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ASSESSMENT OF GROUNDWATER MANAGEMENT FOR DOMESTIC USE FROM IWRM PERSPECTIVE IN UPPER LIMPHASA RIVER CATCHMENT, MALAWI

By

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DECLARATION

I, the undersigned hereby declare that this thesis entitled, **Assessment of groundwater management for domestic use from IWRM perspective in upper Limphasa River catchment, Malawi,** is my own original work which has not been submitted to any other institution for similar purposes. Where other people's work has been used, acknowledgements have been made.

Thokozani Olex Butawo Kanyerere
Full Legal Name

Signature

September, 2012
Date

Dedication

This work is dedicated to my parents, wife, children, sisters, brothers and cousins

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ABSTRACT

The research problem for this study is the limited and unsuccessful implementation of the IWRM concept. This thesis has argued that comprehensive assessment of physical and socioeconomic conditions is essential to provide explanation on factors that limit the successful execution of the IWRM approach. It has further argued that the local IWRM works as proxy for full and successful implementation of the IWRM approach. To contextualise this thesis, the prevailing physical and socioeconomic factors in Malawi in relation to current management and usage of water resources were explained. With 1,321m^3 per capita per year against index thresholds of 1,700-1,000m^3 per capita per year, this study showed that Malawi is a physically water stressed country but not physically water scarce country although economically it is a water scarce country. This novelty is against some literature that present Malawi as a water abundant country. Again, this study showed that executing a full and successful IWRM in Malawi remains a challenge because of the prevailing socioeconomic situation in terms of water policies, water laws, institutions and management instruments. These aspects have not been reformed and harmonised to facilitate a successful operation of the IWRM approach.

The main water-related problem in Malawi is the mismanagement of the available water resources. This is largely due to the lack of implementing management approaches which can generate systematic data for practical assessment of water resources to guide the coordinated procedure among water stakeholders working in catchments. This lack of implementing a coordinated management approach commonly known as integrated water resources management (IWRM) can be attributed to various reasons that include i) lack of comprehensive assessment of factors that can explain lack of successful IWRM implementation at catchment level and ii) lack of methods to demonstrate data generation and analysis on quantity, quality and governance of water that show practical operation of IWRM at community level using groundwater as a showcase among others.

This study revealed that introducing local IWRM requires a prior knowledge of the evolution and role of the full IWRM concept in the international water policy which aimed at addressing broader developmental objectives. Globally, the current status of the IWRM concept has potential to address such broader developmental objectives, but sustaining IWRM projects where they have been piloted showed slow progress. Basing

on the factors that slow such a progress, local IWRM approach has emerged as a proxy to execute the full IWRM as demonstrated in chapter 8 in this thesis. However, the observed lack of sustainable resources to fund continual functioning of local IWRM activities will defeat its potential solution to water management challenges. The main threat for sustainable local IWRM activities is the tendency of national governments to decentralise roles and responsibilities to local governments and communities without the accompanying financial resources to enable the implementation of the local participation, investments and initiatives at local level. If this tendency could be reversed, the contribution by local IWRM towards solving management problems in the water sector will be enormous. Chapter four has provided the general case-study approach used in this study in terms of research design, data collection methods, data analysis methods, ethical consideration and limitation of the current study within the context of water resource management with a focus on groundwater management.

Using geologic map, satellite images, photographs and hydrogeologic conceptual model, the following results emerged: 1) that the Upper Limphasa River catchment has fractured rock aquifer with limited permeability and storage capacity; 2) The topographic nature and north-south strikes of the lineaments explained the north-south flow direction of groundwater in the catchment; 3) The drainage system observed in the Kandoli and Kaning'ina Mountains to the east and west of the Upper Limphasa River catchment respectively (Fig. 5.1; Fig.5.2) formed a groundwater recharge boundary; 4) The regional faults in the same mountains (Fig. 5.1; Fig.5.2) formed structural boundary as well as hydrogeologic boundary which controlled flow direction of the groundwater; 5) the hydrogeologic conceptual model showed the existence of the forested weathered bedrock in the upland areas of the entire catchment which formed no-flow boundary and groundwater divide thereby controlling the water flow direction downwards (Fig. 5.9); 6) The major agricultural commercial activities existed in Lower Limphasa catchment while only subsistence farming existed in Upper Limphasa catchment. This knowledge and visualization from the map (Fig. 5.3) and conceptual model (Fig.5.9) showed interactions between upland and lowland areas and the role of physical factors in controlling groundwater flow direction in the catchment. It also provided the enlightenment on implications of socioeconomic farming activities on water management. These insights enabled this study to recommend the need for expedited implementation of holistic effective management for sustainable water utilization.

Using different physical factors, water scarcity indices and methodologies, this study showed that Malawi is a physically water stressed as well as an economic water scarce country. This novelty is against some literature that present Malawi as a water abundant country. Again, despite the high proportion (85%) of Malawians relying on groundwater resource, groundwater availability (storage in km^3) is relatively low (269 km^3 in Table 6.10) compared to other countries within SADC and Africa. Given the complexity of groundwater abstraction, the available groundwater for use is further reduced for Malawians who depend on such a resource for their domestic and productive livelihoods. Such insights provided the basis for discussing the need for IWRM.

Although daily statistics on groundwater demand (i: 21.20 litres; 116.91 litres; 80,550.99 litres), use (ii: 16.8 litres; 92.55 litres; 63,766.95 litres) and abstracted but not used (iii: 4.4; 24.36; 16,784.04 litres) were relatively low per person, per household and per sub-catchment respectively, such statistics when calculated on monthly basis (i. Demand: 636 litres; 3,507.30 litres; 2,416,529.70 litres; ii.Use:504 litres; 2,776.5 litres; 1, 913, 008.5 litres iii. Abstracted but not used: 132 litres; 730 litres; 503, 521.2); and on yearly basis (i. Demand: 7,632 litres; 42,087.6 litres; 28,998,356.4 litres; ii. Use: 6,048 litres; 33,318 litres; 22, 956, 102 litres; iii: Abstracted but not used: 1,584 litres; 8,769.6 litres; 6,042,254.4 litres) per person, per household and per sub-catchment provided huge amount of groundwater (Table 6.5). Given the limited storage capacity of fractured rock aquifer in the basement complex geology, the monthly and yearly groundwater demand and use on one hand and abstracted but not used on the other was considered enormous. With the population growth rate of 2.8 for Nkhata Bay (NSO, 2009) and the observed desire to intensify productive livelihoods activities coupled with expected negative effects of climate change, the need to implement IWRM approach for such groundwater resource in the study catchment remains imperative and is urgently needed.

In addition to identifying and describing factors that explain the limited groundwater availability in the study catchment, the study developed a methodology for calculating groundwater demand, use and unused at both households and sub-catchment levels. This methodology provided step-by-step procedure for collecting data on groundwater demand and use as a tool that would improve availability of data on groundwater. Implications of such results for IWRM in similar environments were discussed. Despite the time-consuming procedure involved in using the developed methodology, the calculations are simple and interpretation of results is easily understood among various stakeholders. Hence, such an approach is recommended for the IWRM approach which requires stakeholders from various disciplines to interact and collaborate. Nonetheless, this recommends the use of this method as its further refinement is being sought.

The analysis on groundwater quality has shown that the dominant water type in the aquifers of Upper Limphasa catchment was Ca-HCO_3, suggesting that the study area had shallow, fresh groundwater with recent recharged aquifer. Analyses on physicochemical parameters revealed that none of the sampled boreholes (BHs) and protected shallow dug wells (PSWs) had physical or chemical concentration levels of health concern when such levels were compared with 2008-World Health Organisation (WHO) guidelines and 2005-Malawi Bureau of Standards (MBS). Conversely, although the compliance with 2008-WHO and 2005-MBS of pathogenic bacteria (E.coli) in BHs water was 100% suggesting that water from BHs had low risk and free from bacteriological contamination, water from PSWs showed 0% compliance with 2008-WHO and 2005-MBS values implying high risk to human health. The overall assessment on risk to health classification showed that PSWs were risky sources to supply potable water, hence the need to implement strategies that protect groundwater.

On the basis of such findings, the analysis in this study demonstrated the feasibility of using IWRM approach as a platform for implementing environmental and engineering interventions through education programmes to create and raise public awareness on groundwater protection and on the need for collaborative efforts to implement protective measures for their drinking water sources. The use of different analytical methods which were applied to identify the exact sources of the observed contaminants in the PSWs proved futile. Therefore, this study concluded that rolling-out PSWs either as improved or safe sources of drinking water requires further detailed investigations. However, this research recommended using rapid assessment of drinking water-quality (RADWQ) methods for assessing the quality of groundwater sources for drinking.

Despite the study area being in the humid climatic region with annual rainfall above 1,000 mm, many of the physical factors were not favourable for availability of more groundwater in the aquifers. Such observation provided compelling evidence in this study to commend the local IWRM as a proxy for the full IWRM implementation for sustainable utilization of such waters. Although institutional arrangements, water laws and water policy were found problematic to facilitate a successful implementation of full IWRM at national level in Malawi, this thesis demonstrated that local institutional arrangements, coordination among institutions, data collection efforts by local community members (active participation), self-regulation among local community committees were favourable conditions for a successful local IWRM in the Upper Limphasa River catchment. This research recommends continuation of such local participation, investment and initiatives as proxy for the full and successful IWRM beyond the study catchment. However, the observed lack of financial resource from central government to facilitates local IWRM activities were seen as counterproductive. In addition, this thesis recommended further studies which should aim at improving some observed negative implications of self-regulations on community members and the limited decentralisation elements from the Department of Water Development.

Finally, one of the contributions from this study is the scientific value in using different methods to assess the quality of groundwater as presented in chapter 7. The second value is the demonstration of applying practical techniques to evaluate factors that explain the amount of groundwater storage in the aquifers that can be understood by water scientists, water users, water developers and water managers to implement IWRM collaboratively using groundwater as a showcase. The third contribution is the provision of the procedure to systematically generate data on demand (abstraction) and use of groundwater in unmetered rural areas which has the potential to guide water allocation process in the catchment. Fourthly, the thesis has provided a hydrogeologic conceptual model for the first time for Limphasa River catchment to be used as a visual tool for planning and developing management practices and addressing current water problems. Fifthly, the study has shown how local IWRM works at community level as a proxy for the full implementation of IWRM despite the absence of Catchment Management Agencies. The last contribution is the dissemination of results from this study made through publications and conference presentations as outlined in the appendix.

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Chapter 1: General Introduction

1.1 Background to the study

The present study argues that i) improved understanding on comprehensive assessment of factors that limit successful implementation of integrated water resources management (IWRM) approach is critical ii) implementing local IWRM as a starting point for successful implementation of IWRM is feasible and adaptive to conventional methods. It uses IWRM as a conceptual as well as a theoretical framework and groundwater management for domestic use (drinking) as a case study. The research seeks to generate a model for assessing local hydrogeologic and socioeconomic factors that impede implementation of IWRM at catchment level with a focus on groundwater management for domestic use. Determinants for quantity, quality and governance of groundwater are assessed to provide basis for alternative management options to current approaches for sustainable water utilization. As a showcase, the thesis demonstrates how local IWRM functions at sub-catchment level for water service providers to recognise potential for wider replication of such an approach.

Globally, water management from IWRM perspective has been adopted as an accepted approach to ensure sustainable utilization of water resources for socioeconomic progress and environmental integrity (GWP, 2000). Consequently, several countries have reviewed, reformed and developed their water policies and laws to incorporate IWRM principles. However, fewer of them have successfully implemented IWRM principles (UN-Water, 2008). Therefore, it is compelling to investigate local factors in catchments to provide insights for alternative approach to implement IWRM. In this study, managing groundwater for domestic use (drinking) is used as a case study to illustrate the needed alternative approach for wider IWRM implementation at catchment level.

The present study in the Upper Limphasa River catchment in Nkhata Bay District, Northern Malawi is motivated by the 1) existing limited and unsuccessful implementation of IWRM in various countries despite adopting IWRM principles in their water policies and laws; 2) lack of a case study to show the procedure to enable data availability on water resources especially on groundwater that would inform the basis to fully and successfully implement IWRM; and 3) limited efforts by countries to document and replicate the available working local IWRM cases as an entry point for wider and successful IWRM implementation in river basins.

The general comparison with other countries within the Southern African Development Community (SADC) shows that Malawi has abundant water resources, mainly surface water in rivers and lakes (FAO, 2008) suggesting that water scarcity is not a problem in Malawi. Regardless of the abundant surface water resources, 85% of Malawi's total population of 13 million (NSO, 2009) depends on groundwater resources for domestic uses (Kanyerere et al., 2010 & GoM, 2007), hence, the focus on groundwater management. Mkandawire et al., (2008) identified five top priority challenges in the Malawian water sector that need innovative solutions, namely, 1) poor catchment management; 2) inadequate rural water supply and sanitation; 3) inadequate stakeholder coordination; 4) uncoordinated laws and policies and 5) inadequate capacity building.

These challenges highlight the mismanagement problem but not physical scarcity of water. Consequently, these challenges contribute to 1) IWRM not being implemented successfully and 2) absence of data on hydrogeology, groundwater level and groundwater quality for scientific assessment that improves understanding of groundwater resource to guide decision makers in holistic planning (Mpamba, 2008; Baumann & Danert, 2008). The analysis from the key reviewed literature (Baumann & Danert, 2008; FAO, 2008; GoM, 2007; Kanyerere et al., 2010; Mkandawire et al., 2008; NSO, 2009; MDHS, 2010, Malawi-MDG, 2010), shows that inadequate management of water resources is the main challenge for Malawi which leads to economic scarcity of water rather than physical scarcity (IWMI, 2008). Chapter 2 clarifies the concept of physical versus economic water scarcity where physical and socioeconomic factors are assessed to show the status of water resources in Malawi.

Globally, especially in developing countries, difficult hydrologic legacy and poor socioeconomic conditions determine the quantity and quality of water available for human use (Grey & Sadoff, 2007). Determinants of water quantity (availability, demand and use), quality and governance form central aspects for efficient management of groundwater for water supplies in rural communities (UN-Water, 2007). Improving water quantity, quality and governance depends on the prevailing hydrologic and socioeconomic factors of a particular catchment and country. Hence, improving understanding on these factors is imperative for sustainable use and management of water resources. Effects of these factors on water resources become aggravated when the catchment being studied is located in the rural impoverished areas of developing countries (Grey & Sadoff, 2007). This justifies the need for a comprehensive assessment of factors that explain the quantity, quality and governance of water resources with a focus on groundwater to inform alternative management approach that would expedite IWRM operation. In this study, groundwater quantity refers to availability, demand and use; groundwater quality refers to physical, chemical and microbiological aspects; and groundwater governance refers to adaptive management in form of local IWRM.

In Malawi, Ministry of Irrigation and Water Development (MoIWD), Non-Governmental Organizations (NGOs) and private sector have dominated groundwater development activities for rural water supplies. Coordination among such water providers has been problematic (Baumann & Danert, 2008; Mkandawire et al., 2008). For example, although Groundwater Division in the Department of Water Development is an overseer on groundwater resources, submission of data records on groundwater development by water developers is never enforced because it is not legally binding (MoIWD, 2008; Baumann & Danert, 2008), a situation that contributes to lack of systematic data collection and storage for comprehensive hydrogeologic assessments. As a result, understanding aquifer systems that would inform appropriate development, use and management of such resources using knowledge on local hydrogeologic science remains problematic. One of the main limiting factors for the current study is the non-existence of previous comprehensive data collection on groundwater resources in the Limphasa River catchment. However, some nationwide and district data sets are used. Therefore, generating a groundwater conceptual model for the first time for Limphasa catchment forms original contribution of the present work. This model provides a visual planning and management tool which shows interactions among the prevailing physical and socioeconomic factors in the catchment thereby forming a basis to execute IWRM.

Improving understanding of local hydrogeologic conditions for each catchment remains impeccable. For example, systematic data collection on groundwater parameters by water professionals and community committees is central for efficient management of groundwater for drinking water supplies in rural communities. However, the current practice ignores community committees in data collection arguing that they are not trained to do such work, a situation local IWRM solves (Fletcher & Deletic, 2008). In many countries including Malawi, the level of groundwater data collection is inadequate and where data is available such data is scanty (Xu & Braune, 2010). Both situations do not provide informative information for effective management of groundwater resources. For example, Xu & Braune (2010) report that where groundwater data is collected, usually the information is not readily useful because the data is not prepared and processed in a manner that would facilitate groundwater management. The format does not allow data users to readily view factors associated with conditions of groundwater resource. This observation suggests the need to explore the alternative approach such as adaptive management which local IWRM provides that would incorporate systematic data collection on groundwater to improve its management.

In Malawi, groundwater development is largely concerned with water supply in order to achieve the Millennium Development Goal (MDG) number 7 which calls upon states to halve the number of people without access to safe drinking water sources. Thus, investing in the management of rural water supply resources in Malawi is the priority of water developers, the MoIWD, NGOs, private sector and water users themselves (GoM, 2008a). This public-private partnership approach echoes the institutional principle of IWRM which encourages active participation of stakeholders towards water management (GWP, 2000). However, the analysis by Baumann and Danert (2008) reveals that the required investment for rural water supply sector in Malawi is beyond the capacity of both water developers and users to generate the needed financial resources for managing water resources in terms of operation and maintenance. Again, without systematic data on groundwater sources developed, plans to managing such sources for sustainable use remain futile. This analysis justifies the need for local IWRM to systematically collect data on groundwater to improve understanding on the factors that influence the quantity, quality and governance of groundwater resources so that effective management practices can be implemented.

The poor understanding of aquifer systems due to lack of systematic data on local hydrogeologic environments from borehole drilling activities coupled with lack of coordination among water developers result in poor management practices. For example, groundwater system and socioeconomic dynamics of Limphasa River catchment have not been assessed to highlight major insights for effective management of groundwater, hence, the aim of the current study. In addition, the current research explores community participation in providing data on local hydrogeologic and socioeconomic conditions by assessing operations of local IWRM. The link between hydrogeologic and socioeconomic conditions has remained poorly understood and the opportunity to actively involve local community to collect data on groundwater resources has been missed in groundwater studies. The current study was initiated to address such gaps. The aim is two-fold i) to assess factors that affect implementation of IWRM and ii) to illustrate how local IWRM can bridge such as gap in resource poor countries with anticipation that water providers and managers would recognise the role of local IWRM in national socioeconomic development plans. Assessing groundwater management for domestic use in the Upper Limphasa Catchment in Malawi is used as a showcase for this argued thesis.

1.2 Scope of the study

This study focuses on groundwater sources (boreholes and hand-dug wells) and associated institutions that govern such sources in the eight villages of the Upper Limphasa River Catchment in Northern Malawi. In this thesis hand-dug wells are called protected shallow wells (PSWs) (GoM, 2005). Due to the complex natural environment, spatial heterogeneity of hydrogeologic and socioeconomic conditions, a conceptual model is developed which covers the entire Limphasa River catchment in chapter 5. The aim of the model is to demonstrate groundwater flow dynamics, interactions and relationships among factors and potential influence of such on implementing a successful IWRM. But to demonstrate the impact of land use activities on the quality of groundwater, recharge process and types of aquifer systems in the study catchment, a conceptual model of recharge process is presented in chapter 6. From that model, factors for groundwater availability, contaminant flow pattern for groundwater quality are presented but discussed in relevant sections of chapters 5, 6, 7 and 8.

In addition to assessing factors that influence groundwater availability, demand and use, chapter 6 largely demonstrates a methodology on calculating actual demand and use of groundwater per capita, per household and per sub-catchment. The extrapolation for a week, month and year has been made on assumption that the demand and use is constant. Water quantity in chapter 6 refers to general water availability, groundwater availability, groundwater demand and use. Water availability for Malawi and the study catchment are compared to widely cited water availability threshold of 1,000-1,700 m^3 per capita per year by Falkenmark (1989). The aim is to confirm whether or not Malawi has abundant water resources. Water demand and use are compared to Malawi recommended values of 36 litres per person per day (GoM, 2005; Baumann & Danert, 2008) and international recommendation of 50 litres per person per day (Gleick, 1996; Falkenmark & Widstrand, 1992). A comment has been made in the current news that Africa has huge untapped groundwater resources (MacDonald et al., 2012). However, common methods on calculating water demand and use have been estimations such as modelling water consumption demand and use (Brown & Matlock, 2011). Even the World Bank standard of 50 litres per person per day which is adopted as an international standard to meet basic human needs is based on modelling (Gleick, 1996).

Based on the above description, this study aims at providing a procedure on how to calculate measured data on demand and use that could assist in such models. In so doing, the study contributes to solving the problem of data scarcity on groundwater at both household and sub-catchment levels in unmetered rural communities. The current study is motivated by the lack of systematic data generation procedure and the method provided is considered one step towards making data available for use and for further refinement where need arises. A regression statistical model is used to explain major explanatory variables for the observed demand and use of groundwater in the Upper Limphasa River catchment and such results are discussed with a focus on implication for a successful IWRM implication. The outcome is to improve understanding on factors that influence water availability, demand and use in the sub-catchment so that a successful operation of IWRM approach is based on practical context with evidence-based facts provided by a case study rather than basing on an idealistic situation.

In chapter 7, the focus is on assessing the quality of groundwater from sources and from sampled houses using rapid assessment of drinking water-quality (RADWQ) methods as recommended by WHO & UNICEF (2010). Both physicochemical and microbiological parameters are tested and factors that explain the status-quo of such water are investigated. The aim is to explain the determinants of groundwater quality from sources and households so that scientific as well as socially accepted measures can be implemented to protect such water from contaminants. The overall assumption is that such measures will provide an opportunity for communities (water users), water providers and water managers on how they can protect water from contaminants for sustainable utilization holistically thereby implementing practical collaborative efforts supporting both ecological and institutional principles of IWRM in the catchment.

The chapter on local IWRM is a showcase whose analysis is limited to showing how groundwater management as part of IWRM works despite catchment management agencies (CMA) or river basin organisations (RBO) being not established. The chapter uses adaptive management perspective to highlight the need for local IWRM that adapts to local environment and conventional practices. It shows how global agreed IWRM principles are applied in a local context and best management practices were highlighted. To enable such analysis, the four principles of IWRM in managing groundwater for drinking as a showcase for working local IWRM were identified and then assessed to emphasize the need for scaling up local IWRM approach.

The present study underscores the increasing importance of groundwater for domestic and productive livelihoods especially in rural areas. According to Baumann and Danert (2008) the coverage of groundwater sources in Malawi was estimated to be 71% and Kanyerere et al., (2010) report that 85% of the 13 million people in Malawi depend on groundwater source for drinking water. The important part of international best practice in this situation is access to operational, sustainable and safe groundwater sources (Malawi-MDG, 2010). Thus, managing groundwater resources in Malawi calls for an alternative approach supporting sustainable development objectives and international groundwater best practices. Such an approach is envisaged to inform appropriate best practices at community level that would ensure sustainable utilization of groundwater as part of wider IWRM concept. In addition, the local IWRM has the potential to fulfil such a mandate in the current physical and socioeconomic context of many countries.

Water management in terms of development and data collection system on water parameters are well-established but have remained i) fragmented where stakeholders do not share data; ii) sector-based where stakeholders work independently; iii) focused on water experts only. Paradoxically, such stakeholders provide water services in the same communities and the same excluded communities from data collection and records keeping on water resources are expected to manage their water resources for sustainable use (Fletcher & Deletic, 2008). This observation partly explains the observed and reported continued scanty and unavailability of data on groundwater resources that limit wider water assessment to inform a thorough planning by decision makers. The argument for this thesis is that local IWRM has the potential to narrow such a gap.

The advent of the IWRM approach, though in many countries remains theoretical, seems plausible to address problems of managing groundwater when a phased approach is employed (Braune et al., 2008). From the experience of many countries including Malawi (Xu et al., 2010) and with increased pressures on land and water resources due to human activities and climate change effects (Brown & Matlock, 2011), major concerns on how to improve quantity, quality and good governance of water resources are anticipated especially with existing limited and unsuccessful implementation of the IWRM approach in many countries. Such scenario when left unchecked will be counterproductive to efforts invested in the IWRM concept and will likely affect the performance of efforts for effective groundwater management as part of IWRM.

The first thesis for the current study is that a comprehensive understanding of the local hydrogeologic and socioeconomic factors in the catchment and their systematic consideration in the planning, development and operation is the basis for the sustainable utilization of water resources for people’s improved livelihoods and integrity of their environment. According to UN-Water (2008), countries have different physical characteristics and exist at different stages in their economic and social development. Therefore, management approaches need to be tailored to individual circumstances of catchments and countries. Since demand for water is ever increasing due to increasing human population with their increasing economic quests and climate change effects that threaten water resource, the traditional fragmented approach is no longer viable and hence a more holistic approach to water management is essential. The rationale for

IWRM approach has become internationally accepted as a solution for sustainable development and management of water resources (UN-Water, 2007). Such an approach must start in a phased manner and local IWRM is a phased approach which remains a suitable holistic management practice as this thesis argues.

The second thesis for this work is that local IWRM is feasible even in the absence of Catchment Management Agencies or River Basin Organisations and it needs to be considered as an entry point for implementing a wider and successful IWRM. However, the need to first improve understanding on local hydrogeologic and socioeconomic environments that inform effective management of groundwater as part of IWRM framework remains imperative. Groundwater management for drinking illustrates how data on groundwater resources should be collected systematically by both water professionals and community members (water-point committees) but not independent of community members as practised in the past. Such a process needs a phased approach with initial training and monitoring on local communities, structures and catchments. This should be within an overall IWRM framework with full stakeholder participation and in collaboration with other key water resources management instruments (Mpamba, 2008). To facilitate implementation of such an approach, factors that influence quantity, quality and governance of water need to be assessed to provide evidence-based information that would contribute to science-led policy reform process that will accelerate IWRM implementation for sustainable water utilization.

The study provides evidence to support the first thesis in chapters 5, 6, 7 and second thesis in chapter 8. It links case study findings to national, regional and global pattern and shows why and how replicating such results in other catchments of similar physical and socio-economic environment is necessary. The status of physical and socio-economic conditions at catchment level is a measure of effective management of groundwater resources. Therefore, appropriate practices for water development within a catchment have crucial implication on productive rural livelihoods and human health than policies and laws that operate largely at national level with limited bearing on local scale. The hypotheses outlined in section 1.5 are based on these assumptions.

1.3 Rationale of the study

The rationale for the present study is based on the limited progress towards IWRM implementation in many countries when such countries face threatened sustenance of their environmental resources such as water. IWRM principles provide countries with means of ensuring sustainable use of natural resources and generating scientific knowledge that is essential for sustainable development. Yet the available scientific information on water resources at catchment level remains largely untapped and hardly known to the public and their decision makers. Therefore, assessing hydrogeologic and socioeconomic environments at catchment level with a focus on local IWRM initiative using groundwater management practice is well placed. Such assessment raises public awareness on critical factors that need improved understanding to facilitate wider application of IWRM in catchments of similar conditions. This study shows that local IWRM initiatives have potential for wider IWRM implementation at catchment scale to ensure sustainable development, utilization and management of water resources for improved domestic and productive livelihoods. Promoting the use of local IWRM for decision making process on societal issues is one of the arguments of the current study.

