". To most of the scholars, "groundwater resource over-exploitation" is when the abstraction is greater or close to an aquifer recharge rate. The safe yield which is defined as the groundwater withdrawal that does not lead to undesirable effects such as; reservoir exhaustion, excessive pumping cost or water quality deterioration has been suggested as the most sustainable approach (**Caro and Eagleson, 1981**). The continent of Africa which has a variable climate is very vulnerable to groundwater over-exploitation (**Xu and Braune, 2010**). In Kenya, groundwater over-exploitation is a national problem. Between 1991 and 2004, Kenya's borehole numbers increased by 51%; that is, from 9453 to 14,260, translating to 344 boreholes per year (**Pavelic et al., 2012**). The residents of Nairobi, Kenya's capital city, are known to rely on groundwater supplication during drought years. But several studies have indicated a decline in groundwater rest levels here which are being considered as a depletion threat signal (**Simiyu and Dulo, 2015**).

From the foregoing, it is notable that, groundwater over-exploitation threat is an ongoing global problem which has attracted many detection studies. The pioneer investigators on detection of groundwater over-exploitation "syndrome" have successfully used water table fluctuation; commonly known as water balance method to assess the impact of sustained abstraction on aquifer recharge (**Shamsudduha et al., 2011**). Other studies have used methods such as; literature reviews to profile general trends in groundwater-hit water levels within an area. Similarly, scenario analyses based on demand projections have also been tried.

The most preferred approach however, in many places, is the crafting of new policy tools to enforce expert advice from engineers and geologists (**Vrba and Zaporozec, 1994**). For the present study site, the focus was to establish if there existed a groundwater-grab "syndrome" from the relationship between the area's drought information; extracted from time series mean annual rainfall and the historical borehole commissioning data. As groundwater resource has become an instant source of alternative water supply systems, the consumers could perhaps be getting exposed to poor quality. This presents a need to assess the general potability of the groundwater resource from target area.

2.4 Assessment of the potability of groundwater resource

Drinking water quality measurement and control is an essential safety kit for the coupled human-natural environment system. Poor water quality is a threat to all life forms, and that is the reason why the statement, "water is life" was coined. The quest to monitor and control drinking water purity was first discussed by (**Frost , 1915**). Developing countries are the most at risk of poor-quality drinking water, since most of their citizens do access water through non-improved sources. It is reported that, up to 80% of diseases affecting their citizens, mostly children below age five, are waterborne. For example, 21% of communicable diseases in India are associated with groundwater use; a water source that is often prone to contamination, but which serves nearly 85% of the Indian population (**Iyer et al., 2014**). This case parallels the situation in the Sub Saharan Africa where groundwater resource is heavily relied on, especially in the cities (**Lapworth et al., 2017**). In Kenya, fluoridated groundwater is a source of dental health risk (**Mbithi et al., 2017**). This situation is gravest for the Nairobi city residents who are known to rely on groundwater sources supplied by the informal water vendors during drought periods (**Coetsiers et al., 2008**).

Water quality measurement is a social accounting method for evaluating water resource's use-characteristics. Water quality assessment is a relative comparison of measurable; physical, chemical and biological parameters of a water sample against expected safe levels for specific usage to satisfy a welfare need of both human and natural systems (**Dinius, 1972**). The potability of a water source is defined by it's; taste, odour, colour and the abundance of organic to inorganic substances. Standards of ambient water at source may require to be improved through treatment to qualify it for human use. Water quality standards keep changing as the human understanding of the effects of substances released to the environment grows. The measurement is realized through a structured framework of quality assessment activities in which the bio-physical / chemical parameters are evaluated against a known set standard and their levels monitored as time passes by (**Bartram and Balance, 1996**). Water quality control is a concern of all world leaders and is a mandatory service by all nations to their respective citizens (**UNEP, 2007**).

Since for a long time, the language used in water quality measurements has been a little bit complicated to the lay population, water quality index computation method (WQI) was adopted in the mid-19th century to simplify quality reports' technical lingo (**Abbasi, 1999**). Beginning from the pioneering application of WQI method by Horton in 1965 in the United States of America, its use has spread everywhere (**Horton, 1965**). Horton Index (HI) was used to produce atlas of water quality maps as well as to categorize water quality for different usages (**Shweta et al., 2013**).

For the current study area, like in most other places, the municipal water supply system has a very robust water quality control system. Since many households in Langata sub county turn always to groundwater when the municipal taps run dry, it is still challenging for them to trust the quality of the water from such sources. That is the reason, this study followed the procedure presented by (**Soltan, 1999**) for evaluation of groundwater quality to assess the potability of the groundwater in the area; a method which was again reinforced with the recent suggestion by (**Shah and Joshi, 2015**).The dependence on the informal water supply service has cost implications on the customers, which also require assessment.

2.5 Assessment of the cost implications of informal water supply service

Urban water supply service reliability is hinged on its distributive flow efficiency. And the reliability of a piped water system's flow is metrically achieved if the water reaches the consumer in the desired quantity at the right; pressure, time, quality and price (**Pentecost, 1974**). For a long time, the water supply service was believed to be a sole duty of engineers, who were meant to identify a water source, a treatment site and a transmission pathway to the targeted consumer (**Kirmeyer et al., 2000**).

In the olden days, rainfall system was taken by these engineers to be stationary; a position which has been disputed in a study by (**Milly et al., 2008**). Climate change impact on water resources has forced modern day urban households to consider other alternative sources of water especially from water vendors to cope (**Boehlert et al., 2015**). This coping practice is predominantly found in cities of the Global South. But the practice is, however, not affordable to a significant number of urban households (**Molinos-Senante and Donoso, 2016**). Due to this, research interest on water supply service improvement has been growing.

Many times, the studies on this area have always followed the path of massive engineering solutions to expand supply infrastructure; being the known conventional method globally. Today, however, the combined approach of conventional and unconventional alternatives is considered collectively. But this integrative path can only succeed if the water is equitably made affordable to all, even if the source is from the informal sector. A study conducted in Kenya for example, found that only about 50% of Nairobi city households receive conventional municipal water.

The rest; mostly poor households in Nairobi, depend on informal water alternatives, for which they spend up to 11% of their monthly income (**Ledant, 2013**). Further, studies on water supply service affordability have mostly focused on cost recovery of the investment cost. This has been pegged on sustaining both operations and expansions, so that the system is self-sufficient. By the time this cost recovery approach was found not to be working well, the World Bank came up with another formula for pricing water known as; the increasing block tariff (IBT) as a provider of equity (**Bernajee et al., 2010**).

Later, IBT approach was again discovered to have a certain major weakness. Basically, it does not consider the fact that, poor households share with each other water from a single water meter. With this practice, the one meter could serve more than ten families at times. So, the consumed volume ends up being too large per month. The registered meter owner, therefore, pays very expensively. To counter this weakness, the second approach known as the uniform price with rebate (UTR) was proposed. But a notable common challenge with both of these two approaches to solve water affordability remains, that; they both rely on piped water supply systems (**Le Blanc, 2008**), yet most urban households in poor countries today, rely on the vendor water supply systems.

The vendor water supply services are known to cost many times more (**Nyarko et al., 2008**). Several studies on the implications of unreliable urban water supplies have also suggested for the control of the informal water markets through tariff setting. Other studies in this area using household survey methods have assessed the quality implications in terms of health care costs. In most of the studies, cost burden has been singled out as a common problem, like the one reported for Kenya's major towns by (**Sunman, 2017**). In Langata sub County, many households depend on vendor water supplies, but little if any, had been done to assess the cost implications, a gap that this study has filled.

2.6 Technology for tracking water quality

Water quality sustains natural systems and human activities. As the Earth's population and the resulting anthropogenic footprint and impact on climate change increase, the need to maintain and protect freshwater resources gains importance. Human wellbeing is dependent on water and the ecosystem that it supports. The delivery, timing, storage and quality of water influences people's health. On a larger scale at the watershed level, the hydrologic information system consisting of the physical infrastructure and human resources that must be established to measure, process, store and share the interlinked data through a monitoring network for both surface and groundwater systems. The internet technology has allowed for the use of smart solutions for water quality monitoring, which is the collection of information at set locations at regular intervals to highlight water conditions say for lakes, sea water, rivers or groundwater systems based on certain agreed parameters.

Nowadays, climate change is one of the most prominent challenges facing humanity especially among the resource-dependent citizens from poor nations, who however, are less equipped to cope with the resulting adverse impacts. When surface temperatures are altered, for example, the ambient temperature also changes in water bodies thereby lowering levels of dissolved oxygen in water and or modifying parameter values (physico-chemical ,micro pollutants and biological) hence affecting both the aquatic and human life. The International Initiative on Water Quality (IIWQ) has since the Paris 2015 COP 21 meeting been discussing the influence of climate change on water quality with a view to devising adaptation measures to deal with the challenge. Water quality experts are rooting for the integration of information and communication technology in this endevor.Traditionally,water quality data collection has followed the menial field sampling methods, but in the recent times, real time sensor monitoring has been adopted to increase efficiency.However,the smart sensor systems only can work with limited parameters such as water level,velocity,temperature,conductivity,dissolved oxygen and pH.Information

Communication Technology experts are tinkering to advance the system to cover other parameters and that is why technology transfer aspect was discussed in the Paris climate forum.

Technology transfer and adoption was suggested as an enabler that was meant to increase poor people's response resilience in areas like; water resource management (**Tessa and Kurukulasuriya, 2010**). Besides the initiatives on building of coping capacity of the vulnerable communities, in parallel, mitigation efforts were put in place. The evidence of these latter efforts is seen in the race to fulfill the carbon budget towards the 1.5^{o}c safe global warming limit as per the Paris Agreement. Specifically, state parties to the agreement committed to work through the Internally Nationally Determined Contributions (INDCs) aimed at lowering their individual carbon emissions. And these efforts are being augmented by carbon sequestration geo-engineering technology supported actions such as; Solar Radiation Management (SRM), Carbon Dioxide Removal (CDR) and emission trading market mechanisms where blockchain technology has established an immediate application through smart contract transactions (**Lockley et al., 2019**).

In the drinking water quality tracking problem, wireless communication developments are creating new sensor capabilities especially under the deployment of Internet of Things (IoT) to reap from the automation potential of industry 4.0.This was debated from the view point that about 40% of deaths are caused by contaminated water in the world. Supplying purified drinking water for the people in cities and villages require round the clock water quality monitoring. Interestingly, the use of blockchain technology fits in here. According to the UNFCCC, blockchain technology can help manage the climate crisis in water sector by improving accountability, transparency and efficiency in all transactions (**Chen, 2018**). One of the climate crises of our time is the drought induced freshwater shortage which has exposed nearly 4 billion people to a severe water scarcity at the global level (**Mekonnen and Hoekstra, 2016**). That is why the focus on sustainable water resource management has shifted to efficient use, where blockchain technology platform has been suggested (**Lin et al., 2018**).

In cities of developing nations and in some parts of the Global North, informal water alternatives form very crucial supplementary sources of water for millions of households facing municipal water supply intermittency (**Wutich et al., 2016**).In both scenarios, the major driving force in the use of informal water alternatives is the mistrust in quality of the sources of water. For some developed nations, tap water quality is not trusted, and so consumers prefer water from water vending machines, like the case reported among families in South Texas (**Jepson and Brown, 2014**).In developing nations on the other hand, the public tap water system is unreliable, forcing residents to rely on vendor supplies, even though, they rarely trust their quality. These experiences reveal the urgency of the need to have a system for water quality verification by consumers. For that reason, this study proposed use of blockchain provenance quality tracking system to establish trust in the quality of the informal water alternatives.

This decision was motivated by the fact that, blockchain is a user-friendly digital ledger for people who wish to share and agree on the same information, but who do not want to rely on a centralized authority (**Chen, 2018**).There are however pertinent explanations that communities ought to understand to boost their value orientation. As is known that environmental valuation has had no known market price definable by Marxian value theorem (**Huber, 2016**), collaborative work is the best pathway to designing the most adaptive coping system. To achieve this, this study chose to facilitate the understanding of some basic concepts like; technology, provenance and blockchain. This was followed by the profiling of the origin of android application used in mobile phone devices. Finally, the explanation of theory of protection motivation and its reinforcement in this study by discrete choice model is briefly discussed.

2.6.1 Technology

The term "technology" is defined as a functional system or an artifact made from an engineering knowledge to perform a role in any organized human social system. The application of technology in the human production processes for example, is said to be as old as the existence of mankind. Further, it has been noted that, the improvement in technology types, has progressed with the growth in science and Industrial Revolution-driven capitalism. But importantly, a significant number of technologists agree that the adoption and diffusion of a given technology does play a crucial role in the entrenchment of innovative strategy to improve performance in the targeted sector (**Markard and Truffer, 2008**).

Pioneer sociologist, Gabriel Tarde through his book "laws of nature", erected the foundation pillar of technology adoption studies. He explained that technology adoption or technology acceptance is the acquisition by an individual or a community of a piece of an artifact followed by its deployment to undertake a role in a given human social system (**Tarde, 1890**).The work influenced his colleague, Earl Pemberton, who used his approach to profile the diffusion of new cultures across communities (**Pemberton, 1936**).

Later, other scholars extended the work in different sectors. For instance, in the adoption of hybrid corn seed in Iowa as reported by (**Ryan and Gross, 1943**) and the sketching of the history of economic analysis by (**Schumpeter, 1954**).These early work fertilized the abstraction of the first adoption model by (**Rogers, 1962**) which, he named as ; technology adoption model (TAM).Progressively, TAM has found widespread application in countless number of studies across the world (**Lai, 2017**).And today, TAM also exists as a unified model version (**Venkatesh et al., 2012**).

2.6.2 Provenance

The word "provenance" is from the French word "provenir", which means, to come from. In the simplest form, provenance is the documentation of the origin details of a material whose use value in a typical human social system attracts some investigative interest. For example, the documentation of authorship details of a given work of art, is its provenance metadata (**Bidwell, 1996**).Today, it is common for a random shopper of a consumer product to confirm and verify crucial packaging details such as; the name of the manufacturer, the expiry date and its constituent ingredients , which altogether are the product's provenance information.

Provenance recording first emerged in the works of art like paintings and later got deployed in the recording of workflow schedules in the scientific experimental laboratories (**Davidson and Freire, 2008**).Today ,it is very popular in food industry for safety assurance (**Moreau and Groth, 2013**).Given that informal water market is characterized as having a "byzantine general's problem", meaning distrust in quality, provenance tracking of quality information of water sources is very much needed (**Lamport et al., 1982**).This was proposed to be realized through blockchain technology.

2.6.3 Blockchain technology

Blockchain is the newest technology system that runs on the backbone of internet technology as a distributed and immutable ledger in which the digital events are shared to all constituents through peer to peer network. Its origin is traced to Satoshi Nakamoto, whose identity remains anonymous to date, when he released a paper describing peer-to-peer version of crypto currency going by the name, Bitcoin in 2008. Blockchain technology is the reigning revolutionary big thing in the technology innovation highway credited for providing; data security and anonymity. Its ability to preserve data integrity without third party intermediation is unparalleled. Many modern-day technologists praise its ability to provide instantaneous and less costly transactions. In a basic sense, blockchain is a networked database entity with a sequenced chain of blocks, with each block storying information of the network activity as new blocks are added to the chain according to (**Risius and Spohrer, 2017**). Every piece of information in the blockchain remains accessible to authorized network constituents who in turn can add data to it through a verifiable transaction in the system.

Once the data is accepted consensually by a majority vote of the membership set, it remains permanently immutable according to (**Elsden et al., 2018**). The data history of the network is visible to all nodes thereby eliminating the role of a centralized trust authority. Trust is achieved through a 'mining process' which guarantees the data fidelity and validity as reported by (**Tumasjan and Beutel, 2018**). On retrieval, a similar confirmation by network nodes ensues. In the end a new block is created by an algorithm according to (**Abeyratne and Monfared, 2016**). The verification process before acceptance in the registry significantly fortifies the transparency, trust and tracking in the system.

For the provenance system to be functional, a smart contracting system is created following the model by (**Kim and Laskowski, 2018**). The smart contract system depends on a computer protocol or program running the blockchain platform. The program's basic architectural configuration is such that; it has a layer for program code and a layer for storage of files. Any authorized user in the network creates a contract by initiating a transaction event. It begins with creation of a protocol code of a contract which remains immutable according to a study by (**Delmolino et al., 2016**). So, we have the user interaction face, the message relay framework, contracts storage and mining blocks. The storage file of the smart contract is kept in a block and the program logic is executed by the agreeing nodes to allow for the adjustments in the blockchain as illustrated by Figure 3.

The proposed blockchain provenance tracking has 4 layers; the overall system, registration, protection and authority organizations. The decentralized distributed system which uses a blockchain based database to store and manage relevant data of the informal water market is proposed. As usual, there are different actors in this market typically comprising of; borehole operators, water tanker operators, water vendors of other categories, water agencies tasked with different roles of authorization (Certifiers) and consumer organizations at the community level.

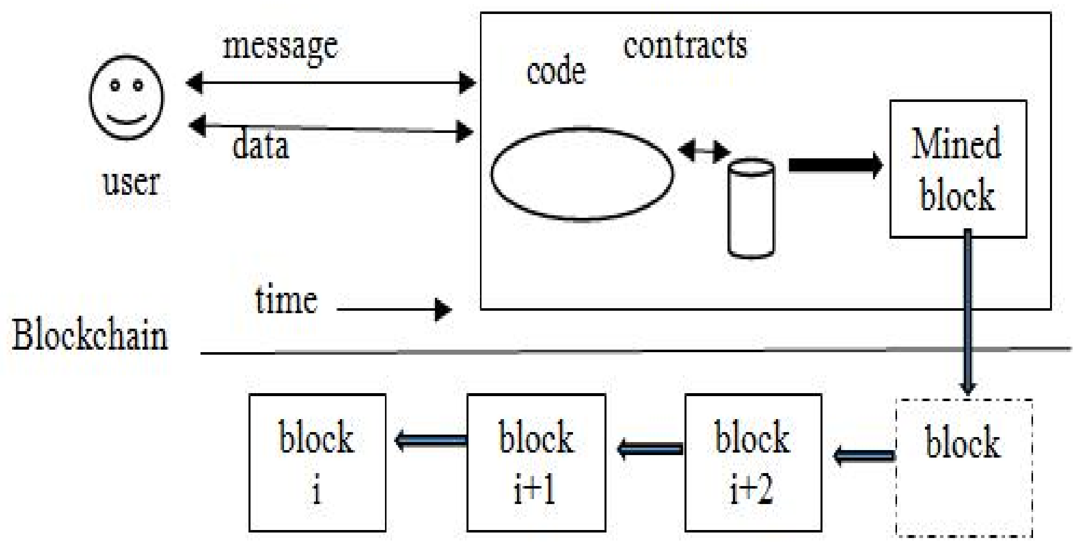


Figure 3: Conceptual framework of a blockchain (Source: Ochungo et al.,2019)

Each of these actors can add, update and check the information on vendor water quality in the database if, he / she, is a legitimately registered user in the system. Each water source is assigned a unique code with a digital cryptographic identifier that links the physical source with its virtual identity in the system, like the bio-physical and chemical attributes information profile of the individual water source, known as a water quality index presented in the area contoured map. Similarly, users in the system are assigned their digital profiles, which amongst others, include; introduction, location, certification and relationship with the water source. The whole suite of data is kept in a blockchain ledger accessible to permissioned users. The system has governing rules which outlines interaction with the system by users and data sharing protocols.

With regards to registration, data updating and adding, an interested member is free to register through a system registrar, in this study's case, the mobile phone app "Maji Safi". Such a member is provided with credentials and unique identifier codes with a pair of cryptographic keys; public and private. The public key is to help identify the user within the system and the private key is to authenticate user interaction with the system for digital participation in all transactions. In the informal water market, a consumer receiving a delivery adds a new data into the water supply profile with his / her private key. When the borehole operator transfers water delivery to the vendor, both sign a digital contract to authenticate the exchange. This transaction data is added to the database and the system updates itself automatically.

When it comes to data security and fidelity or protection, the system allows users to provide the defining attributes and status to all consumers. For secrecy of private sensitive information, the system embedded protection conceals such layered information from other parties while still transferring authorized data. For example, the consumers can sign a digital contract with dealers or vendors from upstream while keeping their identity private. On the role of certifying agencies, each organization’s inspectors can monitor operations with aim to enforce compliance with relevant standards to allow them to update the profile of the actors. All the verification data are published in the system to enhance transparency of the informal water market product’s quality.

The linkages between the constituents; borehole operators, delivery operators, community storage and authority organizations are in Figure 4below. The linkages shown between users are to match their unique identities so that one digital profile of the system is established. For the borehole linkage, the commissioned borehole water quality information; physical, chemical and microbial are entered into the system on borehole operator profile which is trackable by the other users within the wireless network running the blockchain database. The same is repeated for the delivery operators; vendors and tankers. For the community linkage, the system is expected to shift from the existing hydraulic network where water utility company has direct connection with customers to one where, there is a community central storage.

The storage is at two levels; one for underground reservoir and the other is elevated tank for direct gravity delivery into user tap. This will retire all existing lot level pumping as well as lot level storage. Secondly, the consumer linkage with the community management unit is through smart meter system which can automatically update consumer water use information for billing and for future planning. The authority linkage will allow for close monitoring by responsible agencies on the standard compliance and updating of the committed user profiles to weed out fraudulent players. The entire water quality tracking system is through an android application.

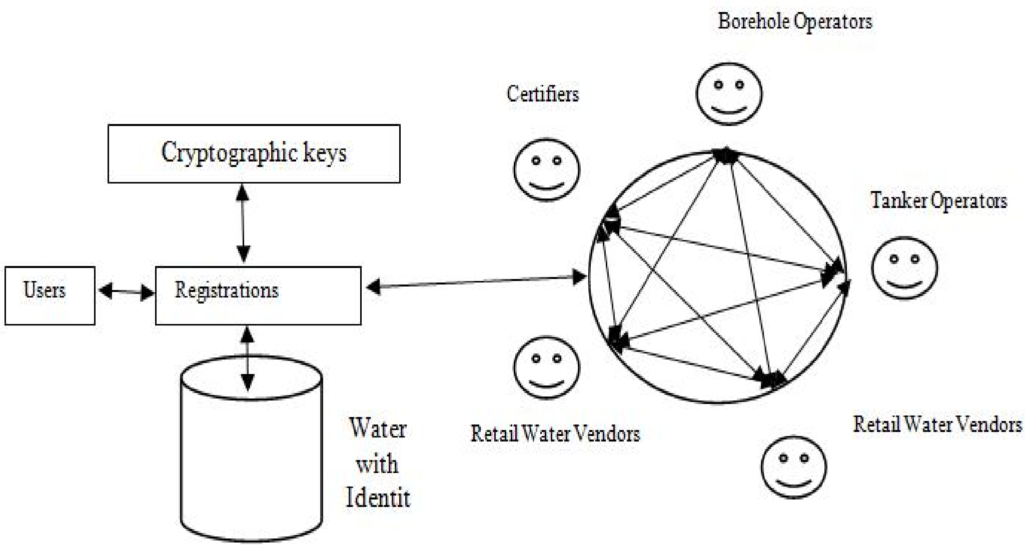


Figure 4:Conceptual framework of the provenance system (Source: Ochungo et al.,2019)

2.6.4 Product information asymmetry

The revelation of a product's attributes by a seller to a buyer in the market is known as the product's information signaling (**Nelson, 1970**). Should the seller decide to conceal some part of the product's quality data, then a state of information asymmetry arises as was first explained by George Akerlof in his study of market of "lemons" in the United States of America (**Akerlof, 1970**).This inspired a correction study from Michael Spence in his labour market investigative work in which he recommended that both the prospective employee and the potential employer must remain transparent in their exchanges to establish trust (**Spence, 1973**).

In this current study, the informal water market actors lack a system to allow for verification of source water quality. Most of the time, the water vendors fail to disclose to their customers, the true quality status of the water they sell to them. This information asymmetry in the informal water market is counterproductive to the wellbeing of the system. Accordingly, this study drew inspiration from the work by the French criminologist, Alphonse Bertillon in which he created a database of criminals' identity based on the catalogue of their physical body parts' measurements (**Raymond, 1916**). So, the informal water alternatives' quality bertillonage was formed and made traceable through an android software application to stand in as a trust cornerstone. Trust establishment on consumer goods has seen the deployment of user action on social media where actors engage their mobile phones to mine product information (**Hajli, 2014b**).For that reason, Android system has been chosen to help develop the an application that will fix the asymmetry problem.

2.6.5 Android Operating System

From around the year 2005 when Google Inc acquired Android from Andy Rubin and his colleagues; it has been used as a trust cornerstone in e-commerce. Android is a mobile operating system based on the Linux Kernel and is designed for mobile devices like smartphones and tablets. Its source code is run by Google under Open Source License which has spurred its use (**Krajci and Cummings, 2013**.) For instance, the various consumer product barcodes have utilized camera devices in mobile phones. In the other sectors like geology, agriculture, medicine et cetera, android platforms have registered tremendous successes in establishing trust. This is mainly because it is powered by Open Handset Alliance and Google, making it freely accessible to many practitioners. Its Software Development Kit (SDK) which has its own modern user interface framework is an added advantage. This again, is backed up by own optimized Java Virtual Machine (JVM) which does help to counter handheld device limitations such as memory, processor speed and power (**Wei et al., 2012**).

These developments have fanned the popularity of android from the year 2007 when its use began proper. Android operating system architecture for new application development has five layers; application, application framework. Libraries, Android runtime and the Linux Kernel. Application is at the top providing user interface. Application framework provides the basic tools used to build applications. The libraries layer is the C or C++ language layer for data management. Android Runtime layer runs applications based on Java Virtual Machine (JVM).The Linux Kernel layer is the lower layer which is the core of the operating system (**Krajci and Cummings, 2013**), see Figure 5 below.

In the water sector, developed android applications have been used to book water tanker for emergency water distribution (**Tewatia et al., 2017**). It has also been used by water companies to track water quality results in some rural communities (**Andrici, 2012**). Other water companies have used it in the form of wireless water flow monitoring (**Jamaluddin et al., 2016**). From the foregoing, it is clear that the existing literature on android application in the water sector has focused on a centrally managed system or rather the formal water supply systems and not on the side of the consumer to enable him / her verifies the quality of water in real time, more especially the one from the informal water market.

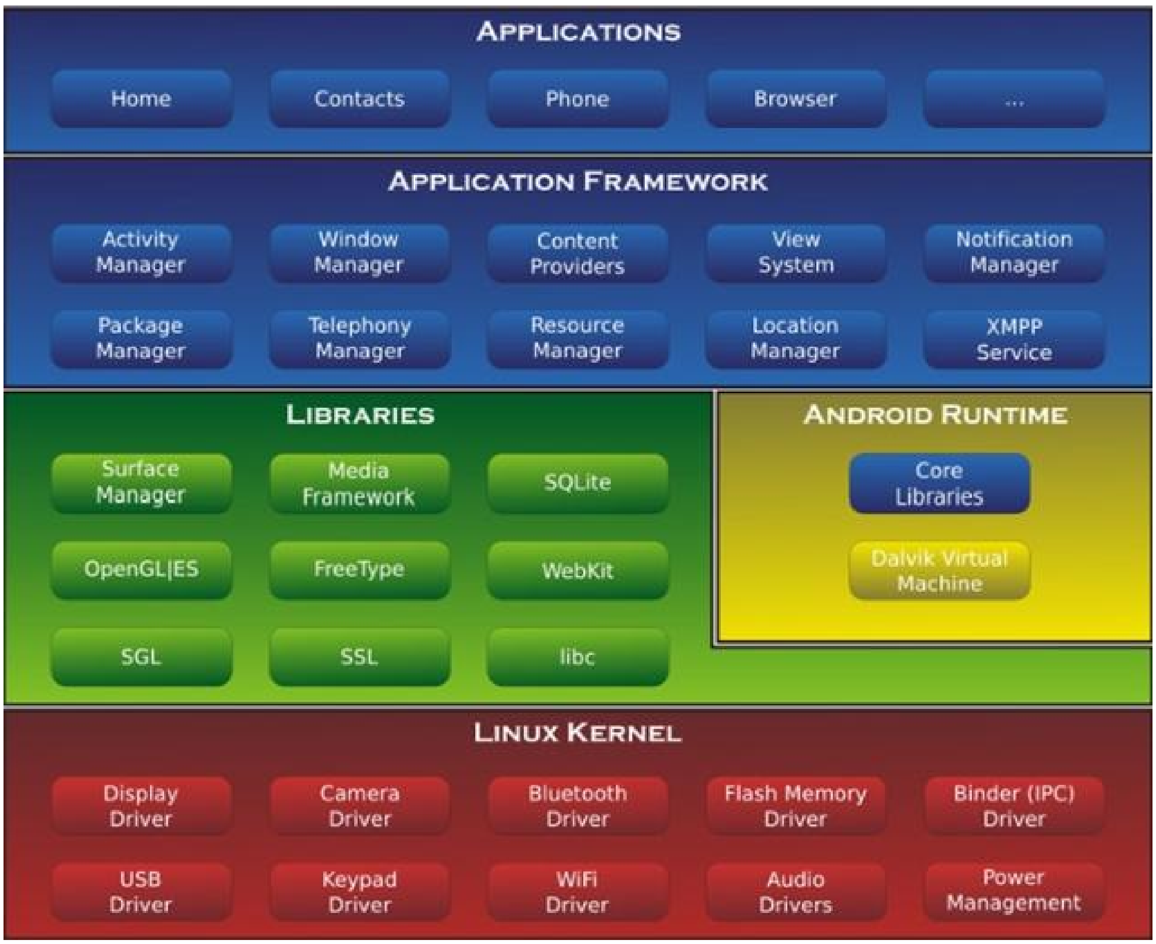


Figure 5:The Android System Architecture **(** source**:**Krajci and Cummings, 2013)

2.7 Stated preference model

In environmental valuation, it is always possible to estimate how much an individual is willing to pay on average for a given ‘good’ or ‘service’. In this PhD study, a water quality tracking system (WQTS), known in this study as a “blockchain provenance tracking system”, was presented to decision makers as a set of choice bundles of a product with varying attributes and price tags as was earlier suggested by (**Louviere et al., 2010**). Although WQTS is a market ‘good’, fixing the estimate price that individuals are willing to pay for their future installations is only possible using a hypothetical market in the thinking of (**Brouwer, 2008**).

The usual way in market interventions is to promote the adoption through consumer subsidies and or mandated adoption. And the most important idea in the process is to identify the gap between the value individuals are willing to pay (WTP) and the actual market price (**Day et al., 2012**).This explains the reason as to why, stated preference models are commonly described as discrete choice experiment (DCE) models(**Davis et al., 2016**).DCE models are usually applied in environmental protection studies because they are flexible in assessing customer preferences in hypothetical conditions according to (**Genius et al., 2008**).