This research develops a hydrogeologic model for alternative approach to effectively manage water for domestic and productive functions so that the quality of human life and their environment improves. It has policy relevance in that, the chosen approach adopts a systems approach with a focus on groundwater management as part of IWRM framework which is a globally agreed upon water management framework. Such a framework is strongly interdisciplinary whereby social science (demand, use and governance of water) and natural science (local hydrogeology, groundwater availability, physicochemical and microbial parameters of water) aspects of groundwater are equally considered in providing solution to a research problem for the current study. As a case study, the research is based on a unique geographic location (rural area) and developmental challenges (poverty-prone area) which provides critical analysis on current practice on water development, water service delivery and policy-practice discourse on water for improved human livelihoods within the paradigm of promoting environmental integrity for socioeconomic and sustainable development.

The study design has followed principles of ecologic and epidemiologic approaches where water as an environment explains risks to human health and where active involvement of communities to manage their water explain the potential for such communities to improve their productive livelihoods. This design agrees with the ecological and institutional principles of IWRM which call for protection of water resources and participatory approach by stakeholders. Findings are envisaged to contribute to the international knowledge base through scientific publications (Appendix). Such findings have potential to be locally relevant and support the required type of research through provision of knowledge-base economy (data, information, knowledge and wisdom) that would improve water-health policy reform and practice based on systematically collected data sets. In that way, the study provides a better understanding on how groundwater system functions to support efforts by key stakeholders in groundwater development as part of IWRM approach.

The study is also relevant to water-health practices as it provides evidence-based information on reliability and effective use of groundwater system with associated governance aspects. It takes into consideration contemporary discussions on best practices for groundwater protection versus existing water policy and practices by highlighting the need for adaptive approaches that lobby for groundwater quality protection rather than curative approach that lobby for water purification technologies. In this way, using precautionary and benefit sharing principles become tools for environmental protection goals through groundwater management as part of IWRM.

Studies (Xu & Braune, 2010; Adelana & MacDonald, 2008; Fletcher & Deletic, 2008) have demonstrated that disjointed data collection system on water management has resulted in management problems within the water sector. These studies report that interactions between different water components remain poorly understood resulting in water mismanagement being a major problem. For example, Fletcher and Deletic (2008) state that data collection on water variables has been duplicated by different stakeholders and linkages with previous data on the same variables are not well known resulting in difficulties to conduct spatial-temporal trend analysis on the status of water such as groundwater. The result has been lack of coherent basic knowledge on water resources especially groundwater to inform practical policy reform that would guide orderly water development for the benefit of communities especially in rural poverty-prone communities that largely depend on groundwater for drinking and productive activities (Braune & Xu, 2010; GoM, 2007 & Kanyerere et al., 2010).

This research provides a better understanding of approach that is likely to succeed on practical level by focusing on key aspects of local IWRM. Furthermore, it highlights key gaps in knowledge that would require further detailed studies to empirically demonstrate barriers for IWRM implementation on catchment level. The study has focused on local IWRM as showcase to demonstrate solutions that would work for i) rural communities to manage their water, ii) water scientists and managers to ensure orderly provision of water service, iii) utilization and management of potable water in rural resource-poor areas. To show the feasibility and cost effectiveness of local IWRM, analysis on improving understanding of current water usage and management for domestic and productive livelihoods with its associated impact on the environment has been emphasised. Chapter 3 has reviewed previous interventions with associated beneficiaries as a learning platform. It has also presented information on conventional approaches for groundwater management that may hold key to future water management that informs the argument for the current study.

1.4 Problem statement

1.4.1 Analysis of study problem

Fig.1.1 shows the major existing thematic issues within the water sector in Africa as identified by Africa Water Vision 2025. The current study focuses largely on providing safe water for drinking (groundwater protection) with some aspects of sanitation, water pollution, water demand, water for food security (water use around water sources) and water cooperation (water governance also known was local IWRM).

The management challenges facing Malawi regarding water resources has elements of all the nine thematic issues identified by Africa Water Vision 2025 making a successful IWRM implementation difficult. It is noteworthy that of the 17 major catchments existing in Malawi, IWRM was only experimented partly in Ruo Catchment (Dzimphutsi area) where assessment shows no indication to achieve sustainable utilization of water resources (Shaba & Van Kopper, 2008). Furthermore, of the 18 monitoring boreholes planned in 2009 to generate data on hydrogeology, groundwater level and groundwater quality, only 8 were drilled by 2010 (Nkhata, 2011). This observation indicates that an alternative approach (local IWRM) to generate data for effective management of groundwater resources as part of a successful and full IWRM is unavoidable in Malawi.

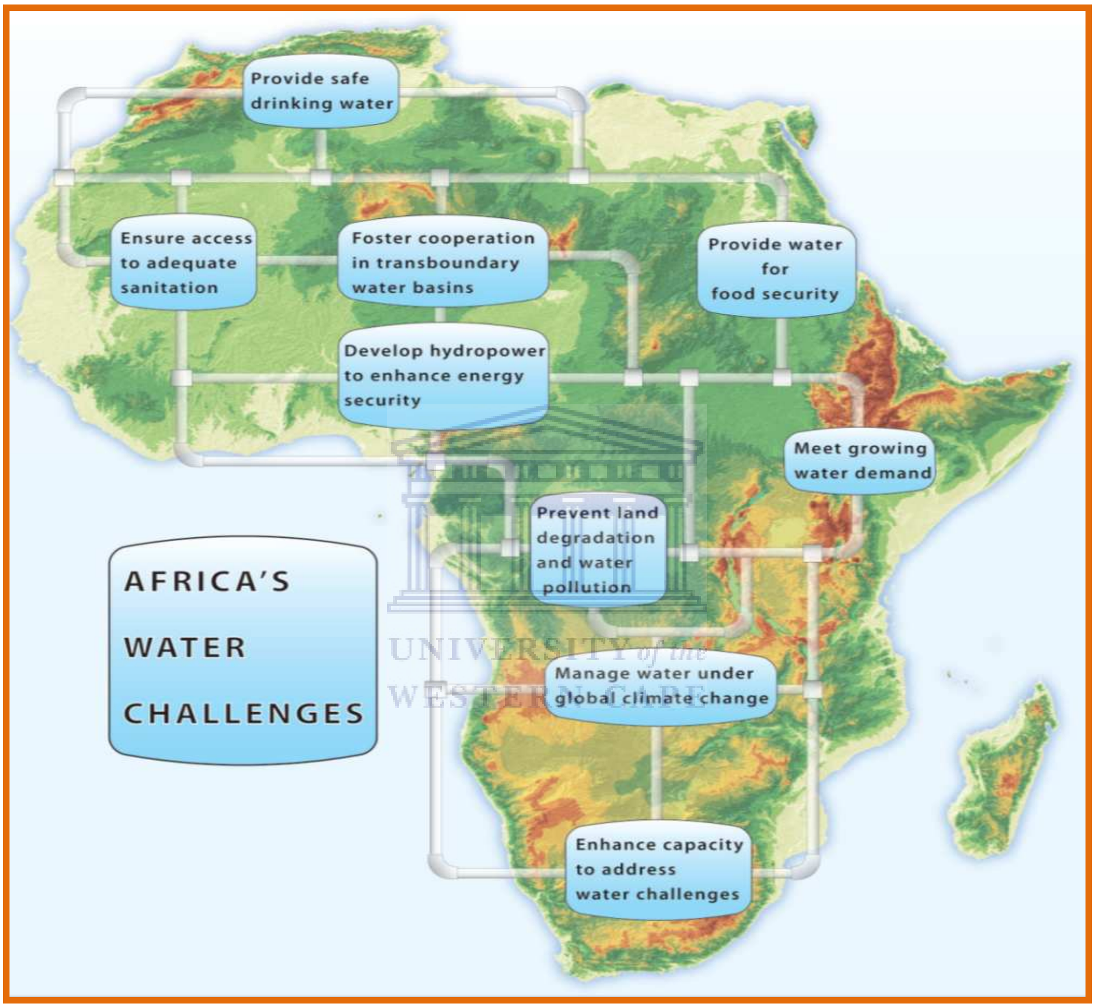


Figure 1:1.1 Nine current water challenges in Africa

Source: UNESCO, 2011

On global scale, 27 developed countries were assessed on IWRM implementation progress where results showed that only 6 countries had fully implemented IWRM while 10 countries had partially implemented IWRM (UN-Water, 2008). When 77 developing countries were assessed, only 2 countries had fully implemented IWRM while 17 countries had partially implemented IWRM (UN-Water, 2008). These results confirm that implementing IWRM remains problematic despite the reported improvement on IWRM planning process at national levels in various countries.

Douglas et al., (2006) cited lack of data on water and indicators as some reasons for not implementing IWRM while Colvin et al., (2008) reported that countries know reasons for not implementing IWRM but they do not take action largely due to governance issues. So, an alternative approach to reduce such challenges needs demonstration. The current study aims at illustrating such a solution using a case study at a sub-catchment.

Not implementing a successful IWRM approach is counterproductive to the progress made on advancing IWRM concept and principles. It means that i) previous problems that IWRM wanted to solve will remain problems hindering sustainable development goals; ii) all financial resources and time spent on conferences, research activities and trainings on IWRM approach are wasted and iii) that knowledge and skills gained through IWRM conferences, research and trainings will remain not utilized when capacity development is urgently needed in the water sector. The overall effect on socioeconomic development, environmental integrity and human well-being will remain dormant. Section 1.4.2 characterizes the general problem and section 1.4.3 explores the drivers which possibly triggered the research problem being investigated in this thesis.

1.4.2 Description of general problem

In Malawi, between 2004 and 2008, water point mapping for rural water supplies was conducted by several researchers whose work provided inventories on sources, functionality and coverage of rural water supplies (Baumann & Danert, 2008). Update mechanisms for these data sets are still weak. NGOs work in isolation and rarely report their new constructions in the catchment to the District Assemblies or District Water Offices. In addition, diagnostic data to provide information on why some groundwater sources become non-functional or abandoned does not exist. The Village Health Book which represents another data source does not contain information on water resources in the village. Coordination between government departments and NGOs offices on the one hand and within government departments on the other hand does not exist, making the situation worst on groundwater information. For example, numerous cases exist whereby the District Water Offices know about new water facilities in their district by chance or when water facilities break down or when communities seek assistance from the water department office to repair the break down wells (Baumann & Danert, 2008).

Water development such as borehole drilling contributes to availability of data about groundwater resources in terms of physical, chemical and microbiological status of the water at the time of borehole drilling and installation. The practice is that water quality assessment of groundwater is normally carried out soon after pump installation of a newly constructed water source or after rehabilitation by drilling constructors (water professionals) as part of their contract agreement. Local people are not involved in data collection and record keeping, a practice which is not adaptive to local institutions (water point committee). The current practice is a top down approach lacking active community participation as required by the institutional principle of IWRM approach.

At national level, groundwater quality in Malawi is generally acceptable for domestic use (drinking). However, studies have shown high concentration levels of fluoride, iron and sulphate in groundwater in selected areas in Malawi which is not fit for human consumption (GoM-UNDP, 1986). Currently, no catchment specific studies exist to establish the status of water quality and analyse contraction levels of physicochemical and microbiological parameters deemed harmful for human health. Chapter 7 of this study addresses this gap. In addition, areas where groundwater quality is not suitable for human consumption are not yet delineated (GoM-UNDP, 1986). Understanding hydrologic environment only is not enough as the need to match such knowledge with water service delivery institutions becomes unavoidable in catchments where multiple stakeholders operate, hence assessment of socioeconomic factors in this study.

1.4.3 Drivers to study problem

The background to the research problem is the growing threats to meeting Millennium Development Goal (MDGs) on environmental sustainability goal which aims at halving the proportion of people who are unable to access safe drinking water and sanitation by 2015 (Malawi-MDG, 2010). It was envisaged that growth and development efforts to improve people’s livelihoods would be derailed by sporadic outbreaks of waterborne diseases from unspecified sources in the catchment. The key security challenge is the threat to i) reliability of the groundwater system in terms of groundwater quality at sources and households, access to such sources and functionality of such sources and ii) effective use of groundwater at households. In addition, the quality and quantity of groundwater consumed at household level in rural areas remain speculative hence the assessment. Again, the effect of climate variability through increased dry spells is expected to reduce quantity and quality of water available and increase demand for the water hence the assessment of the current demand hence the assessment on rainfall pattern in chapter 6. This described scenario threatens human health and people's livelihoods which in turn slows the growth and development progress of the Limphasa River catchment in particular and Malawi in general as water becomes scarce for productive livelihoods, hence the assessment (Malawi-MDG, 2010; UN-Malawi, 2010).

The second concern relates to the enabling environment to managing groundwater resource particularly good governance aspects in terms of water laws whose review and enactment are overtaken by ever-changing events resulting into difficulty to enforce old legal tools on new challenges (GoM, 2009). As a result, the current drilling, development and construction of groundwater points remains legally unbinding. In Malawi, it is not legally binding to submit all data generated during groundwater development to either the Water Point Committee in the community or the Groundwater Division in the Department of Water Development. Therefore, exact numbers and associated data on geology and hydrogeology of existing water points remain unknown. In addition, Groundwater Division does not deal with development of protected shallow wells, making NGOs develop these water sources following their respective guidelines (Nkhata et al., 2009). Thus, at catchment and country levels groundwater monitoring remains problematic due to the absence of data on hydrogeology, groundwater quantity and groundwater quality. This explains why the absence of systematic data on previous work in Limphasa Catchment largely limited the robust analyses in the current study.

These concerns emerged because firstly, Malawi is known to have relatively abundant fresh water resources in rivers and lakes; hence, there was no need to worry about managing the resource, especially groundwater (FAO, 2008). Secondly, standards on drinking water quality and quantity are not legally binding for enforcement. Malawi Bureau of Standards and Water Department merely set standards and guidelines respectively which are neither practised nor monitored systematically by all districts' water offices (Mponda & Ndhluli, 2008). Thirdly, department of Water Development decentralized and centralized some water services resulting in uncoordinated roles among stakeholders (Mponda & Ndhuli, 2008). This situation leads to scanty data collection on water points resulting into difficulty to comprehensively assess the status-quo of water quantity, quality and governance aspects. This study argues for wider application of local IWRM approach which has the potential to provide a systematic data collection procedure and record keeping that can be used to standardize reporting efforts from the water point committees at catchment level to the department of Water Development at national office through District Water Office for spatial and temporal analyses. Such an approach adapts government professional procedure to local structures in catchments which has the potential to ensure sustainability of the practice.

1.5 Research question and research hypothesis

Two main research questions for the current study are: 1) What are the local hydrogeologic and socioeconomic factors that explain limited and unsuccessful implementation of IWRM approach? 2) As a showcase, how does groundwater management for domestic use demonstrate the feasibility of local IWRM at sub-catchment for wider replication?

The following are specific guiding assumptions with associated sub-research questions:

i) Local hydrogeologic and socioeconomic factors have influence on implementing a successful IWRM approach. How do local hydrogeologic and socioeconomic factors influence a successful IWRM operation? What model can be used to assess the influence of local hydrogeologic and socioeconomic factors on IWRM operation?

ii) Improved knowledge on calculating groundwater demand and use at household and sub-catchment levels provide systematic procedure on generating data in unmetered rural areas thereby forming the basis for implementing a successful IWRM. What are the procedures for generating data on groundwater demand and use in unmetered rural areas? What steps are needed to generate data on demand and use of groundwater in unmetered rural areas? How does data generating process act as a tool for implementing a successful IWRM approach in a catchment? How much water is abstracted from groundwater sources per day, month and year in the study sub-catchment? How much of the abstracted groundwater is used and not used at household and catchment levels per day, month and year in the study area?

iii) Improved knowledge on groundwater contaminants helps to develop practical measures to protect groundwater for drinking. What methods can be used to assess groundwater contaminants to protect groundwater for drinking? How reliable are groundwater sources to supply potable water in rural communities? What major determinants explain groundwater quality in Upper Limphasa River catchment?

iv) Assessing application of IWRM principles in the management practices of groundwater sources in communities provides evidence on feasibility of local IWRM. Which IWRM principles practically work in local IWRM? How does local IWRM work as a proxy for full IWRM? What lesson can be learned from local IWRM which could be applied beyond the study catchment to facilitate successful implementation of IWRM approach? Does local IWRM need modification?

One of the arguments for local IWRM as one of the best management practices of groundwater for rural water supplies is that it promotes good governance in that local institutions (water-point committees) become integrated in regulations on developing groundwater supplies as reflected in drilling contract and drilling supervision forms (MacDonald et al., 2005). For example, communities alongside drillers participate in data collection during siting, drilling, development, construction of water points and have the potential to continue with data collection and record keeping during monitoring if trained. This integration harmonizes coordination of data and information among stakeholders for managing groundwater steadily. The current study argues that regulations on groundwater development when adapted to local institutions in a catchment with proper training have potential for systematic collection, availability and accessibility of data for stakeholders who work on groundwater planning, development, assessment and management (Fletcher & Deletic, 2008). Such an adaptive approach within local IWRM is one step towards a successful operation of IWRM as demonstrated in findings from the case study in chapter 8 of this thesis.

1.6 Study objectives

1.6.1 Main objectives

The main objectives of this study are i) to improve understanding of local hydrogeologic and socioeconomic factors that influence successful implementation of

IWRM and ii) to demonstrate how local IWRM works as a proxy for wider and successful implementation of the IWRM approach.

1.6.2 Specific objectives

The specific objectives of this study are to:

1) Illustrate how local hydrogeologic and socioeconomic factors influence successful IWRM implementation using the hydrogeologic conceptual model.
2) Demonstrate data generation procedure on groundwater demand and use in unmetered rural areas that provides practical tools for IWRM implementation.
3) Assess groundwater quality for drinking from sources and selected households to explain determinants of water quality using RADWQ methods.
4) Demonstrate feasibility of local IWRM to facilitate a successful IWRM operation at sub-catchment level using multiple-use-service (MUS) analytical methods.

1.7 Study approach: Theoretical and conceptual framework

A case study approach is used in this research to investigate problems that explain unsuccessful implementation of the IWRM approach with a focus on groundwater management. The case study is based on the Upper Limphasa River catchment in Malawi, a country with a tropical climate where annual rainfall occurs from November to April. Despite the presence of many perennial rivers and the five fresh water lakes, the countries faces challenges in managing water resources especially groundwater which provides drinking water to 85% of the 13 million population. Nevertheless, improved knowledge on groundwater system is limited for several reasons, but local communities have the potential to contribute positively to managing such a resource.

The study examines options to improve water management with a focus on groundwater for drinking in a context of increasing tension between socioeconomic development (water for livelihoods) and ecosystem (physical) over conflicting requirements for water in a catchment. The framework for the study is the IWRM approach with a reflection of Millennium Development Goals (MDGs) of halving the proportion of people without access to safe drinking water sources and to using water for improved livelihoods in a manner that sustains the environment. The approach recognizes that water management lies within the sphere of environmental systems as a part of the greater natural resource base including people, land and water resources. Their interaction has both negative and positive effects in a social-political context (Molden, 2007).

The IWRM framework considers dynamic interactions between environment, water systems and people in time (years and seasons) and space (scale at various levels). The analysis in a conceptual model considers site specific and scale context. The framework relates drivers of change in a model to water management and the evolution of IWRM since its inception. The framework provides a perspective on the interactions between key components, namely, hydrogeologic environment (chapter 5), groundwater availability, demand and use (chapter 6), groundwater quality (chapter 7) and groundwater governance (chapter 8). Such interactions are only a snapshot of the existing linkages in reality and the framework fails to fully capture the value and effects of social-cultural, political, economic and institutional dimension of water management in a catchment system and in all changes within rural settings (Molden, 2007). Furthermore, the framework cannot empirically establish linkages and changes in some variables in the catchment on water system hence, the focus on potential influence of factors that affect IWRM implementation. The value of the framework then shows the complexity of implementing the IWRM approach. Such revelation forms the basis for proposing operation of a proxy innovative management approach, the local IWRM, to full IWRM that sustains utilization of water resources and promotes the integrity of the environment (ecosystem) for sustainable growth and development (UNESCO, 2009).

The first part of the study focuses on recognizing concerns that affect management of groundwater for drinking in Malawi. Such concerns include socio-economic, legal framework, technical and hydrologic environments. The discussion on these aspects has provided the context to understand how and why groundwater management in Malawi result in the current state (chapter 2). In chapter 3, the study provides the status of groundwater management in various countries for improved livelihoods as part of the IWRM framework with a focus on examples about the progress of IWRM operation.

The second part of the study focuses on development of a conceptual model to generate management scenarios for managing groundwater for domestic uses in rural areas within sub-humid tropical environment using Upper Limphasa River catchment as a case study. In order to generate this understanding, preliminary knowledge on quantity, quality and governance of groundwater is provided through field investigations and measurements as well as through data collected from existing secondary sources.

The third part of the study focuses on demonstrating the feasibility of local IWRM at community which needs publicity as an alternative approach for wider and practical application to facilitate a successful execution of IWRM at catchment levels. In order to develop this thesis on local IWRM, elements of IWRM principles have been assessed in the management of groundwater for domestic use in all water sources in the Upper Limphasa River catchment in Northern Malawi as a showcase for wider application.

1.8 Thesis contribution

One of the contributions of the thesis to the field of groundwater management is the scientific value in demonstrating the use of various methods covering most aspects required to assess groundwater quality for drinking. For example, the application of RADWQ methods is relatively new in the drinking water sector and such methods are successfully applied in this study. Another contribution is made towards demonstrating the practical methodology to evaluate potential factors that explain groundwater availability in a particular catchment which has the potential to create groundwater awareness among scientists, users, developers and managers of water resource for IWRM execution. The third contribution is made towards demonstrating the procedure to systematically generate data on demand and use of groundwater in unmetered rural areas which has the potential to form the basis for a successful operation of IWRM and to engage in useful debates innovations on groundwater availability.

The fourth contribution of the thesis is the provision of hydrogeologic conceptual model for the first time for Limphasa River catchment. This model provides a basis for developing alternative management approaches that address current water mismanagement practices which are associated with unsystematic data collection structure within the groundwater sector in Malawi. The model is conceived significant due to multiple stakeholders involved in groundwater development. It highlights interactions between physical and human environments, land and water resources, upstream and downstream resources, groundwater and surface water which provide wider analysis indicating positive potential for operating a successful IWRM approach.

The fifth contribution is the pragmatic demonstration of local IWRM as an alternative approach to facilitate successful IWRM operation at catchment level thereby providing solution to the observed problem of limited and unsuccessful IWRM execution. The entire study relates directly to the current debate on groundwater as part of IWRM framework. Since groundwater development for rural water supply occurs in an environment of limited financial and technical resources as well as socio-political pressure, the participation of local communities in data gathering as shown in local IWRM is cost-effective although room for improvement exists. For instance, involving local communities in collecting scientific data on groundwater resources is adaptive to conventional data collection tradition whereby only water professionals collect data on groundwater aspects. Local IWRM approach if nurtured by water professionals will enhance systematic data collection; availability and accessibility thereby providing the basis for data standardization for various analyses.

The sixth contribution is the publications made from the findings of this work as provided in the appendix. For example, i) Chapter 4: Best practice for groundwater quality protection (published in Xu & Braune, 2010); chapter 16: Rural water supply and sanitation in Malawi, a groundwater approach by Kanyerere et al., 2010 (published in Xu & Braune, 2010); iii) Assessment of microbial contamination of groundwater in Upper Limphasa River Catchment, Northern Malawi by Kanyerere et al., 2012 (published in WaterSA Vol.38 No.4) and iv) Understanding groundwater contaminants for improved human health (forthcoming). The aim of these publications is to share findings with wider scholars that advance understanding on groundwater-local IWRM.

This study aims at exploring factors that explain limited application of IWRM approach in many countries and then attempted to demonstrate how local IWRM can work as proxy for a successful IWRM operation Through data collection and analysis, the study is able to (i) identify and explain potential factors for groundwater availability in the study area; ii) demonstrate procedure for systematic data generation on demand and use of groundwater (iii) establish groundwater contaminants and their potential sources with the use of different methods and practical need for IWRM application iv) Using hydrogeological model to describe the groundwater system, the study provides insights into challenges and possibilities for a successful IWRM execution to reduce the observed challenges; and v) illustration on how local IWRM works as a proxy for successful operation and best management practice approach for IWRM is provided.

1.9 Structure of the thesis

Chapter 1 provides the general introductory aspects of the research in terms of scope, rationale, research questions, objectives, approach and contribution of the study. Chapter 2 describes groundwater management in Malawi with a focus on key concepts, physical and socioeconomic environments and rural water supply situation. The status of groundwater management is presented in chapter 3 while chapter 4 describes research design and methods that were used to generate and analyze data. Chapter 5 presents the conceptual model and explains how local factors influence successful operation of the IWRM approach. Chapter 6 provides factors that influence water availability, demand and use in addition to providing a methodology on data generation for groundwater demand and use in unmetered rural areas. Chapter 7 demonstrates the use of current methods in assessing groundwater quality for drinking from sources and households as one way of generating data for water assessments and assessing implication for a successful IWRM execution. Chapter 8 demonstrates the feasibility of local IWRM at community level, a proxy for wider IWRM. Chapter 9 summarizes the findings by highlighting major insights and recommending actions for practical considerations and for further research work in the study river catchment and beyond.

In the thesis, the in-text references for all figures and tables have two sets of numbers separated by colon (aabb:cc.dd). The first set (aabb) refers to the continuous numbering of either the figure or table throughout the thesis and such numbering does not appear in the text. The second set (cc.dd) refers to the chapter (cc) and the figure or the table (dd) in that specific chapter. This set (cc.dd) appears in the text in each chapter that is being described or discussed or at times between chapters.

Chapter 2: Assessment of Water Resources in Malawi

2.1 Introduction

The current chapter describes groundwater management for domestic purposes in the Malawian context. The chapter argues that the need to advocate for a new approach in managing water resources depends on prevailing environments. Description of such environments provides insights on factors that limit wider execution of the IWRM approach. Such description provides the basis for new approach to implement IWRM principles in the local context. Therefore, this chapter presents the prevailing circumstances that influence management of water resources in Malawi. Key concepts for water management, physical and socio-economic environments are described to contextualise the management of groundwater resources. References have been made to literature within and beyond SADC region to provide a wider perspective.

2.2 Location and Coverage of Malawi

Malawi is a land locked country in Sub-Saharan Africa (Fig.2.1), lying in the southern end of the Great East African Rift Valley. It lies between latitudes 09º 25'S and 17º 08'S and longitudes 32 º 40'E and 35 º 55'E. It is bordered by Tanzania in the North and North East, Mozambique in the East, South and South West and Zambia in the West and North West. The country is about 901 km long and 80 to 161 km wide. The total surface area of the country is about 118,480 km^2 of which 94, 080 km^2 is covered by land and 24,400 km^2 by water, mostly by Lake Malawi which is about 580 km long and is the country's most prominent water reservoir (MDHS, 2010; NSO, 2009).

Administratively, Malawi is divided into three regions (provinces), namely, North, Centre and South with 28 districts (Fig. 2.1) each being under a chief executive known as District Commissioner (DC). Districts in Malawi are distributed as follows: six in the North, nine in the Centre and thirteen in the South. The districts are administratively subdivided into traditional Authorities presided over by chiefs commonly known as Traditional Authorities (TAs). These Traditional Authority areas are further subdivided into villages which form the smallest administrative units (NSO, 2009). They are headed by the village Head (VH). The Upper Limphasa Catchment, the study area, is located in Nkhata Bay District (Fig. 2.1) in the Northern Region, in TA Timbiri and

Nyaluwanga. The study area covers eight villages, namely, Upper Kango, Chisindilizi, Chaola, Kamphomombo, Chipaika, Chivuti, Kayuni and Mjutu-Karonga (Fig. 2.2).

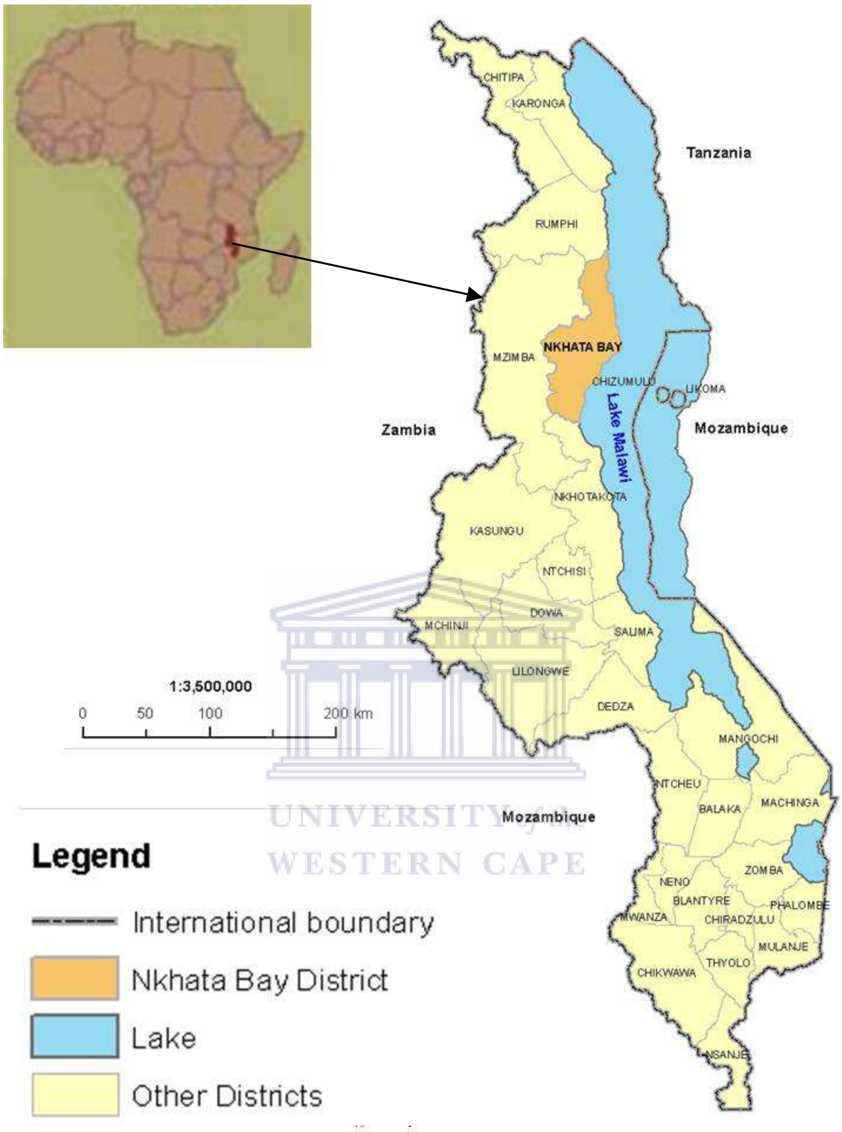


Figure 2: 2.1 Nkhata Bay District in Northern Malawi and other districts in Malawi

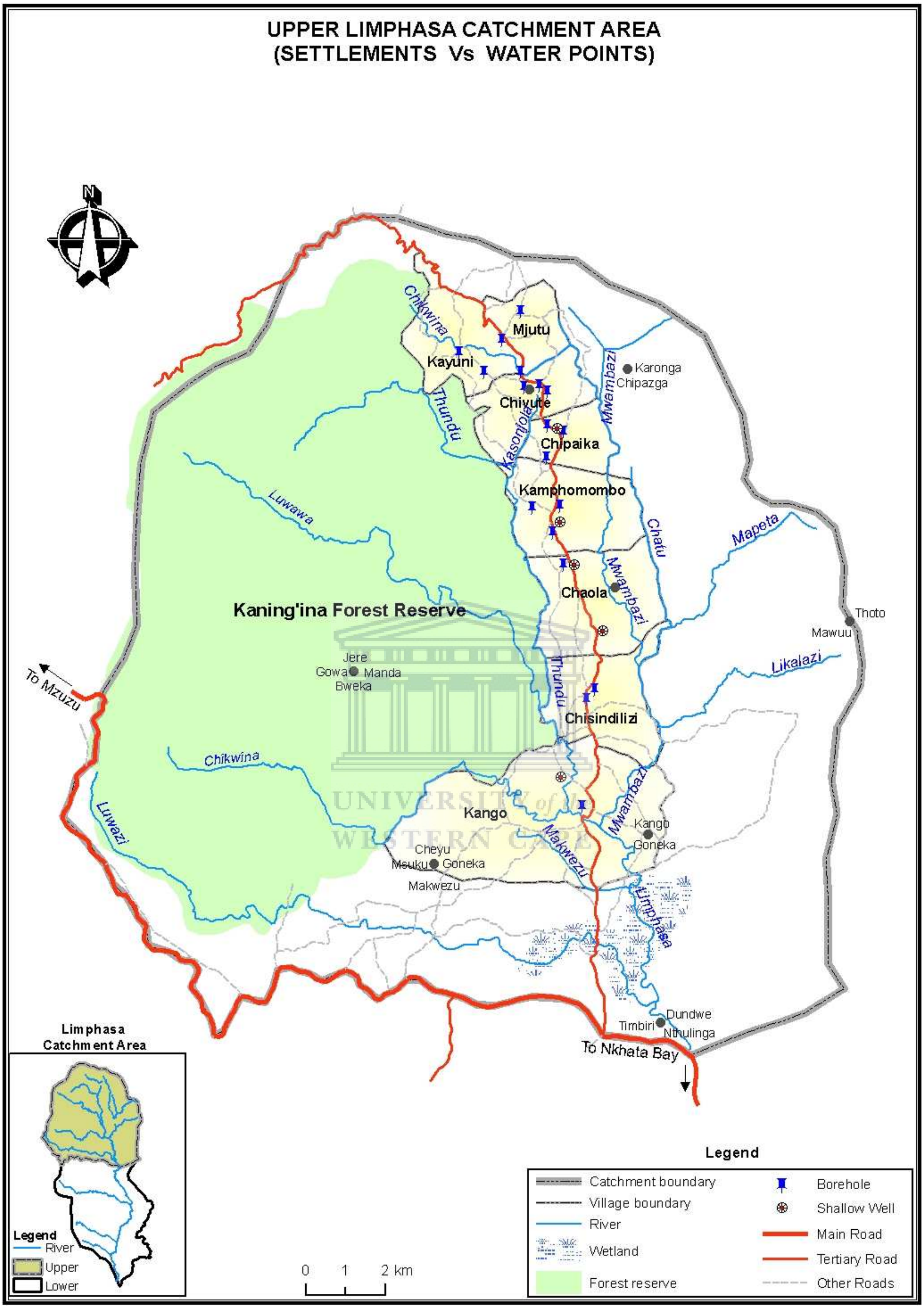


Figure 3: 2.2 Distribution of study villages in Upper Limphasa River Catchment

2.3 Current situation and key concepts in water management

2.3.1 Overview on water management in Malawi

One of the challenges in Malawi is the management of water resources rather than physical water scarcity. The challenge is how to sustainably respond to increasing demand for improved livelihoods using water and how to find practical solutions to manage water. This thesis argues that innovative solutions are needed to improve management of water resources in general and groundwater in particular within the IWRM framework. Since the SADC regional water policy (2005) recognised IWRM as part of regional development, seeking practical solutions to manage water from the IWRM framework remains imperative (Braune, et al., 2008). One of the key arguments of this thesis is that ways to ensure socioeconomic development and environmental improvement while satisfying the increasing needs for safer and sustainable practices to use and manage water exist on case study basis. However, wider application of such innovative local solutions is lacking, hence the rationale for the present study.

In the domestic water sector, modern practices in water purification technologies and water supply services have increased coverage and access to improved water sources thereby globally increasing water use for domestic activities (Malawi & UNESCO, 2007). Challenges that remain include: a) accessing safe water sources without paying for it; 3) practising clean technologies that ensure environmental integrity; and c) managing water resources holistically to improve people’s livelihoods and national economies (MEA, 2005 & Pritchard et al. 2009). This thesis argues for the provision of safe groundwater sources for potable water supply and not just improved groundwater sources for drinking water (MDHS, 2010; Malawi-MDG, 2010).

In Malawi, the task of providing safe drinking water sources to people remains unsatisfactory. Although water is generally abundant in Malawi, 60% of the population lacks safe drinking water and improved sanitation (Pritchard et al. 2007). Although MDHS (2010) reports that 81% of households in Malawi have access to improved drinking water sources, not all improved sources are safe sources and this is one of the arguments in this thesis. However, MDHS (2010) reported that only 51% of households draw water from boreholes, the safest sources for potable water. This revelation makes the argument of this thesis more justifiable on assessing the quality of groundwater sources. Again, the assessment is required on groundwater sources so that the number of boreholes that produce safe water should be monitored in terms of operation and maintenance to ensure sustainable access to such safe water sources.

The role of local IWRM with a focus on groundwater has been neglected for sustainable utilization and management of water resources within the goals of socioeconomic and environmental improvement. For example, there are many incidences in Malawi and beyond about the prevailing fragmented and uncoordinated practices for water management in addition to practices that lead to polluting water sources (Mkandawire et al., 2008; GoM, 2006; Molden, 2007). Groundwater sources as an increasingly preferred source of domestic and productive livelihoods are becoming polluted, sources non-functional and depleted to levels that make access difficult, uneconomical and unsustainable for sustainable utilization of the resource for demand in the near future (Xu & Braune, 2010; Xu & Usher, 2006; Adelana & MacDonald, 2008; GoM-UNDP, 1986). Thus, there is need to implement local solutions within local IWRM to address the management problems of water resources at community or sub-catchment level.

2.3.2 Operational key concepts used in the study for water management

Managing groundwater from the IWRM perspective requires various disciplines and dimensions which the present study does not exhaust due to its scope. Seven selected operational key concepts that are used frequently in the study are explained as follows:

1) **Water sources and flows:** Water source in this study refers to a place(s) where water is drawn/ abstracted/originate and water flow alludes to the movement of water. In the model developed in this research, the assessment starts with rain as a source of water. In domestic water studies, the norm is to focus on drinking water sources where water is drawn. Rainfall is partitioned into a) runoff which contributes to surface water sources as some evaporate and transpire; b) seepage that contributes to groundwater as it infiltrates the ground and percolate through unsaturated zone and recharges groundwater at water table (Molden, 2007). This thesis uses rainfall, geology, geomorphology and vegetation to describe groundwater recharge, flows and storage systems. Drinking water management system depends on several sources such as rainfall, groundwater and surface water. This thesis focuses on two types of

groundwater sources i) boreholes (BHs) and ii) protected shallow dug wells (PSWs) locally known as hand-dug wells.

2) Water management: Within a catchment, water is managed for domestic and productive purposes to meet specific livelihood objectives. Water is only one input to community livelihoods system and its importance and the way it is managed vary from community to community. Impacts of water uses for livelihoods are extensive because water management draws heavily on natural and human resource bases (Molden, 2007). The present study considers various management systems to assess quantity, quality and governance of groundwater. Using the conceptual model, the study describes the recharge processes, flow directions and discharge systems of water from rain to groundwater to rivers and to Lake Malawi. The study area is the Upper Limphasa River catchment but the hydrogeologic conceptual model that is developed for this research covers the entire Limphasa River catchment to highlight interactions, potential effects and implications for implementing a successful IWRM at catchment level. The assumption is that human modifications of landscape affect quantity, quality and governance of water resources, hence, the need for a successful IWRM. However, agreeing on benefit sharing for water protection between upstream and downstream dwellers requires several management tools alongside critical analysis on conflict management approaches. As the benefit sharing principle is complex, the current study advocates for implementing precautionary principle using insights from the developed conceptual model. Important dimension of groundwater management include the scale of management system, institutions with policies and finances to operate and maintain the proposed local IWRM for sustainable utilization of water resources (UNDP, 2010).

3) Livelihoods: The concept of livelihoods includes various ways that enable people to meet their needs for survival using water among others. Achieving sustainable livelihoods means supporting people through measures that ensure a healthy environment to enhance their well-being. The sustainability component of livelihoods approach is achieved by maintaining the long-term productivity of natural resources among others (MEA, 2005) thereby, mimicking the rationale for IWRM. Effective responses to livelihood issues emerge from policies, institutions and approaches that emphasize governance aspects to support livelihood outcome and address the needs of individual communities rather than those that view communities as homogeneous group (Chambers & Conway, 1991). This is where countries stumble in trying to implement full IWRM in their catchments uniformly using national water reforms. This study using groundwater management in communities argues for the reverse thinking (local IWRM) but which compliment and facilitate the full operation of the IWRM at catchment scale.

4) Institutions: Roles, rights and responsibilities of people within communities are socially defined, culturally-based and are reflected in formal and informal power relations that influence how management decisions are arrived at (UNDP, 2008; Molden, 2007). Water management and all other activities related to it have an impact on social interactions and structures. Understanding social dynamics in water management requires strengthening or adapting existing social stratifications to water management interventions. This thesis argues that learning by doing (adaptive management) facilitates successful implementation of the IWRM. Therefore, aspects of the IWRM principles need to be assessed from water management practices that work in communities and build on such practices for wider IWRM. This is the argument of this thesis in chapter 8.

5) Ecosystem services: These are the benefits that people obtain from ecosystem. Two crucial ecosystem services for this study are provisioning (freshwater) and regulating services (water purification and waste treatment) (MEA, 2005). This study applies these services in chapters 5, 6, 7 and 8 where local hydrogeologic and socioeconomic environments factors are assessed to show how such factors limit successful implementation of IWRM at catchment level. Determinants for groundwater quantity, quality and governance are discussed in relation to managing groundwater from IWRM perspective for sustainable utilization and to ensure environmental integrity.

6) Water productivity in relation to demand and use: The amount of water per person per day in litres is the most common measure of household water use. With the need to improve efficiency in the demand management, calculation of water demand and use per person per day is relevant (UN-Water, 2008). This study calculates water demand, water use and the difference between the two in chapter 6. It also assesses the instrument principle by asking study participants whether or not a) economic aspects feature highly for water management in unmetered rural areas; b) people in rural areas practically consider the use of groundwater as a free good or economic good. It also compares the calculated demand in this study to national recommended demand of 36 litres per person per day in Malawi (GoM, 2005) in order to provide insights on how the IWRM reformed water policy operates and also to assess implication of return flow concept on environmental integrity and/or water security for improved livelihoods.

7) Catchment refers to the geographic area contained within the watershed limits of a system of streams and rivers converging towards the same terminus, Lake Malawi in this case (Malawi & UNESCO, 2007). The origin of IWRM uses a catchment as a unit of analysis because water flows within a catchment connecting users and ecosystem, thereby sidelining groundwater resource which is transboundary by its nature (IHP, 2009). This research uses geomorphology (topography) to highlight local groundwater flow direction in the study area bearing in mind that regional flows are possible in this Rift Valley Floor area. The study uses both the entire Limphasa River catchment in a model to demonstrate how physical and socioeconomic factors interact in the river basin. The model shows opportunities and challenges for applying both IWRM and benefit sharing concepts to enable upstream and downstream dwellers manage water resources in a coordinated manner for sustainable utilization for both groups of dwellers. The Upper Limphasa River catchment in this research is used as a case study to illustrate how local IWRM approach at community is operated.

2.4 Physical environment with focus on hydrologic environment

The state of water resource availability, quality, variability and spatial distribution in catchments partly depends on the inherited natural legacy of societies (Grey & Sadoff, 2007). These natural legacies include physical factors such as climate, geology, topography, soils and vegetation. These factors influence management of water resources and a successful IWRM implementation would need to consider such factors.

2.4.1 Climate variability and groundwater resources

In Malawi, many areas receive 760-1150 mm of rainfall per annum with about 90% of the rains occurring from December to March and almost no rains from May to October (FAO, 2008). The mean annual rainfall is 1037 mm with 63.1%, 17.1% and 19.8% of the country receiving annual rainfall ranges of 650-1000 mm and greater than 1200 mm respectively. The study area is in a district which gets more than 1200mm per year. The mean monthly temperature ranges from 10^{o}C to 16^{o}C in the highlands, 16^{o}C to 26^{o}C in the plateau areas, 20^{o}C to 29^{o}C along the lakeshore, 21^{o}C to 30^{o}C in the Lower Shire Valley. Temperature has effect on quantity and quality of groundwater through evapotranspiration (UNDP, 2009). Nkhata Bay District where Upper Limphasa Catchment is located experiences warm tropical climate and receives both convectional and topographic type of rainfall which is influenced by altitude and Lake Malawi (GoM, 2008b). Total annual rainfall for Nkhata-Bay where the Limphasa River catchment is located receives over 2,000 mm. Fig. 2.3 give below shows the rainfall pattern for Nkhata Bay District. Knowledge from Fig. 2.3 is essential for estimating groundwater recharge to provide rough insights on groundwater quantity and quality in the study area for effective management of water resources in general and groundwater management in particular. This study uses hydrogeologic conceptual model to assess groundwater flow directions, influence on quantity and quality on groundwater in order to explain factors that need consideration when implementing IWRM at catchment level.

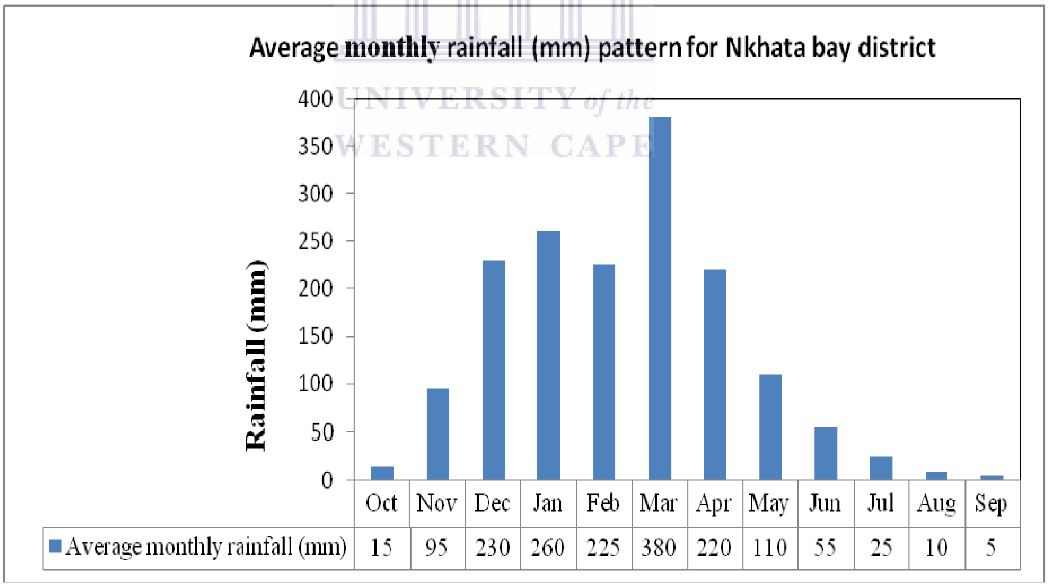


Figure 4: 2.3 Average monthly rainfall pattern for Nkhata Bay District
Source: GoM, 2008

2.4.2 Geologic influence on groundwater resources

Knowledge of rock types facilitates understanding of regional and local hydrogeologic context of groundwater in different catchments areas. Lithological and structural variations of rock types control the occurrences, movement, quality, availability of groundwater resources among other factors (Carter & Bennett, 1973). Based on these variations, aquifers in Malawi are grouped into two systems, namely, basement and alluvial aquifers (GoM-UNDP, 1986). About 80% of Malawi is underlain by crystalline metamorphic and igneous rocks of Precambrian to Lower Palaeozoic age, commonly known as Basement Complex which is tectonically stable shield area such as gneiss. For example, basement aquifers are less productive than alluvial aquifers. Groundwater flow and discharge to rivers in basement aquifers follow secondary porosity formed through weathering, faults and fractures (GoM-UNDP, 1986). The study used rock types and fractures/faults to describe the flow directions, quantity and quality of groundwater as some of factors that need to be understood for implementation of IWRM. Rocks of sedimentary origin are also common along the lakeshore plain and Shire Valley.

2.4.3 Topographic influence on groundwater resources

Variation in relief pattern influences climate, hydrology, groundwater movement (local flows) and human settlement pattern in Malawi (Sophocleous & Buchanan, 2003). Malawi is part of the Great African Rift Valley (GARV) which extends from Red Sea to the Zambezi River with 75% of the land surface ranges from 750 to 1,350 meters above mean sea level (m.a.m.s.l). Highland elevations are over 2,400 m.a.m.s.l and the lowest point on the southern border is 37 m.a.m.s.l (Agnew & Stubbs, 1972). Such a variation resulted in a country being divided into 17 water resources areas (WRA) largely based on its hydrology (Fig. 2.4). Current water studies have focused their investigations in 16, 15 and 1 WRA (Fig. 2.4). The Upper Limphasa River catchment that is marked 16f in Fig. 2.4 and it is part of the Limphasa River catchment within Nkhata-Bay Lakeshore as a major WRA (Fig. 2.4). Thus, the study area falls on escarpments of GARV System.

Malawi has four major topographic descriptions as follows: 1) Plateau areas which occur on both sides of GARV system, 900-1,300 m.a.m.s.l and covered by a thick weathered materials forming extensive basement aquifers; 2) Mountainous/upland areas with elevation of 2,000-3,000 m.a.m.s.l forming good recharge areas; 3) Rift valley escarpments which fall steeply from plateau areas and their slopes are commonly dissected with considerable faulting forming poor and discontinuous aquifers. This is where the study area is located and 4) Rift valley alluvial plain areas of low relief with elevation below 600 m.a.m.s.l but have high yielding aquifers (GoM-UNDP, 1986).

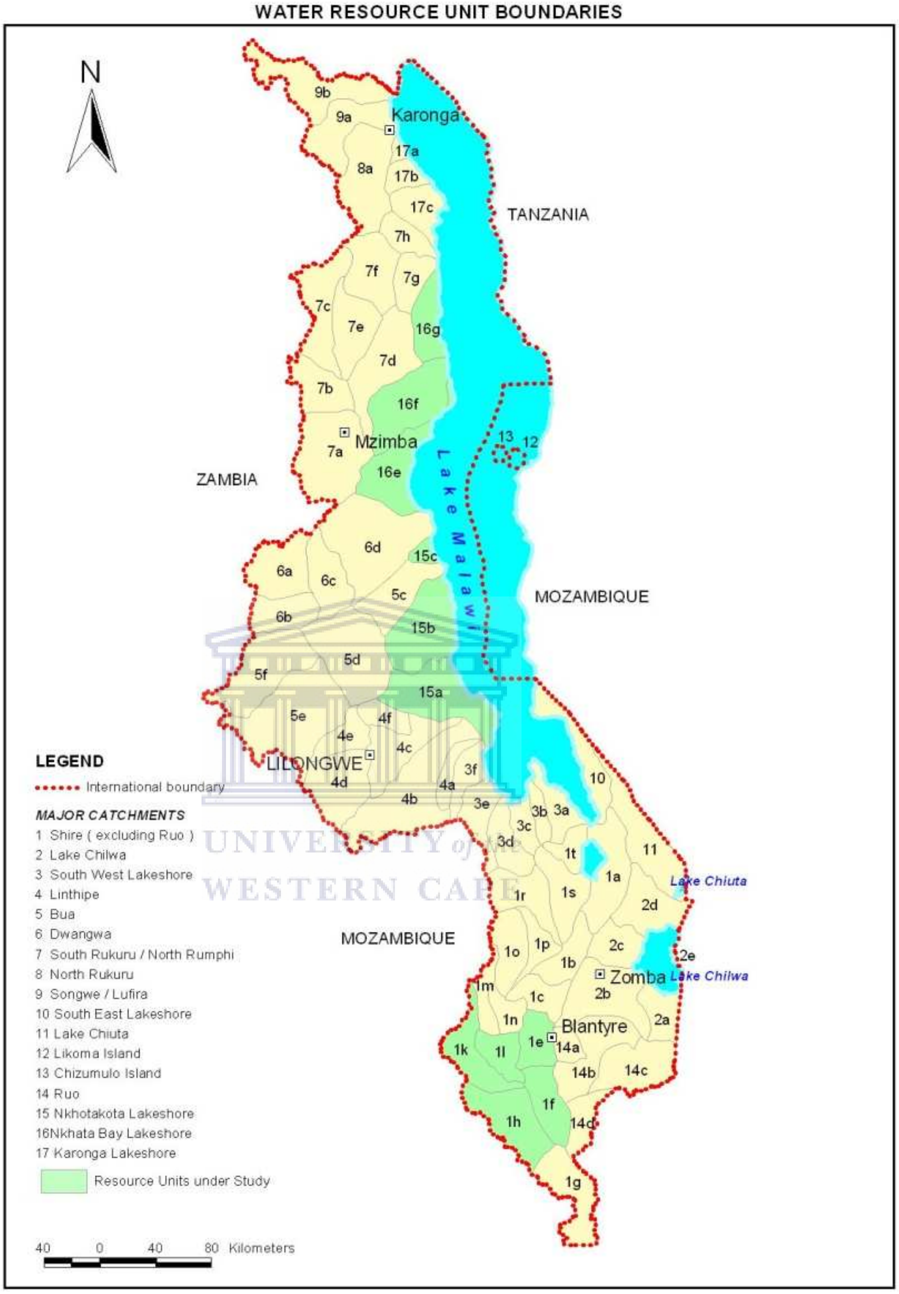


Figure 5: 2.4 Boundaries for water resources areas and units in Malawi

2.4.4 Vegetation cover/land use and groundwater resources

The main type of vegetation in major drainage basins in Malawi is predominantly a mixture of woodlands with evergreen forest and Brachystegia woodland (Fig. 2.5). Most of the gentler slopes are under cultivation and hillsides are mostly forest covered

(Fig. 2.5; GoM, 2008). Between 1990 and 2005, proportion of land area covered by forest declined from 41% to 36%; will further decline to 33% by 2015 and the Government's solution remains reforestation and afforestation (Malawi-MDG, 2010). In Nkhata-Bay district, 58% of the total land area is under forest (Fig. 2.5; GoM, 2008). The district has three major vegetation types, namely, semi evergreen forest on the Kandoli Mountains dominated by *Brachystegia Spiciformis*; Perennial wet grasslands around Limphasa Dambos; and the closed canopy woodlands of wetter uplands mostly in the Viphya Mountains where *Brachystegia Speciformis* and *Brachystegia Longifolia* are dominant. Trees in these forests are generally taller and denser than in the semi evergreen forests (Fig. 2.5; GoM, 2008).

Cultivation on gentler slopes with ridges made to control soil erosion forms focussed recharge pathways which increase groundwater quantity or pullet groundwater quality depending on farm chemicals applied to crop fields. Management approaches that protect groundwater from such potential pollutants water need to be demonstrated. Furthermore, highlands are recharge areas and yet they are densely covered with vegetation which interferes with recharge mechanisms affecting groundwater quantity (De Vries & Simmers, 2002). In addition, reforestation and afforestation as solutions by the Malawi Government may solve the deforestation problem and potentially affect groundwater quantity as such trees interfere with the recharge system. With these factors in place, this thesis argues that improved knowledge on relationship between vegetation cover, land-use and groundwater provides insights about factors that may interfere with groundwater quantity as well as quality for both domestic and productive purposes. Therefore, there is need to explore mechanisms to create public awareness among stakeholders on such relationships so that approaches protect water resources for sustainable use are implemented with collaborative efforts among users.