DCE models being an attribute trade-off method are also known to present a series of scenarios from which respondents are expected to state their preferences (through choosing). Additionally, each of the scenarios usually describes the 'good' or 'service' in a colorful pre-defined attribute (**Kwak and Russell, 1994**). By extension, the method is used to value individual attributes packaging the 'goods' or 'services' as it facilitates the estimation of a trade-off between different attributes. A trade-off is defined as a balance of opportunity costs which maximizes utility. Attribute based methods are grounded in random utility theory which suggests that an individual consumer has a unique value for features of goods or services rather than the product in a heterogeneous manner. Representing a choice task as used in DCEs is natural, because they more closely represent decisions made by humans in everyday life. DCEs method also allows for the use of pictorial representations of choice sets to aid in cognitive reasoning as was illustrated in the study by (**Clark et al., 2014**).

Further, mounting historical evidence suggests that DCEs are less burdensome and possibly do produce more reliable results. For that reason, in this study DCEs were used to determine whether households in Langata are WTP for WQTS. All attribute-based valuation methods, including DCEs, are based on theories developed by Lancaster in his 1966 paper, "anew approach to consumer theory". More specifically, this study deployed the traditional theory of consumerism that "goods are goods" based on three fundamental underpinning assumptions as elucidated in random utility theory by Lancaster; the latter being the building block of all stated preference studies. These include;(1) consumers value the attributes that a good possesses, rather than the good itself;(2) goods are made up of many attributes which are not necessarily unique to that good; and (3) two goods together may possess different attributes from those when they are separate (**Lancaster, 1966**).

DCEs method incorporates these three threads of thoughts through the development of alternative profiles, choice sets and interactions between attributes, respectively. The Random Utility Theory (RUM) explains that the way individuals choose between the alternatives presented in a DCE can be explained using probabilistic choice theory. The choice behavior by individuals can be understood from either of these two perspectives ;(1) decisions are random in nature and utility is always deterministic; and (2) decisions are deterministic, utility is random, and that 'actual' behavior cannot be modeled. In the first perspective, the individual can be assumed to choose on impulse as influenced by psychological factors (**Tversky, 1972**). In contrast, the second perspective regards individuals as utility maximizers, but there is a random component to this maximization as was discussed by Thurstone in 1927 (**Thurstone, 1927**). The second perspective suggests that decisions are not made randomly but rather utility has a random component.

The random utility model is used to explain the uncertainty around predicting consumer and respondent choices are underpinned by Random Utility Theory (RUT). RUT was originally investigated by Thurstone, who looked at the derivation of satisfaction, or utility, through a "law of comparative judgment" with a psychological perspective. The theory was developed substantially in the 1970s with econometric input from the 2000 Nobel Prize Winner, Daniel McFadden (**McFadden, 1986**).

RUT provides a deterministic-decision framework which is not trying to explain irrational behavior but model the researcher's lack of information. The lack of information results in an error which could be due to measurement errors or latent attributes that influence choice or heterogeneity in preferences, that is; the un-observed differences in taste (**Hammitt and Herrera-Araujo, 2017**). Therefore, the psychological factors which influence choice are incorporated into this random component of utility (**Louviere et al., 2010**). RUT is based on the simple axiom that conceals the 'actual' utility function; however, it infers the impact on utility from deterministic decisions being made.

2.7.1 Previous application of DCE model

Despite the usefulness of DCE model, this study noted that significantly, less work seems to have been done on citizens' reaction to a technology driven water quality verification system. The small body of literature that does exist situate drinking water quality verification role at two institutional levels. One, on governments which are meant to create legal and institutional frameworks to ensure delivery of safe and reliable drinking water (**Hrudey, 2004**). And two, on governments' subsidiary agency arms commonly referred to as water service providers, which as per service level agreement provisions, are to develop and implement drinking water safety plans to facilitate water quality monitoring (**Jalba et al., 2014**).Talk of wireless sensor node-based water quality tracker (**Pule et al., 2017**), GPRS-based remote water quality analysis (**Ionel et al., 2015**) or any other form of crowd sourcing for water quality monitoring (**Goodchild, 2007**); the interest continues to grow especially in the face of drought and water contamination challenges confronting our cities today.

There are however, two perspectives at play in this continuum; informal water alternatives and their quality verification capability. The alternatives take such forms as: rainwater, treated grey water and groundwater which are close sources of water to the point of use such as within property boundary of a typical urban home (**Cook et al., 2014**).The informal water market alternatives supplement municipal water supplies through vendor delivery in push carts and / or tankers (**Whittington et al., 1991**). On the other hand, drinking water quality aspect is taken as a foundational matter that affects all stakeholders in water provision services' landscape (**Storey et al., 2011**).Accordingly, all water service providers are expected to monitor the quality of water they supply; a requirement which the informal water market players (vendors) are least prepared to comply with (**Brown et al., 2012**).

The water vendors are only in a rent seeking sort of festival, but remain unaccountable to the resulting negative implications on their customers (**Lovei and Whittington, 1993**). In order to transform the informal water market enterprise, the consumers ought to make a choice using mobile phone application run quality tracking system (**Peletz et al., 2018**). Since such a system has no shelf price; a non-market valuation method was used to market the bundle of choice options as earlier suggested by (**Millock and Nauges, 2010**).

The application of DCEs models has been witnessed in many studies, for example; in valuing of tap water quality improvement, assessing willingness to adapting to less water in urban Australia, assessing social benefits of improved water supply service and in weighing public perception on desalinated water. Further DCEs models have assisted in determining factors for adoption of safe water technologies (**Hulland et al., 2015**), use of household level chlorination products in Kenya (**DuBois et al., 2010**) and assessing end user preference for water treatment technologies in rural Kenya (**Albert et al., 2010**).

Additionally, it has been used to assess welfare effect of improved water quality, to estimate WTP for watershed protection by domestic water users in Tugueragaro City, Philippines, the valuation of groundwater protection in Denmark (**Hasler et al., 2005**) and to assess the adoption of water efficient equipment by households. One notable feature in all these studies is the heterogeneity of individuals in making decisions on a choice based on the available attributes.

Even though WQTS is a market good, there is lack of market data to reliably link socio-economic and attitudinal information to the (WQTS) purchasing behavior. As a result, in this study, stated preference choice experiment; a form of DCE model was applied due to its rising popularity in water sector studies. This was to help in determining whether households in Langata are willing to pay (WTP) for any one of the four different types of WQTS with the existing arrangement of water access being a baseline as ‘status quo’ choice. The four choices are; Individual WQTS as presented in Figure 6, Communal WQTS where houses are connected to water source via smart meters as illustrated in Figure 7 and Figure 8, Combination of Individual and Communal WQTS as demonstrated by Figure 9.Option four is the existing set up, Figure 10 and Figure 11.The design of choices was based on the advice sought from studies by (**Lanz and Provins, 2015**).

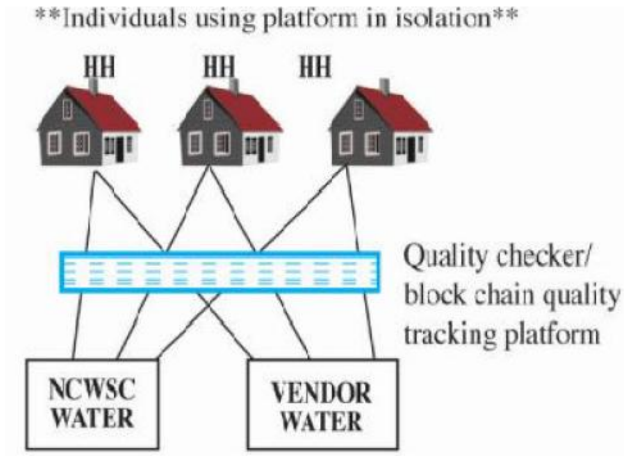


Figure 6:Individual WQTS installation (Source: Ochungo et al.,2019)

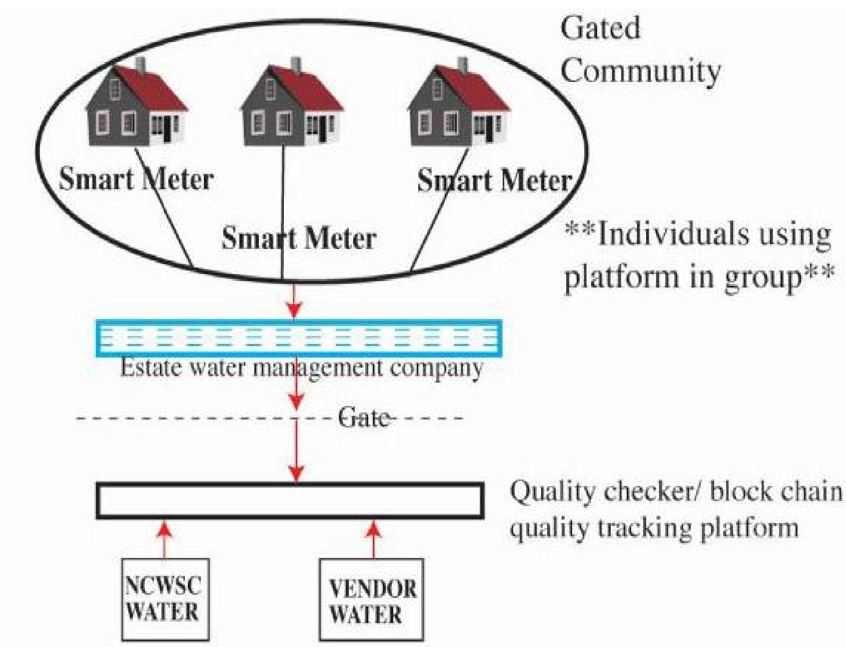


Figure 7:Communal WQTS installation (Source: Ochungo et al.,2019)

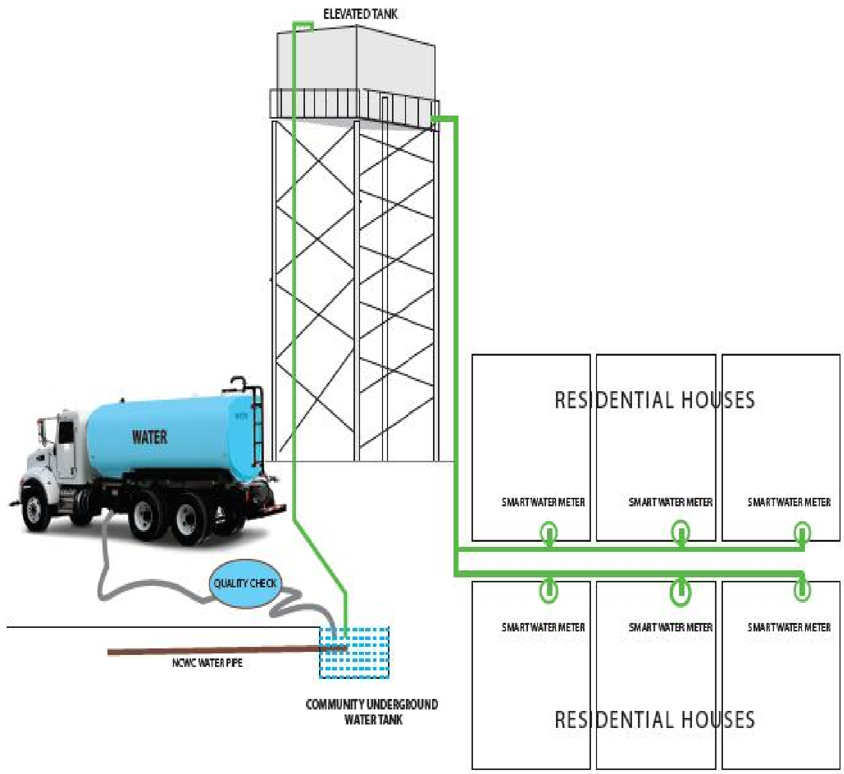


Figure 8: Communal WQTS installation with smart meters(Source: Ochungo et al.,2019)

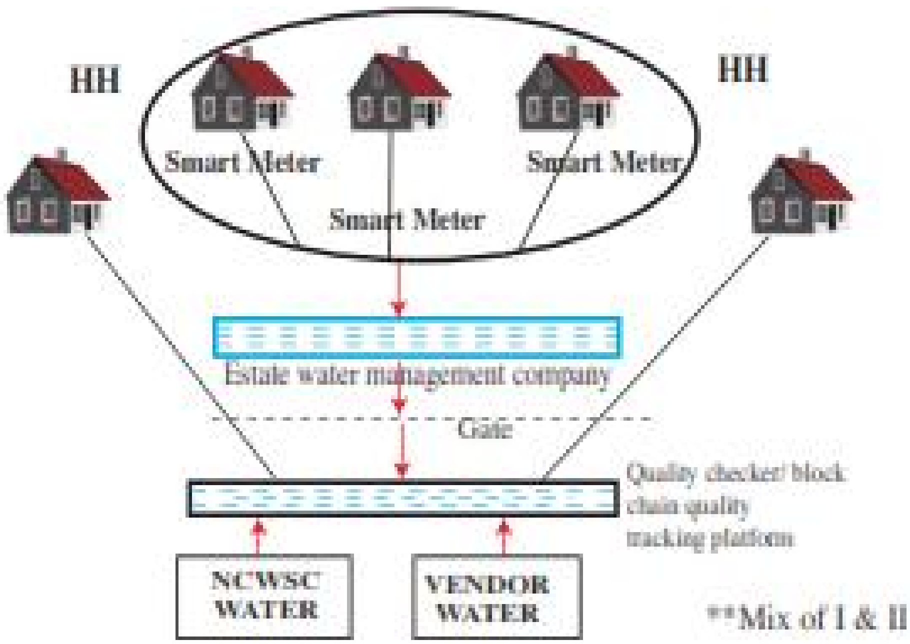


Figure 9:Individual and Communal WQTS installation(Source: researcher)

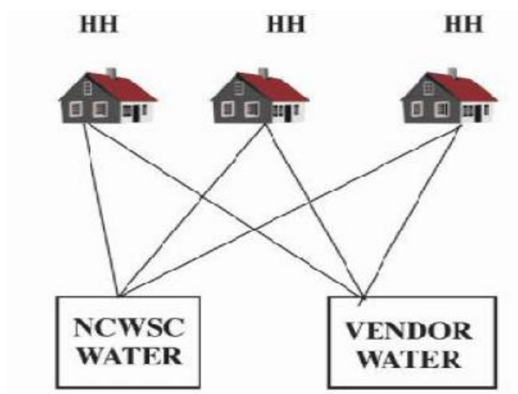


Figure 10: Existing status of household water access (Source: Ochungo et al.,2019)

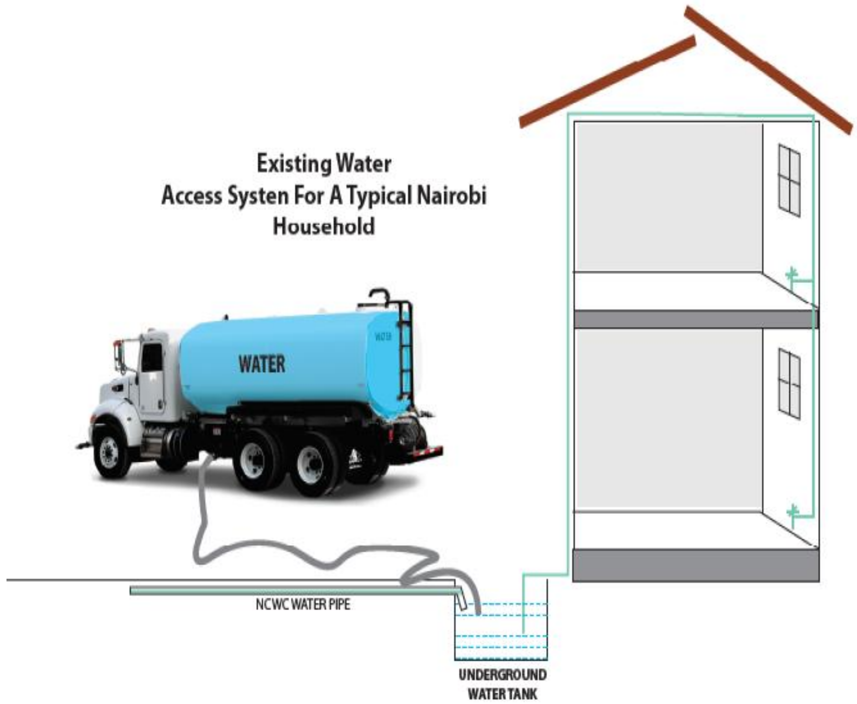


Figure 11: The existing status of household water access(Source: Ochungo et al.,2019)

The amount of money that an individual is willing to pay (WTP) is used to reflect his or her preference for one system over the other as was proposed by (**Hanley et al., 2001**). In this study, the payment is presented as a percentage adjustment to the current average household's monthly water bill, being a payment type as discussed by (**Willis et al., 2005**).And the investment on the new system is supposed to be undertaken by the utility company beforehand, so that the cost recovery is done via the tariff adjustment .The real hidden reasons for the first three choices' attributes were mainly to; bring in social benefits in water access (**Latinopoulos, 2014**) and to provide the much needed protection to the local groundwater environment (**Hasler et al., 2005**).

The existing water shortage response types continue to overburden consumers in several ways. For example, the monthly bill on vendor water consumption is steeply expensive. As a matter of fact, the averting expenditure ought to be equitably affordable (**Yoshida, 2009**). Secondly, the craze in borehole drilling in Langata may trigger groundwater depletion risk soon (**Chakava et al., 2014**). And this is at the backdrop of the assertion by (**Wayumba, 2001**) that Langata falls within an earthquake disaster fault line.

There are, however, several ways to allow for the individual heterogeneities in DCE models. The study took the approach of latent class model as earlier used by (**Rosato and Baer, 2012**). Latent Class (LC) approach is hailed for allowing for the identification of diverse classes of respondents who may hold quite different preferences (**McCutcheon, 1987**). Within the constraints inherent in the number of classes identified, there are no limits on the distribution of preferences nonetheless, unlike the alternative approach of random parameter conditional logit models (**Train, 2009**).To the extent possible within the literature sought by this study, little if any, has been done to equip the households in such a manner. One of the fundamental pillars in water supply service industry is that change decisions require communal endorsements (**Ostrom, 2014**). This was realized using Conditional Logit Model

2.8 Estimation of preferences on a Conditional Logit Model

A conditional logit model assumes that the utility for an individual (or a decision maker), **i**, must make choice from a set of **J** alternatives from which he / she derives a certain level of utility $\mathbf{U}_{ij}$ expressed as;

Chapter 2-Eq- (2.1)

$$U_{ij} = V_{ij} + \varepsilon_{ij}$$

Where ε_{ij} is unobservable unknown. Collectively, these assumptions are of extreme value type **I** often referred to as the independently and identically distributed (**iid**) conditions. While V_{ij} is the representation of the portion of the utility with linear attributes.

Linearly $V_{ij} = \beta_{ikxijk}$ Chapter 2-Eq- (2.2)

Where **k** are the attributes for X_i alternative from **j** alternatives and β_{ik} is the marginal utility derived by individual 'i' from choice X with k attributes. Now if yi=j>individual 'i' selects option j from available alternative 1 and 2, then the probability of that individual 'i' selecting j from a set of N alternatives is expressed as;

$$P\left(yi = J\right) = \frac{\exp\left(\lambda V_{ij}\right)}{\sum_{n=1}^{N} \exp\left(\lambda V_{in}\right)}$$

Chapter 2-Eq-(2.3)

Where λ is the scale parameter given by random term $\lambda^2 = \frac{\Pi^2}{6\,d^2}$ related to β which varies across groups. Should the parameter be same, conditional logit model can be used otherwise mixed logit models is applied. It is taken that choices may be similar in a class but may be different across classes (section of the group) and this is expressed as '**c**';

$$P\left(yi = j/c\right) = \frac{\exp\left(\lambda\beta_{ik}X_{ijk}\right)}{\sum_{n=1}^{N}\exp\left(\lambda\beta_{ck}X_{ink}\right)}. \qquad \text{Chapter 2-Eq-(2.4)}$$

For an iterated bidding process, it is assumed that class behavior will remain constant within the tasks expressed by;

$$P\left(yi = j/c\right) = \frac{\exp\left(\lambda\beta_{ik}X_{ijkt}\right)}{\sum_{n=1}^{N}\exp\left(\lambda\beta_{ck}X_{inkt}\right)}. \qquad \text{Chapter 2-Eq-(2.5)}$$

With increasing group or class diversity, the flexibility of the latent class increases and loses distributive restrictions of mixed logit models. But this reaches a statistical limit of a certain number of class identifiable in a sample, at this point, when '**c**' approaches **N** (respondents), then a specific focus of model becomes real beyond which the experimental design is incapacitated. If the probability of an individual 'i' within class '**c**' from total classes '**C**' is expressed as S_{ic} then the unconditional chance of the same individual 'i' making a series of choices across T choice sets is given by;

$$P(y_i) = \sum_{c=1}^{c} S_{ic} \quad \prod \left(y_{it}/c\right) \qquad \text{Chapter 2-Eq-(2.6)}$$

Each choice by '**c**' is assumed to be empirical with varying criteria being in use to identify number of classes. The functional form for the utility (V_{ij}) for individual 'i' whose taste is alternative j is expressed as;

$$V_{ij} = \beta_s SQ_j + \sum \beta_T TECH_{ij} + \alpha_{pr} PRICE_j \qquad \text{Chapter 2-Eq-(2.7)}$$

Where SQ is the Status Quo dummy variable and $TECH_{ij}$ are the technology options for the water quality tracking system (WQTS) in alternative **j** chosen by individual '**i**'. $PRICE_j$ is the proposed cost adjustment in percentage (%) by utility company to implement the choices upon policy formulation. β_s is coefficient of the status quo dummy variable, β_T is the vector of marginal utility and α_{pr} is coefficient of price variable.

The willingness to pay (WTP) is expected to increase in the way the water access system will be organized at the estate level to allow for the informal water quality tracking. The shift should at the same time act to protect the ground water environment from degradation. Each choice consisted of three options with alternative bundles of community water management system on WQTS, plus a fourth option which is the status quo (SQ), or, 'none of these' alternatives. In the utility algorithm, the SQ dummy and its parameters contained 'no-change' option that is unexplainable from the attributes of the alternatives and is related to individual's unique preference for change. The probability of individual membership to a class S_{ic} is framed as a function of individual characteristics (Z_{ki}) on a multinomial logit model (MNL) expressed as;

$$S_{ic} = \frac{\exp(d_{ck} Z_{ki})}{\sum_{j=1}^{c} \exp(d_{jz} Z_i)}. \qquad \text{Chapter 2-Eq-(2.8)}$$

The variation of class membership summation according to stated preference in choice should be equal to zero expressed as; $\sum_{j=0}^{C} d_{jz} = 0$.The net-worth or maximum amount each respondent will be willing to pay for change as an attribute is a coefficient estimated under the mix logit model. And SQ dummy is a motivation to avoid radical change promoting a win-win or trade-offs for long held beliefs. The value options as part-worth is expressed as;

$$\text{Part-Worth} = \frac{-\beta_S + \beta_T}{\alpha_{pr}} \qquad \text{Chapter 2-Eq-(2.9)}$$

It has been argued before in many studies that incorporating psychological factors such as behavioral attributes and beliefs in choice experiments helps in faster prediction of peoples' choices as was stated by (**Ben-Akiva and Lerman, 1985**).In analyzing the constructs, factor analysis was used as a data reduction technique to come up with a composite variable to represent coping behavior expressed as;

Chapter 2-Eq-(2.10)

$$BEHAVi = W1X1i + W2X2i + ---- + WnXni$$

Where $BEHAV_i$ is the estimated composite score for behavioral variable, W_n, are the factor score of regression weight and X_{ni} are the observed score for each indicator.

2.9 Profile of water security debate

Water security is an emerging paradigm. Traditionally, the term "security" was always associated with a nation's military preparedness. When the Cold War era ended, the term was extended to include the readiness by states to respond to threats to human wellbeing like national disasters, natural resource conflict or environmental degradation (**Ullman, 1983**).In the water sector, the term "water security", was elevated to prominence in the year 2000, when the World Water Council published the article "towards water security: a framework for action by the Global Water Partnership (**GWP, 2000**).

A firmly held view then was that, a condition of water security in a place is when ,every person, had access to enough safe water at an affordable cost to enable him / her lead a clean, healthy and productive life (**Witter and Whiteford, 1999**).This view received a boost at the second international conference on water and climate change, where water was identified as being at the heart of the many challenges facing many communities ,world over, but almost all being attributable to climate change impacts. Many scholars today, agree that the water security debate, has been fashioned using different view frames, beginning with the integrated water resources management (**Cook and Bakker, 2012**). In the 1990s, the debate was coined around sustainable water resources management framework, before water security paradigm established itself proper in the year 2000 and currently, it is carried under the adaptive water management framework as highlighted by (**Pahl-Wostl, 2007**).

Historically, experts in water resource management have repeatedly stated that, the total endowment of our global water resources' stock has not changed from its original volume of 1,385,984km^3 (**Trenberth et al., 2007**).This volume is however not uniformly spread to the various world regions even as it covers nearly 71% of the Earth's surface (**UN, 1997**) .In this, the freshwater volume is only 2.5%.And that ,the available portion for human use is only 0.007% of the total because the rest is locked up in ice caps (**Shiklomanov, 2000**).

Secondly, the available fresh water stock is also under a continuous assault from the growing water demand, increasing groundwater level decline, surface water contamination, aging water infrastructure and a variable hydroclimatic system (**Gerlak and Mukhtarov, 2015**). Water security experts agree that these threats on the global freshwater stock, collectively, provide a compelling argument for considering the security implications of the water resources management (**Conca, 2015**). In addition, the water security situation is further aggravated by the fact that a significant portion of the available freshwater stock is spread in 263 transboundary waterways which requires cooperative action (**Wolf, 2007**).

Studies have further shown that, up to 80% of the global population is exposed to a water risk (**Bakker, 2012**).This requires that water security issues be discussed at the local level (**Kaplowitz and Witter, 2002**).And that the solutions to the identified problems be sustainable ones (**Bogardi et al., 2012**).According to (**Grey and Saddoff, 2007**) there are three factors that define an area's water security condition. These are; the state of the hydrological activities, the type of the area's economic mainstays and the projected state of future climatic condition. Once the factors are known, the solutions prescribed should; provide for a universal access to water and at the same time, should provide a consistent support to the productive sectors.

Further, the solutions ought to promote environmental protection and should be disaster proof (**Lautze and Manthriththilake, 2012**).The pro-dynamic-integrative scholars have looked at water security debate from the standpoint of sustainable and resilient solutions to both the human society as well as the natural ecosystem in the face of uncertain global change dynamics (**Scott et al., 2013**).But, even with these carefully planned solutions, attaining water security is still fraught with major bottle necks, including the ones cited at the Rio + 20 summit ; increasing poverty among the global population amidst mounting pressures on water resources from climate change impacts.

For that reason, scholars like (**Romero-Lankao and Gnatz, 2016**) framed up some five key indicator areas to influence the urban water security conceptualization. These included; the socio-demographic characteristics, ecological demands, built area demands (technological outlay of the service area), the state of the competing demands and the existing water resource's legal framework. In their view, the ideal urban water security situation is a sandwich shell built by two forces from environmental and societal demands. On their part, (**Chamhuri and Ferdoushi,**

2014) discussed the urban water security from five influencing drivers which they identified as; households, economy, urban landscape, the environment and resilience to water-related disasters, which they rolled up into three factors; universal access, universal water safety and universal water affordability.

Despite the ongoing great work in the pursuit of urban water security, other scholars have identified reasons as to why the solutions have been failing. They state that water actors have mostly worked in isolated manner. They in turn have suggested that the water security solution should be a global web for the nation that ties all actors with a delegated action point that contributes to the attainment of the security as a central goal (**Zeitoun, 2011**).

Responding to this concern, (**Hoekstra et al., 2018**) discussed urban water security from four important lenses covering; welfare, equity, sustainability and water related risks. The paper chronicled the various paths from which various disciplines have looked at water security for instance; engineers, environmentalists and public health practitioners. They maintained that most other water security studies have been conducted based on the problem-oriented perspective like; the water shortage approach, flooding risk and pollution threat assessments. In sum they contended that, the term water security is yet to acquire a common consensus in the way it should be interpreted adding that most urban areas depend on external water footprint and as such the urban citizens often end up getting exposed to “imported urban water risk”.

Urban water security is a growing concern in many places. In Kenya for example, the freshwater endowment is only 20.2 billion cubic metres or 548m^3 per capita per year which is quite low compared to her immediate neighbours like Uganda (1273m^3) and Tanzania (2035m^3) (**World Bank, 2010**) .Consequently, Kenya’s capital city, Nairobi is incapable of meeting its internally generated water demand and hence depends 95% on the hinterland-supplied water resources, mainly from the Aberdare’s ecosystem, whose water flow is already exhausted. This has occasioned a development of a transfer scheme from the drought prone, Upper-Tana River ecosystem in the newly adopted Nairobi Metropolitan Water Master Plan covering 2011-2035.The first phase known as Northern Collector Tunnel is meant to pump at least 140,000 m^3 per day to plug part of the existing 200,000m^3 daily supply gap before 2020 (**Njoroge,2011**).

This supply side solution is always affected by rainfall variability challenge. When the source water catchments face drought impacts, the city residents bear the brunt of the "imported urban water risk" in the words of (**McDonald et al., 2014**).Given the sensitivity of the watersheds, this study takes the conceptual view that water security must integrate the societal-ecosystem-hydroclimatic (SEH) interactive processes into account while coming up with solutions, which henceforth is referred to as integrative approach. This view is driven by the fact that water insecurity can result from an instability within one or more of the elements within the SHE-framework (**Scott et al., 2013**).That is why the dynamic water management approach which accounts for uncertainty through flexible planning, knowledge sharing between scientists and decision makers to enhance capacity for respondents' reflexivity to the emerging multiple and uncertain processes of change is encouraged. This is particularly important when we take into account that water security discussions must be hinged on apolitical decision platform. The process to this is to be reinforced by a three-phase dynamic adaptive cycle as suggested by (**Buellow, 1989**).