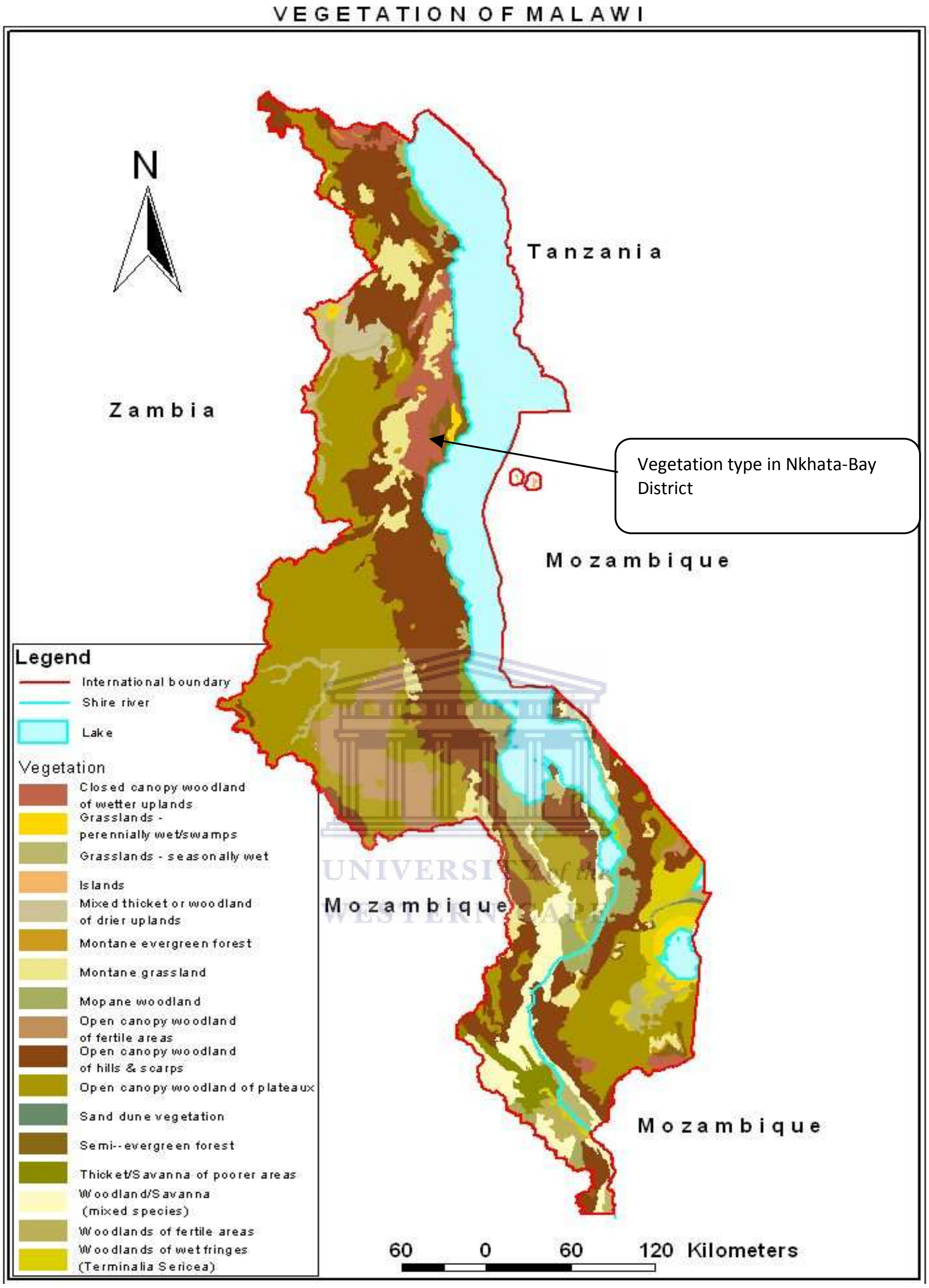
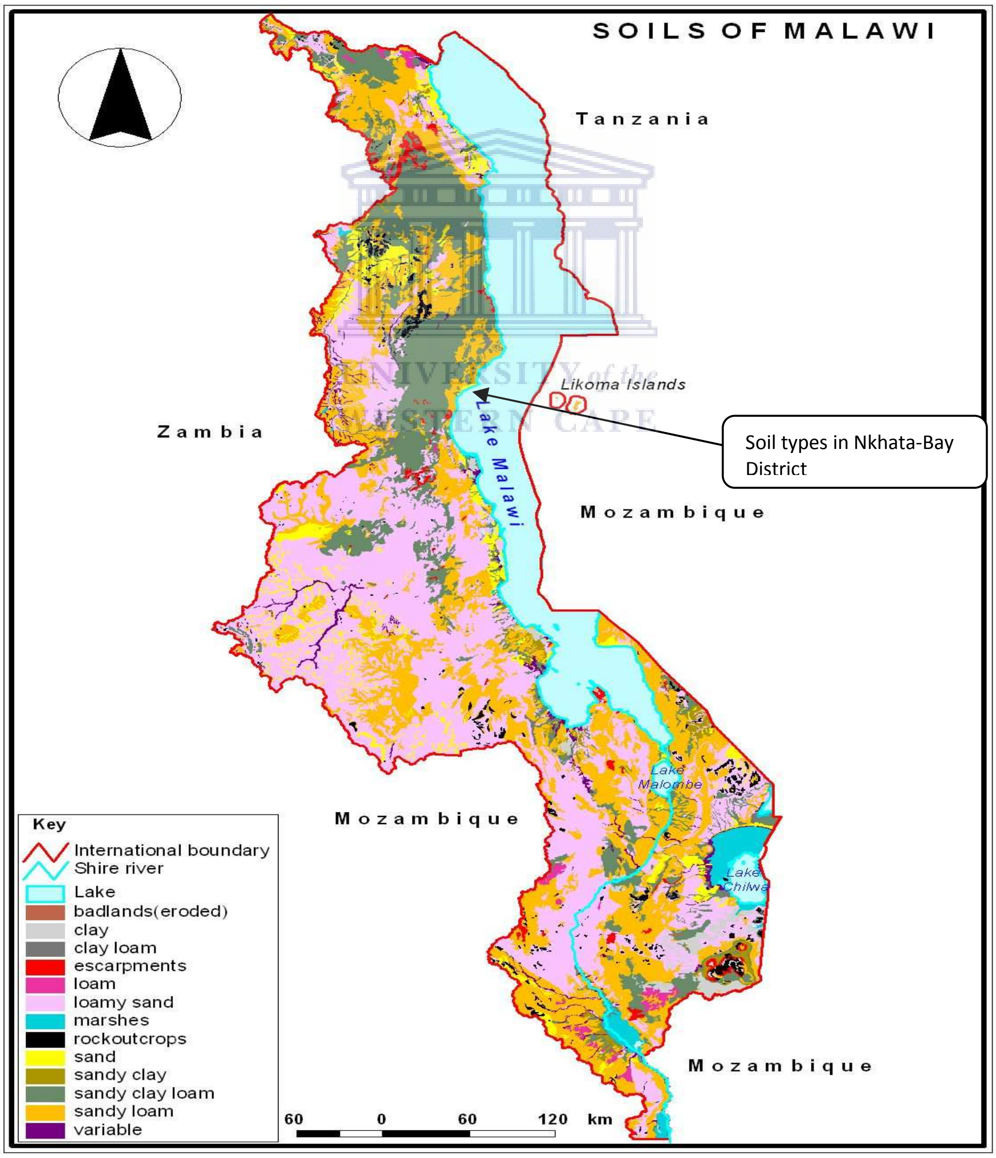


Figure 6: 2.5 Relationships between types of vegetation and water management

2.4.5 Influence of soils characteristics on groundwater resources

Fig.2.6 shows types of soils in Malawi and the main ones are four, namely, latosols, calcimorphic, Hydromorphic and lithosols (Moyo *et al*., 1993). Latosols are red to yellow, leached acid soils where water movement within the profile is mainly downwards. They occupy freely-drained sites on gently-sloping plains and steeply dissected hills. Calcimorphic soils are grey to greyish brown with a weak acid to weak alkaline reaction where water movement is upward occurring on nearly-level depositional plains with imperfect drainage. Hydromorphic soils are black, grey or mottled and waterlogged. Lithosols are shallow or stony soils and regosols that are immature soils developed from sand (Moyo *et al*., 1993). The most predominant soils in Nkhata-Bay district are the latosols and lithosols (Fig.2.6). These soils have influence on groundwater quantity and quality in terms of recharge process. Their characteristics assist recharging the aquifer hence are expected to increase groundwater storage but they can also quickly transport contaminants into shallow groundwater aquifers thereby contaminating drinking sources (Robinson et al., 2008).



Soil types in Nkhata-Bay District

Figure 7: 2.6 Relationships between types of soils and water management

2.5 Socioeconomic environment with a focus on water management

Socioeconomic environment (SEE) refers to the structure of economy and behavior of its actors as reflected in policy options adopted, mechanism to implement such policies and also the history in relation to how water resources are being managed (Grey & Sadoff, 2007; UN-Malawi, 2010) in this case groundwater resource for domestic use. This section highlights four aspects SEE, namely, the enabling environment, institutional roles, management instruments and household environment which have influence on groundwater management in Malawi.

2.5.1 Enabling Environment for water resources management

The global trend has been to utilise the available water resource to benefit formal agriculture, industry and consumers. Water management strategies have focused on the need to protect the limited water resources as well as meeting the need for economic growth, coupled with worldwide changes in attitude towards social, institutional and environmental issues. This situation has resulted in the global shift in legal framework regarding the sustainable use of natural resources including water (UN-Water, 2008).

The 2009 Malawi Water Resources Bill (GoM, 2009) indicates the zeal for the country to have formalized changed approach towards sustainable management and utilization of water resources. However, a change in law does not automatically change the attitude of those who may continue to regard water as ever-present and ever-accessible. For this to happen, a marked change in attitude towards water resources management on the part of those tasked with the responsibility to implement the law is imperative. However, in Malawi, resources in terms of finance, equipment and human personnel are limited to enforce and monitor such legislations on groundwater resources (MoIWD, 2006).

The Rio Declaration on Environment and Development, Agenda 21 and the Statement for the Sustainable Management of Water were adopted by more than 178 governments at the United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro, Brazil in 1992. Together they constitute a comprehensive plan of action to be taken globally, nationally and locally by organizations of the UN, governments and major groups in every area where human activities pose threat to the sustenance of the environment such as water resources (UN-Water, 2008; WWAP, 2009).

Chapter 3 of Agenda 21 proposes an integrated approach to poverty relief through community and stakeholder participation and sustainable resource management and development by dealing with the protection of quality and supply of freshwater resources and application of the integrated approaches to the development, management and use of water resources. Hence, Agenda 21 as a global initiative attracts Malawi's own approach in the management of water resources and this forms the centrality of this study. The revised 2004 Constitution of Malawi based on principles on national policy contains a promise by the government to promote people's welfare through implementation of policies and laws that ensures environmental management to i) prevent the degradation of the environment, ii) provide a healthy living environment for people iii) recognise the rights of future generations through environmental protection and the sustainable development of natural resources (GoM, 2004). Therefore, water management such as groundwater becomes a constitutional duty to be implemented so that communities are provided with access to safe drinking water sources.

The 1969 Water Act dealing with water use and management made no allowance for the IWRM principles. For example, aspects of good governance such as stakeholder participation and institutions, catchment management committees, water users association, groundwater protection, among others were absent in the 1969 Water Act but present in the 2009 WRB. This reform aligns the IWRM approach (GoM, 2009). The 2009 Water Resource Bill recognizes integration of all components of the water cycle to ensure water management as a single resource. This suggests that impacts on water resources need to be protected to ensure sustenance in water availability in acceptable quality. The Bill suggests that strategies designed to ensure these principles should be developed and administered at national level, with implementation that requires input and involvement of representatives at district and catchment levels. This means appropriate institutional roles and practical management instruments need to be established and operationalised (GoM, 2004; GoM, 2006; GoM, 2009; UNDP, 2010).

In Malawi, the 2005 water policy exists for managing water resources (GoM, 2005). The overall water policy goal is to promote sustainable management and utilization of water resources to provide water services of acceptable quality and sufficient quantities that satisfy the requirements of citizens and enhance the country's natural ecosystem.

Therefore, it advocates IWRM principles which provide creation of catchment management authorities, establishment of a National Water Resources Board, participation of stakeholders in water resources management and utilisation, promotes the use of various water resources management tools such as economic instruments by water utility institutions, water quality regulatory guidelines, water allocation rules, water resources assessment and water resources information management (GoM, 2006 & MoIWD, 2008). Its objectives are consistent with the objectives of the Regional initiatives that promote IWRM such as NEPAD and SADC on water for socioeconomic development (Braune et al., 2008; UNDP, 2010).

To facilitate implementation of the water policy, the MoIWD developed strategies and decentralized community-based maintenance (CBM) functions from ministry head office to District and community levels (Baumann & Danert, 2008) whereby stakeholders are involved in making decisions and implementing policy on water resources. This decentralisation enables cost sharing of financial resources for investment and beneficiaries are able to invest in projects of their choice. This study assesses implementation of water policy in terms of access to safe water sources. Access to safe water sources is defined by the MoIWD as the number of people with a minimum quantity of 36 litres of water per capita per day within a maximum distance of 500 metres. This access is measured by assuming that a borehole serves a population of 250 people while a communal standpipe services 120 people (MoIWD, 2008).

Lack of policy harmonization in Malawi is the norm rather than exception. For example, ministries of environmental affairs, forestry and water development develop policies and strategies for implementation to protect headwaters, wetlands and rivers banks among other environmental related. Yet, the Ministry of Agricultural develops and implements policies that encourage people to cultivate on fragile lands such as *dambos* (wetlands) and riverbanks through *pali chinyontho bzalani mbewu* (where there it moisture, grow crops), *ulimi wothirira* (irrigation framing) with treadle pumps programmes (Malawi-MDG, 2010, Malawi & UNESCO, 2007, FAO, 2008; GoM, 2006). The goal is to increase agricultural production for improved food security. By extension, cropping in mountainous and hill slopes is a common sight in Malawi (Malawi-MDG, 2010). Groundwater quantity is expected to increase as recharge areas are cleared of forest cover creating focused recharged areas to speed up recharge process to aquifers (Healy, 2010). But such an increase has potential to negatively affect environmental integrity. For example, the increase of sediments from hill slopes will potentially reduce surface water volume and creation of focused pathways will recharge groundwater with contaminants from cultivated gardens that are applied with fertilizer and chemicals; and the same chemicals will pollute surface waters. Harmonisation of such conflicting policies is urgently required and the IWRM approach provides a suitable starting point to implement such harmonization through institutional principle, hence, the rationale for proposing the local IWRM in this study.

Water laws in Malawi exist for managing water resources. Although the 2005 water policy has been reformed to incorporate IWRM principles, the 1969 Water Act does not and the 2009 Water Resources Bill (WRB) is not yet enacted (GoM, 2009). However, Water Act is critical for successful implementation of IWRM principles because the Act enables creation of catchment management authorities, National Water Resources Board and ensures mandatory implementation of IWRM principles for all development projects as is the case with the Environmental Impact Assessment (EIA) under the Environmental Management Act (EMA) of 1996. The Act also facilitates establishment of National Water Resources Authority (NWRA) to promote proper use of water resources and develop a National Water Resource Strategy (NWRS). Equally important is the Sanitation Act for water protection especially groundwater resources which is not yet available despite developing the National Sanitation Policy in 2006 (GoM, 2006).

Despite the above situation, some Acts to regulate water resources management in Malawi exist, for example, the 1995 Water Works Act. In addition, the 1996 EMA which serves as an umbrella legislation ensures that the national water resources legislation is in harmony with those of the neighbouring countries in the SADC region. For instance, the signed Protocol on Shared Watercourse for SADC region in 2000 provides a framework for harmonisation of policy and legislation among the SADC member states. Again, the amendment process of several Acts related to water resources management included concepts of sustainable management, stakeholder participation, and appreciation of economic value and importance of gender considerations which align IWRM principles. Examples of these Acts include those that regulate management of forestry resources, fisheries' resources, land resources, wildlife resources, agriculture production, energy sector, mining sector and tourism sector. Furthermore, they also regulate human systems (institutions) which are essential in implementing groundwater management as part of the IWRM framework (Malawi-MDG, 2010).

Nevertheless, the management challenges for water resources in Malawi partly exist because the 2009 WRB is not yet enacted and the NWRA is not established. This is because enforcing old water laws, the 1969 Water Act, on new challenges which IWRM would like to address as outlined in the 2009 WRB remains a challenge legally. This means that CMAs do not exist in Malawian river basins. Therefore, implementing IWRM without CMA remains problematic. This strengthens the basis of this study to encourage implementation of local IWRM which works with much legal requirements at community level as a starting point for full IWRM. With such prevailing enabling environment, this study argues for national recognition of the local IWRM as an alternative solution for wider and successful implementation of IWRM. Bauman and Danert (2008) highlighted ill-adapted and adopted policies and lack of coordination among institutions as factors explaining management challenges in the water sector in Malawi. Since policies and laws are enabling environments and institutions are implementing tools, this section has revealed that the present environment does not promote effective water management in Malawi hence the need for local IWRM.

2.5.2 Appropriate institutional arrangements

This section presents existing institutions and assesses whether or not such insitutions are appropriate to facilitate implementation of IWRM principles in Malawi. IWRM emphasizes on the importance of institutions in the successful implementation of the IWRM approach. This is based on the principle of active participation and coordination which requires stakeholders to discuss their activities on water resources. Coordination and devolving responsibility to catchment levels are among the two key elements in this principle to ensure effective management. Most barriers to implement policies relate to the inability of institutions to implement developed approaches due to lack of political will or rigidity of institutions or weak capacity (UN-Water, 2007). Institutional arrangements as sets of working rules that are used to determine who is eligible to make decisions; what actions are allowed or not; what procedures must be followed or not;

what information must or be provided or not; and what payoffs must be assigned to affected individuals or not (UNDP, 2008).

The MoIWD has the authority over the management of water resources through Department of Water Resources which has three technical divisions a) Surface Water Division, b) Groundwater Division and c) Water Quality Division to co-ordinate, plan, develop, conserve and protect water resources. The divisions also collect, process, analyse, monitor, explore, archive and disseminate hydrological and hydrogeological data (GoM, 2007). However, it is not legally binding that all data on all developed water points should be sent to the MoIWD for a comprehensive assessment of groundwater resources in Malawi (Water Aid, 2005; Bauman and Danert, 2008).

The 1995 legislative instrument (Water Works Act No. 17 of 1995) enabled creation of regional Water Resources Board (WRB) for supplying potable water in urban areas while the MoIWD remained responsible for supplying water to the rural communities. Currently, there are five WRBs which are responsible for enforcing water laws by: i) granting water rights for abstraction; ii) providing consents to discharge effluent into public waters; iii) regulating the Shire river flow which is vital for hydro-electricity supply to the nation; and iv) collaborating with other institutions responsible for environmental monitoring among others. The WRB operates through its Technical Sub-committees (MoIWD, 2006). On the other hand, rural areas under MoIWD used community based organisations for capital contributions to operate and maintain their water supplies through village management system (UNICEF, 2008).

The management of water resources requires an integrated approach involving various stakeholders including government line ministries/department such as a) Agriculture and Food Security ministry manages water resources for irrigated agriculture; b) Forestry department manages catchments to protect headwaters for major rivers; c) Parks and Wildlife departments protects water resources through restrictions imposed in the park areas which happen to be part of the water catchment; d) fisheries department prevents catchment degradation of rivers and lakes to preserve them as spawning habitat for endemic fish thereby protecting receiving watercourses from qualitative degradation; e) Environmental Affairs department manages the environment through the conservation and sustainable utilisation of all natural resources such as water; f) Meteorological department manages meteorological data for water resources assessments; g) Education ministry provides training and conducts research work on water related subjects (UN-Malawi, 2010; Malawi & UNESCO, 2007).

In Malawi, the private sector is largely involved in the water supply than in the water resources management. Such a sector provides water through provision of protected shallow dug wells which are hand-dug by communities or contractors hired by projects and boreholes which are drilled by government or private contractors (UNICEF, 2008) In addition, NGOs such as religious organisations, World Vision International, Save the Children Fund, UNICEF and others complement the government efforts and have played and continue to play an importance role in water services delivery, especially to the rural communities (UNICEF, 2008, GoM, 1995; MoIWD, 2006).

Although the MoIWD encourages combined efforts of the government and the private sector to provide resources for further development and improvements (MoIWD, 2006), practically, the same MoIWD admits that the water supply sector is characterised by an uneven distribution of resources, poor coordination of efforts and fragmented institutional arrangements resulting in a) waste of resources through duplication and b) variations in quality of work and approaches. The MoIWD (2006) i) recognised that procedures adopted by key stakeholders in water development are not consistent with one another and cause confusion at community level; iii) did not have a coordinated and consistent approach to avoid such duplication of efforts and waste of resources by key stakeholders and iii) existing implementation manual needed further refinement to make it less ambiguous so that it provides a clear framework within which implementing organisations can function. Further to this ambiguity, the utility boards administratively report to the Department of Statutory Cooperation which technically falls under the MoIWD. This shows that the MoIWD lacks a coordinated approach for water services delivery and that the relevant legal framework for the coordination process is lacking.

In addition, there is that lack of policy to encourage the private sector to invest in integrated water resources management for the purpose of sustainable water supply. Emphasis has been on provision of new facilities such as boreholes and rehabilitation of existing structures, but not incorporating Community Based Management (CBM) approaches in their undertakings as part of IWRM process. This section concludes that at country level in Malawi, the appropriate institution to facilitate implementation of IWRM principles is still in its infancy. Therefore, exploring alternative approaches such as local IWRM at local level to facilitate full implementation of IWRM is important.

2.5.3 Practical management instruments

This section describes existing management instruments and assesses their feasibility to facilitate implementation of the IWRM approach. The local IWRM appraoch assesses these instruments using groundwater management system at community level to show the validity and reliability of the alternative innovative approach for scaling up IWRM.

The existing regulatory management instruments are not harmonised to facilitate progress of the IWRM approach. Evidence for this is that although the 1969 Water Act was revised to incorporate IWRM principles as captured in the 2005 Water Policy, such revised regulations known as the 2009 Water Resources Bill have not been enacted into water law (GoM, 2009). Therefore, implementing IWRM with old laws will be futile as some institutions such as catchment management authorities cannot be legally created.

Currently, water resources assessment, information and communication management instruments do not produce data systematically to offer better IWRM advisory services to planners, managers and the public to inform better decisions on water resources (GoM, 2006). It is notable that having improved knowledge about IWRM operations depends on systematic acquisition of appropriate information on water resources such as quantity and quality of water aspects with spatial-temporal analysis; managing such information to make it available to users. These aspects are lacking in Malawi.

Although some improvements are demonstrated for surface water sector, a systematic data collection network and effective analysis procedures to disseminate information on groundwater resources are not operational. In addition, the analysis on raw data (GoM, 2007) has shown that the existing databank of about 171 river flow stations, 24 water level stations, 57 pan stations and 38 climatic stations do not generate information that can provide better IWRM advisory services to key stakeholders on water resources.

With over 100 key stakeholders working in the water and sanitation sector, the need for a systematic strategy for collecting, compiling, synthesising, storing and disseminating information on water resources cannot be overemphasized especially with the current practice of not sharing data among stakeholders (GoM, 2006; UNICEF, 2008)

Economic instruments through water demand management (WDM) approach where water pricing has been used, no compliance is demonstrated. By way of illustration, the application of water conservation measures at household level in Malawi is not an outcome of WDM awareness, but rather a means of reducing water bills and the eventual disconnection embarrassment (Mulwafu et al. 2003; GoM, 2006). In agreement Mulwafu et al., (2003) reported that although some aspects of WDM are being practised in the country, the existing conditions on the ground militate against its increased expansion as a tool for promoting an efficient and equitable use of existing water resources especially in rural areas where water is supplied at no cost.

Conflict resolution and water allocation tools are far from being developed making catchment management as part of IWRM difficult. As evidence of this, headwaters, escarpments and mountainous areas which are supposed to exist as protected water catchment areas are encroached through deforestation, human settlement and cultivation in marginal lands (Malawi-MDG, 2010). In addition, existing damping sites which do not conform to stipulated health or any scientifically developed standards are common. These practices contribute to deteriorating quality of water resources in Malawi. Again, rural water supply schemes which rely heavily on abstracting water from protected catchments have minimal or no treatment facilities for managing drinking water (UNICEF, 2008). General capacity building is required to solve these problems but the critical aspect is to analyse the existing capacity to identify capacity gap that needs to be tailored for IWRM implementation. Such trainings should be guided by a clear understanding of institutional roles and responsibilities in the context of stakeholder participation and decentralisation process which are not fully functional in Malawi. Such prevailing situation justifies the need to support the local IWRM approach which provides insights and a platform for a wider and successful implementation of IWRM.

2.5.4 Household environment and social economic activities with reference to water

This section gives a brief overview on drinking water sources, sanitation facilities, demographic characteristics and economic activities in Malawi. These aspects are essential because managing water for sustainable utilization depends on understanding threats to contaminate water sources by sanitation facilities and demand for water by population and by economic activities in the study area, among other things.

Water management including water demand, use and governance depend on population characteristics. The major source of demographic data comes from population censuses which took place approximately every ten years and were conducted in 1945, 1966, 1977, 1987, 1998 and 2008 (Table 2.1; MDHS, 2010). Other sources of population data include nationwide surveys such as the 1992 Malawi Demographic and Health Survey (MDHS); the 1996 Malawi Knowledge, Attitudes, and Practices in Health survey (MKAPH); the 2000 MDHS and the 2004 MDHS (MDHS, 2010).

Table 1: 2.1 Total population and growth rate for Malawi from 1966-2008

Year of Census	Total Population	Average annual growth rate (%)
1966	4,039,583	3.3
1977	5,547,460	2.9
1987	7,988,507	3.7
1998	9,933,868	2.0
2008	13,077,160	2.8

Source: NSO, 2009

Table 2.1 above shows that Malawi’s population has grown from 4,039,583 in 1966 to 13, 077,160 in 2008 with an increase of 32% (9 million people) and with varying average annual growth rate of between 2.0% and 3.7% (Table 2.1). Malawi has more females than males with sex ratio of 94.7 meaning there were more females than males. Sex ratio is defined as the number of males per 100 females (NSO, 2009). However, the four cities of Malawi, namely, Lilongwe, Blantyre, Mzuzu and Zomba had more males than females but rural areas had more females than males (NSO, 2009). Spatially, the population was distributed as follows: 45%, 42% and 13% reside in Southern, Central and Northern Regions respectively with Northern Region where the study area is located being the least populated region. Although population density for Malawi is 139 persons per square kilometre, regional variation shows 184, 155 and 63 persons per square kilometer reside in Southern, Central and Northern Regions respectively. At national level, 64% are literate with males (69%) being more literate than females (59%). At regional level, 62%, 62% and 77% were literate in Southern, Central and Northern Regions respectively with 68% : 56%; 67% : 58% and 79% : 74% males to females for Southern, Central and Northern Regions respectively. The national average household size was 4.6 with 4.4, 4.7 and 5.2 for Southern, Central and Northern Regions respectively (NSO, 2009). These figures will be compared with the study area.

The analysis of results from the study area will be carried out in the context of that national provided information which shows that more females live in rural areas of Malawi, Northern Region where the study area is located had a least populated region with the lowest density, highest literacy levels and highest household sizes. This information has implications on water management in terms of demand, use and governance especially in a country such as Malawi where 85% depend on groundwater as a main source of water supply for their domestic uses (Kanyerere et al., 2010).

The type of economic activities pursued in a country has implication on how water resources are utilised and how environmental goals are fulfilled. The economy of Malawi is based primarily on agricultural related activities, which accounts for 30% of the gross domestic product (GDP). The country's major exports are tobacco, tea, and sugar. These account for 85% of Malawi's domestic exports. In 2009, the agricultural sector achieved growth of 13.9%. Tobacco production was high following favourable prices that were offered at auction in the 2008 marketing season. In 2010, the estimated growth slowed to 1.3% because of dry spells and heavy rains (Malawi-MDG, 2010).

The main driving force for economic growth in 2010 has been strong performance in mining, quarrying, construction, financial, insurance services and information technology in that order. Real GDP growth was forecast at 6.4% in 2011 and 6.0% in 2012 reflecting stability in uranium output and levelling off of productivity gains in the agriculture sector as the agricultural growth rate has peaked (Malawi-MDG, 2010). For example, Malawi experienced a food surplus during the 2008-2009 growing season due to favourable weather and use of Farm Input Subsidy Programme (FISP). FISP package include subsidies of 160 000 metric tonnes of fertiliser for maize; 8 000 metric tonnes of improved maize seeds and 1 600 metric tonnes of legume seeds (Malawi-MDG, 2010).

The use of FISP package has the potential to change the land cover/use pattern thereby threatening the quantity (recharge) and quality of groundwater. The groundwater physicochemical assessment in this study sheds light on such threats in chapter 6.

The Malawi-MDG (2010) reported positive progress for Malawi on attaining most Millennium Development Goals (MDGs) targets by 2015 such as goal number 7 on ensuring environmental sustainability target 10 that aims at reducing by half the proportion of people without sustainable access to safe drinking water. Malawi-MDG (2010) shows that 81% of Malawi's population had sustainable access to improved water sources whereas the MDHS (2010) reports that 79.3% of Malawi population use improved drinking water sources. Although the two assessments seem to agree, the target in MDG is not about access to improved source but access to safe sources. Therefore, this study assesses whether or not these improved sources provide safe drinking water to users. This thesis argues that such an assessment would lead to actions for improved water management that ensures access to adequate and safe water supply sources to communities. Such actions protect such sources from contaminants and maintain ecosystem integrity (GWP, 2000). Yet, Malawi-MDG (2010) reported that only 8.8% of Malawi's population had access to improved sanitation, a situation which encouraged this study to assess determinants for groundwater quality in objective three.

Knowledge on main sources of drinking water in a country provides insights on the access to both improved and safe sources of drinking water which, in turn, indicates the management practice/approach needed to improve the observed access pattern. Household information regarding sources of drinking water is used as a proxy of general population welfare of the country. For examples, the NSO, (2009) observed that in Malawi about 55% of households in rural areas used boreholes as their main sources of drinking water. Table 2.2 showed that at national level, 48%, 18% and 12% of the population use boreholes, unprotected wells and community stand pipes respectively as their main sources of drinking water. The same pattern is observed at regional level with almost 54%, 43% and 46% using boreholes; 13%, 25% and 14 using unprotected wells and 15%, 9% and 11% using community stand pipe as their main sources of drinking water in Southern, Central and Northern Regions respectively. Such a pattern has implications on managing water resources in terms of access, demand, use and governance which in turn has negative health implications on human well-being.

Table 2: 2.2 Percentages of population per drinking water source in Malawi

Main source of drinking water	Malawi	Southern Region	Central Region	Northern Region
Piped in dwelling & yard	8	7	7	10
Community stand pipe/tap	12	15	9	11
Borehole	48	54	43	46
Protected shallow well	6	3	9	6
Unprotected shallow well	18	13	25	14
River/Stream	7	6	6	12
Other unsafe sources	1	2	1	1
Total	**100**	**100**	**100**	**100**

Source: NSO, 2009

Sanitation facilities at households in Malawi have implications on water resources management. For example, information on the type of toilet facility per household is a useful proxy of general sources of bacteriological contaminants in drinking water when assessing groundwater quality from sources. Table 2.3 shows that over 80% of households in Malawi use traditional pit latrines which are not improved sanitation sources. Such a pattern threatens the quality of groundwater sources for drinking although the threat depends on distance, slope and other hydrogeologic factors in a particular site. Secondly, 11.7% of households in Malawi lack any kind of toilet facilities, a situation posing threat to polluting groundwater and surface water resources.

Table 3: 2.3 Percentages of households per type of sanitation facility

Type of toilet facility	Malawi	Southern Region	Central Region	Northern Region
Flush toilet	3.1	3.3	3.0	2.4
Traditional pit latrine	82.1	81.3	82.3	83.8
Ventilated improved pit latrine	1.7	2.0	1.3	2.0
No facility	11.7	11.8	11.9	10.8
Other facilities	1.5	1.5	1.5	1.0
Total	**100**	**100**	**100**	**100**

Source: NSO, 2009

However, Malawi-MDG (2010) reported that only 8.8% of Malawi's population had access to improved sanitation, a situation which encouraged this study to assess determinants for groundwater quality in objective three of this study. WHO & UNICEF (2010) categorised sanitation facilities into improved and not improved. For example, public latrines and latrines with an open pit or traditional pit latrines are categorised as not improved sanitation facilities. But ventilated improved pit latrines, pour-flush toilets and toilets with septic and sewer systems are categorised as improved sanitation facilities. NSO, (2009) and Malawi-MDG, (2010) are consistent in reporting that access to improved sanitation facilities in Malawi is low and needs improvement. Their observation also agrees with UNICEF & WHO (2012) which report that many countries are off-track to meet the 75% sanitation target for Millennium Development Goal with 63% of global population using improved sanitation facilities. The worst scenario is observed in Sub-Saharan Africa where Malawi is located (UNICEF & WHO, 2012).

2.6 Water resources management and utilization in Malawi

2.6.1 Surface water resources

Malawi's total renewable water resources are estimated at 17.28km^3 per year. From this, 16.14km^3 per year are produced internally while 1km^3 per year comes from Mozambique via the Ruo River and 0.14km^3 per year comes from lakes Chilwa and Chiuta which are shared with Mozambique (FAO-AQUASTAT, 2005). However, spatial and seasonal distribution of the resource is uneven. Few areas have abundant water resources available throughout the year while most areas experience annual seasonal fluctuations with pronounced water shortages during dry months of August, September, October and November annually (FAO, 2008). This suggests another management approach where water can be transferred from abundant areas to scarce areas as this thesis argues in terms of upstream-downstream management approach in a catchment from the IWRM perspective using the hydrogeologic conceptual model.

At national level, Lake Malawi stores the bulk of the renewable surface water resources, with an average of 90km^3 of live storage that flows out of the Shire River into the Zambezi River in Mozambique (GoM, 2006). Lake Malawi, the third largest in Africa, has a surface area of 28,760 km^2 and an estimated total volume of water of 7,725 x 10^{9}m^3 with a mean level of 474 masl. The Shire River transits an annual average of 18km^3 (500 to 600 m^3/s) into Mozambique. The annual surface water yielding on land is about 13km^3 and which predominately drains into Lake Malawi and the Shire River. However, more than 90% of this runoff occurs in rainy season, specifically from December to April (GoM, 2006; FAO, 2008). Managing such water resources which cut across countries requires the IWRM approach which addresses issues of transboundary management of water resources (Vask, 2008; Turton et al., 2006; Cooley et al., 2009)

Table 2.4 gives the inland runoff contribution to the lake from three riparian countries of Malawi, Mozambique and Tanzania. Malawi though with the largest riparian area of 65.9% contributes only 42% of the total inflow into the lake. In comparison, Tanzania with only a riparian area of 27.2% contributes about half of the inflow into the lake. This entails that Malawi needs cooperation with other riparian countries for integrated management of water resources. Other important surface water resources include Lake Chilwa with a surface area of 683 km^2, Lake Malombe with an area of 303 km^2 and Lake Chiuta with a surface area of 60 km^2, Chia Lagoon 22km^2 while small lakes, lagoons and marshes include Lake Kazuni, Chiwondo Lagoon, Elephant Marsh, Ndindi Marsh and Vwaza Marsh as referenced in Table 2.4 (MoIWD, 2006).

Table 4: 2.4 Contribution of inland runoff to Lake Malawi from three countries

Parameters	Malawi	Tanzania	Mozambique	Total
Catchment area of lake in km^2	64,372	26,600	6,768	**97,740**
Water Flow in m^3/ s	391	486	41	**918**
Total area in %	65.9	27.2	6.9	**100**
Total water flow in %	42.6	52.9	4.5	**100**

Source: MoIWD, 2006

Malawi has a good network of river systems and is rich in surface water resources. The drainage system has been divided into 17 Water Resources Areas (WRA) (Table 2.5 & Fig. 2.4) and each WRA represents one major basin. The WRAs are sub-divided into 78 Water Resources Units (Fig.2.4). Major rivers include Songwe, North Rukuru, South Rukuru, Lweya, Dwangwa, Bua, Linthipe, Ruo and the Shire (Fig. 2.4). The Shire is the largest river and is the only outlet of Lake Malawi whereas all the other major rivers drain into Lake Malawi except Ruo which drains into Shire River. All major rivers are perennial although most of the smaller rivers draining into major ones have ephemeral flow. The mean annual runoff over the land area of the whole country is 196mm which is equivalent of 588 m^3/s. This constitutes 19% of the mean annual rainfall. For details refer to Table 2.5. The mean annual outflow in Shire River at Lake Malawi outlet upstream Mangochi is 395m^3/s. However, implication of such runoff and outflow on managing water resources especially groundwater availability through water balance analysis has not been discussed in this study because of the present scope of the study.

Table 5: 2.5 Major river basins in Malawi with mean annual rainfall and runoff

WRA	River basin	Catchment area km^2	Rainfall mm	Runoff		% runoff
				mm	m^3/s	
1	Shire	18 945	902	137	82	15.2
2	Lake Chilwa	4 981	1 053	213	34	20.2
3	South West Lakeshore	4 958	851	169	27	19.9
4	Linthipe	8 641	964	151	41	15.7
5	Bua	10 654	1 032	103	35	10.0
6	Dwangwa	7 768	902	109	27	12.1
7	South Rukuru	11 993	873	115	44	13.2
	North Rumphi	712	1 530	674	15	44.1
8	North Rukuru	2 091	970	252	17	26.0
9	Lufira	1 790	1 391	244	14	17.5
	Songwe	1 890	1 601	327	20	20.4
10	South East Lake Shore	1 540	887	201	10	22.7
11	Lake Chiuta	2 462	1 135	247	19	21.8
12	Likoma Island	18.7	1 121	280	-	-
13	Chisumulo Island	3.3	1 121	280	-	-
14	Ruo	3 494	1 373	538	60	39.2
15	Nkhotakota Lakeshore	4 949	1 399	260	41	18.6
16	Nkhata Bay Lakeshore	5 458	1 438	461	80	32.1
17	Karonga Lakeshore	1 928	1 208	361	22	35.1
	TOTAL	**94 276**	**1 037**	**196**	**588**	**18.9**

Source: MoIWD, 2006

Table 6: 2.6 Major natural reservoirs and marshes in Malawi

	Reservoir	Surface Area (Km^2)	Location as per District
1.	Lake Malawi	28,750	Covers Karonga, Rumphi, Nkhatabay, Nkhotakota, Salima, Dedza & Mangochi
2.	Lake Chilwa	683	Zomba & Phalombe
3.	Lake Malombe	303	Mangochi
4.	Lake Chiuta	60	Machinga
5.	Lake Kazuni*	-	Rumphi & Mzimba
6.	Chia Lagoon	22	Nkhaota kota
7.	Chiwondo Lagoon	-	Karonga
8.	Elephant Marsh*	-	Chikwawa & Nsanje
9.	Ndidi Marsh*	-	Nsanje
10.	Vwaza Marsh*	-	Rumphi

* Surface area not known; Source: MoIWD, 2006

2.6.2 Groundwater resources

Development of groundwater resources has been primarily for drinking water supply for both rural and urban areas. The construction of boreholes and hand dug wells, which started in the 1930s, is considered the beginning of the utilisation of groundwater resources in Malawi (Chilton, 1982; Foster, 1983). Groundwater is developed from two main aquifer types in Malawi, namely, basement complex (weathered basement aquifer) and alluvial aquifers (Fig. 2.7). The basement complex aquifers are extensive. They are relatively low-yielding i.e. up to 2.0 to 4.0s/l. These occur in metamorphic and igneous rocks covering 80% of Malawi. The second type is called alluvial aquifers which are high yielding of up to 11.0 to 20.0 s/l. These occur along the lakeshore plains and the Shire Valley; where the unconsolidated quaternary alluvium covers the bedrock (FAO-AQUASTSTAT, 2009; GoM-UNDP, 1986). In Malawi, although water resource is abundant, economically exploitable groundwater resources are limited because the existing extensive aquifers are disjointed with characteristic relatively low yields and in most cases these aquifers are highly localised (GoM-UNDP 1986). Thus, improving understanding on the local hydrogeologic factors of such waters to inform strategies for their sustainable management and utilization is envisaged important in this study. Detailed discussion on implication of hydrogeologic factors/environments for implementing IWRM approach is provided in chapter 5.

Management and utilization of weathered basement aquifer is critical. These aquifers are characterized by in-situ weathering of bedrocks producing a layer of unconsolidated saprolite material and their spatial distribution is extensive in Malawi (Fig. 2.7) as is the case throughout Africa. Groundwater storage is mainly dependent on secondary porosity and their yields range from 2.0 to 4.0 litres per second (Stanley International, 1983). About 50% of boreholes in this aquifer type draw water from fractured crystalline and weathered rocks (Carter & Bennett, 1973). The presence of undesirable natural hydro-chemicals and/or contaminants can reduce exploitation value of these low yielding aquifers. However, most of these aquifers at a larger extent do not suffer from natural hydro-chemical problems because rock materials are relatively inert (Xu & Usher, 2006). Bicarbonates dominate waters of these aquifers and total dissolved solids content values are generally less than 1000 mg/l and typically around 350 mg/l (Xu & Usher, 2006). The current study is located in this type of aquifer type.

In Malawi, groundwater quality is generally acceptable for domestic use, although studies indicate that concentration levels of fluoride, iron and sulphate in groundwater in some areas are higher than values of WHO guideline and Malawi Bureau of Standards (GoM-UNPD, 1986; WHO, 2008; MBS, 2005). This suggests that groundwater quality is becoming unsuitable for human consumption hence the physicochemical analysis of drinking water from groundwater sources in this study. Reports (MoIWD, 2006; GoM, 2007; Baumann & Danert, 2008) indicate that extensive drilling to exploit groundwater exists in Malawi. This trend suggests data on hydrogeologic, groundwater level and groundwater quality would be systematically collected and stored to ensure its availability on all drilled boreholes. This is not the situation in Malawi because the existing enabling environments, institutional arrangements and management instruments as described in section 2.5 of this chapter do not enable systematic collection and storage of data on all water sources. This situation impairs a thorough analysis to provide a clear picture on groundwater resources in Malawi that would inform effective and sustainable management.

The present study area does not have alluvial aquifer. However, Taylor et al., (2010) highlighted the importance of understanding the management of both aquifer types when managing groundwater from the IWRM perspective. This thesis briefly discussed such alluvial aquifers in chapter 5. Alluvial aquifers are generally high yielding with recorded yields of up to 11-20 litres per second (Stanley International, 1983). These aquifers are commonly sedimentary rocks and layered volcanic rocks (GoM-UNDP 1986). In Malawi, these are found along Lake Malawi Shore, in the western side of the Shire River Valley and the Lake Chilwa basin on the outer slopes of Zomba Plateau (Fig. 2.7). The sedimentary environments that are likely to produce the highest groundwater yields are buried river channels and littoral zones of the lake shore where the deposits are usually coarse grained and well-sorted (Chilton, 1982; Foster, 1983).

The current thesis does not estimate the recharge rates but describes factors that explain groundwater availability using factors that influence the recharge process. However, groundwater annual recharge for Malawi is estimated to be 15mm to 80mm for the weathered basement aquifers and 3mm to 80mm for alluvial aquifers (GoM-UNDP, 1986). Flow hydrographs analysis, groundwater level fluctuations, flownets and catchment water balances were employed to estimate such recharge amount. In the alluvial aquifers, the recharge also occurs by infiltration from the river beds where these are significantly permeable. Based on the 15mm recharge amount for basement aquifer, estimated recharge for the entire Malawi can be said to be 1414 $10^6 m^3$ per year (GoM-UNDP, 1986). The current study describes factors that affect recharge in the study area.

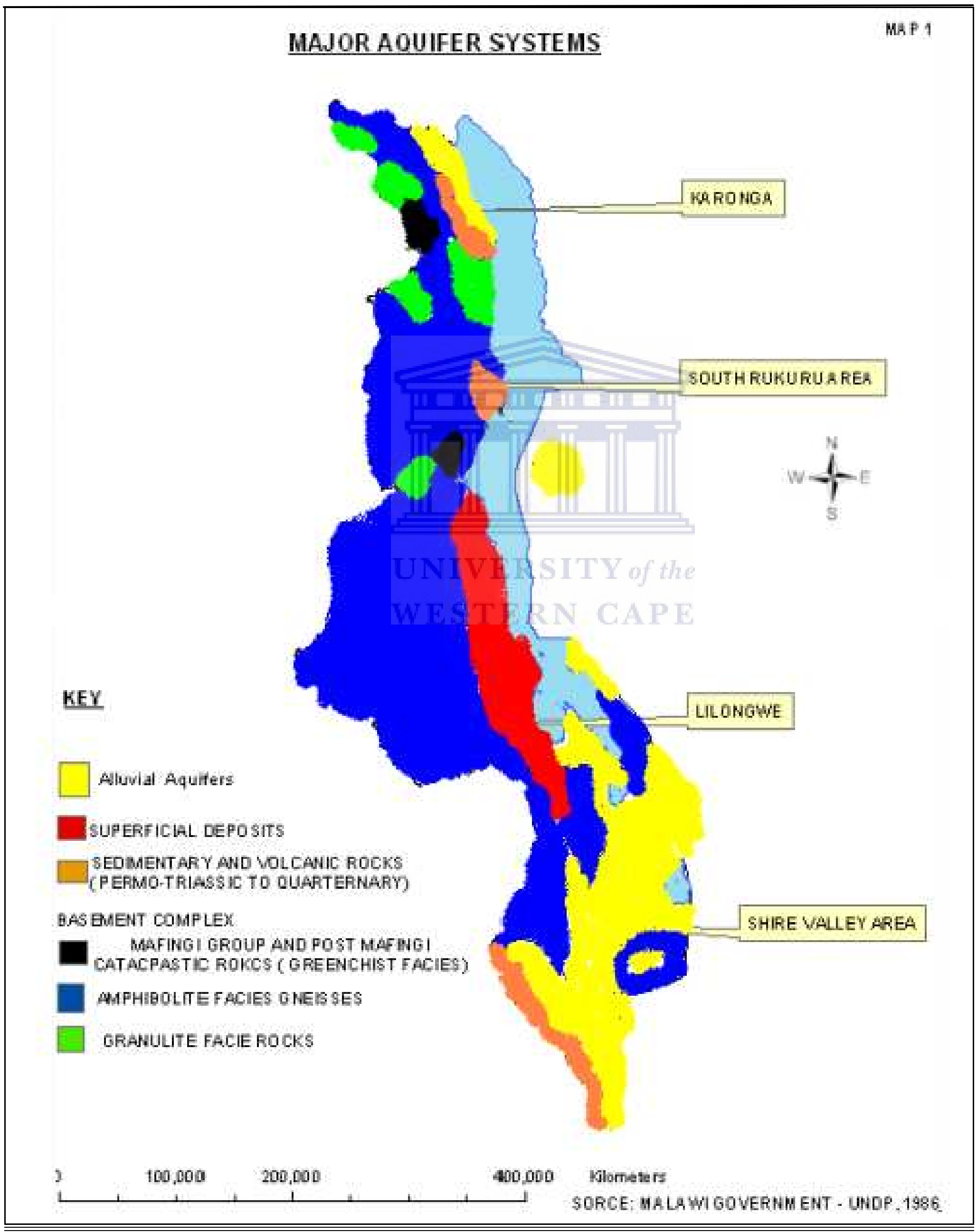


Figure 8: 2.7 Major aquifer systems in Malawi

Source: GoM-UNDP, 1986

2.6.3 Utilization of water resource in Malawi

Water resources in Malawi are mainly used in the following sectors: water supply and sanitation, agriculture, irrigation, industry, energy (hydropower), transport (navigation), fisheries and bio-diversity. The utilization of the resources is categorised as consumptive and non-consumptive uses. The consumptive uses include water supply and sanitation, irrigation and industry while the non-consumptive uses include hydropower, transport, fisheries, bio-diversity and tourism (FAO-AQUASTSTAT, 2005). This study examines consumptive use with a focus on water supply and sanitation of groundwater resources recognising that practices for water management are equally important for non-consumptive uses to improve livelihoods status of people. Utilization of water resources contributes to sustainable socioeconomic development of the nation and improves the environment integrity that sustains such development.

In Sub-Saharan Africa, Malawi's access to safe drinking water sources was leading with 75% by 2007 while Kenya was 49%, Mozambique 26%, Tanzania 46%, Zambia 41%. Sustained further progress for Malawi seems not guaranteed due to terrain difficulties in uncovered areas and non-functionality rate of 31% which reduces effective coverage to 55% (Baumann & Danert, 2008). Managing rural water supply sector is challenging. For example, financing the sector remains uncoordinated with implementation occurring in discrete and fragmented projects. Baumann & Danert (2008) reported that about 0.21 million rural people yearly, need water service provision at an annual cost of USD8.28 million (UDS40 per capita). This amount translates into a total estimated investment requirement of USD193 million to reach 98% coverage in 2025 for rural water supply. Currently, the 5% annual of the capital investment is spent on operation and maintenance (O&M) resulting into USD 12 million needed for O&M per year. The reality is to share this cost between water users (communities), water managers (District assemblies in the Malawi Government ministries) and other service providers. However, the current situation is that districts in Malawi are not even able to invest a twentieth (20th) of that amount (MoIWD, 2006; Baumann & Danert, 2008). This situation justifies the use of local IWRM as an alternative approach at community level in O & M practices in order to sustain management and utilization of water resources.

Another challenge in water utilization is lack of coordination within MoIWD itself and between MoIWD and other stakeholders. For example, district water offices (DWOs) complain that the central office at MoIWD drills boreholes in districts without informing DWOs about such activities. In turn, DWOs are criticised for not sending data to the regional water office for onward transmission to the central water office. Again, NGOs continue to work in isolation without providing information of their plans or output on water activities though some NGOs request DWOs to conduct community based maintenance training, hence, the scarcity of data for effective water assessment.

Decentralising community based maintenance (CBM) to users at water point from the central water office in the MoIWD is challenging. CBM training is an essential part of providing users with the requisite skills and knowledge to manage and maintain their facilities. Although Government stakeholders are familiar with CBM training, training manuals, materials and visual aids are not easy to obtain in Districts. Again, about 40% of communities are not trained on CBM and NGOs delegate the CBM training to the DWO Officers who have no funds for such activities. For village water committee members trained on CBM, they are not given documents as references at a later stage. This means that the MoIWD decentralised CBM function without resources to enable its implementation and such action although had good intention is counterproductive.

The Malawi Government and private sector install improved community water points (ICWP) in many areas of Malawi to provide access to safe drinking water if a functional ICWP exists within 500 metres of people’s households (GoM, 2006). However, almost three-quarters of all water points in Malawi are installed by unknown or unmonitored organisations (Baumann & Danert, 2008) a situation that explains the absence of data on hydrogeology, water levels and water quality of groundwater sources for drinking water. Nevertheless, Malawi Government defines access to safe water as water piped into the dwelling or community stand tap or borehole or protected well or spring located 500metres from a household with recommended maximum number of people using one ICWP being 250 and 120 for borehole and standpipe respectively (Baumann & Danert 2008). However, the traditional sources of water supply in Malawi remain open hand dug wells which are usually dug in flood plains or *dambos* (wetlands) and open surface water bodies such as rivers, lakes or dams (MDHS, 2010). The absence of data on groundwater parameters of health significance and the definition of access to safe water sources formed the basis for this thesis, in particular chapter 7 which assesses whether or not boreholes and protected wells are safe sources of groundwater for drinking.

Table 7: 2.7 % of population accessing drinking water from safe and unsafe sources

Main sources of drinking water	Malawi	Southern Region	Central Region	Northern Region
Piped in dwelling & yard	8	7	7	10
Community stand pipe/tap	12	15	9	11
Borehole	48	54	43	46
Protected shallow well	6	3	9	6
Unprotected shallow well	18	13	25	14
River/Stream	7	6	6	12
Other unsafe sources	1	2	1	1
Total	**100**	**100**	**100**	**100**

Source: NSO, 2009 & MDHS, 2010

Demand for water to generate more and stable hydropower and irrigation agricultural practices is on the increase and the trend seems unabated (Malawi-MDG, 2010). For example, agriculture (irrigation) is the largest consumer of water in the country with 80.6%, 14.7% and 4.7% of water used for agricultural, domestic and industrial uses (FAO-AQUASTAT, 2005). About 70,000 hectares of land in Malawi have been developed for irrigation mostly for sugar, rice and tobacco estates. Of this, more than 20,000 hectares are being used for commercial farming in the Lower Shire Valley and the lakeshore. Sixteen large-scale irrigation schemes in Malawi exist, namely, Bua, Bwanje, Domasi, Hara, Kaporo, Kaombe, Kasinthula, Khanda, Likangala, Limphasa, Lufira, Mpamantha, Muona, Nkhate, Wovwe and Limphasa. In addition, the Vizara rubber plantation in Nkhatabay, tea plantations in Thyolo and Nkhatabay, sugar plantations in Lower Shire Valley, Nkhotakota and Nkhatabay and many smallholder irrigation schemes are being developed to improve food and income security at household level. These activities have an impact on management of water resources both surface water and groundwater in terms of demand, use and governance.

With the ever-increasing urbanisation and negative effects of climate variability/change, the increasing demand for and use of water will not abate both in consumptive and non-consumptive categories. Such an increase will require accurate information on water availability, abstraction trends and usage per sector. Statistics on such variables have been known to be scarce worldwide. However, a starting point has to be launched because most of the existing models on water availability, demand and use would require such data to improve their predictive power. This situation formed the basis for this study and provided a proposed procedure on how to generate such statistics on demand and use of groundwater in unmetered rural areas. This is a starting step towards providing the scarce but most needed statistics on water resources management.

2.7 Summary

This thesis argues that comprehensive assessment of physical and socioeconomic condition is essential to provide explanation on factors that limit successful execution of the IWRM approach. Such an assessment enhances effective management for sustainable utilization of water resource to enable the country improve socioeconomic development and environmental integrity. To contextualise such a thesis, the literature review in this chapter assessed prevailing physical and socioeconomic factors in Malawi in relation to current management and usage of water resources and the influence on ecosystem. The aim was to suggest local solutions that are viewed as simple but form a catalyst to reap quick gains in water management when nationally supported and implemented. Physical and socioeconomic environments are dynamic and the review in this chapter is neither static nor comprehensive. But physical and socioeconomic challenges and opportunities have been highlighted to implement a successful IWRM.