2.10 Theoretical construct for the study

In the general technology adoption studies, the one by (**Kwon and Zmud, 1987**) for instance is known to have inspired a study by (**Wejnert, 2002**) that synthesized the factors influencing technology adoption as three clusters of variables covering; invention, innovation and environmental contexts. From the initial groundbreaking technology adoption model by (**Rogers, 1962**), several improvements and unified versions of the same have been developed as discussed in the literature profile synthesis by (**Venkatesh et al., 2012**). But because of weaknesses in these earlier models as cited by (**Legris, 2003**) and the later confirmations by (**Bagozzi, 2007**), a study by (**He et al., 2014**) for instance, used discrete choice experiment model; a random utility theory structural model proposed by (**Manski, 1977**). The DCE model is credited to be able to accommodate the heterogeneity of participants. Following this reasoning, this PhD study has adapted the discrete choice experiment model.

This study builds on the pillars of innovation diffusion theory erected by (**Davis et al., 1989**) which was reinforced by three other theories. The first one was, the prior exposure information priming theory by (**McGuire, 1961**). And the second was the value orientation theory by (**Kluckhohn and Strodtbeck, 1961**) as cited by (**Hills, 2002**). Most importantly, the third one was the protection motivation theory by (**Rogers, 1975**). The construct uses the application of the discrete choice application paths as laid by (**Ben-Akiva and Lerman, 1985**). This path meshed and weaved the heterogeneous behaviors among the respondents. The study considered the fact that each respondent had to reason before deciding. And that decision choice processing was accelerated by the learning and value orientation.

2.11 Research conceptual model

The study recognized that blockchain technology is still in infancy and is prone to adoption challenges, especially from dogmatic influences by community members' inertia. To counter this, three decision boxes were proposed; learning, valuing and choice boxes. At the top there were individual social characteristics or factors that influence decision steps that influenced the choice for blockchain technology adoption. But these factors were primed in the learning box of risk information. For this study, there were four levels of risk information; drought risk, groundwater depletion, cost and quality risks. The latter three were masked together as coping cost risk, see Figure 12 below.

The risk information box was for learning and appreciating the level of exposure to risk. This ended up facilitating the valuing direction in choosing a safe coping method. At the end, bundles of choices were presented, on one side was the "status quo choice "and on the other, were three options of tariff increment to allow for the implementation of blockchain provenance technology using the existing market structure. The process was dynamic, once a choice was made, after some time; a new decision would be required but following through the same conceptual path. This model was used to conduct the three phases of the study; learning, valuing and choice interactive sessions with the community.

This study model enriches the existing body of literature in presenting a unique way to model the adoption behaviour and take-up of an innovation by households. The model considered the socio-demographics and level of service attributes of the product on the adoption behaviour of the target respondents. It contributed to the initial adoption studies of blockchain technology in the water supply sector.

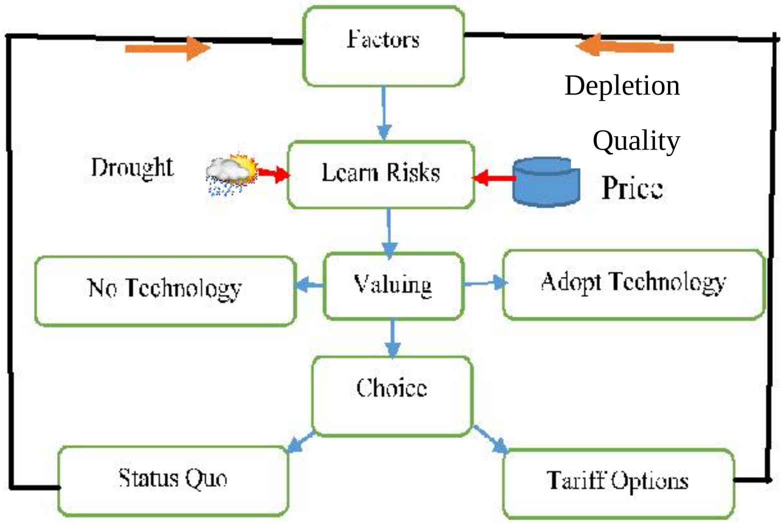


Figure 12:The conceptual framework for identification of factors of adopttion

CHAPTER THREE: METHODOLOGY

3 Introduction

This section presents the specific methods used in the deployment of the above conceptual framework to facilitate the realization of the study's; overall and specific objectives. It begins by presenting the information on the study site. Next, it outlines the analytical and participatory methods corresponding to each respective objective. The analytical approach was applied; to reconstruct the historical drought exposure profile, to detect the area's groundwater resource depletion threat and to evaluate the potability of the area's groundwater resources.

On the other hand, the participatory method was used to assess the cost implication of coping with the vendor water and to identify the major socio-demographic factors that influenced the adoption of the WQTS; a fact which also reciprocally indicated, the willingness to pay (WTP) for the shift to the new system of communal water access. For each objective, the specific detail on; methodology, sampling, data collection and data analysis technique is presented.

3.1 Study site

3.1.1 Location choice and description

This study chose Langata sub County as the study site. This was done for two reasons. One, Langata neighborhood is known to suffer frequently from water shortages. Two, the principal researcher is a resident of Langata area hence has a lived experience of the said water shortage challenge of the area. Geographically, Nairobi County where Langata is one of the seventeen elective parliamentary constituencies is located approximately between Latitudes 1^{o}10'S and 1^{o}27'S in the North-South direction and Longitudes 36^{o}40'E to 37^{o}0'E in the East-West direction over Kenya, see Figures 13 and 14 .Langata alone covers an area of approximately 196.8 km² and is roughly at 1^{o} 22'0" S, 36 ^{o}44' 0"E..It is about 10 kilometers to the south of city centre and is accessible by public transport system on a well traversed road network. It also hosts Wilson AirPort, a major domestic airport in Kenya. Topographically, the area's height ranges from 1,600m to 1,850 m above mean sea level (**Mitullah, 2003**). It has five elective wards, namely; Karen, Mugomoini, Nairob-West, South C and Nyayo High-Rise.

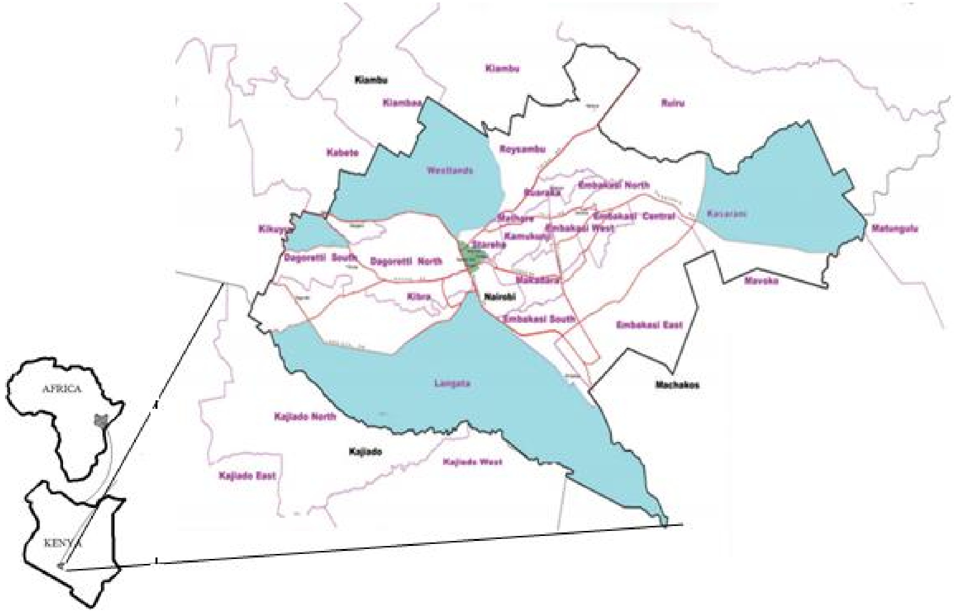


Figure 13: Map of Africa, Kenya and Nairobi City County (Not to Scale) - (Source: researcher)

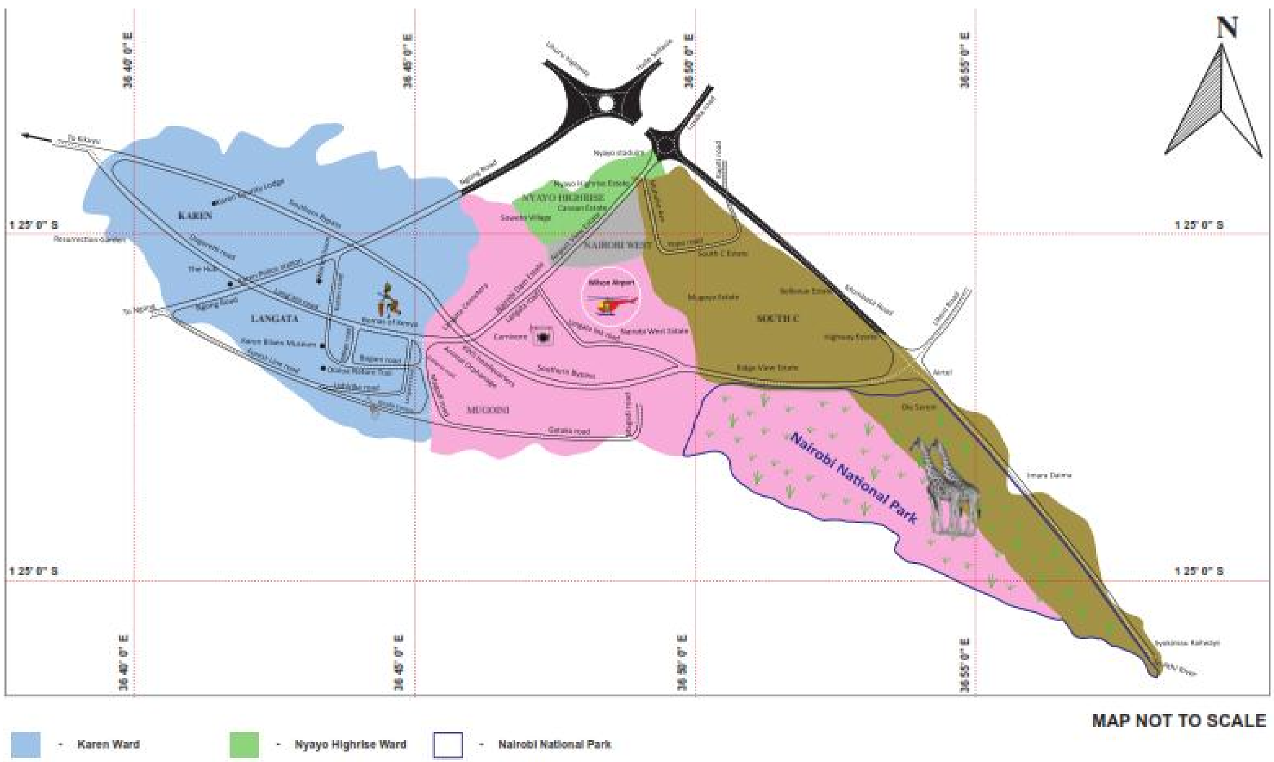


Figure14:Location map of Langata sub County, showing the shaded area in Fig 13

3.1.2 Biophysical setting

3.1.2.1 Climate

Langata enjoys a temperate-tropical climate influenced by monsoonal systems of Asia and Indian Ocean. The area is characterized with cool evenings and with mornings which are distinctively cold during the rainy seasons. It has a bi-modal rainfall system; with long rains coming in April - May-June period and short rains falling around October- November-December window (**Okoola, 1999**). The annual average rainfall ranges between 800-1200mm.There is a constant 12-hours of daylight all year round. Additionally, the average daily temperature ranges from 29º C in the dry season to 24º C throughout the year.

3.1.2.2 Vegetation, flora and fauna

The area is predominantly plain grassland. It has pockets of shrubs, woodland, riparian forest along the Mbagathi, Mokoyeti and Motoine rivers and patches of forest around; Tree Lane, Forest Road and Mwitu Estates on the western side. The forested areas in Langata include; Ngong Forest and Ololua Forest ecosystems, which are very important genetic reservoirs in the area. These forest ecosystems are rich in wildlife, particularly primates, birds and invertebrates. The area is also bordered to the south by a117 km^2 Nairobi National Park; an ecological ecosystem supporting over 400 wildlife species.

3.1.2.3 Land use

Langata is a mixed urban residential and commercial development zone. The inhabitants range from low to upper income households. Some of the famous estates are;Madaraka, South ‘C’, Nairobi Dam, Airport View, Nyayo High-rise,Jonathan Ngeno,Karen, Southlands, Otiende, Ngei, Onyonka, Soweto village and many more. The building types comprise; flats, maisonettes, town houses and bungalows. In Karen estate however, most of the houses are single-family homes standing on a minimum of; half acre parcel of land or larger. Many commercial developments are also found in the area; Galleria Mall, T-Mall, the Well-Karen, the Water-Mark, Waterfront and the Hub; most of them located along Langata road. Many recreational areas and green spaces are also found here including entertainment joints, namely; Nyayo stadium, Carnivore restaurant, Uhuru Gardens, animal orphanage within the Nairobi National Park, Giraffe Center, and etcetera.

3.1.2.4 Physiography and drainage

Langata's physiography and drainage is part of the larger Nairobi River System. The city's main drainage pattern follows the regional slope of the volcanic rocks towards the east, while the subsidiary internal drainage paths stem from the Rift Valley region in the western part. The lava plains east of the line on Ruiru-Nairobi-Ngong corridor are underlain by a succession of lava flows alternating with lakebeds, stream deposits, tuffs and volcanic ash. These plains, comprising mainly; the Athi plains and the northern section of the Kapiti plain, extending westwards, rising from a topographical height of 1493m (amsl) at the Athi River to 1829m (amsl) in the faulted region near Ngong hills area.

The lava plains are crisscrossed with steep-walled gullies and canyon-like gorges, such as those along the Mbagathi valley. Further east, Mbagathi valley widens slightly where soft material is being actively eroded. Water draining eastward from the hill area accumulates on the low-lying ground between Parklands in the North and Nairobi South estate, forming a perched water table above the Nairobi phonolite. The Kerichwa Valley Tuffs lying to the east of the Uhuru-highway functions like a sponge and the contact between them and the underlying impermeable phonolite thus forms a perfect aquifer, so much so that a number of channels containing water occur beneath Nairobi.

3.1.2.5 Water resources

Langata Sub County relies on the municipal water supply from Nairobi City Water and Sewerage Company Limited (NCW&SC). It is within Athi River basin ecosystem which is facing water shortage crisis as a result of rainfall variability and contamination from urbanization (**Agwata, 2005; Samantha, 2011; Kithia, 2007**). This has occasioned water supply to be erratic and many home-owners have drilled tube wells (**Onyancha et al., 2014**). Private water vendors actively supply households with water from these tube wells.

3.1.2.6 Biophysical vulnerabilities

The intensive ongoing urbanization trends and developments being witnessed in the city continues to modify the geomorphology of the local area landscape especially in zones which are adjacent to riverbanks (**Kwambuka and Krhoda, 2016**). Secondly, the increasing spread of impermeable surface cover due to growing built-up areas means a reduced rainwater percolation chance. The evacuation of the storm water build-up ends up in eating into river banks exposing building and population to landslide danger. The runoffs usually discharge sediments onto the water bodies hence causing quality deterioration (**Kithia, 2012; Dulo, 2008**). Anthropogenic waste water disposal onto river system also contributes to the ambient river water's quality reduction (**Ndunda and Mungatana, 2013**).

3.1.2.7 Social setting

Langata constituency is a mixed land use development area priding itself as a host of residential, commercial, educational, security and natural ecosystem landscapes of the city. It is made up of five wards inhabited by 176,314 people out of the total Nairobi city's residents numbering about 3,078,180 as per the 2009 national census report (**CBS, 2009**). See summary in table 1 below for households, population and area size for each ward. In terms of healthcare, as a whole, Nairobi County has 16 sub County hospitals, 9 mission, 32 private, 15 nursing homes, 38 public health centres as well as 45 private health centres. In addition, there are also 30 public dispensaries, 84 private clinics and 22 public clinics. The healthcare infrastructure of the city therefore, provides to Langata residents an adequate access to affordable healthcare both in public and private institutions within and without its boundaries.

Table 1: Households, Population and Area size for each ward in Langata

Ward Name	Population No.	Households No.	Area Km^2
Karen	24,507	9,467	48.00
Nairobi West	33,372	8,311	6.90
Mugoini	47,037	12,867	126.40
South C	47,207	13,637	15.10
NyayoHighrise	24,191	8,374	0.40
Totals	**176,314**	**52,656**	**196.80**

3.1.2.8 Regulatory framework

In the context of water provision, the area is served by the Athi Water Works Development Agency as per Kenya's Water Act 2016. Actually, Nairobi Water and Sewerage Company is the main water company in the County.

3.2 Data

The study relied on both primary and secondary data sources. The primary data were obtained through household surveys and focused group discussions. The secondary data were obtained from concerned government institutions and their transforms.

3.2.1 Secondary data from concerned government institutions

i) Monthly rainfall

Monthly rainfall data from Wilson Airport Meteorological Synoptic Station were obtained for the period between 1957 and 2013.

ii) Borehole commissioning data

The annual borehole commissioning data for 137 boreholes in Langata sub County was sourced from Water Resources Authority offices in Nairobi. The data covered the period 1982 to 2017 and included the mean struck water level depth, aquifer type, total depth installed and use of the borehole, majority of which are domestic.

The file also had various technical details of the borehole development like, the concentration of the geochemical parameters, completion date and the driller. On preliminary analysis using the perspective of hydro-chemical parameters, 98 of the files missed one or more of the eight geo-chemical parameters which were common to most of the boreholes; Potassium (K^+),Sodium(Na^+),Calcium(Ca^+),Iron (Fe^{2+}), Flouride (F^-),Chloride (Cl^-),Sulphite (SO_4^{-2}) and Electrical Conductivity Ec(µS/cm).In the end, 39 borehole files which had the 8 complete parameters as above mentioned were subjected to groundwater potability evaluation.Additionaly,the following pieces of information were extracted from the borehole commissioning data; average annual water hit level, dry year water quality indices and hydrogeochemical parameter concentration levels for the analyzed boreholes.

iii) Second level transformed data from (ii) above and the standard manuals

Appendix 2 is a presentation of the average area's groundwater quality index (WQI) for each year and the drought quantification data in the form of SPI values extracted from the rainfall information. From each year's groundwater quality score, the dry year WQI values are also displayed separately in the same appendix. In addition, using World Health Organization's drinking water standard guidelines, Kenya Bureau of Standards drinking water standards and related studies' work, the study extracted transformed data which included; acceptable contaminant concentration levels, relative weight of concentration of the contaminants and groundwater quality grading scale.

3.2.2 Participatory action research process

3.2.2.1 Survey process design and sampling procedure

(a) General

The design began by first, sampling. The study used a simple random sampling method; in which each unit included in the sample had an equal chance of inclusion in the sample. This technique provided an unbiased and better estimate of the parameters as the study population was assumed to be homogeneous (**Singh and Masuku, 2014**). The study area is a properly planned and built area; a fact which made the planning for the distribution of questionnaires easy.

To ensure randomness and equitable spatial coverage in the sampling process, the study followed the 57 gated communities spread within the five wards. A circular and systematic sampling method was used to select a household within a gated community. By definition, a systematic sampling method is, a probability sample selection method in which a sample is obtained by choosing every kth element of the population, where k=N/n; where N is the population size and n is the sample size. The first sampling unit is selected randomly within the first k units of the list. For instance, if k=10, then a random number between 1 and 10 is selected first. Suppose the selected random number is 8. Then starting with the 8th house in the list of households in the gated community, every 10th house (8th, 18th, 28th….) is sampled until the desired sample size is reached. The study deployed the determination of a sample size formula by (**Watson, 2001**) as expressed in equation (1) below;

$$n = \frac{\left[\dfrac{P[1-P]}{\dfrac{A^2}{Z^2}+\dfrac{P[1-P]}{N}}\right]}{R} \qquad \text{Chapter 3-Eq-(3.1)}$$

Where: n = sample size required, N = total number of respondents in the population (52,656 households in our case, see table 1 above), P = estimated variance in population, as a decimal:

(0.5 for 50-50,) ,A = Precision desired, expressed as a decimal (i.e. 0.05 for 5%) ,Z = Based on confidence level: 1.96 for 95% confidence, R = Estimated Response rate, as a decimal, in this study case 100% which is 1.From the above formula, the estimated target sample size was computed as 382 households. This meant that a total of 382 questionnaires were to be eventually get distributed to the 57 gated communities. For standardization of results, the questionnaire compared to some other previous studies on implications of vendor water on households' welfare like the one conducted by (**Nnaji et al., 2019**).

The distribution plan agreed on by the stakeholders was to follow the population size in each ward. That is; Karen ward with 9,467 households received 69 copies into its 14 zones with 13 zones along major roads receiving 5 copies each and the last 1 zone receiving 4 copies of questionnaire. South C ward with 13,637 households, received 99 copies into its 12 gated communities with 11 receiving 8 copies each and 1 community is receiving 11 copies. Mugomoini ward with 12,867 households with 23 community groups had 22 of them received 4 copies each and 1 community group received 5 copies of questionnaire, making a total of 93.For Nairobi West ward with 8,311 households, each of its 4 gated communities received 15 copies each making a total of 60.And finally, Nyayo Highrise ward with 8,374 households, had 2 of its gated communities receiving 20 copies each and 1 received 21 copies making a total of 61.

(b) **Stakeholder engagement**

The choice-fest was preceded by sessions of stakeholder engagement. The first of these was the training of survey assistants which opened way for the initial learning session or the initial workshop with community leaders, where the community representatives were presented with observations. These were from; risk analysis and briefs on the potential of use of technology in crafting new adaptation strategy. This was done by contacting group chairmen through their telephone contacts to establish the location of their offices to which letters of invitation detailing the research objectives, authorization (University of Nairobi-Graduate School and National Commission for Science, Technology & Innovation) and a request to attend the first community workshop were delivered. The initial workshop was held on 20th February, 2019 at YMCA hall in South "C" ward.

The final version of the questionnaire was approved at the said workshop, the ward leaders were nominated by the stakeholders and the formula for selecting data collectors in each ward was agreed on. In the next four subsequent days after the workshop, the study team assembled for training sessions facilitated by the research team leader (the researcher). A final timetable of activities was made ready for the second stage of community engagement soon after the training.

For the entire study, the main stakeholders are the household heads from Langata sub County region. This was purposefully decided on like this because; this study has an element of water tariff debate. This is usually a controversial topic and the best way is to begin it from the consumer side (bottom up approach).This was intended to foster the spirit of co-creation in which the stakeholders who are likely to protest on changes of water tariff are the same ones challenged to make a guided proposal. During workshop sessions, other stakeholders like Water Resources Authority, Water Services Regulatory Board, National Environment Management Authority and the Ministry of Water team were invited.

3.2.2.2. The questionnaire

(a) Structure and content

The study deployed close ended questions that asked respondents to choose from a distinct set of pre-defined responses, such as “yes” / “ no” or among a set multiple choice questions to gather quantitative data (**Smith, 1972**).The questions which were administered through a survey tool in a face to face interview included; dichotomous questions “yes” or “no”,Linkert 5 point scale to assess the perception on water shortage (**Allen and Seaman,2007**) and rank order-four options choice questions for expression of preference by a respondent (**Mulilis and Lippa,1990;Bateman et al.,2002**). The material list that facilitated data collection were;recosurvey notes,57 gated community contacts from Kenya Alliance of Residents Association, enough copies of survey tool, data clerk training materials like notebooks,maps,authorization and pilot survey notes that included; entry procedure, survey protocol and closure remarks.

The questionnaire form is in four sections with 19 response parts. Preceding the question part was the information sheet and a consent form. The information sheet introduced the research objectives and the voluntary nature expected of a stakeholder’s participation as evidenced by him/ her signing the consent form. The data collection part hard two parts. The first part listed as 1 and 2 was focused on collection the socio-demographic factors of the participating stakeholder. Second part listed as 3 and 4, was soliciting for water shortage risk perception from the viewpoint of the household head and by extension his/ her stated preference of choice from a bundle of four choice options presented of the WQTS.A typical questionnaire used in the study is in appendix 5.Further; the survey team had a translated questionnaire in ‘Kiswahili language’ to assist a respondent who had a challenge with the “English version”.

(b) Questionnaire administration

After that joint planning stage, the second phase of learning sessions through direct interaction with the respondents began proper. This also doubled up as the household survey for data collection. The printed and bound questionnaire sheets were administered to the household-heads by a group of two (male and female) research assistants who explained every detail to the respondents. The literate respondents were left with the questionnaires for a minimum of three days to give them ample time to fill them in. In some cases, repeated visits were made before the questionnaires could be retrieved. A few, who needed help, were assisted to fill in using the Kiswahili version of the questionnaire. The data collected helped in the computation of the coping cost burden and the identification of the key factors that determined the public adoption of WQTS.

3.2.2.2 Focus Group Discussions

The study deployed a qualitative data collection process as earlier discussed by (**Sampson,1972**) in the form of Focused Group Discussion as reviewed by (**Morgan,1996**).In brief, the process followed the outline sketched by (**Morgan and Margaret,1984**) which talks about; process planning, group members’ selection, moderation and field team composition, format for recording the proceedings, training of support team, execution plan, conduct of the discussion sessions and their analysis together with the interpretation of the transcripts and or logbooks.

The study team did an adequate preparation following the above guidelines. Subsequently, two leaders from each of the 57 gated community units were invited for a one day seminar on 23rd May, 2019 at CORAT Conference facility, Bogani road-Karen. The choice on who to attend was left with the discretion of the chairman of each community unit. On this day, 29 community leaders attended the FGD seminar for endorsement of the general stakeholders' decision on the new coping decision as captured during the household survey process. The 29 members were split into six groups; five of which had five members and the sixth had four members. To fully tap from the group dynamics, the seminar was organized in three sessions. The first session was the briefing by the principal researcher who had behind him a group of seven support members to help in the moderation of group sessions. The second session was the dispersed focused group discussion sessions. And the final session was the wrap-up session. Because the conference facility's layout could allow for in-field seating, groups were requested to separate and be seated under tree shades and each research assistant was assigned a group with the principal moderator left to go round.

Ina typical focused group discussion setting, the group members sat comfortably under a tree shade around a low coffee table with one research assistant also in attendance. At the beginning of the session, and again after a brief break in the middle, the researcher (principal moderator) gave instructions to the participants; during the bulk of the session, the research assistants were busy making notes to aid in the later transcription of the proceedings. Each of the two halves of the discussion took 15-20 minutes, with additional time for question and answer, instructions, and open discussion between participants and the research team after the focus group. The total time for the group session was about one and one half hours. The sessions were organized to validate the scientific findings on choice of new adaptation strategies as earlier conceived by (**Calder, 1977**).

Following a successful conduct of the second session, participants regrouped back to the seminar room for a final wrap-up session. Each group was given a chance to present a summary of their deliberations. In the end, the study findings were endorsed. Based on what the study had heard in the groups, the principal researcher designed a substantive coding system for the final transcripts, using mentions of the most popular adaptation option choice and key factors that could have influenced its preference from among the study correspondents. After compiling a list of such factors e.g. gender, university education et cetera, the study tallied all mentions of the factors in each group, separating them according to whether they occurred in a story about residential location or in a general discussion. In addition to coding the determining factors to the choice of a new adaptation measure, the study compared the course of the discussions across groups, looking for factors which led them to move, first from simple exchanges of experience to attempts at understanding these experiences, and then to some general conclusions based on this shared knowledge, as per advise in the review study on FGD by **Ochieng et al., (2018**).

In summary, the study's conceptual framework covered; the selection of participants, instrument development, data collection, analysis and endorsement of the decision. As per the theoretical construct comprising; risk priming information development and value orientation to condition minds towards decision making in choosing a new coping measure as a protection mechanism against identified risk, the study followed the three dynamic phases proposed by (**Buellow, 1989**), see Figure 15 below;

Phase I: This was risk information development stage which was basically for the observation and reflection phase that entailed; the course work on the part of the team leader to equip him on: research project's concept note preparation, proposal development skills, study site selection criterion, stakeholder selection steps, research project's problem definition and research objectives' framing. These preparatory processes eventually culminated to the first community workshop session which was held to apprise all stakeholders on the scheduled field activity processes.

Phase II: This was the learning phase which entailed; the household survey process design, option choice bundling, questionnaire tool development, population sampling, conduct of the face to face interviews, data collection, data cleaning, data analysis and reporting.

Phase III: This was the decision endorsement phase which entailed; a focused group discussion with the key stakeholders on the analyzed results. In the end, they (the key stakeholders) affirmed the final choice of the new coping strategy. Since climate change risk is dynamic, the same framework (see figure 15) can be used after sometimes to improve on the coping method by the community members.

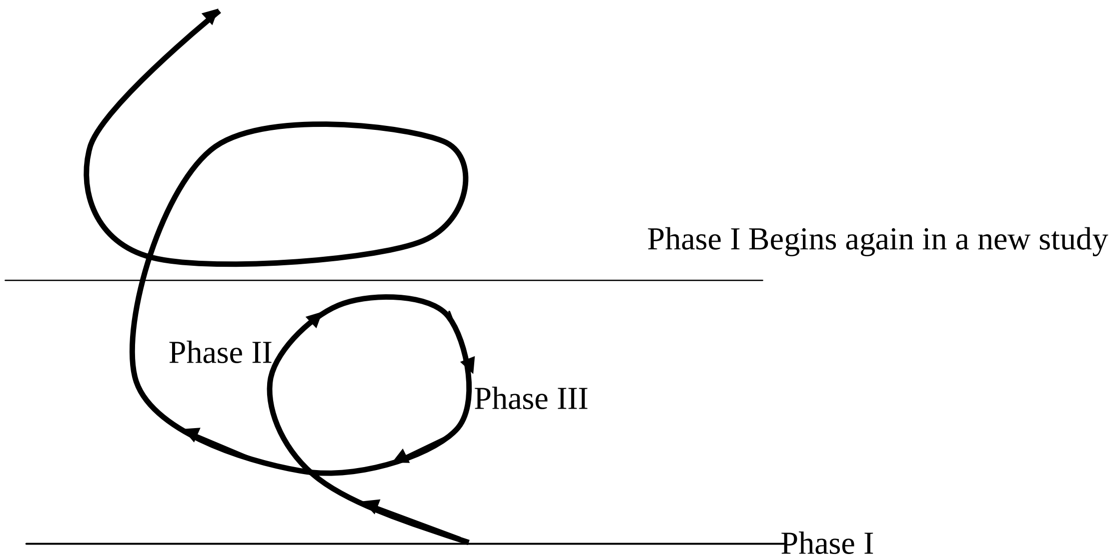


Figure 15:Dynamic adaptive learning and action cycles **(**source;Buellow,1989**)**

3.3 Methods of analyses

The methods deployed for achieving each specific objective are presented hereafter;

3.3.1 Reconstruction of the historical drought exposure profile

The duration, severity and spatial extent are the three very important features of a given drought event that usually aid the rational decisions by authorities and stakeholders on the type of coping strategies to be instituted (**Tsakiris et al., 2016).**This study deployed the most commonly used indices formulae , Standard Precipitation Index (SPI) formula by (**McKee et al., 1993**).