Malawi’s groundwater resources are both physically and economically difficult to exploit due to existing extensive aquifers that are fractured; discontinuous and disjointed; give low yields of 2.0 - 4.0 l/s; are highly localised and their storage capacity is low. This study is located in this type of aquifer. In addition, the prevailing socioeconomic situation also hinders groundwater exploitation. This is in terms of water policies, water laws, institutions and management instruments which are not reformed and harmonised. These challenges need to be overcomed to facilitate the full and successful operation of IWRM approach in Malawi. The next chapter describes the global status on IWRM implementation as the theoretical framework for this study. Throughout this thesis, literature is reviewed to contextualise groundwater management from the IWRM perspective so that a broader analysis on IWRM execution is provided.

Chapter 3: Global Status of Groundwater Management

3.1 Introduction

This chapter argues that improved understanding is vital on how key agreed upon principles and concepts guide global utilization and management of water resources including groundwater. To do this, the chapter presents a review on progress of 1) IWRM in the broader development context, 2) IWRM implementation, 3) current management approaches for groundwater, 4) global assessment of groundwater and 5) adaptive management. The focus is on groundwater as part of IWRM for rural water supplies and sanitation (RWSS). The review has been discussed from international, regional and national perspectives in order to justify the need for local IWRM. The conclusion of the chapter highlights the known and unknown aspects on groundwater management to enable this study contribute to the body of knowledge.

3.2 IWRM in broader development context

This section highlights key aspects of evolution on the IWRM concept in the international water policy sector because broader developmental objectives have influence on existing enabling environments (water laws and policies) that guide institutional arrangements to implement programmes and enforce management instruments. The link between sustainable development and environmental integrity to relatively new understanding of IRWM has been emphasised in relation to the focus of the study, namely, groundwater management from the IWRM perspective.

3.2.1 Water resources management and sustainable development

The evolution of the IWRM concept in the international water policy sector shows how socioeconomic factors guide sustainable management and utilization of water resources. Snellen & Schrevel (2004) stated that the historical development of the IWRM concept shows four types of integration, namely, a) integrating WRM in the broader developmental context (socioeconomic needs); b) integrating sectors that use water (sectoral integration); c) integrating biophysical resource base such as water and land (environmental integrity); and d) interlinking upstream and downstream (spatial integration). The idea of comprehensive planning of natural resources utilization combined with economic, social and environmental integrity that resembles the current IWRM concept, first emerged in 1933 in the Tennessee Valley Authority (TVA) in the

United States of America (Muckleston, 1990; Mitchell, 1990). The integration in the TVA focused on supporting services needed to develop irrigated agriculture (developmental context) but not the coordination between irrigation and other water users (sectoral integration). It is the sectoral integration that brings comprehensive management of water by bringing together sectors to plan and manage socioeconomic needs of people, environmental integrity and spatial integration in a coordinated manner to ensure sustainable utilization of water resources for people's continued progress. This thesis argues that socioeconomic and physical factors need to be assessed first to improve understanding on how to successfully implement such holistic management using a local adaptive approach (local IWRM) rather the whole IWRM approach.

The coordination in the water sector (sectoral integration) started in 1977 during the international water conference in Mar del Plata where it was stated that institutional arrangements adopted by each country should ensure that there is practical coordination among sectors responsible for investigation, development and management of water resources. However, high demand for water due to increased agricultural and industrial activities to satisfy the needs of global growing population and negative effects of such activities on the environment did not emerge as major global concerns (Snellen & Schrevel 2004). But the following were highlighted: a) community water supply as fundamental human rights stating that access to available supply of clean water for healthy survival and betterment should be upheld; b) the increasing pollution due to anthropogenic activities require solution and; c) on shared water resources, countries were called to harmonise their different interests to develop a more effective framework to facilitate cooperation among them. These three aspects are still relevant in the current IWRM and findings of the current study in chapter 7 are based on a) and b) aspects. The conceptual model in chapter 5 for study area is based on aspects in c).

Creighton (1999) reports that the 1992 Earth Summit in Rio de Janeiro identified holistic management of freshwater as finite and vulnerable resources and the integration of sectoral water plans and programmes within framework of national economic and social policies as important coordination aspects for actions in 1990s and beyond. Chapter 18 of Agenda 21 highlights fragmentation of responsibilities for water resources development among sectoral agencies as a barrier to promote and implement the IWRM principles. In water and sustainable development discourse, IWRM means managing water resources as an integral part of the country's social and economic development with full understanding of environmental integrity to fulfil such developmental agenda. Hence, assessing socioeconomic and physical factors of a particular country and catchment is important for implementing a successful IWRM.

Between 1977 and 1992 IWRM was advocated for but the reported progress on sectoral integration was slow because of environmental problems which resulted from development activities that increased the number of poor people (Brundtland, 1987). The proposed solution was to implement sustainable development which seeks to meet the needs and aspirations of present generation without compromising the ability to meet those of the future (Brundtland, 1987). The 1992 Earth Summit sees IWRM as a tool to implement the concept of sustainable development. Thus, the need for scientific assessment on socioeconomic and physical factors in each catchment for IWRM implementation remains significant. For example, Koudstaal, et al., (1991) reported that the real value of sustainable development concept emphasises on assessing the potential of natural resources first, such as water, before planning for socioeconomic development so that protective measures are explored for potential negative effects on the environment. This principle informs the current study on assessing quantity, quality and governance of groundwater using groundwater management as a case study.

3.2.2 Recent understanding of IWRM principles within the era of paradigm shift

The current study on groundwater management from the IWRM perspective is based on the four Dublin Guiding Principles that led to the birth of IWRM in June 1992 during the Earth Summit. Table 3.1 presents a descriptive summary on the four IWRM principles which FAO (2000) regrouped into three, namely, the ecological, institutional and instrument principles. Table 3.1 highlights the link of these principles to the current study on the need for holistic management at lowest sub-catchment level, namely, the Upper Limphasa River catchment in Northern Malawi. The local IWRM as a potential solution to implementing a successful IWRM indicates aspects of participatory approach, women's role in local institutional arrangements, protection of groundwater (ecological principle) and managing water from some aspects of economic perspective.

Table 8: 3.1 Summarised descriptions of the four IWRM principles

Principle 1: Freshwater is a finite and vulnerable resource, essential to sustain life, development and the environment. FAO (2000) calls this principle, the ecological principle.
Since water sustains life, effective management of water resources demands a holistic approach linking social and economic development with more on protection of natural ecosystems (environment). Effective management links land and water uses across the entire catchment or groundwater aquifer with a river basin or catchment or sub-catchment being a unit of analysis during assessments.
Principle 2: Water development and management should be based on a participatory approach involving users, planners and policy makers at all levels. FAO (2000) calls this principle, the institutional principle.
The participation approach involves raising awareness of the importance of water among policy makers and the general public. It means that decisions are taken at the lowest appropriate level with full public consultation and involvement of users in the planning and implementation of water projects.
Principle 3: Women play a central part in the provision, management and safeguarding of water. This principle is also called the institutional principle (FAO, 2000)
This pivotal role of women as providers and users of water and guardians of the living environment has been seldom reflected in institutional arrangements for the development and management of water resources. Acceptance and implementation of this principle requires positive policies to address women's specific needs and to equip and empower women to participate at all levels in water resources programmes including decision-making and implementation in ways defined by them.
Principle 4: Water has economic value in all its competing uses and should be recognised as an economic good. FAO (2000) calls this principle, the instrument principle
Within this principle, it is important to first recognise the basic right of all human beings to have access to clean water and sanitation at an affordable price. Past failures to recognise the economic value of water has led to wasteful and environmentally damaging uses of the resource. Managing water as an economic good is important to achieve efficient and equitable us, to encourage conservation and protection of water resources and to improve water allocation and quality.

Source: FAO, 2000

The main outcome of the Earth Summit was Agenda 21 report, which is a comprehensive blueprint for global action to solve environmental problems and to promote sustainable development. Chapter 18 of Agenda 21 is on the protection of quality and supply of freshwater resources which describes application of an intergraded approach to development, management and use of water resources recommending that IWRM should be implemented at catchment or sub-catchment level (Snellen & Schrevel 2004). The scholars continued to report that the IWRM concept perceives water as an integral part of the ecosystem, a natural resource, social and economic good whose quantity and quality determine the nature of its utilization. This requires its protection considering its functionality of aquatic ecosystem and perennial status of the resource to satisfy and reconcile needs for water in human activities. In developing and using water resources, priority should be given to satisfy the human basic needs first then followed by safeguarding the ecosystem and then beyond these two requirements, water uses should be charged as an economic good for efficiency use (WB, 2004).

Recent development of IWRM concept in WB (2004) reports show that although global consensus embodied in the Dublin principles remains relevant and appropriate, progress has been slow in getting actions on the ground. A review by World Bank (WB) and OECD indicated that even most advanced countries are far from practical implementation of IWRM principles in full (WB, 2004). Biswas (2004) asserted that such slow progress for IWRM implementation is largely due to lack of establishing measurable criteria at operational management level, the point that Mitchell (2004) feels should not underplay strides achieved at normative and strategic levels. Mitchel's argument is that IWRM values are significant at normative and strategic management levels and the weakness at operational level only provides an opportunity to develop and implement an alternative approach to ensure that IWRM is implemented.

WB (2003) in agreement with Mitchel (2004) highlighted the need for a practical approach that considers existing ecosystem and socioeconomic structures in catchments before implementing projects to fulfil IWRM concept. All in all, there is evidence that practical progress for IWRM has been slow (WB, 2004; Biswas 2004). These results form the basis for the current study to provide a local but practical solution at operational management level that complement normative and strategic managements. Operation refers to implementation (action); strategic refers to intended initiative (policies) and normative management refers to conforming to standards of correctness through rules, norms or recommendations (institutions) (Nag et al., 2007). The three management types form socioeconomic factors central to this study.

Cosgrove and Rijsberman (2000) suggest that for IWRM to be implemented and fit in the paradigm shift era, a) ambiguity need to be excluded in its definition and b) authoritative definition must be provided. This suggestion was accepted and the first authoritative definition for IWRM as it is today was provided, which states that *IWRM is a process which promotes the coordinated development and management of water, land and related resources in order to maximise the resultant economic and social* *welfare in an equitable manner without compromising the sustainability of the vital ecosystem (GWP, 2000).* From this definition, this study sees management of water resources as a learning process, namely, adaptive management (Seward et al., 2006). Adaptive management is informed by precautionary principle in managing the environment such as groundwater protection (Xu & Braune, 1995). How this principle facilitates IWRM implementation is elaborated in section 3.5 and demonstrated for groundwater management in chapter 5, section 5.7.

Table 9: 3.2 Progress in paradigm shifts in water resources management

Paradigm shifts in water resources management		
Projects	→	Process
Functional engineering systems	→	Environmental issues
Water supply management	→	Water demand management
Harnessing water resources	→	Sustaining water resources
Top-down political decisions	→	Bottom-up public participation
Few capital intensive major schemes	→	Many smaller schemes
Extreme value design requirements	→	In-stream flow requirements
Disciplinary focus (e.g. engineering)	→	Inter-disciplinary focus
Problem solving	→	Conflict management
The volume of water	→	The value of water
Prediction (i.e. magnitude)	→	Forecasting (when)
Channel control/management	→	Whole catchment management
Water quantity	→	Water quality

Source: Schulze, 2010

Table 3.2 showed the agreed upon paradigm shifts in water resources management. This table suggests that various scholars, researchers, managers, decision makers and all stakeholders in the water sector need to be aware of the existing paradigm shift in water resources management so that their efforts to implement IWRM should align with such a focus in the sector. In addition, six approaches (Fig.3.1) were suggested to facilitate implementation of IWRM, namely, the systems approach which focuses on linkages/interactions between human and nature, land and water, local and global whereas integrated approach focuses on coordinated development and management between surface water and groundwater, upstream and downstream, regulations and institutional arrangements. The management approach highlights implications of seeking equitable solutions and enhancing quality life. It also assesses effects of implementing a mixture of top-down and bottom-up, supply and demand management, economic and human right management aspects of water. The stakeholder approach is concerned with repercussions of decentralizing powers from government to the lowest level (individuals) alongside participatory decision whereas the partnership approach focuses on effects of having common objectives, having collective rules alongside responsibilities and having commitments to principles of stewardship. The sustainable approach focuses on the outcome of promoting equitable access, protection of resources integrity and compromise between development and protection. The current study assesses aspects of each of the six suggested approaches to show the feasibility of local IWRM to ensure sustainable management and utilization of water. Figure 3.1 shows the six suggested approaches that would facilitate IWRM's operated strategies and goals.

Figure 9: 3.1 Common six suggested approaches for IWRM implementation
Source: **Schulze, 2010**

Apart from the paradigm shift, the suggested six approaches, Schulze (2010) highlight five general socioeconomic and physical factors with examples under each factor (Table 3.3) that explain the observed variations in terms of IWRM implementation pattern between the developed and developing countries. Since these factors are applicable at global and national scales, assessment of similar factors remains significant at catchment or sub-catchment level in each country where IWRM is implemented. The current study is informed with such thinking that assessing socioeconomic and physical factors in the Upper Limphasa River catchment provides a good basis to advocate for the implementation of local IWRM in other catchments of similar environments.

Table 10: 3.3 General factors that influence successful IWRM execution

Factors that influence successful execution of IWRM in Developed & developing countries	
Developed countries →	Developing countries
1. Infrastructure	
Highly developed →	Fragile
Improving →	Retrogressing
Ethos of maintenance →	Constructed and neglected
Data: Available and accessible →	Data: Poor, scanty and inaccessible
Resilient to disasters →	Vulnerable to disasters
2. Capacity	
High skills: technical and administrative →	Limited skills: technical and administrative
Available expertise: central to local level →	Expertise centralised with none at local level
Technological adaptability →	Often in survival mode
3. Economy	
Mixed and diverse →	Land/climate dependent
Independent and sustainable →	Aid and/or NGO dependent = unsustainable
Long term planning →	Short term planning
Money available for IWRM →	Less scope for IWRM; no money for IWRM
4. Socio-political	
Low or no population growth →	Population pressure on land resources
Public well informed →	Public poorly informed (political interference)
Stakeholders empowered →	Stakeholders less empowered
5. Environmental awareness/management	
Re-naturalisation →	Rehabilitation
Desire for aesthetics →	Desire for survival

Source: Schulze, 2010

3.2.3 Water resources management and environmental integrity (ecosystem)

Global assessments (UN-Water, 2008; Molden, 2007) reported that water is a finite and vulnerable resource and the ecological principle in IWRM implies that improved understanding on factors that affect the hydrologic cycle is required to meet the increasing demand for water by people and the ecosystem. This suggests assessing physical factors that might threaten the quantity, quality and governance of water so that an appropriate management approach is implemented to ensure sustainable regulating and provisioning services of the ecosystem (MEA, 2005). In addition to assessing physical factors, the rest of the IWRM principles are about socioeconomic factors and

FAO (2000) reminds us that the scarcity of social resources (economic scarcity = demand side) are equally crucial in adapting to physical scarcity (supply side) in managing water. These scholars indicate that changes are inevitable in many catchments. But at the same time assessments are significant for a management approach that integrates socioeconomic and ecological systems holistically at local scale. This is the reason why this study is advocating for local IWRM implementation.

3.3 Status of IWRM implementation with a focus on groundwater

This section provides examples of countries that have adopted IWRM as a key concept and highlights countries that are partially or fully implementing IWRM. From the case studies reviewed in this section, the focus is on the progress on best practices in groundwater management from the IWRM perspective. For example, the UN-water (2008) reported that a total 104 countries were assessed in terms of IWRM implementation where 77 were developing countries and 27 were developed countries. Results revealed that 10 of 27 (37%) developed countries partially implemented IWRM whereas 6 countries (22%) fully implemented IWRM. Of the 77 developing countries, 17 (22%) partially implemented IWRM whereas 2 countries (3%) fully implemented IWRM. Regardless of the low (22% and 3%) global implementation rate of IWRM, evidence exists that IWRM principles are being incorporated in national plans of many countries and that tangible benefits prevail but are not documented systematically or are likely to be realised in the near future (UNESCO, 2009). The implication of this trend on groundwater management is further discussed in chapter 6 section 5.7.

A sample review of 48 countries globally shows that at national level (ministerial level), countries adopted and incorporated IWRM approach as a central concept in their socioeconomic and environmental development plans. Evidence for this is that the 48 countries that were reviewed reveal that action plans for IWRM exist; water policies, water laws and water strategies were reformed and revised to incorporate IWRM principles; roadmaps, master plans and frameworks were developed to align with IWRM principles (UN-Water, 2008). However, despite such evidence of countries adopting and using IWRM approach as pivotal concept at national level, implementing such a concept remains a rare practice largely due to lack of methods to operate such an approach. In addition, the focus to demonstrate groundwater management practice as part of IWRM approach is not highlighted in the reviewed 48 countries and continue to receive insignificant publicity within IWRM discourse hence the focus in this study on groundwater management for drinking from the IWRM perspective as a case study.

3.3.1 Global best management practices for IWRM

From the few selected countries where the IWRM approach was implemented, groundwater management remains silent. However, global best management practices for IWRM in those countries in terms of scale, issues, actions and tangible impacts (benefits) are demonstrated (Table 3.4). Hence the need to improve understanding factors that limit wider implementation of IWRM is essential as this thesis argues.

Table 11: 3.4 Examples of selected countries where IWRM has been implemented

Spatial coverage: Scale	Problem for IWRM	IWRM action	IWRM benefit
1.Local level: Malawi (Dzimphutsi Village in Chikwawa District: Lower Shire valley)	-Water management -Existing old water laws versus new water policy -Appropriate institutions -Coordination issues	-Established IWRM priority issues -Set up coordination unit -Piloted IWRM in Dzimphutsi village	-Piloted & assessed Dzimphutsi IWRM -Started coordination meetings: national level -Drafted water laws
2.Transboundary level: Mozambique/Zimbabwe	-Floods -Water quality	-Started studies withinPungwe project	-Strengthen interstate -Gained knowledge
3. National level: Uganda	-Water quality -legal & institutions issues	-Set up coordination -plan piloting IWRM	-Coordination was set -PilotedIWRM in2008
4.National level: Morocco	-Water scarcity (demand) -Water reform not practiced	-involved NGO -Pilotedwater projects -Set up best practices	-Soussa Massa Agency implemented reform -Provided water
5. National Level: Sri Lanka	-Waterpolicynot practiced -Water related disasters -inadequate water	-Baseline assessment -set up institutions & disaster management	-Floodimpact reduced -Early warning given -water storages set up
6. National level: Chile	-Increasing water demand -Increasing water use	-Water assessment -New water laws	-Water use improved -Clean environment
7. National level: Kazakhstan	-Disputes -Water shortage -Water pollution	-Basin council set up -IWRM & WE set up -Legaltools developed	-Created basin council -Created organisation -Amended water law
8. State Level: United States of America (New York City: Croton & Catskill/Delaware Watershed)	-Water quality (building new treatment water supply plant or improving the protection of water sources)	- Chose to protect the source of water -Set up partnership & programmes with stakeholders	-350 farms started best management practices with watershed -Saved US$4,400 million on water costs
9. Provincial level: China	-Water pollution -Water shortage -Deforestation upstream	-Set up coordination commission -Enforced water policy	-Reduce conflicts -Reduced pollution -Stopped deforestation
10. Local level: Colombia	-Deforestation -Water diversion of water Amazon river to Pacific	-Set up partnership with stakeholders -Set us committees to participate in decision making process	-Committees worked with ministry of environment to stop plans to divert water -387 families doubled

			their income and food
11. International level: Fergana Valley (Central Asia)	-Disputes -inefficient use of water -Safe drinking water	-Set up commission for coordination -Train stakeholders -Set up committees -Give service as pilot	-Partnership set up -28water committees -28 village got safe drinking water; 320 Ecosan toilets built

Source: UN-Water, 2008; Shaba & Van Kopper, 2008; GoM, 2008

3.3.2 Implementation status of IWRM in Malawi

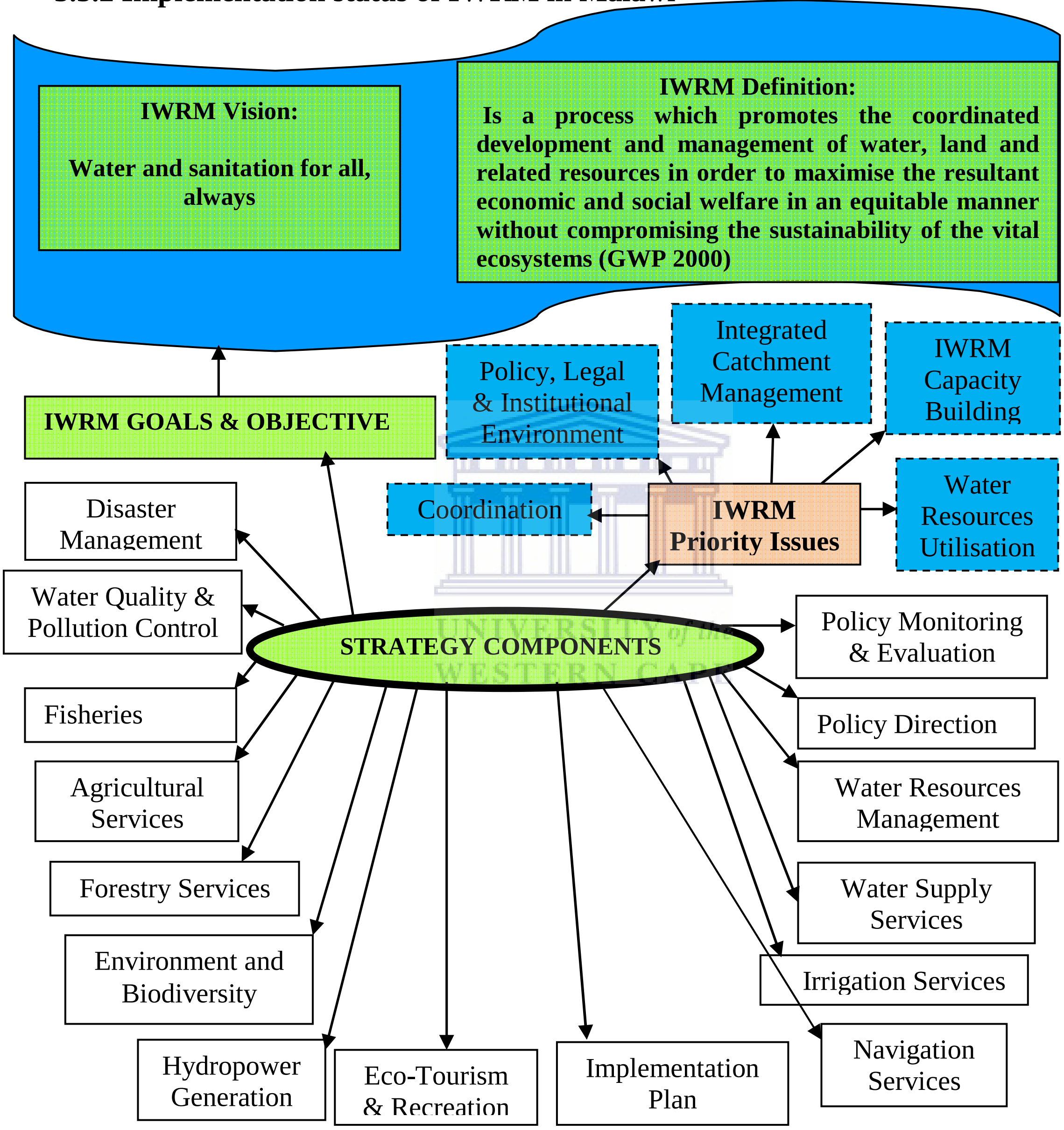


Figure 10: 3.2 IWRM priority issues in development strategy plan of Malawi

Source: GoM, 2008c

In Malawi, to facilitate the implementation of IWRM principles, the process of integrating IWRM into the Malawi Growth and Development Strategy (MGDS) was undertaken through the Ministry of Irrigation and Water Development (MoIWD) and various stakeholders who actively participated in the consultative processes for developing the MGDS. The MDGS is a medium-term national planning framework which forms the basis for funding activities of government and cooperating partners. The Malawi Government prioritised the water and sanitation sector whose main thrust is to supply sources for safe drinking water and construct small multi-purpose community dams for improved rural livelihoods through irrigation and fish farming.

In order to evaluate progress achieved through implementation of IWRM initiatives, three forms of indicators were identified to be used for assessing the direction and pace of progress as follows: 1) impact indicators on water resource availability and quality 2) process indicators on where the country is with reference to IWRM implementation and MDGs; and 3) performance indicators on how the IWRM framework works and their impact on peoples' livelihoods (GoM, 2008c). The monitoring process is to use the existing implementation structures already in place by the National Statistical Office (NSO). NSO conducts national census at least once in a decade and undertakes surveys within every 5 years whereby access to water and sanitation facilities by the people in Malawi is monitored among others (MDHS, 2010; NSO, 2009).

Dzimphutsi project in the Lower Shire Valley district of Chikwawa aimed at improving rural livelihoods through IWRM. The main issues were to develop irrigation scheme and conserve water due to water scarcity; fish farming due to food insecurity; improve hygiene, sanitation and build human capacity due to low health status. Dzimphutsi area experienced erratic rainfall and crops were no longer sufficient to feed the entire population of 284 people (Shaba & Van Kopper, 2008). More than 60% of the people did not have access to safe drinking water and basic sanitation resulting in wide spread of waterborne diseases. Irrigation infrastructure was observed inadequate and the water use was reported to be inefficient (Shaba & Van Kopper, 2008).

IWRM actions resulted in improved management of water resources based on IWRM principles which emphasized on higher efficiency and capacity building (trainings) within the river basin management. The project demonstrated bottom-up approach by involving local leaders in resources allocation and revitalising existing water point committees. Small canals were constructed to ensure water availability for irrigating small demarcated plots that increased food security. Fish ponds were rehabilitated to improve fish farming. SADC and Denmark Government assisted the Malawi Government to implement, monitor and evaluate Dzimphutsi IWRM project in Malawi (Shaba & Van Koppen, 2008).

Tangible impacts of IWRM Dzimphutsi project included the development of partnership between SADC, Denmark Government and Malawi Government and all water management actors in Dzimphutsi area. It rehabilitated 6 communal managed fish ponds and the distribution was 10 households per fish pond. Two dams along Nkudzi River were constructed to conserve water. For irrigation scheme, the project developed 10.5 hectares (350 metres by 300 metres) and demarcated plots into 0.1 hectares with communities. The irrigation therefore expanded and in turn improved water management practices. The project constructed one borehole to supply safe drinking water, revitalised existing water-point committees and trained them in water-point maintenance, resource mobilisation and participatory hygiene and sanitation transformation (PHAST). It also produced and distributed information, education and communication (IEC) materials to communities as references. One ecological sanitation toilet was constructed as a demonstration facility (Shaba & Van Koppen, 2008).