SPI formula calculates the rainfall record for a chosen period by fitting it into a probability distribution subsequently transforming it into a normal distribution so that the mean SPI for the area under review is zero (**Edwards and McKee, 1997**).Actually, the standardization procedure transforms rainfall data to come up with standardized anomalies. The advantage of using the standardization procedure is that it aids in discerning normal and typical values and is symmetrical for the occurrence of wet and dry events (**Sutton and Kempi, 1993**).

Positive SPI values indicate greater than median precipitation and negative SPI values indicate less than median precipitation. According to the work on SPI computation by (**Kumar et al.,2009**), a meteorological drought occurs when the index is continuously below the zero line with drought intensity value (SPI) moving towards -1.0 or less. A drought event ends when the SPI becomes positive (**Kim et al., 2002**).Each drought event is defined by its on-set and its cessation time. Drought magnitude is the value of SPI value of a given drought year (**Hayes et al., 2007**).There are many computer software applications for computing SPI to profile a given drought event like the android application "ProfileDroid" by (**Wei et al., 2012**).In this study however, the data were standardized using the formula as defined by (**Goddard and Melville, 1996**) which was fitted in MS Excel;

$$SPI = \frac{x_i - \bar{X}}{\sigma}$$ Chapter 3-Eq-(3.2)

Where X_i is the annual rainfall of the i-th year, $\overline{X}$ is the mean annual rainfall over the full study period (sample mean), SPI is the normalize standardized departure and ± is the sample standard deviation. This study has adopted the drought severity classification by (**McKee et al., 1995**) where the SPI values are taken to range between "**-2.5**" and "**2.5**". The "**0"** value is the turning point between wetness and dryness. In this study, the value "**0"** indicates the normal rainfall year. Further, the SPI formula was programmed in Excel to help plot the results using a continuous bar chart representation, with each bar representing each year. The percentage share of dry years over the total 57 years of data was calculated by simply counting the SPI values below zero and dividing by 57 and then finally expressing the same as a percentage. From the bars, the driest year was also read out from a visual observation of the plotted profile.

3.3.2 Detection of the area's groundwater resource depletion threat (syndrome)

To establish if there existed a groundwater-grab "syndrome" in Langata, transformed information from SPI values and the statistically processed commissioned borehole data, known here as borehole development data for each year following the **Marzaban et al., (2013**) method were used. In addition the struck water level depth for each year was also superimposed over the same plot in time series format. The described data set; year, drought event record, number of commissioned boreholes in each year and the struck water level depth in meters is presented in appendix 1.Note that the drought event's score for each a given year is represented by 1 in appendix 1 and each wet year is represented by a zero score in the data set. In this study, the correlation coefficient of drought events and borehole development data was used to determine whether there exists a linear relationship between the pair. In algebraic notation, the study coded a single year's drought event as "X" and the number of boreholes drilled in the same year as "Y" following the example of work by (**Helsel and Hirsch,2002**).Therefore, the pair of variables X and Y built into "**n**" pairs according to the number of years with available data thereby forming time series pairs of data of the type; [x_1, y_1], [x_2, y_2], [x_3, y_3] … [x_n, y_n]) .Therefore, the correlation coefficient r is computed using the following equation;

$$r = \frac{\sum_{i=1}^{n}(x_i - \tilde{x})(y_i - \tilde{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \tilde{x})^2 (y_i - \tilde{y})^2}} \qquad \text{Chapter 3-Eq-(3.3)}$$

Where $\tilde{x}$ the mean of the X is values, and $\tilde{y}$ is the mean of the Y values. Correlation coefficient r computation was first demonstrated by (**Galton, 1888**) in a paper that discussed the measurement of the relationship between human height and the forearm length. Its popularity grew very fast and today, it has been established that the value of r always lies between –1 and +1. A value of the correlation coefficient close to +1 indicates a strong positive linear relationship (i.e. one variable increases with the other). A value close to –1 indicates a strong negative linear relationship (i.e. one variable decreases as the other increases). A value close to 0 indicates no linear relationship (**Pallant, 2011**).

To determine the significance of r, the hypothesis test of correlation is done using the above calculated correlation coefficient to test whether there is a linear relationship between the variables in the population as a whole. The null hypothesis is that the population correlation coefficient equals 0. The value of r can be compared with those given in p-value tables similar to the one generated in the working of the paper by (**Bewick et al., 2003**). The strength of the correlation is obtained from a confidence interval for the population correlation coefficient. To calculate a confidence interval, r must be transformed to give a Normal distribution through Fisher's Z_r transformation equations below as was earlier explained by (**Mudholkar and Chaubey, 1976; Plata, 2006**);

$$Z_r = \frac{1}{2}\log\left(\frac{1+r}{1-r}\right) \qquad \text{Chapter 3-Eq-(3.4)}$$

The standard error of Z_r is approximated by;

$$\frac{1}{\sqrt{n-3}} \qquad \text{Chapter 3-Eq-(3.5)}$$

And hence, a 95% confidence interval for the true population value for the transformed correlation coefficient Z_r is given by;

Z_r – (1.96 × standard error) to Z_r + (1.96 × standard error) Chapter 3-Eq-(3.6)

Because Z_r is normally distributed, 1.96 deviations from the statistic will give a 95% confidence interval as per the below equation;

Fisher's transform value for $Z_r = \left(\frac{e^{Zr\ error} - 1}{e^{Zr\ error} + 1}\right)$ Chapter 3-Eq-(3.7)

Using the same analogy for coding data variables as above illustrated, the study took notice that in the period 1982-2017 (36 years), Langata had received a total of 122 borehole developments. A superimposed time series profile of average year's borehole water struck depth level was mounted on the borehole developments time series profile plot using MS Excel. The trend lines of the twin time series profiles, that is, the one for borehole developments and the other of the average year's water struck depth level were drawn using MS Excel command. The gradients of the two trend lines; borehole development per year and drop in groundwater level per year was computed as the indicators of the groundwater "grab" syndrome in Langata as was earlier demonstrated by (**Onyancha et al., 2014**) for Nairobi city as a whole.

3.3.3 Assessing the influence of drought events on ground water quality in Langata

To assess the influence of drought on the ground water quality, the study is to deploy two approaches. The first approach is the probability of exceedance and the second is the display of the graphical plot or the profile showing drought influence on ground water. To do this the study used the transformed monthly rainfall data in the form of SPI values as in appendix 2. This was backed up with the discussion on 2016 drought by **Uhe et al., (2016**) that extended the data period from 2013 to 2016.Using the information from groundwater quality evaluation by indices approach as explained in the next section 3.3.4, the average year's water quality information was obtained as presented again in appendix 2. Using MS Excel, the study plotted the time series profile of the two data sets as a superimpose display over each other in order to visually show the interplay between drought SPI values and the groundwater WQI values. Further, in the working to evaluate Langat's groundwater quality in 3.3.4 as mentioned above, the average quality index for the area will be read out from Table 3 and the upper quality bad limit as read out from Table 5 to give exceedance limit for the groundwater grade. Using the area's groundwater grade and the upper band of the grade envelope, the study calculated the probability of exceedance of this limit due to drought action following the working as shown by **Moser and Huibregtse, (1976**) as expressed in the following equations;

$P(X > X_S) = P(Z > Z_\alpha) = \alpha$ Chapter 3-Eq-(3.8)

Where $Z_\alpha = \frac{X_S - \mu}{\sigma}$ Chapter 3-Eq-(3.9)

It is the Z_α which is read out from Z-Table to give the probability of exceedance in percentage.

3.3.4 Evaluation of the potability of Langata's groundwater resources

Water quality is usually described by the level of concentration of the physicochemical and microbiological contaminants (parameters) found in a water body constituting the source of drinking water (**Chowdhury et al., 2012**). Expressing water quantity in any water body is always an easy task because; one needs to mention only the volume or the flow units at any given time. On the other hand, it is always a complex matter to express the quality aspect of water in such a water body because the latter is influenced by many contributing parameters. To help navigate a solution to this complexity, water quality indexing method was proposed.

According to (**Thivya et al., 2014**), water quality index (WQI) is a rating that reflects the composite influence of the contributing quality parameters. In a review paper done by (**Lumb et al.,2011**),WQI system has been there for more than one and half century and by 2011,there were more than 500 indices for expressing water quality. However, the most popular WQI method is the weighted arithmetic index derived by (**Horton, 1965**) especially its later refined version by (**Brown et al., 1972**). In this study, the borehole commissioning data described in section 3.2.1 (iii) were used to evaluate the groundwater potability in Langata. The following steps were used in developing WQI for Langata.

Step 1: Assigning allowable concentration levels as per the guidelines of World Health Organization and Kenya Bureau of Standards on drinking water. In these guidelines, the permissible concentration limits in milligrams per liter (mg/L) are as follows for the parameters specific to this study; Potassium (50),Sodium (200),Calcium (250),Iron (0.3),Flouride (1.5),Chloride (250),Sulphate (400) and Electrical Conductivity (2500)

Step 2: Ascribing weights to individual parameters. In this step, the study followed the working by **Thivya et al., (2014), Vasanthavigar et al., (2010), Tyagi et al., (2013), and Tripaty and Sahu, (2005**).Each parameter was ascribed a weight value ranging between 1 and 5 depending on the its perceived impact on human health when taken beyond daily tolerable dose limit (**Shah and Joshi, 2015)**.The lowest weight of (1) represents the parameter with the feeblest influence on water quality. On the other hand, weight (5), the highest in the range, is designated to a parameter possessing the most adverse immunological toxicity and whose occurrence beyond allowable limit prohibits the use of water for drinking purposes (**Iteccescu et al., 2013**).Following the guide in **WHO, (2011) and KeBS, (2010**), the 8 geochemical parameters in this study were ascribed weights. Chloride was assigned (4), Calcium (3), while Potassium, Sodium, Fluoride and Electrical Conductivity were each assigned (2). Weight (1) was assigned to Iron and Sulphate.

Step 3: Computation of relative weight Wr

The relative weight (Wr) is the ratio of the weight (Wa) to the total sum of the weights of all parameters expressed as;

$$Wr = \frac{Wa}{\sum_{i=1}^{n} Wa} \qquad \text{Chapter 3-Eq-(3.10)}$$

Where, Wa is the assigned weight of i-th parameter is the number of parameters, in this study

Step 4: Quality rating of each parameter

Quality rating of the i-th parameter is obtained by the observed value in the sample divided by its set allowable limit as expressed by

$$Q_i = \frac{Ci}{Si} X\ 100 \qquad \text{Chapter 3-Eq-(3.11)}$$

Where Q_i is the quality rating of i-th parameter,C_i is the concentration value as observed in the sample,S_i is the standard concentration allowable for the i-th parameter in drinking water. For each i-th parameter, the quality rating value Q_i was computed simply by first dividing the observed concentration in the raw data by allowable concentration in the guideline and multiplying by 100.For example, for Potassium, the observed concentration in borehole serial number 16 is 10mg/L, and the allowable concentration is 50mg/L.Therefore,Q_i for Potassium for this borehole is 2.35.This repeated for all elements and all the 39 boreholes in the list.

Step 5: Computation of Sub-Index and the overall WQI

In this study, Sub-Index is the water quality for each of the 39 boreholes whose water quality is being evaluated. Sub-Index is simply the summation of the quality rating Q_i of each parameter for a single borehole. For example, for borehole serial number 16, the Sub-Index value is 32.16.The overall Water Quality Index (WQI) for the area is the average of the totals from each borehole's Sub-Index water quality value given by the equation

$$WQI = (\sum_{i=1}^{n} SI)/n \qquad \text{Chapter 3-Eq-(3.12)}$$

Where n is the number of boreholes in this study (39) and SI is the individual Sub-Index of each borehole.

Step 6: Water quality grading scale

There has been a lot of debate around the grading scale. Some scales have larger numerical values showing excellent water quality. This study however followed the recent reasoning by (**Kalagbor et al., 2019**) which was motivated by the works of (**Thivya et al., 2014; SAFE, 1995**) by adopting level zero score as being excellent groundwater quality .This approach was also recommended by (**Yadav et al.,2010**) during the water quality index assessment of groundwater in Todaraisingh Tehsil , Rajasthan State, India. Consequently, the study designed a scale in six bands; 0-20 (excellent-grade A), 20-40 (very good-grade B), 40-60 (good-grade C), 60-80 (Fair-grade D),80-100 (suitable-grade E) and any score greater than 100 (unsuitable-grade F) .This produced Table 2, below;

Table 2: Water quality grading scale

Water Quality Rank	WQI (%) Scale	WQI	GRADE
Excellent	<20	<0.2	A
Very Good	20-40	0.2-0.4	B
Good	40-60	0.4-0.6	C
Fairly Good	60-80	0.6-0.8	D
Suitable	80-100	0.8-1.0	E
Unsuitable	>100	>1.0	F

Step7: Production of water quality index maps

The results in step 5 were used to produce graphical presentation of WQI in the form of maps as was earlier suggested by (**Harkins, 1974**).This study deployed the service of Surfer software version 6.The water quality map will help track the water quality and focus will then shift to controlling water contamination during transportation and handling at the point of delivery as discussed by **Nnaji et al., (2019**) for Enugu in Nigeria, see Figure 16 below.

Figure 16:Undermining of informal water quality through poor handling (Source:Nnaji et al., 2019)

3.3.5 Development of the mobile phone application protocol

The development of a Water Quality Tracking System (WQTS) application followed a standard iterative process in creating a mobile application named “Maji Safi app” in line with Agile-Scrum methodology as proposed by **Kaleel and Harishankar, (2013**). It all began with the assumption that there exists a deep-seated mistrust that water consumers hold on the informal water quality. Stemming from this standpoint, the study picturized how to program in terms of data sources, needed algorithms (or the software application programme), features and functions, and levels of risks. The central issue was to understand the propagation of water contamination risk in society today. As is well known that, the modern-day urban water consumer in a developing nation like Kenya is usually exposed to a cascaded water shortage risk level.

At the apex is the climate variability, manifesting itself in varying signals. For this study, the primary risk signal is taken as drought considered as risk level one. This triggers water shortage at the consumer doorstep. This quickly snowballs into risk level two in three ways. One, the high price charged on consumers by the informal water vendors. Two, the intensified and the unregulated groundwater abstraction activities. Thirdly, the one-sided nature of the informal water quality information where it is only the vendors, who alone know the legitimate quality information of their merchandise. The latter can potentially spread the exposure risk further downwards in terms of health implications on consumers. It was the idea of this study to manage the risk at level two using water quality tracking system (WQTS).

For the idealized system, the app functionality was narrowed down to the consumer level. The proposed quality tracking system seeks to mitigate the cost escalation arising from coping with drought induced water shortage. It also aims to manage the exposure risk arising from the public perception that water from the informal water market is of poor quality. And this it will do by allowing registered water consumers to inquire for such information using the app. The programming began with the outlining of the information flow schematically as illustrated in Figure17 below;

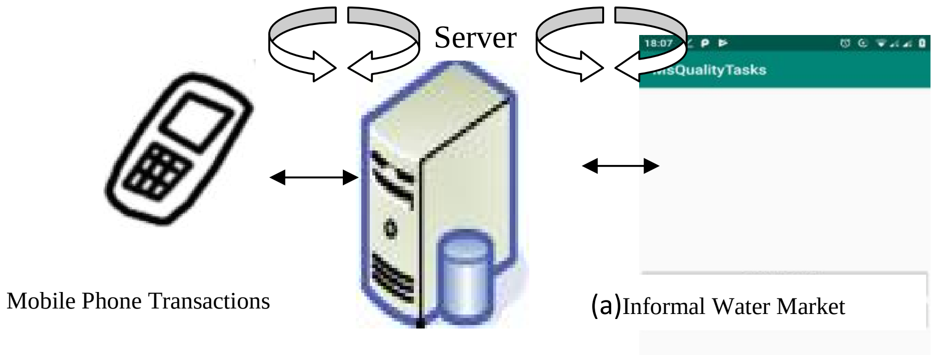


Figure 17:Idealized bi-directional communication between server and system users

3.3.5.1 The design of the application system workings

This study limited the working to how the informal water quality is tracked. Basically, the communication between the server and the holder of mobile phone device, usually known in communication lexicon as the client; a water consumer or interested agent, is bidirectional. First to be in the system, there will be mandatory registration requisites for both the borehole operator and water delivery vendor. This recruitment protocol will fall in the ambit of the water sector quality regulatory agency. The server as the monitoring centre has three critical roles viz;

- User registration and verification.
- Receiving water delivery requests and assigning system generated feedbacks.
- Receiving water quality inquiry request and sending quality feedback for the specifically assigned water source.

The bi-directional exchanges between a water consumer and the server entails; account creation for a first-time user, login for a continuing account holder, making orders for water delivery, user verification, quality confirmation, order verification through price display and user payment. On the other hand, the communication between server and vendor is similarly bi-directional and consists of; user registration and verification, delivery dispatch and water source quality request. The consumer and vendor then communicate through the delivery of the actual water quantity as per the made request. The transactional records remain stored in the server for future water use planning needs.

This basic model was reviewed repeatedly and a prototype of Maji Safi app was produced, to operate on Google's Android Operating System (OS), version 23 or higher. In the creating of the app the study used Google's Android Studio Integrated Development Environment aka IDE ver.3.5 running on windows 10. The primary programming languages used were Kotlin for the app functionality and XML for the app User Interface. Firebase System Development Kit (SDK) was also utilized within the IDE to provide the cloud-based database functionality. The prototype was tested for usability and later modified to refine it through several series of usability tests. The software has three basic functions which are explained below;

- User Registration and Login
- User Requests and feedback
- Water quality verification requests and dissemination

In terms of user experience, the app operates in the English language through message prompting approach. Currently, this study has not created a public access system for the prototype app, which may include avenues like; Google Play Account, web link and /or cloud-based account. For the trial purposes, the set-up link to the proto-type is;

https://drive.google.com/open?id=1VS8PtN4t73cj-oC_HQGOz_Dim87Y16ua.

Remember; this set-up link can only be installed in an android phone. Secondly, the user experience has been made to be simple and interactive. Upon installation and to begin operation, the user is prompted with a command to create an account, preferably using an email address (even a dummy one can work) followed by a request to insert a personal password. It is also important to note that even if the user forgets the first account detail, in the repeat, he/ she can create a new account and proceed as before explained above. This prototype is only a proof of concept for water quality tracking in the informal water market. Otherwise for commercial purposes, the app will be made more robustly intelligent in multi-directions for security reasons. For the application in the Kenya's water sector set up, the Water Services Regulatory Board, the agency responsible for the monitoring of water quality supplied by water companies in Kenya will be the custodian or certifier of the WQTS.

3.3.6 Participatory approaches

The participatory approaches were used in realizing two specific objectives. The first activity was to assess the cost implications of unreliable municipal water supply system whose other aim was to help establish the affordability status of the vendor water deliveries to households. The second and perhaps the most critical activity in the study, was to identify the key factors that determined the public adoption of WQTS through discrete choice experiment survey.

3.3.6.1 Assessment of the affordability status of the vendor water supplies

The affordability assessment of vendor water supplies to the households was to establish the relative cost of the three sources of water; municipal, vendor and bottled water. The analytical computation of the coping cost burden followed the descriptive statistics of the household survey data collected as described in section 3.2.2 .The collected information from the survey questionnaire were sorted into wards .Next, the data was key into MS Excel before being imported into SPSS Software and Surfer Software Version 6.0 with analytical codes.

To assess the implication of water vending in terms of cost burden to the households, the study began by estimating the exposure index factor of water shortage in the study area as a measure of risk avoidance costs among the households. The exposure index factor is a proxy manifestation of the physical dimension of water security at the community level. The exposure index factor formula was modified from the objective index formula of water security (OI) by **Shrestha et al., (2018**).The total cost of water access for a household was taken as the sum of monthly water bill for Municipal delivery (Mp), Vendor delivery (Vp) and Bottled water purchase (B_p).

The total cost of water access (Tt_h) per household in a month is expressed as;

$$Tt_h = (M_p) + (V_p) + (B_p) \qquad \text{Chapter 3-Eq-(3.13)}$$

And the cost of coping with water shortage (Tc_h) per household when municipal water supply fails is;

$$Tc_h = (V_p) + (B_p) \qquad \text{Chapter 3-Eq-(3.14)}$$

The Exposure Index Factor (EI) expression as modified from (**Shrestha et al., 2018)** is;

$$EI = 1 - (\frac{V_p + B_p}{M_p + V_{p+B_p}})$$ Chapter 3-Eq-(3.15)

When EI is 1, then, households are absolutely dependent on municipal supply which is the ideal condition. Next, the study computed the household's vulnerability (V_h) to a water shortage situation; being the potential loss stemming from risk avoidance cost as per equation (2) above. During an extreme dry period, the cost of coping was expected to be high for each household. And mathematically, (V_h) was expressed as a ratio of total cost of coping to the overall cost of water access, being a modification formula from the work by (**Liu et al., 2017**);

$$V_h = \frac{V_p + B_p}{M_p + V_{p+B_p}}$$ Chapter 3-Eq-(3.16)

As the value V_h approaches 1, then water shortage risk is at its peak. And the combined vulnerability index (VI) of all households to water shortage was expressed as;

$$VI = 1 - \sum_{i=1}^{N} (\frac{Tc_h}{Tt_h}) = 1 - \frac{\sum_{i=1}^{N} V_h}{N}$$ Chapter 3-Eq-(3.17)

Finally, the study computed the coping cost burden (CCB) as an index ratio of the total household's monthly water bill less the municipal monthly bill to the municipal monthly bill, expressed as a percentage;

$$CCB = \left(\frac{T_{th} - M_p}{M_p}\right) x\ 100$$ Chapter 3-Eq-(3.18)

3.3.6.2 Identification of the key factors that determined the public adoption of WQTS

Using data collected from household survey as described in section 3.2.2 the study then deployed descriptive statistics in the IBM SPSS Statistics Version 25's environment to profile the demographic structure of the stakeholders which informs how their behavior to adopt new coping technologies (**Mugabi et al., 2007**). To fish out their coping behavior, the study deployed, MPlus version 8.3 Demo for factor analysis. And to isolate the major determining factors for adoption of WQTS, an extended latent class analysis using LatentGold®version

5.1.0.19164 was deployed. These processes were in line with the guidelines of Conditional Logic Model discussed in section 2.8

3.3.6.3 Endorsement of the WQTS adoption decision

Using the qualitative data collected through a Focused Group Discussion (FGD) process as described in section 3.2.2.2, the study deployed analytical skills. The notes that were recorded during the process were transcribed and from it conclusive remarks were developed regarding the key endorsement outcomes using MS Word.

CHAPTER FOUR: RESULTS AND DISCUSSIONS

4 Introduction

This section presents the results and discussions on the five themes of this study. The first theme is the reconstructed drought history of Langata during the period 1957-2013 to establish the drought exposure risk. The next theme discussed is that of Langata's groundwater depletion threat. This is followed by Langata groundwater resource's potability assessment theme. The section ends with results of the household survey to establish affordability of the vendor water and the identification of the major socio-demographic factors that determined the adoption of the WQTS as a new coping method.

4.1 Historical drought exposure profile of Langata

In this section, the historical drought exposure profile of the study area is presented. It was established that between 1957 and 2013, the area was under drought condition for about 60% of the time. Drawing insights from the larger national scale, Kenya's drought disaster condition is often a source of devastation to many households (**Uhe et al., 2017**).According to **Nkedianye et al., (2011**), drought occurrence in Kenya is slowly becoming an annual ritual thereby affecting many sectors. But most notably, the water sector is the most vulnerable according to **Wandiga, (2015**).For that reason, Nairobi city for instance is always having a water shortage challenge (**Njoroge, 2011**).Consequently, a significant number of Nairobi residents depend on borehole supplication (**Chakava et al., 2014**).Langata sub County's households are affected by the water shortage. Using the monthly rainfall data discussed in section 3.2.1 (i), this study developed the drought exposure profile over Langata, see figure 18.

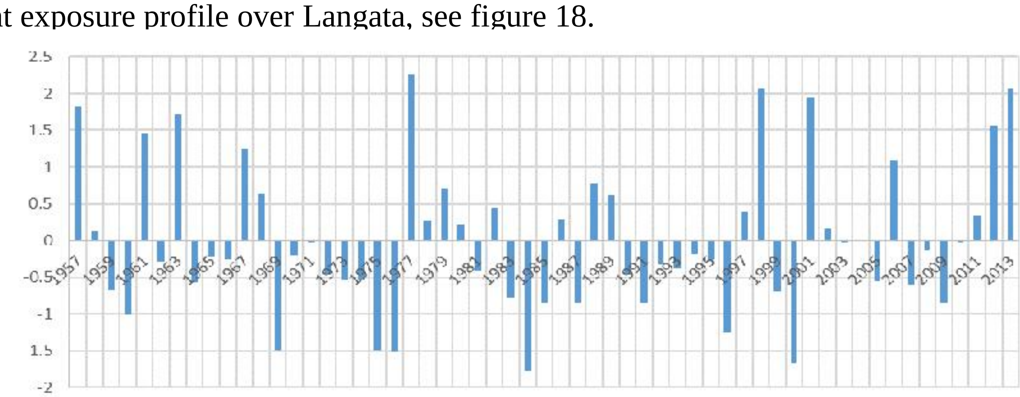


Figure 18: SPI plot as a drought exposure profile over Langata for the period 1957-2013

In the profile, the X-axis is the time in years and Y-axis is the SPI values. The bars that projected upwards above "0" are taken as "wet years" and the ones facing downwards or the negatives are read as "dry years" which in this study is taken as the drought exposure. This profile clearly provides the evidence that Langata is exposed to frequent drought occurrence as earlier alluded to by **Nkedianye et al., (2011**) while discussing Kenya's situation. The drought exposure over Langata is up to 59.65% since 34 out 57 years (1957-2013) were drought years. From Figure 18 above, 1983-1985 and 2011 were the most severe drought periods as per the analyzed data which sort of confirms Kenya's drought devastation chronicles pieced together earlier by **Chisanya, (1990)** and most recently by **Loewenberg, (2014**).

4.2 Groundwater resource depletion threat syndrome

In this section, the results of the correlation and trend analyses between drought and the number of boreholes installed to cope with the resulting drought induced watershortage are presented.

4.2.1 Relationship between drought episodes and the number of boreholes installed

Results of the simple correlation analysis show that the borehole numbers were increasing but the corresponding relationship with drought events in Langata is not clear. However, an earlier finding by (**Simiyu and Dulo, 2015**) indicated that the borehole density in Nairobi city was menacingly on the rise. Since drought is a single year event, what is observed from the data is that installation of boreholes was highest in 2011 and the rest of the years, the numbers were minimally increasing up to 2010.There was a spike in 2011 and a drop in 2013 before rising slightly in 2014 as the numbers dropped to less than 6 in 2017,see Figure 19.The simple correlation coefficient between drought events and borehole development data in Langata is 0.12 which falls within the first envelope of classification by (**Pallant ,2011**) but is not statistically significant. Additionally, the coefficient of determination (**R**) usually known as r-squared ($\mathbf{r^2}$) x 100 is 1.4%.

The data's sample size is 26 (see appendix 1) and as mentioned above, r is 0.12 and checking the ρ=0.01 from the ρ –table in (**Bewick et al., 2003)** a bigger value is confirmed. This big ρ value for ρ=0.01 indicates that there is a sufficient evidence to suggest that, the pair of the variables' correlation coefficient is not zero and that there is a linear relationship between drought occurrence and the borehole drilling. The significance of this relationship is shown by the transform correlation coefficient Z_r between drought episodes and borehole development. The Z_r equation gives 0.12 with a standard error of 0.209.The 95% confidence interval for Z_r is therefore -0.292 to 0.527.Using Fisher's transform value for Z_r equation, the lower and upper limits of the confidence interval for the determination of the 95% confidence level ranges between 0.28 and 0.48. The values are small which confirms the statistical insignificance of the relationship between drought episodes and the number of boreholes installed in Langata as above mentioned.

4.2.2 Trend

Figure 19 below plotted from data in appendix 1 displays the boreholes' struck water level depths data is in two ranges. The visual observation of Figure 19 indicate that ,from the year 1982 to 2004, the struck water level depths fall between 200m and 243m.Similarly,from the year 2005 to 2017, the struck water level depths range deepened and therefore fall between 256m and 337.5m.The implications of this latter deepening phenomenon is interpreted here to mean that the aquifer's water resource storage is under threat of depletion and further that the cost of borehole investment is on the rise from the borehole drilling and operation costs perspectives. From the struck water level depth of 2017 (337.5m) and 1982 (200m) the slope of level decline over the 36 years of data is found to be 3.82m / year. This slope indicates that the drop in groundwater level per year is 3.82m.This decline rate may not be matching the aquifer recharge (replenishing) and is 14.7% increment above the 3.33m/year rate earlier computed by **Onyancha et al., (2014**) for the entire Nairobi city. The trend in the drop of the groundwater level almost parallels that of borehole installation in Langata from the physical observation of the trend lines in Figure19 below. From this revelation, it may be inferred that as the borehole numbers rise so does the drop in struck water level in the area which therefore requires an intervention as earlier proposed by **Silvestri et al., (2013**).

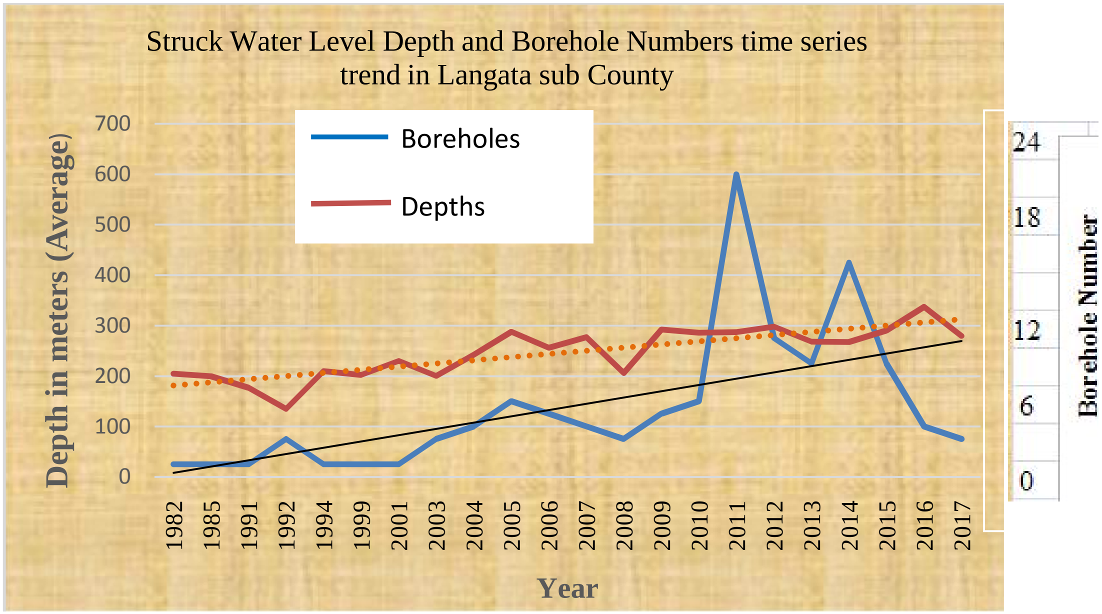


Figure 19: Trend analysis diagram

4.3 The influence of drought on ground water quality in Langata

In this section, the impact of drought on the groundwater potability in Langata is presented by the plot of water quality index (WQI) values and the drought indices (SPI values, see appendix 2). The blue line in Figure 20 is a time series plot of the average annual WQI of the installed boreholes .It represents the groundwater quality profile, which ranges from excellent to unsuitable as per the grading scale in Table 2 presented in section 3.3.4.The red line is a superimposed time series plot over Figure 20 showing the rainfall performance based on the computed SPI values. The rainfall performance profile shows that 60% of the time was dry. In Figure 19, it is evident that the borehole installations were in an increasing trend which coincides with the recent finding in a study by (**Oiro et al., 2020** .The increasing drought risk may in future affect the city's groundwater quality as was earlier reported by(**Rendilicha, 2018**).

The visual reading of the plot in Figure 20 indicates that, in the 1970s to 1980s the groundwater quality was in the excellent grade range as per guidelines in Table 2.Further, the geo-chemical analysis of the Langata borehole parameters has shown that the Flouride concentration is high in at least 77% of the analyzed boreholes, see section 4.4.6. This reinforces the earlier finding by (**Coertsier et al., (2008**) for the entire Nairobi city's groundwater. It has been reported before by (**Macdonald et al., 2009**) that drought events may affect groundwater quality of a place. For this study, the analyzed data have shown some element of groundwater quality decline in time series as the drought events unfold. It is however not possible to conclusive state that there is a direct relationship between drought events in Langata and the decline of groundwater quality.

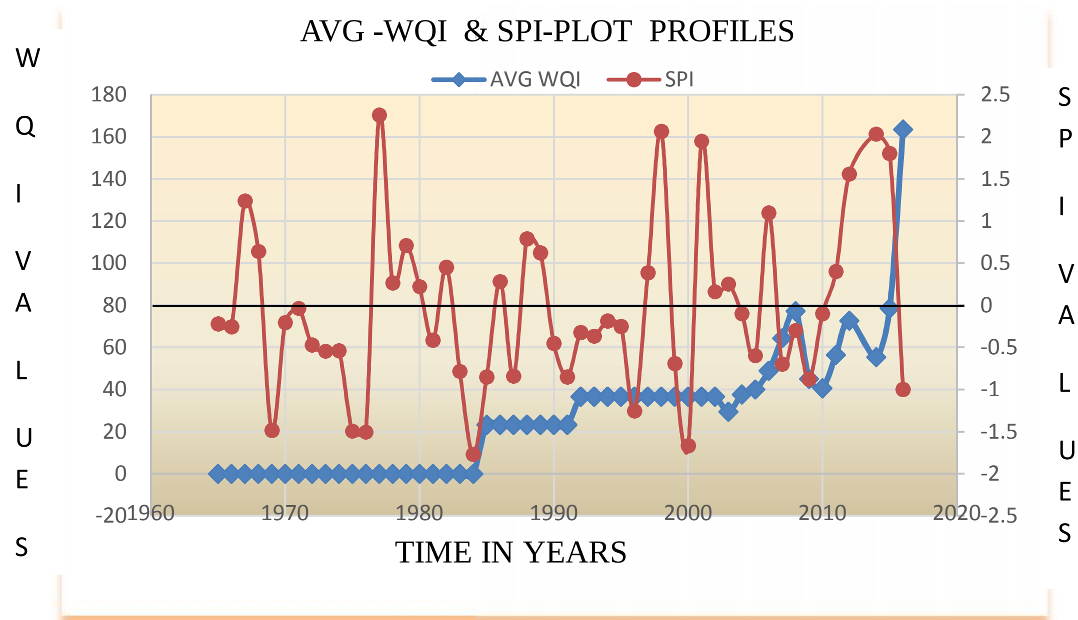


Figure 20:Profile of drought events and ground water quality in Langata

The second presentation of the drought impact on groundwater quality is through the probability of exceedance formula equations' *Chapter 3-Eq-(3.8)* and *Chapter 3-Eq-(3.9)* outlined in section 3.2.2.3.From Table 5 ,see section 4.4.1 below,X_S is 60 and the area's groundwater quality on WQI scale is 53.18; this value is the average Sub-Index water quality of the 39 sampled boreholes as presented in the last column of Table 3,see section 4.4.1, having a standard deviation, σ of 29.92 and all together posting a $Z_\alpha$value of 0.16. This $Z_\alpha$value gives a probability of 0.4365 from the standard Z-Normal Distribution Table. This probability value therefore means that the drought events in Langata have up to 43.65% probable chance of lowering the ground water quality by exceeding the grade "C" limit of the area whose upper bound value is 60 on the WQI scale, see Table 2. Inferring from these results, it is perhaps appropriate at this point to state that drought in Langata has a direct influence on the deterioration of the potability of the groundwater. This means that during dry season, households who depend on groundwater must as a necessity strive to exercise due care lest they get exposed to unsuitable water for human consumption as **Tripaty and Sahu, (2005**) had advised in their work.

4.4 Evaluation of the potability of Langata's groundwater resources

4.4.1 Overall Groundwater Quality Index (WQI)

According to **Ramakrishnaiah et al., (2009**), water quality index is calculated from the point of view of ascertaining its suitability for human consumption.Accordingly,this study followed the steps highlighted in section 3.3.4,specifically using both the listed steps and equations; *Chapter 3-Eq 3.10* to *Chapter 3-Eq (3.12)* to develop the water quality index for Langata. It began first by developing geo-chemical acceptable concentration limits as presented here in Table 3 below;

Table 3: Acceptable concentration levels (mg/L)

Parameter		Acceptable Level
K^+	Potassium	50
Na^+	Sodium	200
Ca^{2+}	Calcium	250
Fe^{2+}	Iron	0.3
F^-	Fluoride	1.5
Cl^-	Chloride	250
SO_4^{-2}	Sulphate	400
Ec(µS/cm)	Electrical Conductivity	2500

The result of WQI for the 39 boreholes is shown in Table 3. Note that SI is the Sub-Index water quality of each borehole as a summation from 8 parameters.

Table 4: Statistical analysis of 8-geochemical parameters from 39 boreholes

WQI Computations								
K+	Na+	Ca2+	Fe2+	F-	Cl-	SO4-2	Ec(µS/cm)	WQI {∑ SI}
2.35	3.46	0.68	11.18	10.82	1.98	0.02	1.67	32.16
0.24	6.12	0.45	8.82	21.18	1.60	0.04	2.32	40.76
0.89	4.62	0.00	1.37	67.45	1.04	0.02	1.77	77.16
1.67	5.01	0.56	0.20	78.43	4.24	0.09	1.60	91.80
0.31	9.56	0.17	9.61	50.98	5.74	0.67	3.57	80.60
2.19	6.05	1.13	0.00	51.76	0.47	2.21	1.78	65.59
1.41	4.41	0.06	5.88	38.43	1.79	0.18	1.34	53.51
0.33	3.62	0.79	8.24	9.80	1.60	0.06	1.71	26.16
2.05	6.05	1.98	29.41	19.61	6.59	0.21	2.40	68.29
2.42	5.44	1.13	3.33	5.73	2.45	0.17	2.56	23.23
5.65	5.06	2.19	3.92	30.59	7.15	0.32	1.81	56.69
7.06	5.59	0.36	0.59	10.98	3.67	0.14	1.79	30.17
5.88	5.29	1.84	1.96	30.59	7.06	0.32	2.35	55.30
3.53	4.73	0.11	16.86	69.73	1.69	0.14	1.88	98.68
2.49	6.50	0.51	0.39	26.67	1.69	0.10	1.46	39.82
2.94	2.94	1.02	4.12	20.00	2.26	0.11	1.73	35.11
2.19	3.00	0.79	0.59	2.35	1.04	0.18	1.27	11.40
2.14	3.10	0.56	5.06	9.41	1.51	0.06	1.41	23.25
0.38	2.94	1.47	0.78	21.18	2.45	0.03	1.82	31.04
0.33	4.81	0.17	2.35	47.06	1.32	0.14	1.78	57.96
6.16	5.48	0.34	0.59	15.69	3.01	0.12	2.49	33.88
1.98	4.19	0.28	19.22	12.55	1.41	0.09	1.69	41.40
2.35	3.45	1.41	6.86	4.86	1.88	0.33	2.36	23.51
2.07	3.38	1.30	1.76	61.18	1.88	0.05	2.20	73.83
1.88	3.41	1.41	2.16	20.39	2.07	0.12	1.98	33.42
4.00	3.55	0.79	0.20	12.71	1.51	0.03	1.85	24.63
4.49	4.43	0.37	0.98	8.24	5.08	0.26	5.60	29.45
2.12	4.18	0.68	14.12	36.08	1.60	0.14	1.84	60.75
2.35	3.53	0.62	2.94	14.90	1.13	0.10	1.63	27.20
1.04	4.85	0.85	5.49	14.90	3.39	0.17	2.10	32.79
1.65	4.71	0.17	11.76	83.76	1.79	0.14	2.00	105.99
1.13	3.76	1.41	0.02	39.22	3.76	0.07	1.71	51.08
2.05	4.65	0.11	1.71	52.55	2.35	0.12	1.51	65.04
0.80	5.00	0.17	0.20	45.49	1.13	0.00	2.02	54.81
2.82	5.21	0.23	0.20	86.27	1.60	0.15	2.13	98.60
1.60	4.28	0.71	5.88	47.06	6.40	0.29	1.42	67.63
0.26	3.88	0.28	5.10	25.88	0.85	0.09	1.63	37.97
2.28	7.18	0.85	8.43	130.20	11.29	0.54	2.60	163.38
1.29	17.56	0.00	7.84	9.41	5.74	0.67	7.52	50.04
Average SI=WQI For Langata								**53.18**

The study then assigned weight according to the relative importance of each parameter in the overall water quality for drinking purposes as presented in Table 4 using the method discussed in section 3.3.4 using steps 2 and equations; *Chapter 3-Eq 3.10* that produced Table 4be

Table 5:Weight in order of importance

Parameter		Wa	Wr
K^+	Potassium	2	0.118
Na^+	Sodium	2	0.118
Ca^{2+}	Calcium	3	0.176
Fe^{2+}	Iron	1	0.059
F^-	Fluoride	2	0.118
Cl^-	Chloride	4	0.235
SO_4^{-2}	Sulphate	1	0.059
Ec(µS/cm)	Electrical	2	0.118
Total		17	1

In addition, the study borrowed heavily from the examples of similar investigations (**Thivya et al.,2014;Vasanthavigar et al.,2010;Kalagbor et al.,2019;SAFE,1995;Iticescu et al.,2013;Varol and Davraz,2015;Raju,2006**) to develop the water quality index rating scale as presented in Table 2 using steps 4 and 5 of section 3.3.4.Based on the Sub-Index values of each borehole from Table 3 above, the study computed the average of the 39 boreholes' Sub-Indices (SI) and posted an overall water quality index of 53.18.Consequently and using Table 2, Langata area's groundwater quality is ranked as good as it falls within the 40-60 percentage band or grade "C". In addition, the study deployed Surfer software version 6 to plot the spatial water quality map. For the overall groundwater quality map, see Figure 21 .The map shows that both Karen ward and Mugomoini ward have a common groundwater quality ranging between 20-60 using the appended color-scale on the right side of the map.. The scale ranges from 0 to 140 and should be read together with the guide in Table 2.

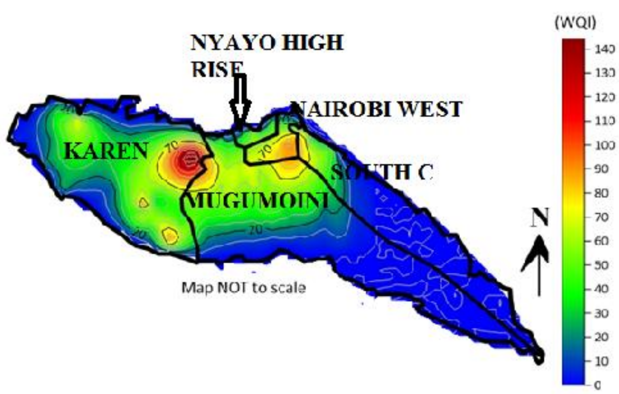


Figure 21: Overall Water Quality Index map

From Figure 21 of the overall water quality index map for Langata,it is clear that groundwater quality is generally good (grade C) save for a few spots with an elevated concentartion of hydrochemistry which could be linked to the nature of the contributing subterrean rock materials.The boundary of Mugumoini and Karen wards seem to have an intense case of this elevation followed by the boundary between Nairobi West and South C wards.This finding confirms the earlier arguements presented by a number of scholars,among them; **Nyanchaga,(2016),Mwenda et al., (2019)** and **Cowman et al., (2017)** to the effect that Nairobi Aquifer System's waters could be having contaminants in certain zones.This assertion is common for groundwater in most urban areas which are prone to contamination (Saana et al.,2016).This situation is not good especially for Nairobi where 60% of residents live in slums (**Crow and Odaba, 2010;K'Akumu, 2004**) and whocmostly depend on groundwater which they access exorbitantly from vendors (**Bird et al., 2017**).

4.4.2 Concentration of Potassium

Potassium concentration is presented in the first column of Table 4.It is worthy to note that the Potassium concentration is falling within permissible limit as per the WHO's guidelines inTable 3. Potassium is described as being both an electrolyte and a nutrient. It works with Sodium to maintain the body's water balance, nerve function; muscle control and blood pressure control. Excessive ingestion of Potassium is not good for health. Karen, Nyayo High rise and South C wards have higher spots of concentration but within the limit as indicated in Figure 22.

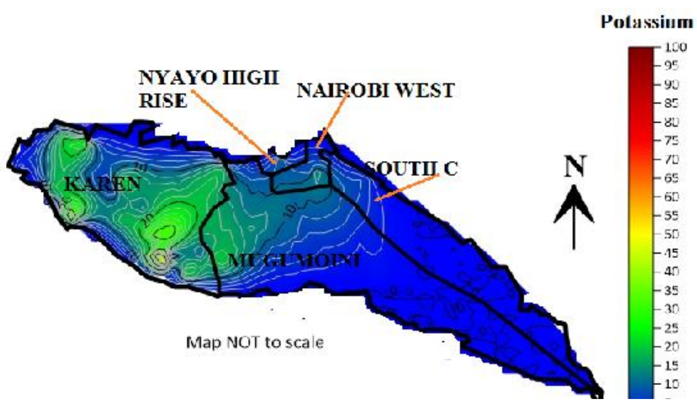


Figure 22: Concentration of Potassium

4.4.3 Concentration of Sodium

The concentration of Sodium in the study area ranges from 50-298.5mg/L.One borehole out of the 39 analyzed had a Sodium concentration above the 250mg/L permissible level as per the guideline in Table 3. High ingestion of Sodium is not good for health with regards particularly to hypertension. Figure 23 is a representation of Sodium concentration spatial display. Karen ward has a higher Sodium concentration spot followed by South C ward read from the chroma scale as explained in section 4.4.1.

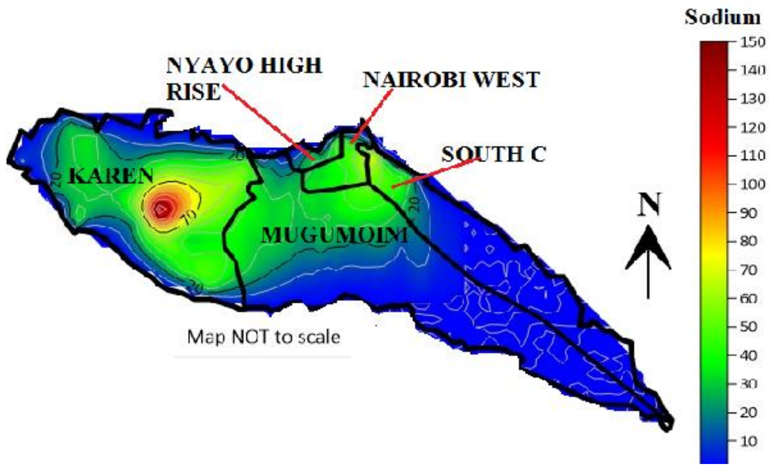
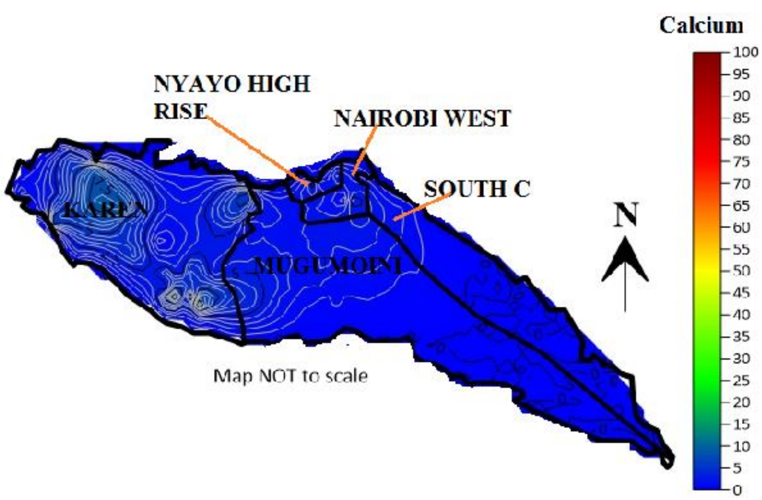


Figure 23: Concentration of Sodium

4.4.4 Concentration of Calcium

The concentration of the Calcium in the study area ranges between 0.01 -30mg/l, which is within the permissible limit of 250mg/l as per guideline in Table 2. In the normal circumstances, 99% of Calcium in the body functions as the structural element in bones and teeth. The other 1% performs vital physiological processes. Inadequate intake of Calcium is associated with increased risk for diseases such as kidney stones. Excessive intake of Calcium can cause crippling skeletal fluorosis and possible increased bone fracture risk. Figure 24 shows the spatial display of Calcium concentration in Langata's groundwater. It is evident from Figure 24 that Karen Ward has an elevated concentration of Calcium but within permissible limit as per guideline in Table 3.



4.4.5 Concentration of Iron

Iron concentration in groundwater samples in the study area varies from 0.001-1.5mg/L. The standard acceptable limit is 0.3mg/l as per the guideline in Table 3.In the sample of 39 boreholes, 12 (30.7%) have higher concentration above the permissible limit. High Iron contamination is an indication of the presence of ferrous salts that precipitate as insoluble ferric hydroxide and settle out as rusty silt. Toxic effects may result from the ingestion of large quantities of iron. At concentrations above 0.3 mg/L, iron can stain laundry and plumbing fixtures and cause undesirable tastes. Iron may also promote the growth of certain microorganisms; leading to the deposition of a slimy coat in piping. The variation of Iron concentration in the study period is shown in Figure 25, where Karen parts of Nairobi west, north western tip of South C and Mugoini wards share the elevated concentrations.

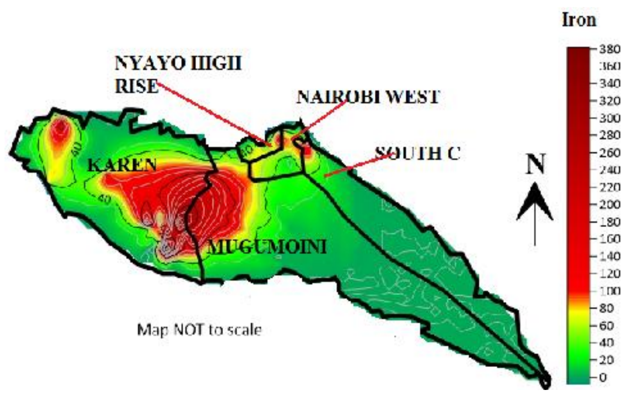


Figure 25: Iron Concentration

4.4.6 Concentration of Fluoride

The Fluoride concentration in Langata groundwater resource ranges from 0.30-16.6 mg/L.Within the 39 sampled boreholes, nine have their Fluoride concentration being within the acceptable limit of 1.5mg/L as per guideline in Table 3.This means only 23.7% (9/39) of the area boreholes have safe limit of Flouride. The variation of Fluoride concentration is dependent on a variety of factors such as the amount of soluble and insoluble Fluoride in source rocks, the duration of contact of water with rocks and soil temperature, rainfall, oxidation- reduction process.

The presence of small quantities of Fluoride in drinking water prevents tooth decay. However it has a poisonous toxicity challenge at high concentration levels. The high concentration levels may cause easily noticeable dental fluorosis and skeletal damages; the latter being not clinically obvious until advanced stage has occurred. Fluorosis is a source of aesthetic concern, because, discolored teeth could affect an individual's facial appearance and a sense of wellbeing. Groundwater with high Flouride concentration should be deflouridated for drinking. The spatial variation of Fluoride in the study area is shown in Figure 26 in which Karen, parts of South C and Nairobi West wards are shown to have elevated concentrations.

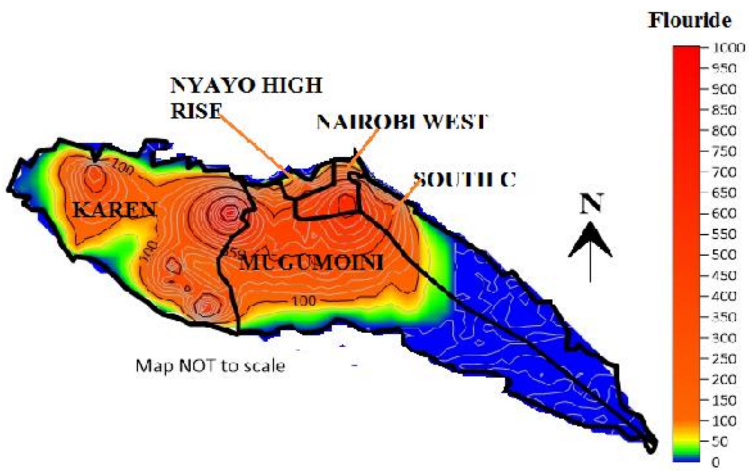


Figure 26: Fluoride Concentration

4.4.7 Concentration of Chloride

Chloride concentration in Langata groundwater is in the range of 5-120 mg/L, which is within the permissible limit of 250 mg/Las per Kenyan Standards as well as WHO Standards as presented in Table 3. The spatial variation of Chloride concentration in the study area is shown in Figure 27. Chloride concentration in groundwater is usually high where the temperature is high and rainfall is less. Spots of elevated levels are found within Karen, Nyayo High rise and South C wards

.

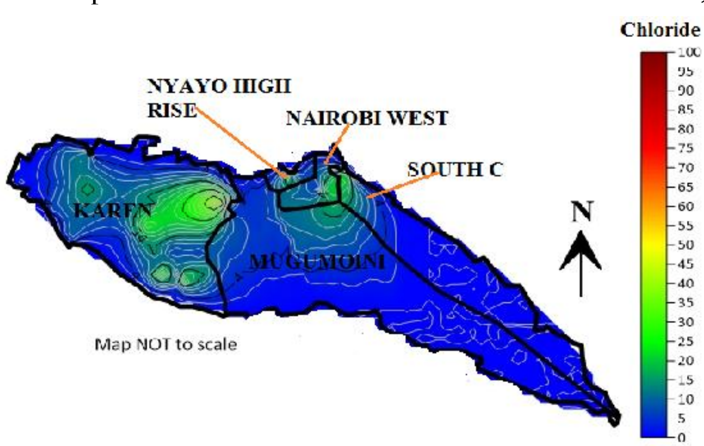


Figure 27: Chloride concentration

4.4.8 Concentration of Sulphate

Sulphate concentration in Langata groundwater ranges from 0.29-150 mg/ L which is within the permissible limit of 400mg/Las per Kenyan Standards and WHO drinking water guidelines at 250mg/.Ingestion of water containing high levels of Sulphate may cause diarrhea. The variation of Sulphate concentration in the study area is shown in Figure 28 where Karen ward is exhibiting the highest level of concentration.

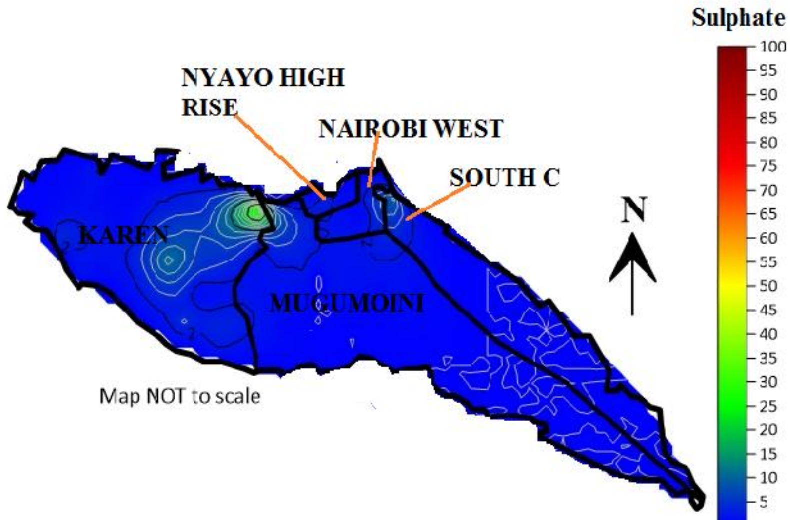


Figure 28: Sulphate Concentration

4.4.9 Electrical Conductivity

The Electrical Conductivity (EC) of the groundwater in Langata sub County ranges from 270-1598 µS/cm which is within the permissible limit of 2500, as per Table 3 allowable limits. Conductivity is an indicator of other water quality problems. Water with high mineral content usually exhibits a higher conductivity and this is a general indication of high dissolved solids concentration of the water. The variation of Electrical Conductivity in the study area is shown in Figure 29with Karen Ward having the highest EC.

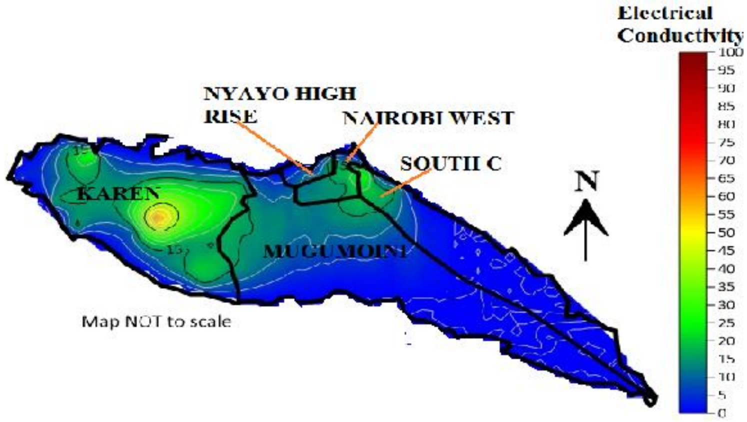


Figure 29: Electrical Conductivity

4.5 The developed "Maji-Safi" application prototype

As explained in section 3.3.5 the prototype was developed successfully.The application's Uniform Resource Locater (URL) link in the web is presented thus;

https://drive.google.com/open?id=1VS8PtN4t73cj-oC_HQGOz_Dim87Y16ua.

The prototype has an inbuilt quality tracking algorithm in a similar fashion as described by **Srivastava et al., (2018**).From the prototype, the user functions that can be executed in a typical android smart phone have been explained in appendix 9.

4.6 The affordability status of the vendor water supplies (cost burden)

4.6.1 General

In this section the study aim was to assess the affordability status of the informal water alternatives relative to the municipal water supplies by the utility company. In this section the focus is on the statistical summary of the household survey conducted between 20th February, 2019 and 23rd May, 2019 whose synthesis details are presented in Table 6.In Table 6, the gated communities (estates) have been coded from number 1 to 57.In terms of distribution ,Code 1-23 are from Mugumoini ward, code 24-27 (Nairobi West ward),code 28-30 (Nyayo Highrise ward, code 31-43 (South C ward) and lastly code 44-57 (Karen ward). The general finding from the survey data is that, 99.7% of the 382 sampled homes confirmed that Langat sub County does experience intermittent municipal water supply shortage. Further, the analyzed results show that, 91.1% of the households depend on informal water alternatives' supplication to survive during outage period thereby justifying the need to assess the level of cost burden on the households

4.6.2 Understanding the unit rates in use

To assess the affordability status of the informal water alternatives, the study first began by evaluating the prevailing water tariff rate Nairobi City County that the water company uses to bill its customers. The water company's unit rate is based on the Increasing Block Tariff (IBT) as per Kenya Gazette Notice No.7335 dated 5^{th} October, 2015 (The Kenya Gazette, p.2372). Further, the study assumed that each household's water connection is half inch meter type and hence the meter rent per month is taken as Kshs.50. With that in mind and in accordance with the prevailing municipal water supply's Increasing Block Tariff, the initial lower range consumption volume from **0** up to 6 units is Kshs. 204.And the next range of consumption, above 6 up to 60 units, is charged at Kshs.53 per cubic meter.

Two issues should be noted. Firstly, one cubic meter is 1000 litres which actually is one unit according to the municipal water metering system. On average, if we consider up to 60 units, the rate is (50+204 + (60-6) *53)/60, which is Kshs.51.93. The study used the prevailing foreign currency exchange rate at the time of the survey in which 1 USD was equivalent to Kenya Shillings (Kshs) 102.27.The survey data captured water consumption per households in litres.In fact when making orders for water tanker delivery respondents stated that orders are always made in litres. But this runs contrary to the municipal metering system where one unit (that is $1m^3$) of supply is equivalent to 1000 litres. Accordingly therefore, the study expressed the cost in USD per litre as 0.0005078.When this converted to unit tariff rate by multiplying by 1000 x 102.27, you get $59.93/m^3$.