Fig. 3.3 shows active participation of local communities in various components of the Dzimphutsi IWRM project in Chikwawa District, Southern Malawi. For example, photo 1, shows community members during public consultation meetings about the project; photo 2 shows active participation of one of the community members managing gate for water flow at the dam; photo 3 shows active involvement of women during fish-pond construction; photo 4 shows irrigated fields with crops; photo 5 shows active involvement of community members in managing the dam and photo 6 shows men and women working together to construct channels for pipelines for water supply.


1. Public consultation meeting with communities


2. Community member managing water flow


3. Women participation in fish-pond building


4. Irrigated crop fields & water channels


5. Community members managing dam


6. Men & women constructing pipelines

Figure 11: 3.3 Active participation of community members in IWRM project

3.4 Current management approaches for groundwater

3.4.1 'Laissez-faire' management approaches for groundwater

Laissez faire in groundwater management refers to the situation whereby existing laws are ill-prepared to settle resource disputes due to absence of effective regulatory regime for groundwater abstraction (Younger, 2007). Applying absolute dominion doctrine under the English common law, landowners have the right to abstract and use as they please unlimited amounts of groundwater lying beneath their land, unconstrained by liability to negative effects of their action on neighbours' wells (Younger, 2007). Such a situation enables those who can afford the most powerful pumps to abstract without limitations causing the most drawdown. In most developing countries *laissez faire* approaches to managing groundwater abstraction rights are still the norm, often to the ultimate disadvantage of the impoverished communities. Review on IWRM practices showed this approach to be unsuitable for sustainable utilization of groundwater resource hence the need to facilitate of IWRM using local IWRM at community level.

3.4.2 Reactive management approaches for groundwater

Globally, in 1960s, most developed countries began to enact laws and enforce legal codes/ permit system to allocate and protect the right of groundwater use based on prior appropriative rights of first come, first serve. The system meant that the first person to use water (senior appropriator) acquires the right (priority) to future use against all subsequent users. The right to use water was regulated and managed by the permit system which specifies pumping rates, well spacing and construction requirements (Younger, 2007). This was a reactive approach because water management authorities simply responded to proposals made by others and it works better in humid regions where extensive aquifers with high permeability and storage capacities are located because all demands for groundwater are met without signs of aquifer overexploitation.

Although the current study is located in sub-tropical environment, its extensive basement aquifer are of low yielding and have negative threats due to climate change effects which are increasing. The 2009-Water Resources Bill which was formulated to replace the 1969 Water Act was not enacted (GoM, 2009) and demand for groundwater has political priority due to socioeconomic forces such as irrigation, political votes and humanitarian recognition by NGOs among others (Baumann & Danert, 2008). In reality, the permit system still faces implementation challenges globally including in South Africa which has the most world-class water laws (Younger, 2007; Kresic, 2009). Thus, countries such as Malawi where the permit system seems unfit, providing an alternative management approach such as local IWRM remains crucial as this study illustrates in chapter 8.

3.4.3 Active management approaches for groundwater

In this approach, a government agent or department is given a sole right or authority to abstract groundwater in a country and to allocate the pumped water to different users basing on nationally agreed priorities (Younger, 2007). This is a command-and-control management approach for groundwater management which is common in communist and autocratic governments (Kresic, 2009). Although the approach helps aquifer storage and recovery, river augmentation scheme and regional water transfer as evidenced by the Great Man-made river project in Libya (Salem, 1992), it is not sustainable. Implementing such most strict approach leads to undemocratic governments and results show that poor records for sustainable management of groundwater are found in world's most authoritarian governments such as Libya (Younger, 2007). With such revelation, this study views such an approach as unfit for groundwater management, hence, the need to assess factors that affect IWRM to explore the suitable management approach.

3.4.4 Holistic management approach for groundwater

The three approaches described above are unsustainable and faulty due to their design with doctrines that ensure only the people's rights to use water at the expense of the ecosystem. Therefore, a holistic approach is being proposed which functions at a local scale. For example, the *laisse faire* management promotes unlimited use by landowners due to its absolute dominion doctrine; the use of permit system in reactive management promotes segregation between first comers versus subsequent users due to its prior appropriation doctrine and active management promotes autocracy through its command-and-control principle. As a result, the holistic management approach argues that prior rights of existing abstractors need to consider integrity of the ecosystem which regulate and provide services. This ensures availability of groundwater which depends on sustaining the ecosystem through the enabling environment by political decision makers leading to appropriate management (Molden, 2007; Younger 2007). The holistic management approach is what IWRM promotes for water sustainable utilization but to facilitate execution of full IWRM as is intended, this study advocates for local IWRM.

3.4.5 Managing groundwater as part of IWRM

With the advent of IWRM, it has been agreed among the water community to manage groundwater as part of IWRM. This aligns the SADC policy development plan which embraced IWRM as part of its regional development agenda (Braune et al., 2008). Despite this knowledge, countries continue to manage groundwater with approaches which are not sustainable especially (Kresic, 2009), a situation which needs urgent redress. Braune et al., (2008) provided two reasons why many countries fail to embrace groundwater management in the contemporary integrated water management: 1) links are not noticeable between users of the resource and resource itself and 2) many benefits associated with using groundwater are public goods, hence the overall economic value of using groundwater goes unrecognized. Public goods include: a) maintaining environmental integrity (ecosystem), b) improving human health and c) alleviating human poverty/improving human livelihoods. Kresic (2009) added a third reason which is the lack of creating groundwater awareness among water resources managers and decision makers whose background in hydrogeology is limited. That limited understanding on the role of groundwater in water cycle process, disables them to make decisions on holistic management of water resources to highlight the unique nature of groundwater system that underpins the whole resource base (Braune et al., 2008).

However, for the IWRM approach to be implemented, institutional development remains critical where policies, plans, strategies and programmes are coordinated. This implies that key issues on the roles and responsibilities of different institutions would require clarity in addition to creating effective coordination mechanism between different agencies. Yet, for Malawi, Baumann & Danert (2008) observed that coordination in the water sector was problematic. It was reported that officers from the head office would authorise water service providers to operate in any village in the district with the knowledge of the district water office among other issues. As a solution, Braune et al., (2008) proposed that for groundwater management, one of the important principles to successfully implement IWRM is to supplement or indeed partly replace traditional top-down approaches to management by bottom-up strategies. This approach ensures that the water sector is demand-driven, follows participatory elements of the institutional principles of IWRM and can deliver welfare gains which facilitate end users to achieve their socioeconomic gains.

3.5 Managing groundwater from adaptive management perspective

Globally, management instruments (toolbox) for groundwater have been already developed. However, to successfully implement IWRM, the ability to know the available elements in the toolbox then select, adjust and apply the mix of tools appropriately to the given circumstances is lacking (Braune et al., 2008). One needs to consider the agreed policies, available resources, environmental impacts and socioeconomic consequences in order to apply the toolbox (GWP, 2002). These elements by (Braune et al., 2008 & GWP, 2000) mimic aspects of adaptive management thereby suggesting that groundwater should be managed from the adaptive management perspective. In the adaptive management practice, the focus is to i) use both scientific and social processes in order to build understanding on factors that influence management of resources; ii) enhance institutional flexibility by maintaining and where possible creating political openness among stakeholders and encourage formation of new institutions that are required to develop new institutional strategies that would apply the understanding on a daily basis; iii) learn about the system by identifying uncertainties then finding methods to solve them through hypothesis testing with reflective analysis of the situation (Walters, 1986; Holling, 2005; Habron, 2003).

Agreeing with the school of adaptive management, Seward et al., (2006) although they referred to groundwater discharge estimation methods, they showed that global or regional scale approaches are usually not suitable for implementing water laws or policies at a local scale. They concluded that through a process of public participation, location specific approaches should be selected and applied using adaptive management principles. Levy and Xu (2011) concluded that the application of adaptive management depends of the economic and human-resources constraints as well as social, economic and ecological importance of geographical specific locations. The two scholars also noted that adaptive management is a powerful tool which prepares for implementing resource directed measures (RDM). This is by ensuring that the allocation of groundwater use goes beyond the reserve needs and that the process becomes interactive where smaller areas are studied in greater details and all allocations are considered experimental (Levy & Xu, 2011). Holling (2005) highlighted similar sentiments. The sentiments in the above two paragraphs formed the basis of the current study as illustrated in chapter 8 where adaptive management practices have been presented in the case study. Local IWRM is about adaptive management of water resources.

However, for proper management of the groundwater resources, various data sets need to be collected at the appropriate temporal and spatial scales. For example, data on groundwater level, pumping rates, groundwater quality, precipitation, recharge, hydrogeologic characteristics, among others, are essential for various analyses on managing the groundwater resource. Lack of comprehensive groundwater data sets from the previous study to inform the current study is one of the weaknesses of the present study. However, this did not come as a surprise because several scholars (Xu & Braune, 2010; Lawford et al., 2003) observed that in many parts of the world groundwater data are either non-existence or unreliable if available or irregularly collected to provide adequate inventory of not only national status but even global groundwater reserves. Although MacDonald et al. (2012) have provided data base at continental level in terms of the quantified amount of groundwater in Africa, no centralized global groundwater database exists to enable comparative analysis on groundwater availability. This shortage of data set is partly explained by the complexity and expensiveness of the methods used to generate such data. Such a gap forms the basis for the current study to provide a methodology on generating groundwater data at catchment level as a starting point and the proposed methods can be refined with time.

3.6 Status on global assessment of groundwater resources

This section presents key findings from global assessment on groundwater that show factors that explain a) quantity of groundwater available to meet its demand and use; b) quality of groundwater for such use and c) available institutions to govern such water. The review discusses such findings in relation to the current study's objective which is to assess factors that limit wider and successful implementation of IWRM.

3.6.1 Groundwater quantity: Availability, demand and utilization

Most assessments of physical constraints on groundwater utility require quantification for each specific case of the two properties: First, potential yield which is defined as the yield of a commissioned source or groups of sources as constrained only by well or aquifer properties for specific conditions and demands (Beeson et al., 1997). Potential yield reflects physical limitation on groundwater availability with a focus on transmissivity (T) and storativity (S) of aquifer which determines the ability of aquifer to yield a certain volume of water to a pumping well. Younger (2007) citing Charles V Theis 1940 reported that availability of water in aquifer/well depends on a) increase in natural recharge; b) decrease in natural discharge and c) removal of stored water that does not lead to undesirable effects. Second is the deployable output which refers to abstraction of groundwater or output of commissioned source (s) or bulk water supply constrained by licence or water quality or environmental issues or water treatment or system capacity among other constraining socioeconomic or technological factors.

The discussion on factors that explain water availability in the aquifer has been contentious. For example, Todd (1980), Khan & Mawdsley (1988) use a modified version of safe yield concept when they talk of perennial yield and reliable yield concepts respectively to explain factors for available water in the aquifer. The concept of safe yield believes that availability of water in aquifer depends on predevelopment recharge rate. However, Bredehoeft et al. (1982) demonstrated that water available in aquifer has no relation to the safe yield concept. Although studies (Bredehoeft et al., 1982; Johnston, 1997 & Younger, 1998) disagree with the use of the safe yield concept in favour of the potential yield concept, Das Gupta & Onta (1997) and Clarke & King (2004) stated that in reality when establishing rules for aquifer management, the potential yield becomes one of the many constraints in addition to the safe yield. Since this study uses physical factors such as geology, topography and rainfall that have the potential to affect the quantity of water in aquifer and socioeconomic factors such as institutions, regulations and economic activities that affect demand and use of such water, the potential yield is preferred to highlight factors vital for water availability in aquifer that managers need to consider when implementing IWRM plans and practices to sustain water use in the catchment.

Global abstraction of groundwater grew from 150 km^3 in 1950 to 1,000 km^3 in 2000 with the bulk of this growth being in the agriculture sector mainly in Bangladesh, China, India, Iran, Pakistan and the USA. These countries accounted for 80% of global groundwater use (Shah et al., 2007). While millions of households in Africa and Asia are improving their livelihoods using groundwater resources, threats to depleting and polluting aquifers are on the increase due to this intensive utilization of groundwater resource (Shah et al., 2007; Xu & Usher, 2006). This situation implies that the existing management practices cannot be sustained with prevailing physical and socioeconomic factors unless alternative approaches to managing such resources in a sustainable manner are shown with full participation of the stakeholders at all levels.

Molden (2007) and Shah et al. (2007) in their assessments advised that such alternative approaches to sustainable groundwater management need to combine supply-side measures such as artificial recharge, aquifer recovery, interbasin transfer of water among others, with demand-side measures such as groundwater pricing, legal and regulatory control, water rights and withdrawal permits and promoting technologies that reduce water wasting. In several countries, supply-side measures have proved easier to implement than demand-side measures even in technologically advanced countries. However, depending on the prevailing physical and socioeconomic factors in most developing countries such as Malawi, not all these measures are immediately appropriate if they are approached from a formal water management perspective, hence the argument for local IWRM in this study which uses several aspects of adaptive management from the informal leading to the formal water management perspective.

The global intensive and largely unplanned groundwater utilization encounter several challenges because the push factors for groundwater use seems not abating (Molden, 2007). However, the long term sustainability of groundwater system is not easily understood by all stakeholders including managers. Therefore, to manage groundwater resources properly and identify effective management approaches that are urgent among the poorest societies such as Malawi, an improved understanding of local hydrogeologic environment (physical factors) need to be combined with an understanding of socioeconomic drivers for such intensive use for groundwater as this study argues.

3.6.2 Groundwater quality: Microbial and physicochemical status

In water assessment studies, the norm is to first establish that sufficient water exists to meet a given demand then assess suitability of such water for intended use. Although technologies exist worldwide to purify contaminated or polluted waters, such technologies are not cost effective to many countries such as Malawi. In general, groundwater has been free from pathogens although in some cases it requires minimal treatment before being used for human consumption (Adelana & MacDonald, 2008). Many groundwater sources are vulnerable to contaminants because typically such sources are not equipped to provide treatment for potential contaminants, hence the need to assess the quality of such water for drinking. Access to improved sources for drinking water has improved although access to safe sources for drinking water remains problematic (MDHS, 2010, Malawi-MDG, 2010; UNICEF & WHO, 2012). This study explores determinants for such a pattern in chapter 7 on groundwater quality.

The quality of water is assessed for different intended uses. For instance, water for agricultural use is assessed for salinity and toxicity of particular dissolved substances. The focus is effects of salts and toxins on crop growth and crop yield. Since the present study focuses on drinking water, analyses on salts and toxins in water for agricultural purposes are beyond the scope of the current study. In addition, reviews by Younger (2007) reveal that every industry has its own specific requirements on the quality of water for industrial use. Since this study is not on water for industrial use, such sector-specific guidance is beyond the scope of this study. Although groundwater has the potential to generate electricity for rural areas as reports by (Molden, 2007) show, in most cases surface water is used for hydropower generation. This research is not on water for energy hence such aspects are not stressed in this study which reviewed water for domestic purposes focusing on groundwater management from IWRM perspective.

The main concern for assessing groundwater supplies for domestic use such as drinking is the suitability for human consumption. The current WHO guideline (WHO, 2008) represents the closest approximation to worldwide standards for drinking water quality. However, many countries depending on local physical and socioeconomic circumstances developed their own guidelines and standards for drinking water. For example, Malawi Bureau of Standards (MBS) contains a checklist for elements of health significance in its drinking water quality standards for Malawi (MBS, 2005).

Most groundwater sources are relatively secure from gross contamination by pathogens. However, in shallow-gravel aquifers and where improper engineered works exist, contamination by pathogens is a possibility (Xu & Usher, 2006). Microbes such as bacteria, viruses and protozoa have the potential to cause diseases on people such as diarrhoea, gastroenteritis and dysentery. However, in surveillances of groundwater sources, the common method to assess microbial water quality is usually by testing for the presence or absence of easily detected organisms which indicate the presence of faecal contamination (Nielsen & Nielsen, 2007).

Usually the organism which is tested for is the bacterium *Escherichia Coli (E.coli).* Its presence provides conclusive evidence of recent faecal contamination. WHO (2008) recommends that *E.coli* should not be detectable in water intended for human consumption. Where possible, treatment system should ensure that no pathogens exist in the final drinking water for people. These are the guiding principles in this study for testing the quality of groundwater from sources and in selected households. The current study identifies determinants for drinking water quality so that effective management practices to protect drinking water should be explored and implemented collaboratively among key stakeholders in the study area. Key stakeholders in this study refer to water scientists, water developers/providers, water users and water managers. However, elimination of *E.coli* does not indicate absence of all pathogens such as viruses and protozoa which are more resistant to disinfection than *E.coli.* (Kresic, 2009). WHO (2009) suggests testing for more resistant microbes such as bacteriophages where high potential of water borne viral and parasitic diseases exist in local population. For this study area such diseases were not anticipated hence tests for *E.coli* were appropriate.

3.6.3 Groundwater regulations: Water laws and policies

Water management decisions and policies should have water laws as their fundamental basis (Todd & Mays, 2005). For example, water laws for surface water are different from groundwater in the USA and such laws have two basic functions: 1) to create private property rights in scarce resource and 2) to impose limitation on private use. Surface water laws follow principles of *riparian laws* which state that the right to use water is a real property but water itself is not a property of the landowner (Wehmhoefer, 1989). Management strategies for groundwater use the absolute dominion doctrine or doctrine of absolute ownership under the English common law which states that landowners have the right to abstract and use as they please unlimited amounts of groundwater lying beneath their land (John et al., 2007). These differences in legal principles explain the challenges and opportunities for managing groundwater from that IWRM perspective hence justifying the basis for the current study. IWRM calls for collaboration and coordination among stakeholders responsible for different resources.

The norm is for governments to create enabling environment whereby such governments as enablers rather than top-down managers, formulate national water policies and enact water resources legislations. Managing groundwater resources would require a policy as a guide and legislation as a management instrument/tool. In many countries, policies are easier formulated that enacting water resources legislations making enforcement difficult where the two are not updated at the same time. For example, Malawi uses the 1969 Water Act as water resources legislation because the 2009 Water Resources Bill is yet to be enacted (GoM, 2009). While the 2005 national water policy for Malawi contains elements of IWRM, the 1969 Water Act does not. Such a mismatch explains the legal difficulty to enforce water laws and the complication to implement the IWRM which requires creating Catchment Management Agencies. Creation of these institutions would require legal support which could be difficult in the absence of legislations reflecting IWRM. In this situation, the local IWRM serves as a remedy because it works even in absence of these legal requirements. This formed the basis for this study to show that local IWRM facilitates the full IWRM.

3.6.4 Groundwater institutions for good governance: Coordination & stakeholders

The communitarian model of groundwater management which resembles aspects of local IWRM was experimented in Mexico and Spain. It argues that organised and empowered groundwater users can mobilise their collective strength to monitor groundwater behaviour and protect the resource to ensure its long-term sustainability. So, groundwater user associations (GUA) to manage water at local level were formed based on the new mandate from the EU framework directive to protect groundwater. However, the model does not serve as a panacea to water management as no evidence exist to show how Mexico and Spain moved towards sustainability as GUA became defunct and water laws were widely bypassed (Shal et al., 2004).

Molden (2007) observed that cross-country analysis globally suggests that governing groundwater economy in a sustainable manner concerns not only hydrogeology of aquifers but also the larger political and social institutions of a country. How countries respond to the challenge of the sustainable management of groundwater depends on factors related to the context of each country. These factors can have a decisive impact on whether an approach that has worked in one country will work in another with a different context (Narayana & Scott, 2004). For example, key priorities in Sub-Saharan

Africa including Malawi are to develop groundwater for improving livelihoods of the people but in a regulated and planned manner. Comparatively, in most Asian countries key priorities are to develop effective means to regulate withdrawals and step up investments for groundwater management (Molden 2007). However, in all developing countries common key priorities remain improving database to understand groundwater supply and demand conditions to implement effective management strategies for sustainable utilization of the resource which is a challenge Lawford et al. (2003). This challenge gives credibility to this study which explores the coordination among key stakeholders by analysing the feasibility of local IWRM at community level. The aim is to show how groundwater users mobilise themselves to collaboratively manage their water for sustainable utilization when they become aware of long-term sustainability.

3.7 Summary

A proper understanding of IWRM is a key for managerial efficiency. Good management of water resources reduces costs to maintain the ecosystem that sustains water and has immediate and long term impact on sustainable utilization of the resource. The theoretical framework for this study is IWRM whose wider operation is shown to be limited. Groundwater management as part of IWRM continues to lag behind giving the basis to suggest implementing adaptive management which is also known as local IWRM. Introducing local IWRM requires prior knowledge about the evolution and role of the full IWRM concept in the international water policy which aimed at addressing broader developmental objectives. The reviewed literature has shown that the current status of IWRM globally has the potential to address both socioeconomic development and environmental goals but sustaining IWRM projects where they have been piloted shows slow progress. Again, current management approaches showed weaknesses due to legal and institutional principles that inform their operations. Hence, they cannot be utilized fully as management tools for water resources. The proposed local IWRM approach is a positive starting step towards a more holistic management. But lack of sustainable resources for its continual functioning will defeat its potential because usually national governments decentralise responsibilities only without the accompanying human-financial resources that facilitate successful IWRM operations.

Chapter 4: Research Methodology

4.1 Introduction

Chapter one has elaborated the main thesis, scope, problem, rationale and objectives of the current study whereas chapter 2 has assessed the prevailing situation of water resources management in Malawi in order to contextualise the thesis. Chapter 3 has reviewed the literature to show the global status of groundwater management and application of the IWRM approach. The current chapter describes the methods that were used to collect and analyse the needed data to answer the research questions set in chapter one thereby fulfilling the objectives for this study. This chapter argues that detailed description on i) research design; ii) methods for data collection and analysis and iii) ethical consideration are essential because they provide the basis for reliability and validity of the results of the present study for present and future researchers.

4.2 General Approach

The general approach to this study was a case study approach whereby Upper Limphasa River catchment in Northern Malawi was used. A comprehensive approach to understanding factors that limit IWRM was adopted with a focus on quantity, quality and governance of groundwater management from the IWRM perspective. The following procedures were implemented: i) Conducted a desk study, ii) Obtained an ethical clearance, iii) Research design, iv) Fieldwork activities and v) Analyses of data.

First, a desktop study was conducted on water resources management (WRM) and groundwater management. The literature review focused on IWRM in relation to groundwater quantity, quality and governance in Malawi, SADC region, Africa and the world. Literature showed progress and gap analysis in the field of IWRM and groundwater management as presented in chapters 2 and 3. Wentzel (2009) argues for fieldwork measurements because desktop studies provide low intensity information requirements which give low confidence. Nevertheless, desktop studies form the first step i) in planning informative research process and ii) in setting a clear theoretical framework (IWRM perspective) of the study as chapters 2 and 3 have shown.

The proposal was prepared and presented to the Senate Research Committee of the University of the Western Cape (UWC) which approved the methodology and the ethics of the current research project. Its registration number is 11/1/5. For details, refer to appendix. The aspects that were ethically considered are presented in section 4.5 of this chapter. The detailed design of this research is presented in section 4.3. Fieldwork activities and data analyses on fieldwork measurements and some laboratory work are presented in section 4.4. However, each result chapter carries a section on methods to elaborate analytical procedure and contextualise the discussion in that chapter.

4.3 Research design

4.3.1 Description of research design table

Table 4.1 presents research objectives, hypotheses and methods used to answer the two main research questions, namely: 1) What are the factors (local hydrogeologic and socioeconomic = LHSE) that explain limited implementation of IWRM approach? 2) How does groundwater management demonstrate the feasibility of the local IWRM?

Table 12: 4.1 Description of research design table

Research objectives	Research hypotheses (RH) & Research Questions (RQ)	Materials & methods (Methodology)
1. To illustrate how LHSE factors influence successful IWRM implementation using hydrogeologic conceptual model.	RH: LHSE factors have significant influence on implementing a successful IWRM approach. RQ: i) How do LHSE factors influence successful IWRM implementation? ii) What model can be used to assess influence of LHSE factors on successful IWRM implementation?	- Records review -Field observations -Field measurements -Geologic methods -Geomorphologic/ Classification methods - Analytical methods - Conceptual model
2. To demonstrate data generation procedure on groundwater demand and use in unmetered rural areas.	RH: Improve knowledge on calculating groundwater demand & use provides systematic procedure on data generation & forms basis to implement successful IWRM RQ: i) What steps are needed to generate data on demand & use of groundwater in unmetered rural areas? ii) How does data generating process act as tool to operate a successful IWRM? iii) How much water is abstracted from groundwater sources per day, week, month	- Field observations - Field measurements -Hydrocensus methods -Regression methods -Analytical approach -Conceptual model

	and year in the study sub-catchment? Iv) How much of the abstracted groundwater is used and unused at household and catchment levels per day, week, month and year in the study area?	
3.To assess groundwater quality for drinking from sources and selected households to explain determinants of such quality using RADWQ methods.	RH: Knowledge of potential sources for groundwater contaminants helps to develop practical measures on groundwater protection for drinking. RQ: i) What methods can be used to assess groundwater contaminants? ii) How reliable are groundwater sources for potable water supply in rural areas? iii) What major determinants explain groundwater quality in the study area?	- Field observations -Field measurements -Hydrocensus methods -DRASTIC methods -RADWQ methods -Correlation analysis -Colorimetric analysis
4.To demonstrate feasibility of local IWRM to facilitate successful implementation of IWRM approach using MUS analytical methods.	RH: Assessing application of IWRM principles of in groundwater management practices provide evidence on feasibility of local IWRM. RQ: i) Which IWRM principles practically work in local IWRM? ii) How can knowledge obtained from local IWRM be applied in full IWRM at catchment level and beyond the study area?	-MUS analytical methods

4.3.2 Type of study design

This research adopted a cross-sectional comparative (CSC) study design which is both descriptive and analytical in nature and was informed by i) limited implementation of IWRM as a problem with as focus on groundwater management, ii) lack of prior systematic data collection system and iii) limited time, financial and human resources for the study. In management studies, good description of the problem and identification of major contributing factors provide better information to take action (Varkervisser et al., 1991). Analytical approaches are apt to unravel management problems because their analyses determine the magnitude and direction of independent variables in a model such as regression analysis (Leedy, 1980). However, Yin (1984) recommends field measurements and experimental studies to reinforce results from analytical approaches before implementing interventions, which was done in section 4.4 of this chapter. CSC study design is quick to implement and inexpensive (Moser & Kalton, 1989). However, the number of stratifications is limited by the size of the study (Kidder & Ludd, 1987). To reduce effects of such limitation, a two-stage research design was used to sample two clusters in each of the eight study villages and then sampled two households in each of the selected cluster as explained in section 4.3.7 of this chapter. This sampling approach was modified from RADQW methods (WHO & UNICEF, 2010)

4.3.3 Description of and justification for studying in Upper Limphasa Catchment

The Upper Limphasa River Catchment, the study area, is located in Nkhata-Bay district of Northern Malawi as shown in Chapter 2. In the study area, water service delivery is done by i) Malawi Government through the Department of Water Development and ii) various Non-governmental organizations (NGOs). The main drinking water sources provided to people included a) boreholes, b) protected shallow wells and c) community stand pipe (NSO, 2009). This study focused on a) and b) groundwater sources.