From the household survey data on the water tanker delivery costs, one-liter costs 0.00976 USD per liter in the area. And for the bottled water using same reasoning as that for the water tanker, one-liter costs 0. 1465USD.The route of market cost of bottled water was avoided because households have varying brands of preference. Stemming from the above, the household survey data which were in cost form in term of Kshs were converted to volumes in litres. The individual household consumption was converted to estates as averages both in costs and in volumes see, Table 6. Using information from able 6 and geographic coordinates of the estates (X, Y) of estates, contour maps were drawn, for the consumed volumes of water and their respective costs. The average cost and average consumption volumes of each estate were taken as 'Z' value when in a triangulated irregular network of the points in the Surfer Software which helped produce 2D contoured surface maps representing either water consumption per ward or cost. The plots have color scale-values.

4.6.3 Cost implications of water access

4.6.3.1 Water from utility company

The survey was conducted in 57 gated communities (estates) spread within the five wards as explained in 4.6.1 above. Using the unit rates and the survey results, it was established that South C ward households spend most on utility followed by those from Mugumoini ward. Karen ward households follow in number three in that ranking; see Figures 30, 31 and 32.

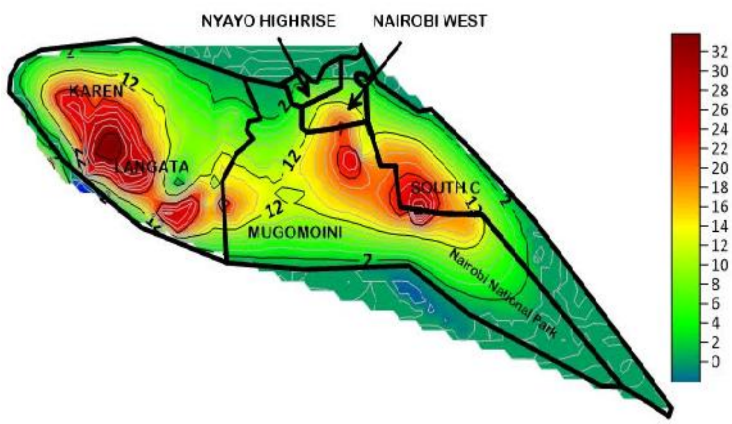


Figure 30: Cost of water access from utility company in USD

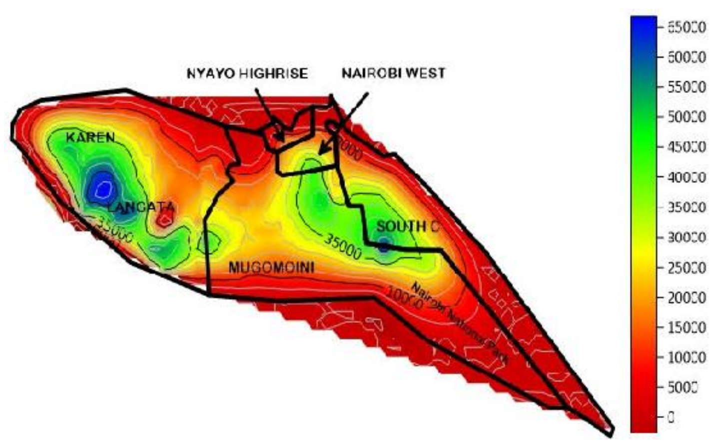


Figure 31: Water volume in litres accessed from utility company

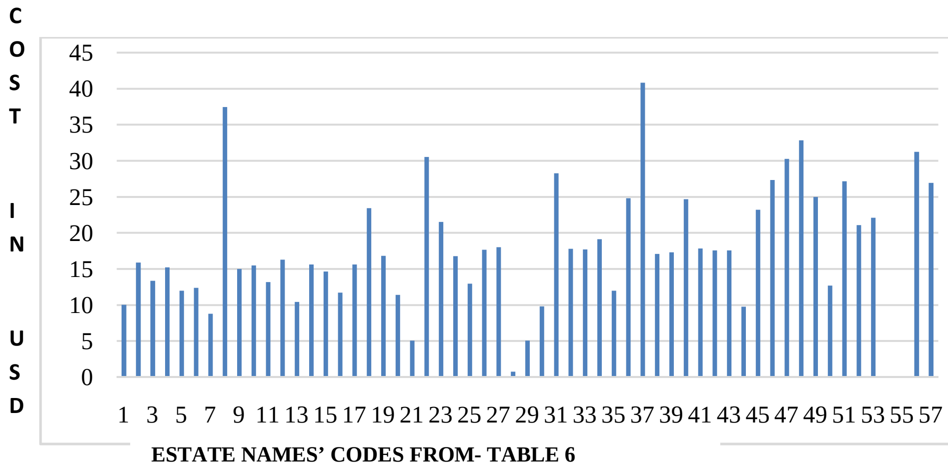


Figure 32: Average cost of water access from utility company in USD per Estate

Table 6:Statiscal summary of household water access cost in Langata Sub-Co

					AVG. Monthly cost per household in USD (USD 1 = KES 102.37)			Corresponding Avg. Volume per Household in Litres		
WARDS	**Code**	**Estates**	**Wards**	**Hholds**	**Utility**	**Tanker**	**Bottled**	**Utility**	**Tanker**	**Bottled**
Mugumoini	**1**	Sun Valley 1	Mugumoini	6	10.05	73.26	15.47	19,801.03	7,500.00	105.56
	2	Civil Servants	Mugumoini	4	15.87	51.28	20.39	31,290.12	5,250.00	139.17
	3	Genesis court	Mugumoini	3	13.35	24.42	16.15	26,315.79	2,500.00	110.22
	4	NHC Langata	Mugumoini	5	15.24	32.24	14.85	30,038.51	3,300.00	101.33
	5	Kianda Close	Mugumoini	4	11.97	40.30	5.74	23,587.93	4,125.00	39.17
	6	David court	Mugumoini	3	12.37	9.77	14.98	24,390.24	1,000.00	102.22
	7	Jordan court	Mugumoini	2	8.79	0.00	4.88	17,329.91	0.00	33.33
	8	Ngei 1	Mugumoini	3	37.45	17.58	9.28	73,812.58	1,800.00	63.33
	9	Ngei 2	Mugumoini	3	14.98	32.56	10.75	29,525.03	3,333.33	73.33
	10	Amani court	Mugumoini	3	15.47	65.12	33.21	30,487.80	6,666.67	226.67
	11	Sinai Court	Mugumoini	2	13.19	18.56	10.26	25,994.87	1,900.00	70.00
	12	Ngeno	Mugumoini	3	16.28	35.82	15.47	32,092.43	3,666.67	105.56
	13	Moi court	Mugumoini	3	10.42	32.56	7.98	20,539.15	3,333.33	54.44
	14	Uhuru Gardens 1	Mugumoini	4	15.63	37.85	9.77	30,808.73	3,875.00	66.67
	15	Uhuru Gardens 2	Mugumoini	1	14.65	39.07	17.58	28,883.18	4,000.00	120.00
	16	Akiba	Mugumoini	4	11.72	19.29	8.55	23,106.55	1,975.00	58.33
	17	Rubia	Mugumoini	5	15.63	29.11	16.80	30,808.73	2,980.00	114.67
	18	Onyonka	Mugumoini	6	23.44	30.45	7.98	46,213.09	3,116.67	54.44
	19	Southlands	Mugumoini	5	16.80	28.33	9.87	33,119.38	2,900.00	67.33
	20	Royal Park	Mugumoini	3	11.40	39.07	12.37	22,464.70	4,000.00	84.44
	21	Southlands Kijiji	Mugumoini	5	5.08	12.70	0.00	10,012.84	1,300.00	0.00
	22	Masai	Mugumoini	4	30.53	20.76	29.31	60,173.30	2,125.00	200.00
	23	Sun Valley 2	Mugumoini	12	23.16	59.47	15.71	45,651.48	6,087.50	107.22
Nairobi West	**24**	Leebon	Nairobi West	11	16.78	43.07	9.01	33,084.37	4,409.09	61.52
	25	South End	Nairobi West	25	14.81	22.86	10.55	29,196.66	2,340.00	72.00
	26	Friends	Nairobi West	10	17.68	26.86	9.32	34,852.37	2,750.00	63.60
	27	Blackspartman	Nairobi West	14	21.28	28.61	11.97	41,949.39	2,928.57	81.67
Nyayo Highrise	**28**	Soweto	Nyayo Highrise	21	0.74	6.40	0.00	1,467.08	654.76	0.00
	29	Canaan	Nyayo Highrise	20	5.05	4.32	0.00	9,950.26	442.50	0.00
	30	Nyayo Highrise	Nyayo Highrise	20	9.92	15.65	13.48	19,544.29	1,602.50	92.00
South C	**31**	Five Star 2	South C	19	28.28	39.59	15.06	55,739.48	4,052.63	102.81
	32	KRA Staff	South C	5	17.78	20.51	14.75	35,044.93	2,100.00	100.67
	33	Green	South C	14	17.72	24.77	12.09	34,934.90	2,535.71	82.52
	34	Ridge A	South C	5	19.15	29.31	10.12	37,740.69	3,000.00	69.07
	35	Five Star 1	South C	8	11.97	17.34	7.69	23,587.93	1,775.00	52.50
	36	Ridge view	South C	5	24.81	38.88	10.16	48,908.86	3,980.00	69.33
	37	Amana	South C	5	40.83	36.14	29.70	80,487.80	3,700.00	202.67
	38	Ruby	South C	13	17.06	25.32	9.09	33,637.80	2,592.31	62.05
	39	Bellevue	South C	10	17.29	27.35	10.84	34,082.16	2,800.00	74.00
	40	Mugoya 1	South C	5	22.66	39.07	14.95	44,672.66	4,000.00	102.00
	41	Mugoya 2	South C	3	25.40	27.68	13.02	50,064.18	2,833.33	88.89
	42	Rangers	South C	6	23.12	33.38	22.47	45,571.25	3,416.67	153.33
	43	South C	South C	1	14.65	39.07	19.54	28,883.18	4,000.00	133.33

Table 6: Cont'd

Karen	**44**	KCB Area	Karen	5	9.77	48.84	20.51	19,255.46	5,000.00	140.00
	45	Miotoni Resident Association	Karen	4	23.20	72.04	18.56	45,731.71	7,375.00	126.67
	46	Karen Country Club	Karen	5	27.35	27.35	21.88	53,915.28	2,800.00	149.33
	47	Karen Plains	Karen	5	30.28	37.12	19.93	59,691.91	3,800.00	136.00
	48	Ojoshoa Residents Association	Karen	5	32.82	60.56	17.97	64,698.33	6,200.00	122.67
	49	Karen Muteero	Karen	5	25.01	73.26	18.36	49,293.97	7,500.00	125.33
	50	Karen Tree Lane	Karen	5	12.70	14.65	21.00	25,032.09	1,500.00	143.33
	51	Karen Brooks	Karen	5	27.16	54.70	20.12	53,530.17	5,600.00	137.33
	52	Rhino Park	Karen	5	21.10	29.11	17.58	41,591.78	2,980.00	120.00
	53	Hardy	Karen	5	22.08	33.21	7.81	43,532.73	3,400.00	53.33
	54	Kambi Kisii	Karen	5	0.00	4.22	0.00	0.00	432.00	0.00
	55	Langata Kuwinda	Karen	5	0.00	12.89	0.00	0.00	1,320.00	0.00
	56	Bogani	Karen	5	31.26	58.61	22.08	61,617.46	6,000.00	150.67
	57	Muiri Lane	Karen	5	20.12	19.54	17.88	39,666.24	2,000.00	122.00
WARDS		**Estate**		**Households**						
5		**57**		**382**						

SUMMARY										
				Sampled	**AVG. Monthly cost per household in USD (USD 1 = KES 102.37)**			**Corresponding Avg. Volume per Household in litres**		
WARD		**Estates**		**Households**	**Utility**	**Tanker**	**Bottled**	**Utility**	**Tanker**	**Bottled**
Mugumoini		23		93	15.80	32.59	13.36	31,149.89	3,336.27	91.19
Nairobi West		4		60	17.64	30.35	10.21	34,770.70	3,106.92	69.70
Nyayo Highrise		3		61	5.24	8.79	4.49	10,320.54	899.92	30.67
South C		13		99	21.59	30.65	14.58	42,565.83	3,137.36	99.47
Karen		14		69	20.20	39.01	15.98	39,825.51	3,993.36	109.05
OVERALL		**57**		**382**	**17.78**	**32.31**	**13.59**	**35,042.19**	**3,307.97**	**92.77**

4.6.3.2 Water deliveries into households by water tanker operators

Dependency by households on water tanker deliveries in the area was found to be highest in Mugumoini ward. The second in this ranking is Karen ward while Nyayo Highrise ward receives the least in tanker water deliveries, see Figures33,34and 35.

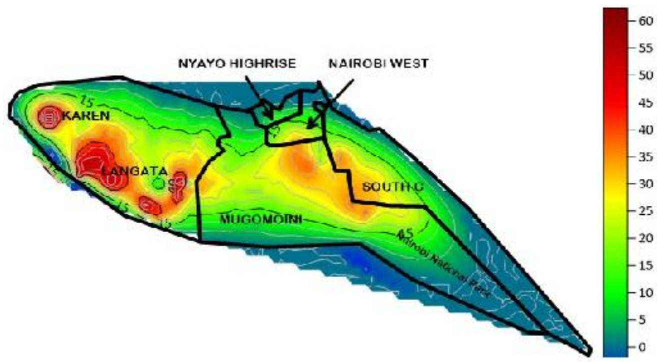


Figure 33: Cost of water from tanker in USD

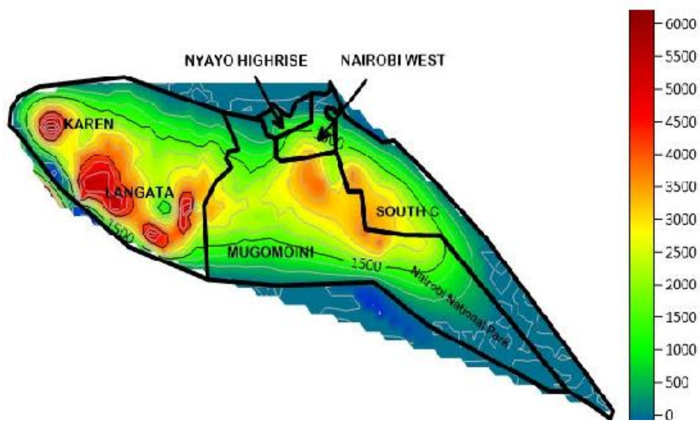


Figure 34: Tanker supplies in liters

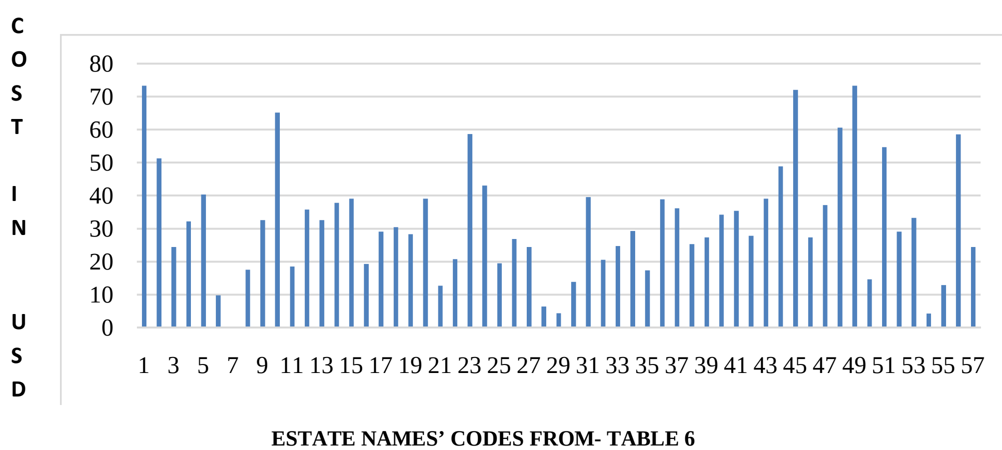


Figure 35: Average cost of water tanker deliveries in USD per Estate

4.6.3.3 Bottled water consumption by households

In terms of bottled water consumption, Mugumoini ward is the heaviest consumer while South C is the least consumer of bottled water, see Figures; 36, 37and 38 below;

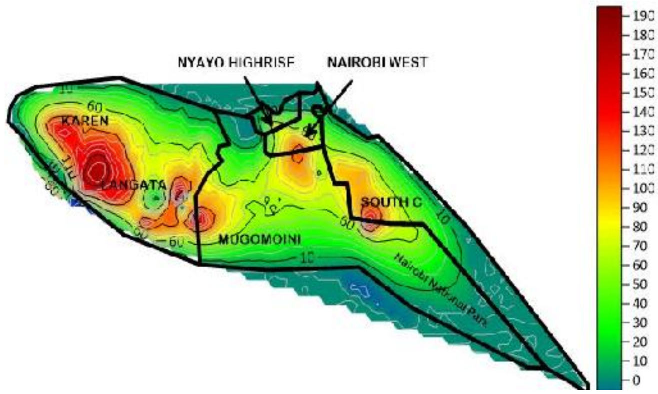


Figure 36: Bottled water in liters

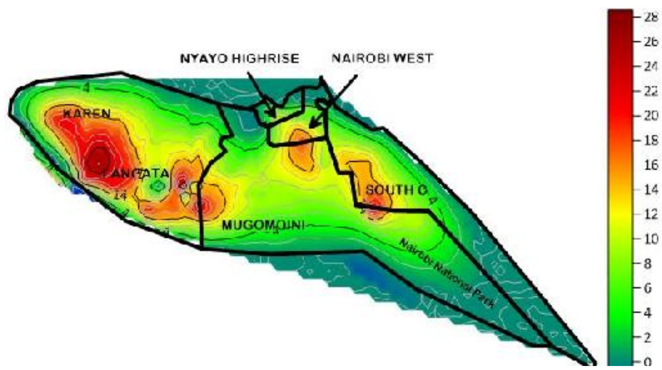


Figure 37: Cost of bottled water in USD

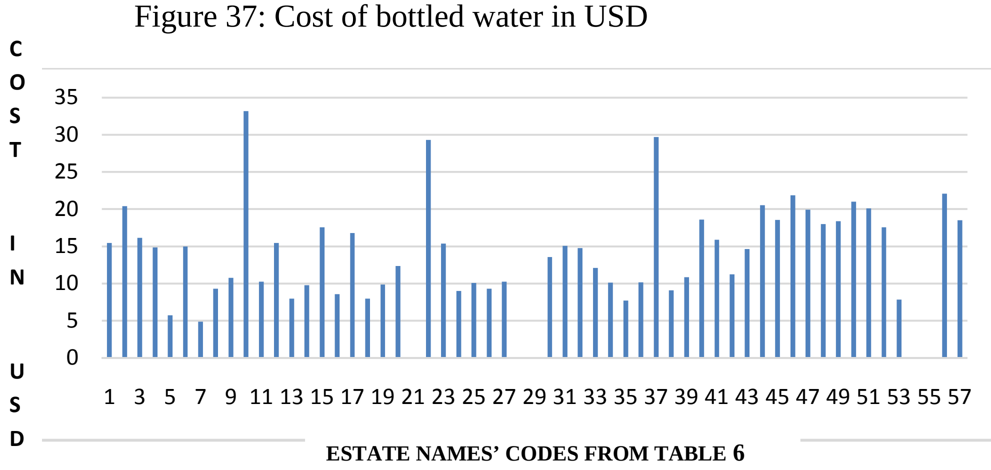


Figure 38: Average cost of Bottled water per Estate

4.6.3.4 Combined consumption from both utility company and water tanker operators

The combined cost of accessing water both the utility company and water tanker operators is most prominent in Karen ward see Figures 39, 40 and 41 below;

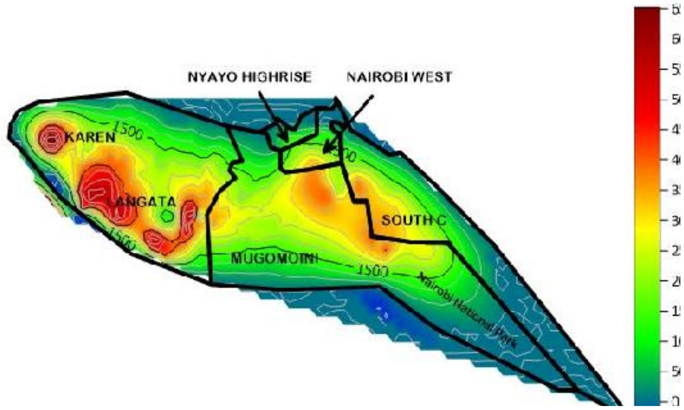


Figure 39: Tanker and Utility water deliveries in liters

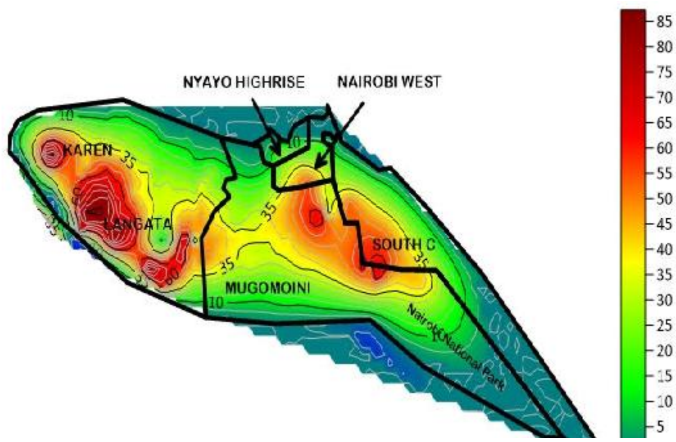


Figure 40: Cost of Utility and Tanker in USD

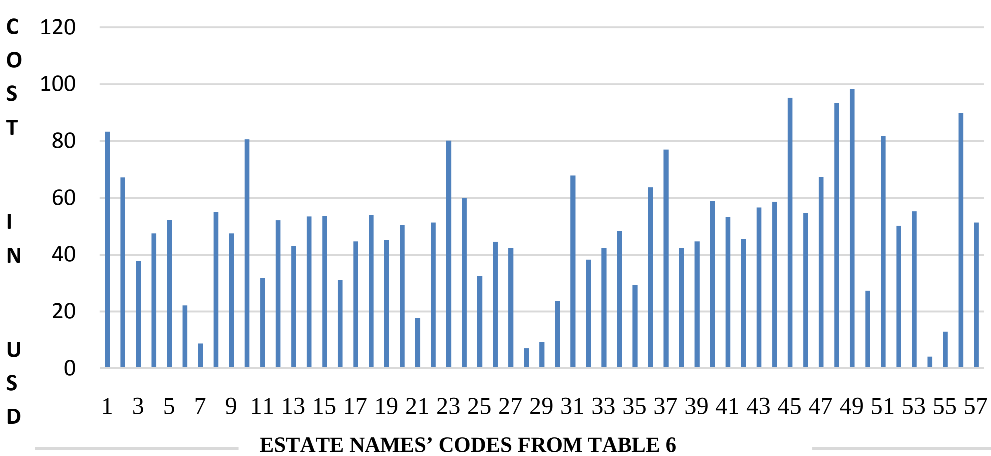


Figure 41: Average cost in USD -Utility and Tanker water deliveries per estate

4.6.3.4 Combined consumption of tanker and bottled water

The combined use of tanker and bottled water in the study area, show that Mugumoini ward is leading Figures 42, 43and 44 below;

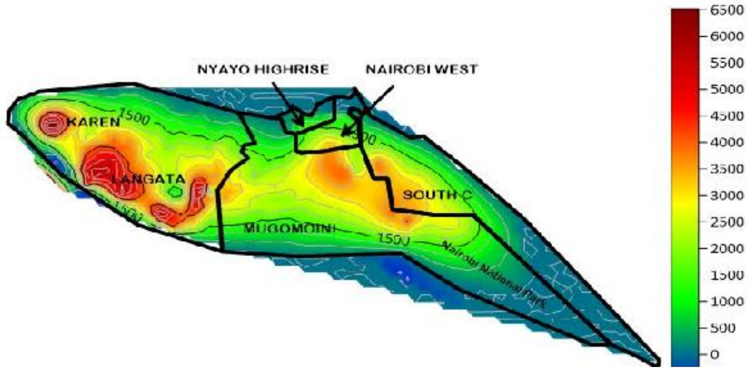


Figure 42: Cost of Tanker and Bottled in USD

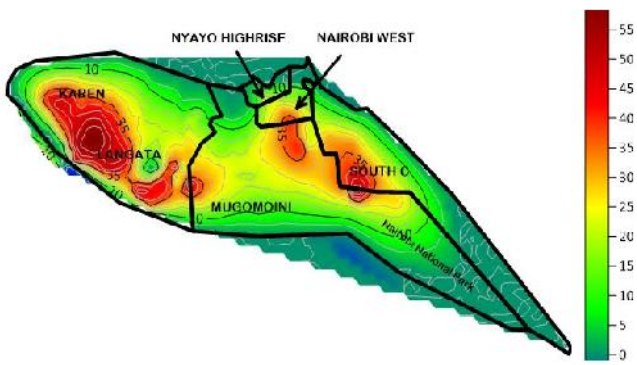


Figure 43: Tanker and Bottled in Liters

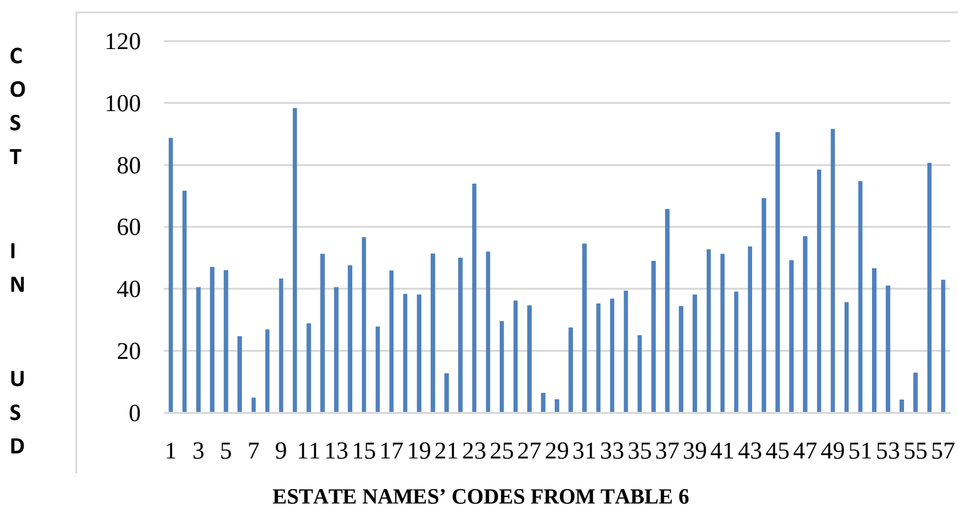


Figure 44: Average Cost of Tanker and Bottled water in USD per Estate

4.6.3.5 Combined consumption of water from utility company and bottled water

The combined consumption of water from utility company and bottled brands is highest South C ward and is least in Nyayo Highrise ward, see Figures 45, 46 and 47;

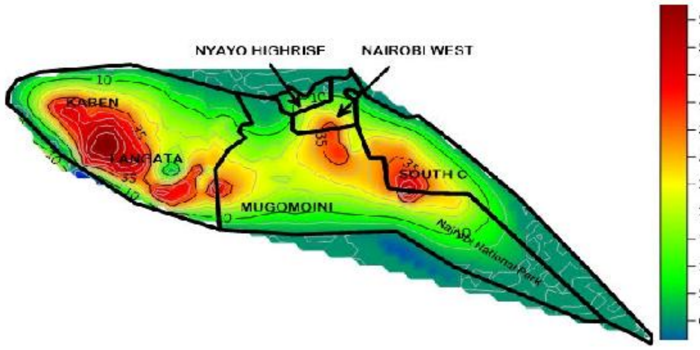


Figure 45: Cost of Utility and Bottled in USD

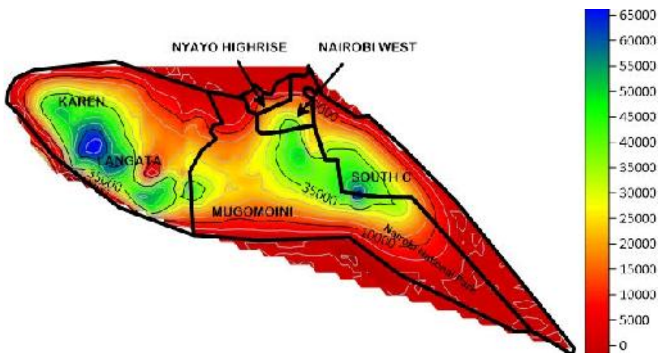


Figure 46: Utility and Bottled in liters

Figure 47: Average Cost of Utility and Bottled in USD per estate

4.6.3.6 Combined consumption of water from; utility (U), bottled (B) and tanker (T)

From the compiled survey results, the study established that; South C ward is the heaviest consumer in the three categories combined while Mugumoini ward is the least user of water in the entire study area, see Figures 48,49 and 50below;

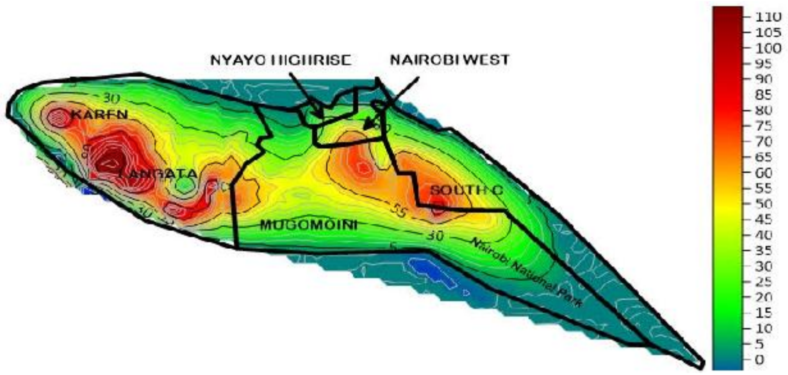


Figure 48: Combined cost (U, T, B) in USD

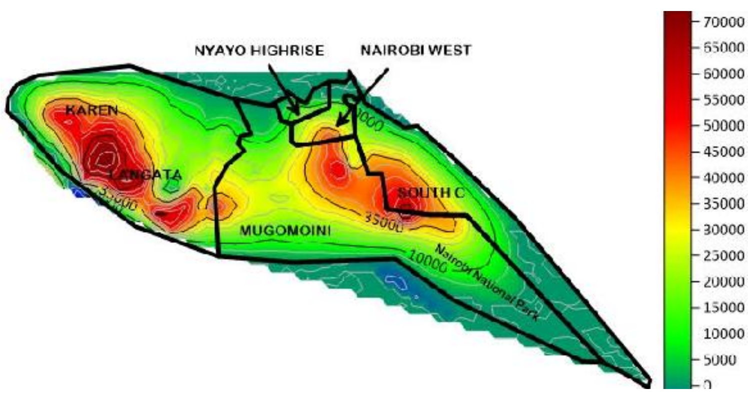


Figure 49: Total consumption in liters (U, T, B)

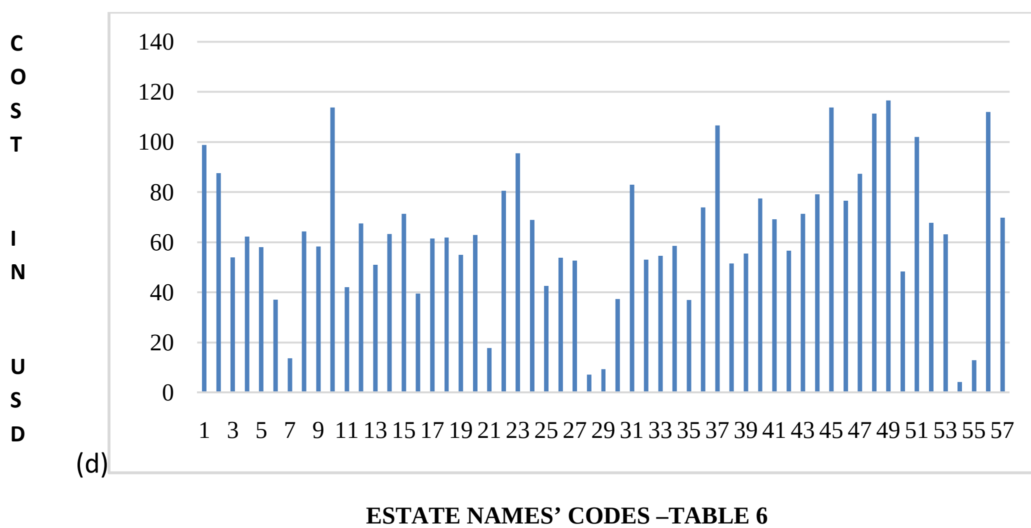


Figure 50: Average total water cost per estate (U, B, T)

4.6.3.7 Wards with combined monthly water bill over USD 100

The following wards have households who spend more than USD 100 per month on their water bills from the three sources combined; Mugumoini. Karen and South C, see Figure 51 below;

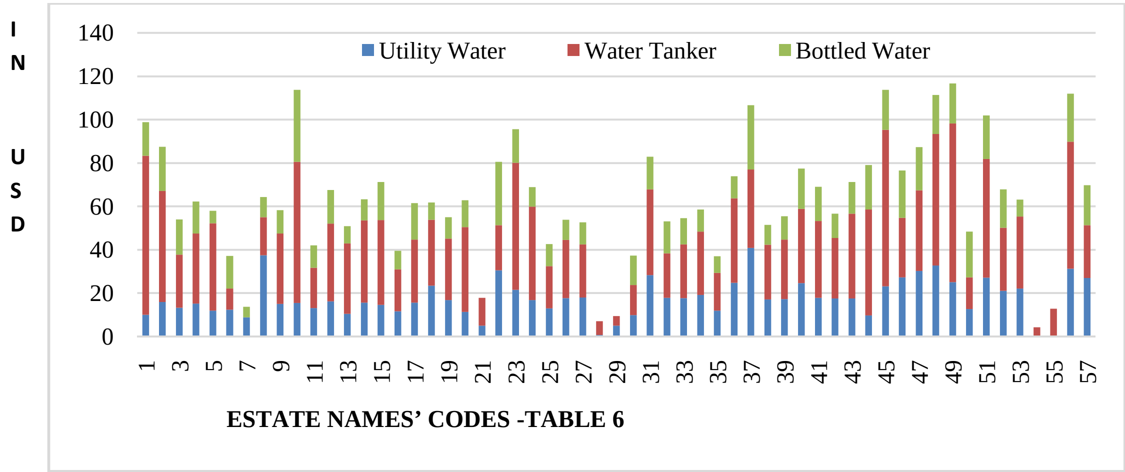


Figure 51: Cost share of each water as ESTATE'S Average in USD

4.6.4 Cost implications from the ward perspective

4.6.4.1 Cost share for each water source per ward

From Table 6, some interesting revelations were discovered. One, a typical household in Nyayo Highrise ward pays the least for utility water on average while those in Karen ward and South C typically pay more than any other ward on average. Households in Karen ward spend most in accessing both bottled and tanker waters see Figures 52, 53 and 54.

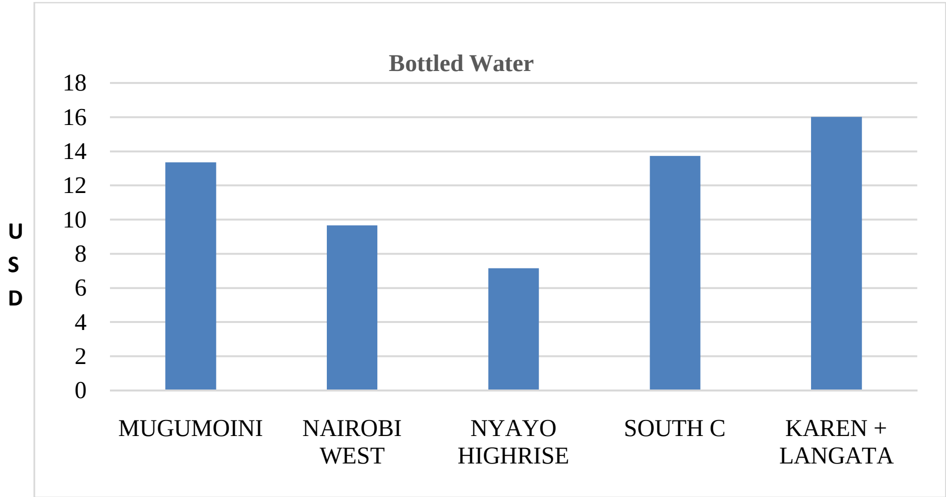


Figure 52: Cost of bottled water as average of each ward in USD

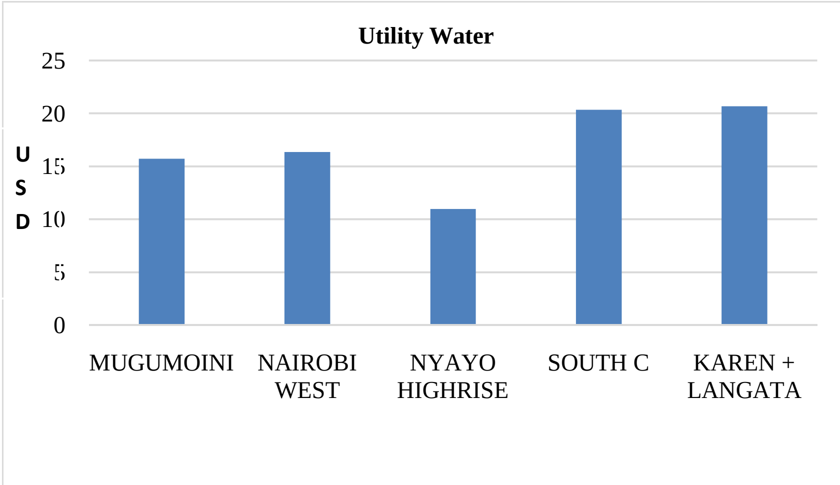


Figure 53: Cost of utility water as average of each ward in USD

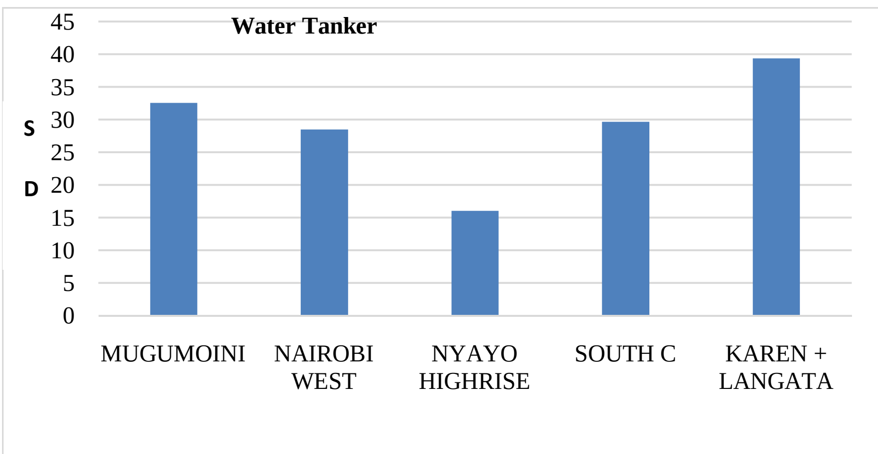


Figure 54: Cost of water tanker as average of each ward in USD

4.6.4.2 Cost share for each water source per ward in aggregate

Karen ward spends the most on water from all sources while Highrise ward the least. Tanker water delivery accounts for the largest contribution to the water bill in all areas while bottled water the least, see Figure 55 below;

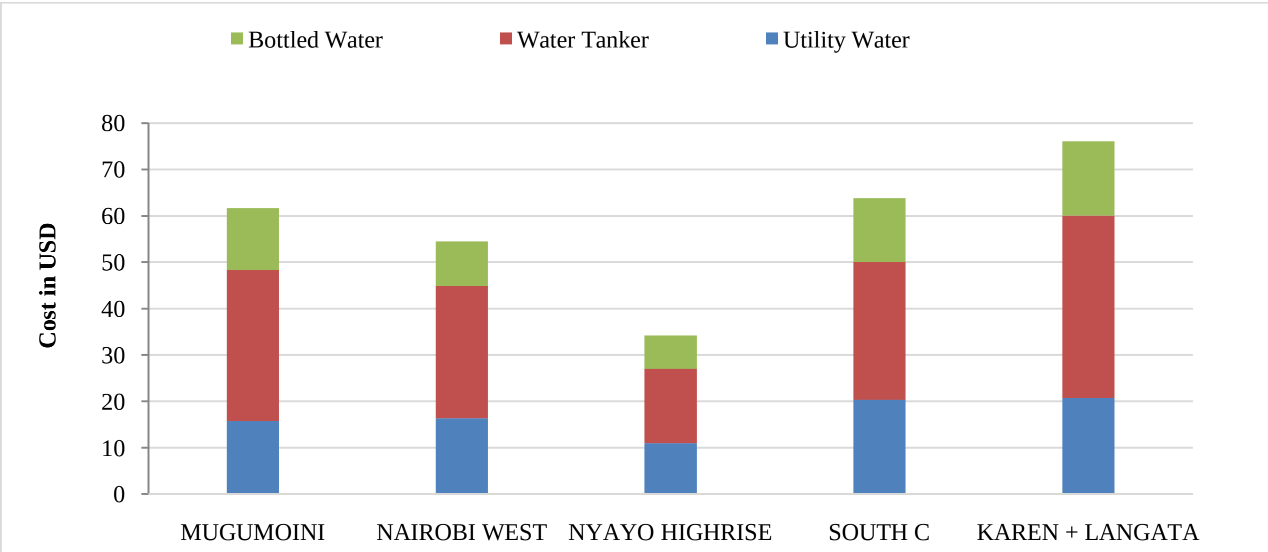


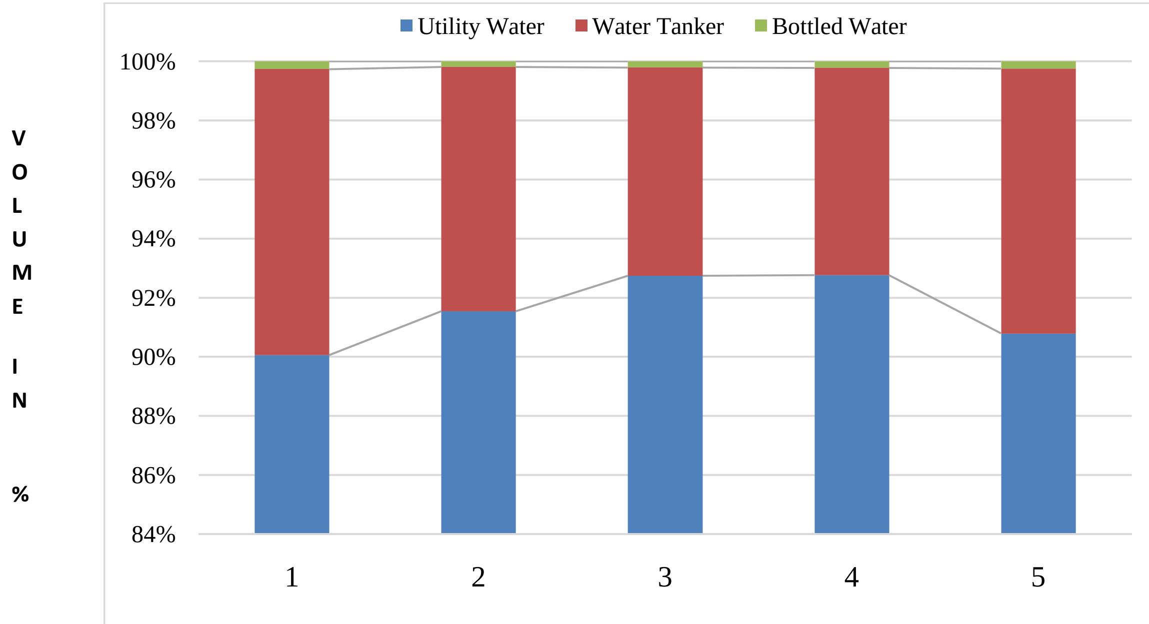
Figure 55: Average cost share of each Ward per source

4.6.4.3 Volumetric Average share as percentage per ward

In terms of volumetric share, South "C" ward, receives the highest utility supply for its monthly demand at 93%. Similarly, Mugumoini ward leads in water tanker and bottled water at 9.56% and 0.27% respectively see Table 7and Figure 56 below;

Table 7: Volumetric average share as percentage per ward

			Volumetric Avg.share as percentage		
CODE	Ward		Utility Water	Water	Bottled Water
1	Mugumoini		90.17	9.56	0.27
2	Nairobi West		91.63	8.18	0.11
3	Nyayo Highrise		91.71	8.01	0.26
4	South C		93.00	6.78	0.22
5	Karen		90.84	8.90	0.26
	AVG.		91.47	8.28	0.25



1, 2, 3, 4 and 5 are Ward Codes from Table 9

Figure 56: Percent volumetric share of the water sources per ward

From the summary presented in Table 6 and Figure 61 above, water from utility company accounts for 91.47 % as per Table 7 of the average water used across the study area. Deliveries from water tanker operators account for between 7-9.6% and bottled water share is less than 0.3%. This indicates that, the implication of the unreliable municipal water supply service in the study area contributes a huge cost burden on the consumers. The demand gap filled by both tankers and bottled accounts for only 8.53% of the area's water demand on average; Table 6.This small supply deficit contributes to a whopping 72% of the households' average monthly water bill as presented in Table 6 above. From that Table 6, the total average monthly household water bill is USD 63.68.In this, the average monthly cost of water from utility company is USD 17.78, tanker is USD32.31 and bottled water is USD 13.59.The most expensive of the three sources is bottled water whose share in the total is 21.3% for a volumetric share of 0.25% per month on average for the study area.

Regarding the assessment of cost burden, the study deployed the equations *Chapter 3-Eq-(3.13)* to *Chapter 3-Eq-(3.18)* in section 3.3.6.1. From these, the average Exposure Index factor (EI) was computed as 0.29.In addition, arguments abound to the effect that drought frequency may increase in the coming years which means that, the absolute dependency on municipal water supply is still remain a pipe dream in the study area given that the utility company draws its water from drought prone Tanathi River basin catchment. Similarly, the computed average Vulnerability Index (VI) is 0.29 which indicates that, the water shortage risk in the study area is yet to reach its peak .The average computed cost burden to a typical household in the area is 258% as per the equation *Chapter 3-Eq-(3.18*) in section 3.3.6.1 above .This means each household on average spends extra more than twice on accessing water ,what it should have spent if the utility supply was sufficient translating to 3.58 times the absolute average utility bill per month per family.

This translates to approximately 246 - 378 litres per person per day. Further, for a household of 5, this would amount to 449 - 689 units per annum or 37 - 57 units of water per month. Take the average (47 units) of this range. Thus, compared with the American scenario which according to (**Lee et al., 2011**) is 246-379 liters per capita consumption, the deficit in the study area is approx. 8.6 units per household, given the average consumption is 38.4 units. The tankers only supply 3.4 units on average translating to 39.53%, while bottled water fills 0.092 units on average or 1.07%. The alternatives still have a 59.4% unserviced gap if we are to go with the American reasoning. Only Karen ward and South C ward come close to the average monthly usage of 47 units getting slightly above 40 units on average i.e. 43.8 units and 45.7 units respectively, but at a huge cost.

4.7 Key factors that determined the public adoption of WQTS

4.7.1 General

This section outlines the proposed improved response to the study area's water shortage challenge. It presents the results of the discrete choice experiment survey in which a mobile app "Maji Safi" (see section 4.5) running on a blockchain quality provenance technology platform was presented for the public adoption. The water quality tracking system (WQTS) run through Maji-Safi app was presented in four choices, each having a cost implication on the household's monthly water access bill.

4.7.2 The factors determining the adoption of WQTS in Langata

The socio-demographic items gathered from the survey questionnaire were taken as the determining factors influencing the adoption of WQTS.The included; the estate of residency, gender, age, years of stay in the estate and the education level of a respondent. The questionnaire had made it clear that as much as possible, the household heads were the ones to fill it in. The result of the analysis of the survey data from the 382 sampled households showed that, 71.5 % of the respondents were male while 28.5% were female. Secondly, in terms of age groups; 24.1% of the respondents were under 35 years of age, 74.9% were between 36-70 years while only 1% was above 70 years of age. In terms of education-level, it was found that ,59.9% of the respondents had university degrees, 18.1% had college qualifications, 15.4% were high school graduates, 5.2% were primary school drop outs while only 1.3% were in the illiterate category see Figure 57 below.

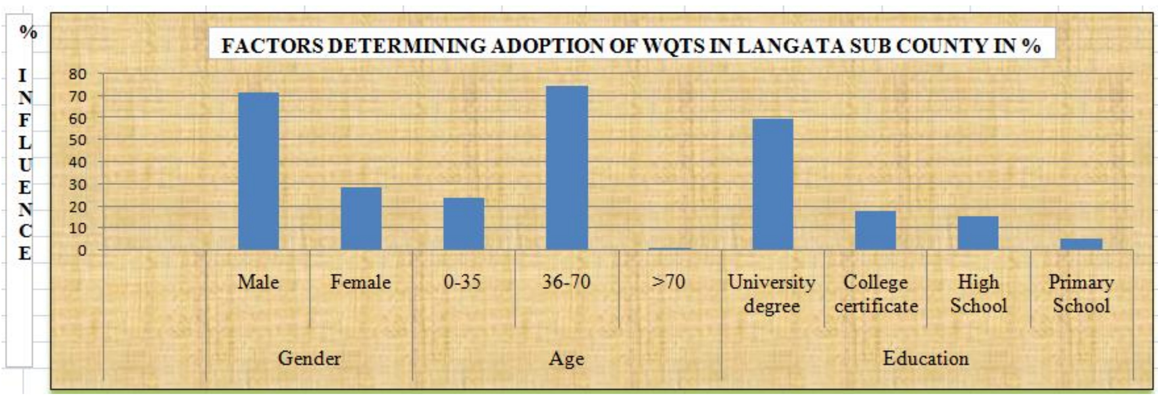


Figure 57:Factors determining adoption of WQTS in Langata

4.7.3 Current coping strategies for water shortage

The respondents were asked to rate the efficacy of the proposed WQTS, its ability to lower water access cost, and their willingness to endorse it for installations using a five-point Likert scale. Additionally, the current monthly bill; municipal tap water, vendor delivered water and bottled water purchases were considered as relating to their adaptive coping behavior to water shortages. The study analyzed responses to: threat vulnerability, response efficacy, response cost, adaptive coping, maladaptive, combination of threat and response statement and combination of adaptive and maladaptive statements. These formed six sets of responses. Results show that these six variables held together well in a congeneric measurement model of adaptive coping behavior with computed Cronbach's alpha scale being equal to 0.576 (**Cronbach, 1951**). The computed mean value for adaptive coping behavior was posted as 3.2 with a standard deviation of 1.002.Cronbach alpha is a coefficient of testing the internal consistency of perceptive response measured on a summated scale like Likert scale. The values range between 0 and 1.The closer it is to 1, the greater the internal consistency of the items in the scale.

Separately, the respondents were further asked to score using the same scale, the much they would agree or disagreed with the five statements relating to the maladaptive behaviors as concerns the minimization of the impact of water shortages in the area. From the results of their scores presented in Figure 58, it was established that respondents with high adaptive scores tended to acknowledge the severity of the water shortage problem in the study area. As a result, this category of the respondents concurred with the proposed solution which promoted the adoption of WQTS.The enthusiasts of the new coping system turned out to be 53.9% of the tallied votes. This dominant decision was again subjected to further confirmatory factor analysis.

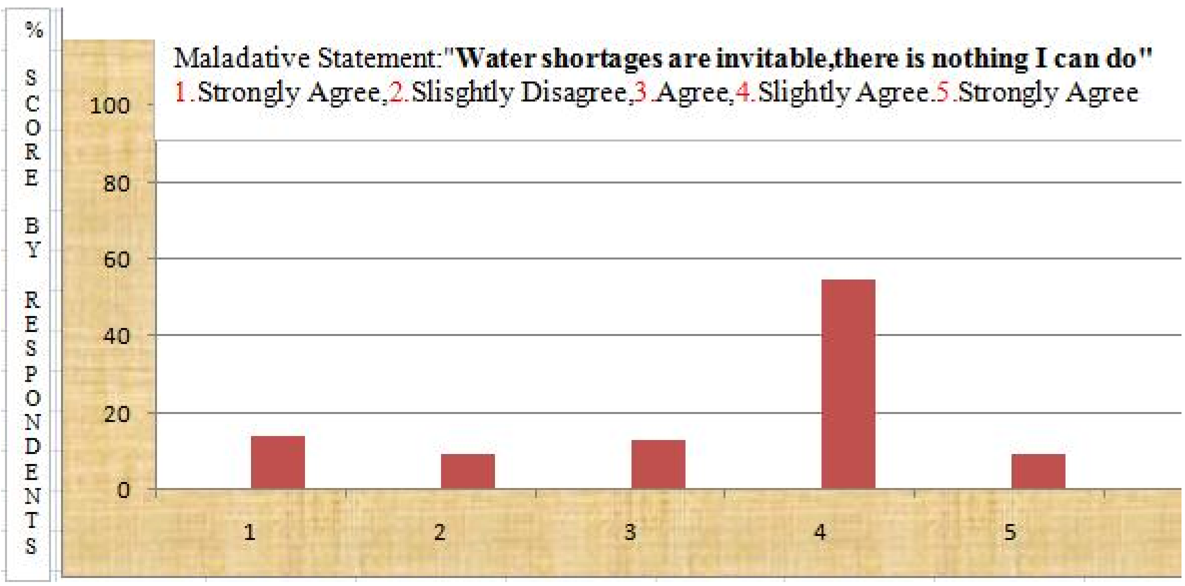


Figure 58:Maladative behavior response score

The confirmatory factor analysis suggested that, the five maladaptive factors fit well as a single congeneric measurement model of maladaptive coping behavior. The mean value for maladaptive behavior was computed as 3.36 and their standard deviation as 1.2. Responses to statements measuring adaptive and maladaptive behaviors were then processed separately and formed adaptive coping score range with a mean of 3.2147 and a standard deviation of 1.00183 for the enthusiasts. But on the other hand, maladaptive coping behavior had a mean of 3.3613 and a standard deviation of 1.19946 for the pessimists.

4.7.4 Analysis of the extended Latent Class Results

The study used LatentGOLD software version 5.1.0.19164 to identify the appropriate Latent Class structure across dimensions; the number of preference classes, with attributes of the solution being spread in four options (see appendix 5 and explanations on the application of Discrete Choice Model in section 2.7.1).Note further, that discrete choice model is a non-market method for soliciting stakeholder valuation statements on a new coping measure as explained in section 2.8.The expected reciprocal benefit of a preferred choice by this study is to help protect groundwater environment through mindful sharing of the finite resource between community members. The indicator variables that were used ranged from coping cost to socio-demographic factors. The real meaning of this analysis was to differentiate the coping characteristics of the respondents, who despite being faced with a common water shortage problem had varied response behaviors. Two major distinct classes emerged; the enthusiasts and the pessimists (those with dogmatic tendencies).Option 2 (the communal or gated community management of water access, see appendix 5) was identified as the popular choice by the enthusiastic class while the pessimists class spread between status quo, individual coping and those with mixed (both individual and communal), see Table 8and Table 9.

Table 8: Results from a 1 scale-2utility latent class models

Cluster	P-Value		Prices
Utility function			
OPTION 1	0.1283	5.1e-33	15%
OPTION 2	0.5393	5.1e-33	12%
OPTION 3	0.3115	5.1e-33	10%
OPTION 4	0.0209	5.1e-33	0%
Predictedprobabilityofutility class memberships			
Class (Gender)		Class1	
Male		0.7147	
Female		0.2853	
Total		1	

Table 9: Part-worths per unit

OPTIONS***	% OF VOTES	TALLIED VOTES
OPTION 1	12.8	49
OPTION 2	53.9	206
OPTION 3	31.2	119
OPTION4	2.1	8
TOTALS	100	382

***The options were to have average monthly household utility company water bill adjusted by 15%,12%,10% and 0%for options ;1,2,3 and 4respectively.

Note that the expected water access tariff rate change are the positive percentage adjustments (increments) by the utility company to enable it partially recover the cost of installing the new water access system once a policy anchoring the same is enacted.0% means status quo is maintained, 12% is the adjustment for choosing option 2 .

4.7.5 The willingness to pay (WTP) or to adopt WQTS

4.7.5.1 Households' Preference for Water Quality Tracking Systems (WQTS)

Although one can consider differences in marginal utilities in Table 8 above, one is still held back by the potential differences in scale across utility classes. Part-worths ordering or marginal WTP measurement on option with most favorable attributes is more informative. In this case the central measure of WTP is the median value of 12% monthly tariff adjustment being taken as the WTP estimate for adoption of WQTS at 53.93% popularity, see Table 8.

4.7.5. 2 Factors influencing the choice of the most preferred option

It is worthy to note that of the 53.93% who prefer option 2, a total of 148 of the 206 endorsing respondents are male (71.46%). This means that male factor was a major determinant for the adoption of WQTS in Langata. . In terms of the role of other indicators, the study established that the level of education (especially university degrees) was the second most influencing factor at 61.65%. This means, of the 206 who prefer option 2, 127 had a university degree. In the third place was the age bracket of 41-55 years in which 87 out of the 206 respondents who endorsed option 2 fall in.

Finally, from analysis, 50 respondents from Mugumoini ward and 47 from Karen ward constituted the majority of the 206 respondents who chose option 2.The preference for option 2 here can be explained from the expected benefits that can potentially be drawn from cooperative action in accessing services of common interest in a community. This explains the reason why gated communities approach security issues jointly. In this study area, it appears that the management of water access services may also be approached in the same way. And that is the reason when the current market price of water access is compared to the stated WTP; you find that the levels indicate that, the WQTS adoption popularity is at 53.93%. This translates to 206 endorsements from the 382 sampled respondents.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5 Introduction

This section presents conclusions of the main findings of the study. Additionally, it outlines some recommendations for the implementation of the findings. It ends with some suggestions for new a study on opportunities wrought by climate variability and change, especially with regards to drought exposure hazard’s impact on the area’s water supply security.

5.1 The key findings

First and foremost, the study set out to determine the distribution of drought years over Langata sub County for the period 1957 and 2013 (57 years).To this end, it has been established that out of this time span, the drought distribution covered a total of 34 years (60% of 57 years).Next, the study assessed the influence of drought on the suspected groundwater depletion threat and quality decline. It was established that the groundwater level decline is 3.82m/year confirming the fear that Langata region may be experiencing an enhanced rate of groundwater abstraction. It was also confirmed that the drought events in Langata have a probable chance of up to 43.65% of causing groundwater quality decline.

When it came to the level of exposure to poor quality water as well as a heavy cost burden of accessing water from the informal market, the study for one established that, the groundwater in Langata is good for domestic use. While on the other, the cost burden imposed on Langata residents is up to 258% over and above what a typical household in the area pays per month to the water company. One of the most important aims of the study was to develop a proto-type water quality tracking system (Maji-Safi app) for the informal water market in Langata .This was done successfully. In terms of identification and documentation of the main socio-demographic factor influencing the adoption process, the study established that male factor prevailed over other factors by 71.46%.

5.2 Conclusions

In this study ,a conclusion is arrived that Langata sub County was exposed to drought to drought risk by close to two thirds of the review period ,1957-2013.This experience turned residents attention to groundwater through installation of boreholes whose impact on groundwater level decline is currently 3.82m per year.On the other hand the drought influence on the decline of the groundwater quality has been established to have a chance probability of about 43.65%.Luckily, the analysis of geo-chemical parameters of groundwater in Langata indicate that the water is still of good quality for domestic use. But it is the cost burden of accessing water from the informal water market which is steeply placed at 258% relative to the water utility monthly cost for a typical household. To correct this, the study successfully developed a water quality tracking system app and presented the same for adoption which also passed with a clear margin from which the main adoption factor was identified as the male gender category.

5.3 Recommendations

The study recommends that the Langata households should shift to a cooperative or communal water access away from the current unilateral coping method which has been confirmed to be too expensive. Secondly, the study recommends that a dedicated groundwater recharge program should be initiated by the government as one strategic intervention to mitigate the rapid groundwater decline rate in the area. For the operationalization of the maji-safi app, the study recommends for collaboration between the Nairobi Water and Sewerage Company and a blockchain technology provider so that the residents can reap the benefit of a digitized water market economy in the area. This however will require first, the formulation of a new water policy that will recognize the role of informal water actors. For the research community, the study recommends that a citywide study be initiated to establish the level of risk exposure on the people with respect to informal water quality, cost burden and groundwater depletion threat.

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APPENDICES

Appendix 1: Table of drought events and average borehole struck water level

Year	X_i Drought	Y_i Boreholes	Average Borehole Struck Water
1982	0	1	204.8
1983	1	0	0
1984	1	0	0
1985	1	1	200
1986	0	0	0
1987	1	0	0
1988	0	0	0
1989	0	0	0
1990	1	0	0
1991	1	1	177
1992	1	3	135
1993	1	0	0
1994	1	1	210
1995	1	0	0
1996	1	0	0
1997	0	0	0
1998	0	0	0
1999	1	1	202
2000	1	0	0
2001	0	1	230
2002	0	0	0
2003	0	3	200.67
2004	1	4	242.5
2005	0	6	287.83
2006	1	4	256
2007	1	4	277.5
2008	1	3	206.4
2009	1	5	292.4
2010	1	6	285.83
2011	1	24	287.38
2012	1	11	298.21
2013	1	9	268.33
2014	1	17	267.71
2015	1	9	290.33
2016	1	5	337.5
2017	1	3	280
	26	**122**	

Appendix 2: Table of drought SPI values and dry year borehole WQI values

	Year	S/N	WQI	SPI	Dry Year WQI	Wet Year WQI
1	1983	465	11.4	0.4		11.4
2	1985	484	23.25	-1.75	23.25	
3	1992	584	33.42	-0.8	36.62	
4	1992	445	39.82	-0.8		
5	2003	622	29.45	0.25	29.45	
6	2004	511	33.88	-0.1	37.64	
7	2004	530	41.4	-0.1		
8	2005	651	32.79	-0.6	40.03	
9	2005	636	27.2	-0.6		
10	2005	463	35.11	-0.6		
11	2005	706	65.04	-0.6		
12	2006	832	98.6	1.1	48.91	
13	2006	540	23.51	1.1		
14	2006	612	24.63	1.1		
15	2007	757	54.81	-0.7	64.32	
16	2007	575	73.83	-0.7		
17	2008	231	77.16	-0.3	77.16	
18	2009	16	32.16	-0.88	45.06	
19	2009	510	57.96	-0.88		
20	2010	132	40.76	-0.1	40.61	
21	2010	492	31.04	-0.1		
22	2010	1412	50.04	-0.1		
23	2011	240	80.6	0.4		56.45
24	2011	243	65.59	0.4		
25	2011	278	26.16	0.4		
26	2011	633	60.75	0.4		
27	2011	853	67.63	0.4		
28	2011	1102	37.97	0.4		
29	2012	237	91.8	1.55		72.65
30	2012	272	53.51	1.55		
31	2014	338	68.29	2.03		55.39
32	2014	373	23.23	2.03		
33	2014	394	56.69	2.03		
34	2014	396	30.17	2.03		
35	2014	401	55.3	2.03		
36	2014	416	98.68	2.03		
37	2015	665	105.99	1.8		78.54
38	2015	676	51.08	1.8		
39	2016	1383	163.38	-1	163.38	
Average WQI			**53.18153846**		**55.13**	
Standard Deviation of WQI			**29.92458754**			

Appendix 3: Information Sheet

Information Sheet

Regarding the household survey to assess the factors for the adoption of a blockchain quality tracking system for vendor supplied water within Lang'ata Sub County

Activity	Assessing factors for the adoption of a blockchain quality tracking system for vendor supplied water within Lang'ata Sub County
Aim of study	The purpose of this study is to understand your thoughts and opinions about how to verify the quality of the vendor water. This will enable us to map out the community perspectives regarding existing alternative water sources that augment the intermittent municipal water supply system in Lang'ata sub county. The resulting information will be used to inform research on the documenting of the informal water quality; from source point to the consumer storage system on a blockchain enabled platform that will provide a common interface with all other interested water actors in the value chain.
What is provenance (quality) tracking system?	For familiarity with provenance tracking system, one only needs to be concerned with the product quality details. Especially, in this case; the bio-physical and chemical data of the vendor water in real time including actor information. Provenance concept is the history of origin and transformations of a product which is crucial to a consumer before using a product. For most consumer products, shoppers do check date of manufacture and date of expiry for instance before they purchase.
What is entailed in this survey exercise?	➢ Your participation is estimated to last about 5minutes and it is voluntary. ➢ There are four sections; ➢ Section 1; General information ➢ Section 2; Your bio-data ➢ Section 3; Coping assessment ➢ Section 4; Choice options for implementation of the water quality tracking system. ➢ Note: Section 3,requires that you score in a scale of 1-5 discretionally (as you decide) ➢ There is no right or wrong answer; we are only interested in your opinion about how to solve water supply shortage. Even if you don't use alternatives (vendors) water, your opinion is still important to the study.
Note	Only household heads believed to be above 18years of age are expected to participate.
Participation & or Withdrawal	Your participation is completely voluntary and you are free to withdraw from this survey at any time without prejudice or penalty. If you wish to withdraw, simply do not fill any part of the questionnaire.
Risks	Participation in this study should involve no physical or mental discomfort and no risks beyond those of everyday life. If, however, you should find any question or procedure to be invasive or offensive, you are free to omit answering the question. If you have any concerns about any aspects of the study, please contact Mr.Ochungo, Akech Elisha (the lead researcher whose details are herewith provided).
Confidentiality	All information collected in this survey will be anonymized using a coding system, so that there can be no association between your identity and the data you provide. The data will only be seen by members of our research team in an aggregated format (i.e all participants' responses will be combined into one file) and will be stored in a secure area that is not accessible to any individual other than the research team. Your information will only be used for research purposes.
Payment	No, payment will be due to you for taking part in this survey.
Use of the information collected	The information you provide to us in the survey will be used to write a general report on community views and preferences regarding informal water quality tracking system. The information will also be used to prepare a manuscript for academic publications. Your personal information will not be identifiable at any stage of the writing process.
Additional Inquiry	The research project has been approved by Board of Post Graduate Studies of the University of Nairobi and by the Commissioner for National Commission for Science, Technology and Innovation.
Ethical clearance and contacts	The study has been authorized by the commissioner for National Commission for Science, Technology and Innovation, the Nairobi City County Commissioner, Nairobi City County Director of Education. Your neighborhood chairperson has been notified and has copies of the authorizations.

Thank you for your help with this very important research.
Yours sincerely,

Ochungo,Akech Elisha
Climate Change and Adaptation, PhD candidate.
University of Nairobi,
Institute for Climate Change & Adaptation
Chiromo Campus
Tel; +254 (0) 721 629706
Email; elishakech1@gmail.com

Appendix 4: Consent form

Consent form:

For the household survey to assess the factors for the adoption of a blockchain quality tracking system for vendor supplied water within Lang'ata Sub County.

Your involvement in this research is highly valued. Please review the information and tick in the box appearing after the sentence in the seventh bullet if you agree to participate in this research project. I acknowledge that;

1. I have agreed to participate in the project.
2. I will not be identified personally at any stage of the project and that all data will be kept confidential to be seen only by researchers involved in this research project.
3. I can obtain further information from the research team at any time during the project.
4. I understand that this study has been cleared in accordance with the ethical review processes and I can only speak to the researcher.
5. I have been provided with the contact details of the researcher (see information sheet)
6. I understand that I am able to stop taking part in this study at any time without penalty and without giving an explanation for my withdrawal.
7. I understand that if I withdraw from the study, all of my data will be removed from the study without penalty or explanation. Data that is removed will not be included in any further analyses. By ticking the box, I confirm that I have read and understood the information sheet and note that my involvement in this research will include participation in the adoption of block chain enabled informal water quality tracking system.

Thank you for your participation ☐

Yours sincerely,

Ochungo,Akech Elisha

Appendix 5: Questionnaire form

1. General Information

Date: --

Name: ---

Estate: --

This data collection form has four sections. It will take approximately five minutes of your time. Your participation in this exercise will help protect our water environment in the face of drought risk over Nairobi.

2. Respondent's Information

Gender: (Tick one): Male ☐ Female ☐

Age-----------------*(Please write)*

Number of years you have stayed in the estate: -----------------------------*(Please write but this is optional)*

Education: (Tick one): None ☐ Primary ☐ Secondaryy ☐ College ☐ University ☐

(In this section, you are expected to score between 1 and 5 where; 1 = I Strongly Disagree, 2 = I Slightly Disagree, 3 = I Agree, 4= I Slightly Agree and 5 = I Strongly Agree)

3. Water scarcity risk coping assessment

A. *Threat vulnerability statement*: I am concerned that Langata sub county will experience water shortages in the future

1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ Score in the box

List your **monthly** household water bills in each of the below categories:

Water Company supply: Kshs ☐

Water Vendor delivery: Kshs ☐

Bottled water purchases: Kshs ☐

Score in the boxes

Provide your water vendor details in the below table;

Vendor name	Delivery Type		Contact
	Cart	Tanker	

B. *Response efficacy statement:* Provenance tracked water system operated by the estate committee sourcing water from public water system and vetted water vendors whose quality is traceable

1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ Score in the box

C.*Response cost statement:* The proposed new method of water access will partly solve household water shortage in Langata sub county.

1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ Score in the box

D.*Adaptive coping statement:* I will be better able to reduce water shortages if I can confirm the quality of the informal alternative water sources.

1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ Score in the box

E. Maladaptive coping statement: Water shortages are inevitable; there is nothing we can do about it.

1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ Score in the box

4. Vendor water-blockchain enabled quality tracking system installation options;

a) Does your estate/Village/Neighborhood experience water shortage?

Yes ☐ No ☐ (Tick One)

b) When your household misses water from Nairobi City Water and Sewerage Company (NCWSC), do you source it from a water vendor?

Yes ☐ No ☐ (Tick One)

i. If yes, for drinking purposes, do you improve the quality of the vendor water?

Yes ☐ No ☐ (Tick One)

ii. If you don't improve the sourced vendor water quality, for drinking purposes, do you depend on the bottled water on a dispenser instead?

Yes ☐ No ☐ (Tick One)

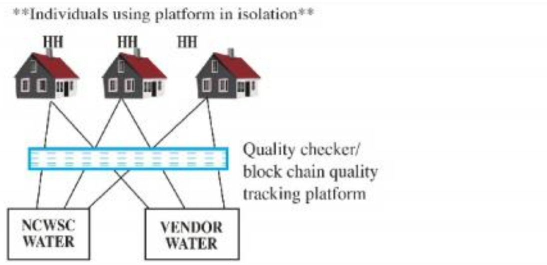
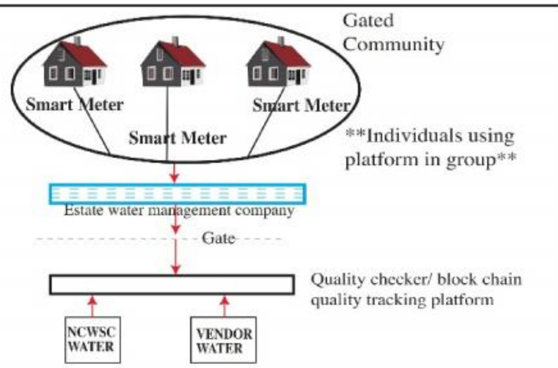
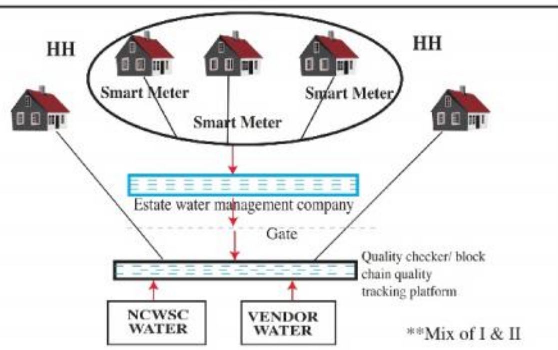
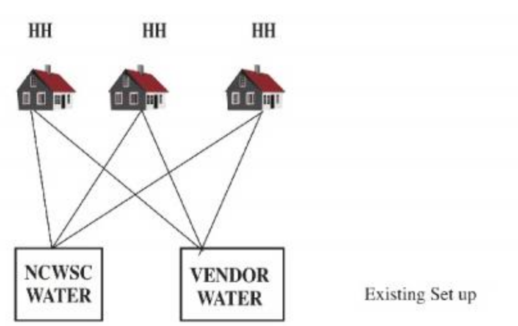
c) Would you agree to verify or confirm the quality of vendor/NCWSC water on a blockchain provenance tracking system?

(*Remember the answer to this question will affect the answer to question (d) in next page)*

Yes ☐ No ☐ (Tick One)

UNIVERSITY OF NAIROBI

d) To track the quality, there are four options for implementation, please choose one by ticking in the box;

Choice Option	Diagrammatic	Effect on your current NCWSC water bill	Tick One
I		15%	
II		12%	
III		10%	
IV		None	

Appendix 6:3 Minutes Ph.D Thesis presentation certificate

Appendix 7: NaCOSTI certificate

THIS IS TO CERTIFY THAT:
MR. OCHUNGO AKECH ELISHA
of UNIVERSITY OF NAIROBI, 30197-100
Nairobi,has been permitted to conduct
research in *Nairobi County*

Permit No : NACOSTI/P/19/61655/28016
Date Of Issue : 31st January,2019
Fee Recieved :Ksh 2000

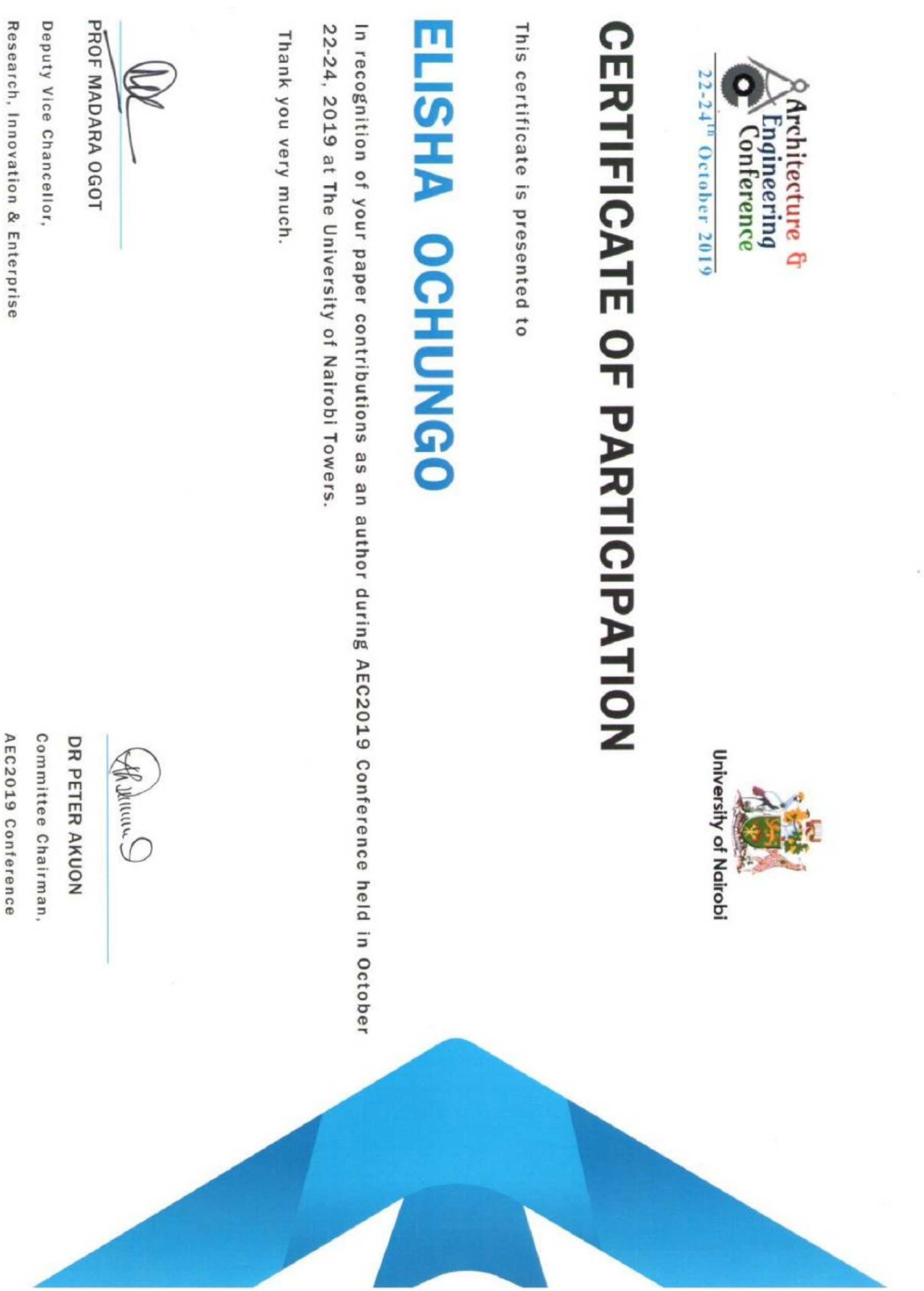
on the topic: *WATER SUPPLY SECURITY IN A DROUGHT EXPOSED NAIROBI: ADOPTING A BLOCKCHAIN PROVENANCE TRACKING FOR INFORMAL ALTERNATIVES*

for the period ending:
31st January,2020

....
Applicant's Signature

....
Director General
National Commission for Science, Technology & Innovation

Appendix 8: Conference appearance certificate



Architecture & Engineering Conference
22-24th October 2019

University of Nairobi

CERTIFICATE OF PARTICIPATION

This certificate is presented to

ELISHA OCHUNGO

In recognition of your paper contributions as an author during AEC2019 Conference held in October 22-24, 2019 at The University of Nairobi Towers.

Thank you very much.

PROF MADARA OGOT
Deputy Vice Chancellor,
Research, Innovation & Enterprise

DR PETER AKUON
Committee Chairman,
AEC2019 Conference

Appendix 9: Operational protocol of Maji-Safi app

User registration and login

A first-time user is expected to run the installation setup on an Android phone. His/her next step is to open the app upon which he will be presented with login menu to which he is expected to click on the "Create account" button upon which he / she will again get redirected to the account creation activity. The user is then expected to enter the details outlined in the available fields, including the email and a suitable password, thereupon after clicking on the "Create Account" button will be redirected back to the login activity to login to the system if the account creation was successful. After login the user is then presented with two options: order water or view water quality information see Figure 59(a) Maji-Safi Launch Screen, (b) Maji-Safi - Login Screen (Seen right after the launch screen) and (c) Maji-Safi Registration Screen (Prompted by clicking the create account button from the Login Screen).

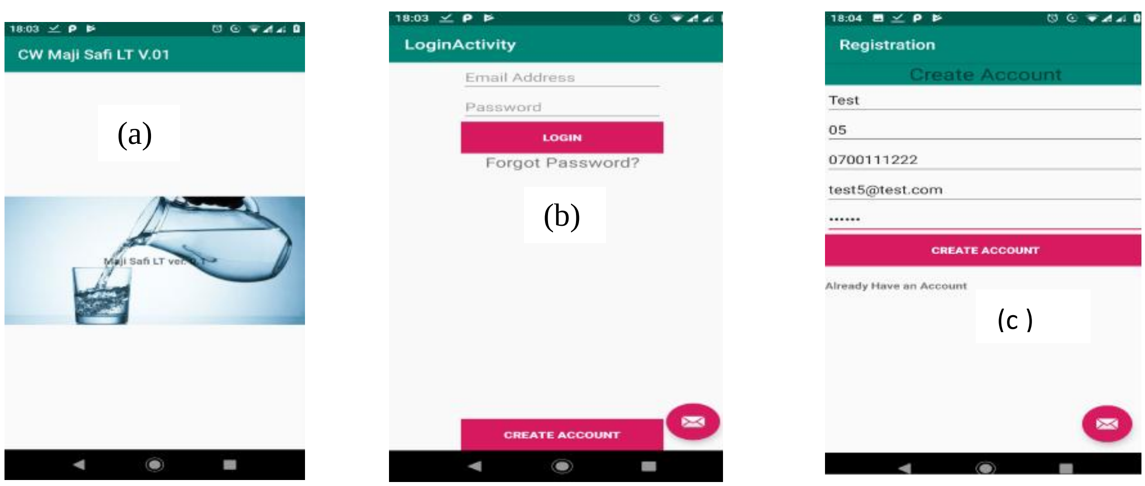


Figure 59:Launch Screen

User requests and feedback

User request is triggered when a logged-in user clicks on the "Request Water" button. The user is then prompted to fill in a form with the amount of water he/she requires and his/ her location coordinates, for the commercial version, the user location coordinates will be system generated. On submission of these details, an invoice is generated providing the cost breakdown of the request, choice of water sources, highlighting the cost of the water requested, cost of transportation to the location, and the total amount as a sum of both. The user is then able to check/verify the quality of the water he / she will be receiving upon which he / she further expected to feed in the payment transaction code provided by the mobile money transfer option (e.g. MPESA in Kenya's case) to complete the transaction. The user will from this point wait for the delivery of his / her paid for water, see Figure 60: a) Maji-Safi : verification notification on successful account creation) automatically redirected back to login screen after successful account creation, b) entering login password and c) Maji-Safi -choose Task screen - choose between making a water request and viewing quality information

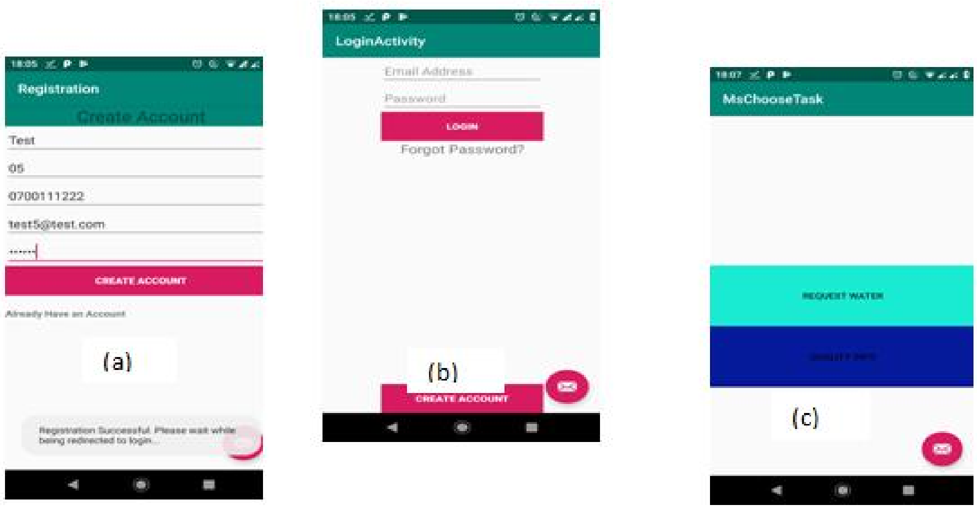


Figure 60:Completion of account creation

The verification of the water quality is triggered when the user clicks on the "Quality Information" button. The user will then once again be prompted to choose between using a verification code (assigned when making a request for water) where the water quality index (WQI) of a particular source of water (borehole with code 'BH' followed with numeric number from '01') can be verified, or to view the water quality index map of the area. These are done by clicking on "Quality Verification" and "Quality Map" respectively. The water quality map is a water quality index contoured map for the operation area which must be developed first by the regulating water quality agency, see figure 61: (a) Maji-Safi Quality related tasks - redirected on selecting the "Quality Info" button from Choose Task,(b) Maji-Safi Quality Map - Displayed on clicking the "Quality Map" button on the Quality Tasks screen,(c) Maji-Safi Source Verification

Screen - Redirected after clicking on the "Quality Verification" button and (d) Result after clicking the "Submit Code” button

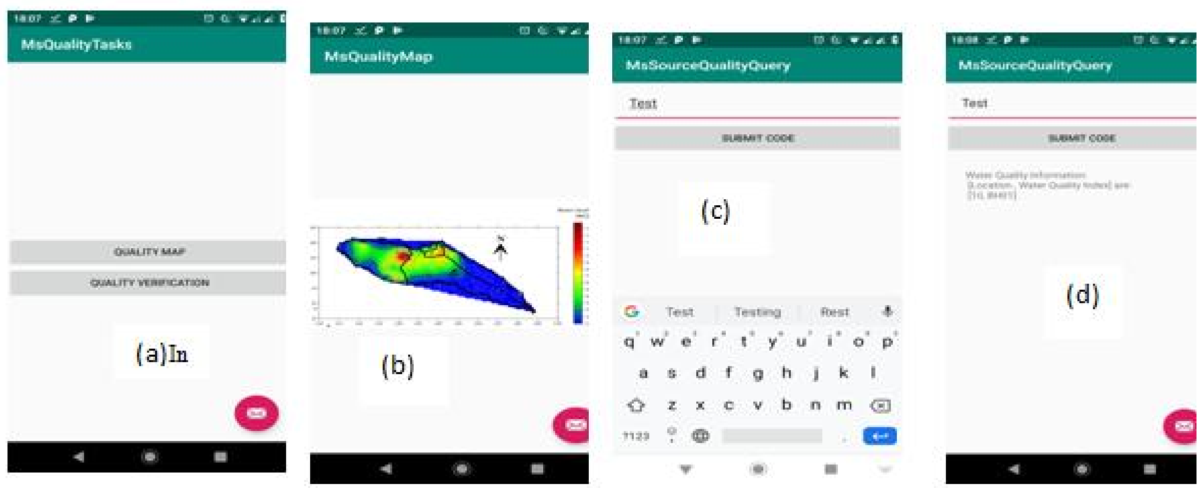


Figure 61:Quality Verification

For the confirmation of order for water delivery upon getting satisfied with the water quality, one simply enters the quantity in litres. The system will post the price, if in Kenya; this will be displayed in shillings. Separately, the system will generate a transport cost based in linear distance for conveyance. In an ideal sense, if the WQTS is being operated by a company, then the payment will go centrally to the dedicated account from which individual actors will get their accounts credited. This app is meant to be operated on Blockchain Technology platform which prides in immutability and transparency. This means, no one actor can alter any record, from quality data, orders and financial records unless permission is granted consensually by all actors.

For water quality data uploads for instance, the agency in charge will have to broadcast this intention beforehand. The same agency remains accountable for the quality of water delivered through the system. The conveyance truck will be auto-tracked in real time to weed out the temptation for fraudulent acts, see Figure 62: a, b, c, d and Figure 63: a, b and c.

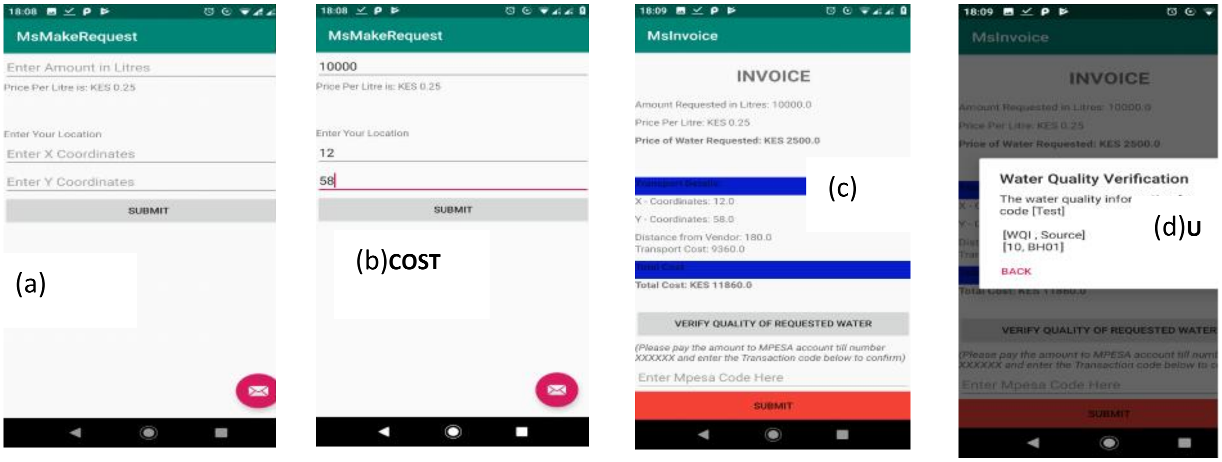


Figure 62: Water delivery ordering process part 1-(a)-(d)

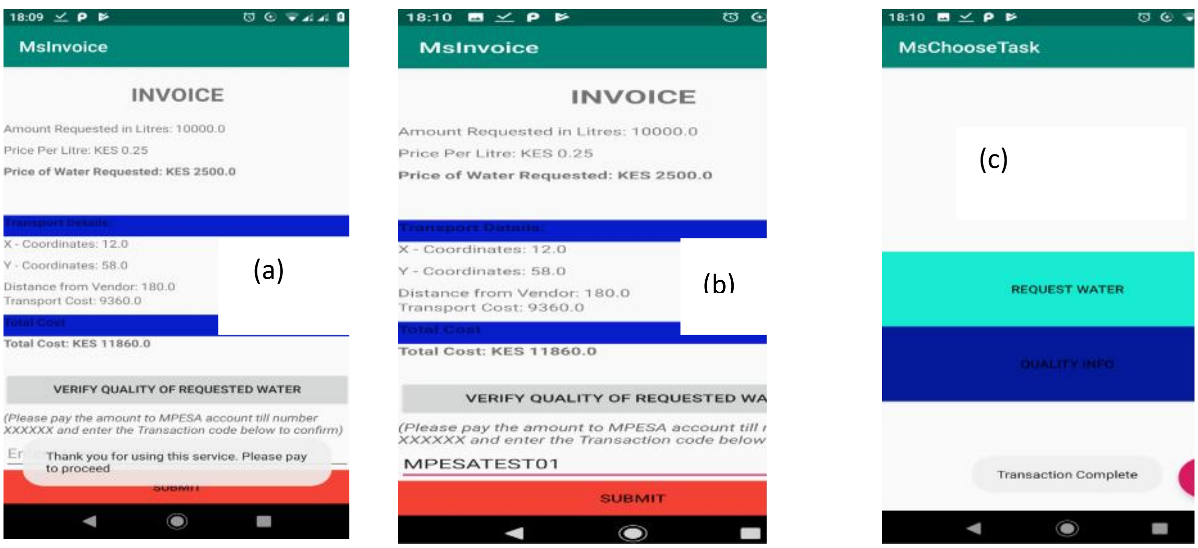


Figure 63:Water delivery ordering process part 2-a,b and c

Where;(a) Maji-Safi Make Request screen - redirected on clicking Request Water button from the "Choose Task" screen, (b) Input of information - litres required and location coordinates, (c) Generated invoice after assignment of suitable vendor, done on clicking the "Submit" button on the Make Request screen,(d) Display of the quality information of the assigned source of water (Displayed on clicking the "Verify Quality of Requested Water" button),(e) Prompt for payment after quality verification of requested water ,(f) Entering the transaction code provided by relevant mobile money transfer service provider and (g) Return to main menu (Choose Task screen) on successful upload of request to the cloud database / server and successful completion verification notification from the server.

Appendix 10: Turnitin Originality Report

Turnitin Originality Report

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