The Department of Water Development follows standardized procedure on locating water-points as best management practice in water development for drinking. However, the practice is not enforced by all NGOs that are involved in water service delivery especially in rural areas (GoM, 2008c; Nkhata et al., 2009). This observation motivated this study to investigate reliability of such sources, effective use of water from such sources and associated governance for effective management of such waters. The aim was to provide information on health-water reform practices for improved human health. Some of the key questions for analysis on groundwater in Upper Limphasa Catchment were: 1. How can physical and socioeconomic factors that affect implementation of IWRM approach be assessed (chapter 5)? How much groundwater is available for people? How much groundwater do people need for their domestic use? How much do people actually use (Demand and use, chapter 6)? 2. Where does this groundwater come from (Recharge process, chapter 6)? 3. Is this groundwater reliable (Availability, Chapter 6)? 4. Is this groundwater sufficient to be distributed for different needs (Demand minus use, chapter 5 & chapter 6)? 5. Is this groundwater safe for people to drink (Quality, chapter 7)? 6. How is this water being managed currently

(Governance, chapter 8)? Answers to these questions aim to provide insights on why people should or should not manage their waters in integrated and a coordinated manner using local IWRM to ensure continuous supply and use of the water in the study area.

Fig.4.1 shows the entire Limphasa Catchment with agricultural activities (plantations) being located in the Lower Limphasa River catchment while no such activities exist in the Upper Limphasa River catchment. Such variation in socio-economic activities in the in the catchment has implication for water management between upstream and downstream dwellers. Limphasa River starts at the confluence where Luwawa to the west and Mwambazi to east meet (Fig.4.1). The sampled eight villages in the Upper Limphasa River catchment have Chikwina Trading Centre as their town seconded by Mpamba Trading Centre in the south on the M5 road which links Mzuzu City in the west and headquarters for Nkhata Bay District in the south east (Fig.4.1). There is Lake Malawi in the east of the entire catchment. Secondly, Fig.4.1 highlights the rural location of the study villages to nearby towns, although the road passing through such villages provides connectivity, a potential for development. Such locality has implications on how water scientists, water developers, water users and water managers would collaborate and coordinate their activities within the required IWRM approach.

The Upper Limphasa Catchment was chosen as a case study area because of: First, major socioeconomic activities such as Rice Scheme, Sugar Plantation, Rubber Plantation and Tea Estate (Fig.4.1) are all located in the Middle and Lower Limphasa River Catchment. Such activities have implications on water demand and use. Thus, knowledge on the factors and activities in the upper catchment that would have potential negative effects on quantity, quality and governance of water downstream were considered important for sustenance of environment and such socioeconomic activities. Secondly, strategically, the upper catchment was chosen as pilot study for future studies in the entire Limphasa Catchment as part of the research in the East Africa Rift Valley Floor on water resources; iii) Operationally, the site is closer to Mzuzu University (40 km) providing laboratory space for storage of water samples and accessories for sample equipments during fieldwork. It was envisaged that the study site would act as field school for water resources students at the Mzuzu University in the years to come. Thirdly, scientifically, and politically, the study wanted to generate data from areas that have lagged behind in terms of research activities. Traditionally, studies on water resources are conducted in central and southern regions of Malawi for various reasons including the aim to reduce operational expenses such as transport costs to research sites, among others. Comprehensive country-wide spatial analyses have been compromised as data from some districts are scanty. This study aimed at narrowing such a gap in data availability by implementing a systematic planned study on groundwater management in a non-researched area on such a subject. However, having previous data about the study area as benchmark for this study was problematic.

4.3.4 Justified study period

The study was scheduled to last for four years 2008-2011. The study commenced in 2008 with literature review and proposal development. In 2009 literature review continued to establish the gap in the field of IWRM and groundwater management. First, fieldwork took place in 2009 which focused on catchment demarcation, preliminary field measurements, hydrocensus and stakeholder consultations in the river catchment. In 2010, a systematic fieldwork was conducted focusing on main variables and key stakeholders for analysis to answer research questions. Preliminary findings resulted in two book chapters and one stakeholder guide by 2010 (Appendix-book chapters). Conferences and seminars were used to disseminate findings and obtain feedback to refine the interpretation on such study findings (Appendix-conferences).

As per study design, the fieldwork was conducted during the rainy season March-April in 2009 and March in 2010. The season was suitable for researchers to detect contaminants from groundwater sources i.e. boreholes and wells in households. Usually, households’ hygienic practices are compromised during the rainy season. With demanding farming activities in rural communities, this was the appropriate time to investigate groundwater demand, use and accessibility to such sources.

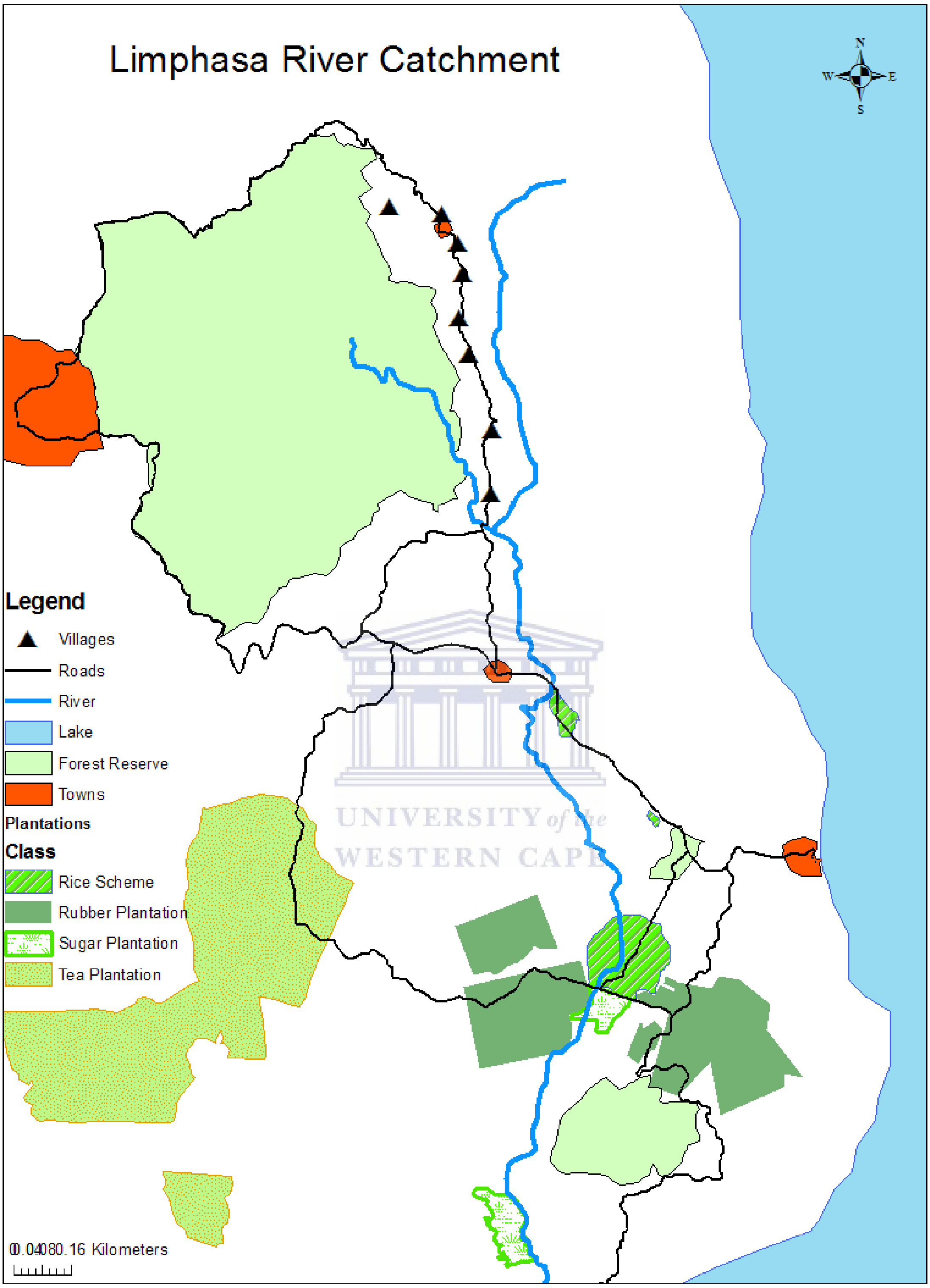


Figure 12: 4.1 Socioeconomic activities Upper and Lower Limphasa River Catchment

Water governance issues are crucial during this period as groundwater sources become the sole suppliers of potable drinking water. Since the study aimed at investigating groundwater management practices in communities, the rainy season provided suitable timing for such a research.

4.3.5 Study population/Unit of analysis (inclusion and exclusion criteria)

This section describes the unit of analysis in terms of reasons for what was studied and what was not studied (inclusion and exclusion criteria). Study variables included water, water sources, people, households, villages and sub-catchment. In terms of water, only groundwater sources were studied. Groundwater from all functioning boreholes and protected shallow wells were sampled and analysed for concentration levels of pathogenic bacteria and also analysed the physicochemical aspects to assess suitability of such water for drinking using different methods. In addition to groundwater from sources, drinking water drawn from groundwater sources, stored in sampled households was also studied. Water from non-groundwater sources was excluded from the study.

Water-point committee members of each groundwater source constituted study population and focus group discussions were held with them. Questions on management of water-points included: regulations for using such facilities; duties and responsibilities of committee members and all users; operations and maintenance of such facilities; participation during development of such facilities. Non-committee members of each water point were excluded from focus group discussions. In addition to water-point committee members, households' heads of sampled households also formed part of the study population. One household head preferably a female adult per sampled household was included in the hydrocensus as a study variable. The verbal informed consent was obtained first before an individual household questionnaire was administered. Because management of drinking water is more associated with female population, male and children were excluded.

Where the female head was unavailable for different reasons and where a child headed the sampled household (child-headed household) for various reasons then such males or children respectively became the study population after obtaining informed consent and assent respectively. Assents were obtained from village leaders for children aged below 18 but heading sampled households or were considered mature minors to consent (Leach et al., 1999; Molyneux et al., 2005). Household members at sampled household who were participating in collecting water from groundwater sources to households for various reasons were excluded from the current study as respondents to interviews.

Water sources and sampled households were units of analysis for the study. Only production boreholes and protected shallow wells were studied. Sampled households with visitors only or that drew their drinking water from surface water sources were replaced with nearby households with similar characteristics. All the eight villages in the Upper Limphasa River Catchment were studied. Clarifying the unit of analysis was considered crucial because it has implications on the analysis and interpretation of results (Dawson & Kass, 2005; Préziosi, 1997).

4.3.6 Levels of assessment and effects of analysis

Wentzel (2009) reports that in groundwater studies, four levels of assessment exist, namely, desktop, rapid, intermediate and comprehensive assessment levels. He summarises that a desktop study kick starts the research process and should not be bypassed as it provides background information that informs and builds the study. The rapid assessment level usually requires a short field trip of about two weeks to assess the present conditions of low impact and unstressed catchments. The intermediate level which requires medium confidence to assess implications of activities in relatively stressed catchment takes about two months. The comprehensive assessments take less than two years to complete and such assessments are based on site-specific data collected by specialists in order to produce high confidence results. However, Wentzel 2009) acknowledges the problems of long-term data sets on groundwater in many areas. The current study falls under desktop, rapid and intermediate assessment levels.

According to the precautionary principle, lower-confidence assessments require more conservative aspects than higher-confidence assessments. The needed level of confidence depends on i) the degree to which groundwater in the catchment is already used ii) the ecological sensitivity and importance of the catchment and iii) the nature, extent and probable impact of water uses for which groundwater assessment is being undertaken (Wentzel, 2009). In practice, methods of determination used do not necessarily coincide with the level of confidence of the results obtained. For example, where good baseline data exist to help define biophysical relationships, then a rapid assessment can produce results of high confidence. Similarly, where poor historical data exist, low confidence results will be obtained – irrespective of the time and cost of study. Therefore, it is incorrect to assume that the degree of confidence in the results would increase in direct proportion to the duration and cost of the study.

4.3.7 Sampling design and sample size calculation

According to rapid assessment for drinking water quality (RADWQ) methods, a two-stage sampling approach was applied (WHO&UNICEF, 2010). Two clusters were selected from each village. One cluster located near the source and the other located away from the source were sampled respectively in order to analyze determinants of groundwater demand, use and accessibility. From each cluster, two households were randomly sampled. Table 4.2 shows names of the study villages, total clusters versus sampled clusters, total households versus sampled households and groundwater sources. All 26 groundwater sources that were functional in the study areas were studied.

Table 13: 4.2 Sample size: Sampled households per village and per water-point

Village Name	Cluster	HH	WP	Sample Size			
				Cluster	%	HH	%
Upper Kango	27	42	2	4(2N;2F)	15	**8** (4N;4F)	10
Chisindilizi	45	173	2	4(2N;2F)	9	**8** (4N;4F)	5
Chaola	19	99	4	8(4N;4F)	42	**16** (8N;8F)	16
Kamphomombo	13	54	4	8(4N;4F)	62	**16** (8N;8F)	30
Chipaika	18	109	4	8(4N;4F)	44	**16** (8N;8F)	15
Chivuti	13	74	3	6(3N;3F)	46	**12** (6N;6F)	16
Kayuni	12	38	3	6(3N;3F)	50	**12** (6N;6F)	32
Mjutu	18	100	4	8(4N;4F)	44	**16** (8N;8F)	16
	165	689	**26**	52		**104**	

NB: N=Near water point; F=Far from water point; HH=household; WP=water point; 4hh per WP

Sample size calculation presents different options for the accuracy to be obtained for sample estimates. The accuracy for sample estimates is dependent on three factors: Distribution (form and variance) of the actual variable; the design of the sample (number of stages, stratification) and the sample size (Wold et al., 2005 & Howard, 2003). This study assumed approximately Gaussian (normal) distribution of the study population to serve as a proxy. The Gaussian approach requires a large sample size and set of prior assumptions. The calculation of accuracy is based upon a pure random sample which is not cost effective. Therefore, a two-stage approach was applied in conformity with RADWQ methods. A design effect of D=1.5 was assumed and to increase the sample size, a square root of a design effect (i.e. by √D) was taken. Therefore, the required sample size (**n)** was calculated from the following equation:

$$n = \sqrt{D} \times p(1-p) \times \left(\frac{Z_{\alpha/2}}{d} \right)^2$$

Where **D** is the design effect, the probability **p** of a certain variable being **1** is assumed to be 0.3, the tolerable error **d** = 0.01, 0.025, 0.05, 0.075 or 0.10 (see below), and where the normally distributed variable **z** has an accuracy of **α** which was set to 0.05.

$$n = \sqrt{1.5} \times 0.3(1-0.3) \times \left(\frac{1.96}{d} \right)^2$$

This sample size calculation was for net samples. Assuming a response rate of 95%, then the gross sample should be adjusted accordingly as follows:

$$n_{gross} = \frac{n}{0.95} = \sqrt{1.5} \times 0.3(1-0.3) \times \left(\frac{1.96}{d} \right)^2 \div 0.95$$

Using the above formula, alternative sample sizes may be calculated as follows at different levels of tolerable errors: 10 400 ≈ 10 404 at tolerable error of (±1%) d = 0.01; 1 664 ≈ 1 656 at tolerable error of (±2.5%,) d = 0.025; 416 ≈ 414 at tolerable error of (±5%) d=0.05; 185 ≈ 180 at tolerable error of (±7.5%) d = 0.075 and 104 ≈ 108 at tolerable error of (±10%) d = 0.10. The sample size for this study was 104 with an accuracy level of 10% tolerable error (Wold et al., 2005; Howard, 2003).

The above formula enable researchers to calculate the required sample size for the national, regional and district levels respectively and with different levels of accuracy expressed in percentages ±1%, ±2.5%, ±5%, ±7.5% and ±10% (Wold et al., 2005). The level of accuracy can be applied to the nation, region or district as a whole, or to sub-groups (by area, socio-economic groups). In this study, the level of accuracy has been calculated for sub-catchment level at 10%. This was suitable for this research because eight villages within the Upper Limphasa River catchment were studied.

4.4 Methods for data collection and analysis

This section describes methods that were used to collect and analyse data; discusses such methods to justify their choice for use in this study. The aim is to provide better understanding of the current situation and suggest feasible measures to protect groundwater. Such a present perspective approach was envisaged to yield more desired results. Hence, descriptive, correlation and predictive methods were suitable to generate data and improved knowledge to inform apt practices on utilization and management of water resources. Such an approach informed methods for data collection and analyses. The core assumption is that objective data-gathering techniques such as field measurements provide more accurate data than subjective techniques such as interviews (Leedy, 1980). Where interviews were used, checks and balances were provided to increase validity and reliability of such responses (Bryman & Cramer, 2001). Therefore, field measurements are given detailed description in section 4.4.3 of this chapter. Interviews with robust statistical clean up techniques were also used. To help synchronize results of the study from various data collection methods, a conceptual model for the catchment and a conceptual model of recharge process were developed and utilized in chapters 5 and 6. Such models enhanced illustrating groundwater status for management practices that should form basis for the IWRM approach at catchment.

4.4.1 Data collection methods

Data on local hydrogeologic environments, availability, demand, use, quality and governance of groundwater were collected from different sources using various techniques and following different procedures. Such data were presented in a workable format, analyzed and interpreted to give useful hydrologic characteristics of the study area. The following three major data collection methods were used to generate data:

i) Field measurements were carried out where water samples were collected from groundwater sources (Fig.4.2) and selected households for physicochemical and bacteriological analyses. Water demand and use were measured from sampled households. Distance from sampled households to water sources and potential sources of groundwater contaminants were measured using a measuring tape (Fig.4.2).

Figure 13: 4.2 Sampling water at source & measuring distance from water source

ii) Hydrocensus (interviews) was conducted with respondents from sampled households (Fig.4.3), water-point committee members (Fig.4.3) and selected key informants on water aspects as per attached questionnaire in the appendix. Interviews validate data that have been collected from records, observations and direct measurements although respondents sometimes over-report or underreport some aspects that are being asked. Nevertheless, the multiple methods adopted in this study, the trained research assistants, the strict supervision throughout the fieldwork period and the use of local language, *Chitonga*, used during hydrocensus enabled the accurate capturing of the information.

Figure 14: 4.3 Data collection using group and individual interviews

iii) The field observation method was used to collect data on water management practices at the sources and at sampled households, land use activities within the catchment, socioeconomic activities in the catchment and general characteristics in the study area. Cameras were used to collect such data which gave first hand information although people often change their behaviour when they are being observed weakening the strength of the observation method (Shapiro, 2007; Chaplowe & Scott, 2008).

4.4.2 Analytical data analysis methods

The water analysis process started in the field at the time of sample collection (chapter 7 has details). For laboratory analysis, to determine metals (cations) although the Atomic Absorption Spectrophotometry (ASS) is the most commonly used technique, Inductively Coupled Plasma (ICP), found in Bem Laboratory in Cape Town in South Africa which is one of the most modern laborites, was used. An ICP machine is the currently preferred option to ASS and it has major advantages over AAS in that it can i) analyze a large number of different elements at once; ii) achieve very low detection limits for most metals; and accommodate large numbers of samples per hour (Younger, 2007). Though an ICP is expensive for most academic research work whose budgets for analyses are usually limited, this study opted for ICP because of its capability to detect very low limits for most metals regardless of its expensive costs to run the analyses.

For the analysis of anions, this study used Ion Chromatography (IC) which is the most common analytical technique at present (Younger, 2007). IC is fast and easy to use for major anions and offers low detection limits for most compounds of interests in groundwater studies. Groundwater in the study area was assumed natural and unpolluted and since little or no analysis of organic compounds tends to be conducted on natural and unpolluted groundwater, organic analysis was not conducted (APHA, 1995).

4.4.3 Credibility of data analysis and interpretation of variables

To ensure that the analysed data were of sufficient quality for wider purposes, established internationally standard methods were followed as outlined in the American Public Health Association (APHA, 1995) for water quality objective whose details are presented in chapter 7. For objectives on quantity (availability, demand and use) and governance of groundwater, standard operating procedures (SOPs) as recommended on these aspects were used as outlined in the method sections in chapters 6 and 8. For physicochemical analysis, the charge balance between cations and anions was determined using Hydrogeochemical Analysis Model (HAM) in Excel (Kan & Xu, 1999; Kan et al., 2004). Younger (2007) states that the charge balance or the cation-anion balance (CAB) value of less than 5% are regarded sufficiently accurate for all uses and those between 5-15% warrant cautious use, while those greater than 15% cannot be justified as reliable for serious scientific purposes. The observed charge balance for most locations 74% (17 out of 23) in this study was less than 5% which is regarded very accurate and almost all locations 96% (22 out of 23) their CAB value was between 5-15% which is acceptable. BH 17 called Chisindilizi-Vwiyapo BH in Chisindilizi Village (Thanula area) located at (X=629452; Y=8732450) has the outlier CAB value of 29.29%. Samples that were more than 5% have high HCO_3^- concentration suggesting errors in titration including BH 17. The analysis showed that 74% of data are below 5% of ionic balance error range while 96% are within the ±5-15% range. These results agreed with suggestions of Younger (2007) on the use of CAB in the analysis.

4.4.4 RADWQ, DRASTIC, Statistical and related analytical methods

In chapter 5, three methods were used to generate and analyse data. The first method was geologic methods. Regardless of their weaknesses, their strengths outweighed their weaknesses hence adopted in this study. The second method was hydrogeologic conceptual model of the study area. Conceptual models used in this thesis were developed using the 2006-Graphisoft ArchiCAD version 10, A Virtual Building Solution Software. The hydrogeologic conceptual model presented in chapter 5, is the first model developed for this catchment hence it is considered to be among the major contribution of this study to the future studies on groundwater resources in the catchment. All maps used in this thesis unless referenced, were generated for this study using ArchGIS Software (ArcMap version 9.3). These maps were georeferenced from both geologic and topographic maps (Bloomfield, 1966; Hopkins, 1973; GoM, 1984). The third method was analytical analysis on precautionary and benefit sharing principles in managing water resources in the catchment from IWRM perspective using insights provided by the hydrogeologic conceptual model on storage capacity and flow pattern of groundwater in relation to land-based features and activities in the catchment.

In Chapter 6, the conceptual model of recharge process was used as an analytical method to analyse the expected availability of groundwater in the study area by assessing physical and socioeconomic factors with potential to accelerate or impede the recharge process. The weakness of this approach is that quantitative recharge estimates are not provided either in terms of amount of annual precipitation or percentage of recharge from annual precipitation. However, the qualitative insights provided on expected groundwater availability are adequate to improve understanding and coordination among scientists, developers, users and managers of water resources to implement IWRM to protect water for sustainable utilization. The weaknesses and strength of all conceptual models and justification of using conceptual models in groundwater studies are provided in chapter 6.

In chapter 7, methods that have been used to analyse the quality of drinking water from groundwater sources include a) The Rapid Assessment of Drinking Water Quality (RADWQ): RADWQ method has the following weaknesses: i) it requires detailed sampling procedure, large sample size and focuses only on improved water sources (WHO&UNICEF, 2010) neglecting those that use unimproved water sources. However, RADWQ is cost effective as it encourages rapid procedure with the use of field testing methods (WHO & UNICEF, 2010). Furthermore, the method provides statistical representative snapshot on the status of the drinking water quality in terms of i) compliance to WHO guidelines and national standards, ii) assessing sanitary risk factors to water sources and iii) analysing proxy indicator of risk-to-health for the households that draw drinking water from the studied sources. Such a focus on critical and limited range of health relevant parameters provides the baseline information for i) building national surveillance, ii) implementing routine monitoring activities and iii) providing prevention interventions (WHO & UNICEF, 2010 & Schmoll, 2009). Since this study aimed at assessing factors that explain the quality of water resources for effective management in a coordinated manner, these positive aspects of RADWQ methods were appropriate to be used in this current study (Nielsen & Nielsen, 2007).

Another method that was used to assess the vulnerability of groundwater sources for drinking was the DRASTIC method developed by Aller et al., 1987). DRASTIC stands for **D**epth to water, Net **R**echarge, **A**quifer materials, **S**oil, **T**opographic Slope, **I**mpact of vadose zone, Hydraulic **C**onductivity of aquifer. DRASTIC was used in this study because i) it is a widely-used approach for assessing aquifer vulnerability to contamination, ii) it complements RADWQ methods by assessing factors that RADWQ through sanitary inspection technique fails to capture, iii) DRASTIC offers a rough management tool in lieu of more detailed hydrogeologic investigation.

However, the DRASTIC method is expensive because it is data intensive and the method was designed to assess aquifer vulnerability on a large regional area therefore downscaling such a method to a sub-catchment or catchment area might pose some limitations in the interpretation of the data. This weakness was overcome by using different methods to triangulate results on the quality of groundwater and possible explanation for such observed quality as elaborated in Chapter 7. A third method and fourth method were correlation and colorimetric analytical methods whose details on their strengths and weaknesses and why such methods were chosen for this study are provided in respective sections of chapter 7.

4.5 Ethical consideration

Globally accepted codes of conducts in research activities that have implications on human health are provided by (Belmont Report, 1979; WHO, 2008; CIOMS & WHO, 2002) among others. From such review, five major ethical aspects were considered: a) informed consent; b) risks to the subjects; c) adequate protection against risks; d) potential benefits; e) importance of knowledge as described in the following sections:

4.5.1 Informed consent

To ensure that study population participated voluntarily in the hydrocensus, informed consent was obtained from participating adults at sampled households i) to collect water samples from their stored containers for bacteria, chlorine and physical parameters analysis; ii) to administer individual household interviews using questionnaires and iii) from water-point committee members to hold focus group discussions on water management. The consent was obtained verbally. Study objectives and procedure for testing water and conducting interviews were explained during village meetings prior to fieldwork. Before going to the study villages, meetings were held with officers at the district head office to obtain permission to work in the district and in turn similar meetings were held in each village with Village Head Leaders for assent to work in the sampled villages as recommended by (Leach et al., 1999 & Préziosi, 1997).

4.5.2 Risks to the subjects

The Upper Limphasa River catchment located in one of the rural areas in Northern Malawi was used as case study to show how to assess availability, demand, use, quality and governance of groundwater for drinking as a starting point for wider operation of the IWRM approach. It was anticipated that people in the study villages would be suspicious of researchers sampling their drinking water hence, the meetings to clarify the study objectives and procedure before water sampling started. It was also anticipated that participants might be uncooperative due to experience in previous studies (Dawson & Kass, 2005). Among the anticipated risks to subjects were talking to strangers (researchers) and suspicions of what strangers would do with their water. These anticipated risks to subjects were considered and clarifications were provided.

4.5.3 Adequate protection against risks

The meetings with officers at the district head office, village leaders, community members in the study villages before hydrocensus and fieldwork measurements were conducted to i) minimize risks to individuals, community and researchers; and ii) clarify fears and expectations and iii) seek collaboration during and after research period. Preliminary findings while in the field were not disclosed to community members to avoid scaring people and raising false hope. Although names of informants were delinked from datasets, key identifiers for the sampled households were kept for future follow up after this initial study and also to provide reliability about sources of analysed data (Leach et al. 1999; Molyneux et al., 2005; Préziosi, 1997; Dawson & Kass, 2005).

4.5.4 Potential benefits to subjects

Some members of the communities who worked as tour guides were trained on some aspects of the study such as water sampling and measuring distances (Fig.4.2). This was partially providing data collection skills to members of the community for continued local IWRM. In addition, community members were provided with free transport service using the project vehicle during fieldwork campaigns. Researchers bought foods and rented houses in the study area as one way of providing monetary benefits to the community (Tindana et al., 2007). After the fieldwork, local people who worked as tour guides to water sources and respondents to individual household interviews were given a small amount of money as a token of appreciation for their time and contribution. For focus group discussion members, soft drinks and snacks were bought and shared as discussions proceeded. Another benefit was transport. For instance, during the fieldwork period, when a sampled household member or a tour-guide or a water-point committee member became ill, the project provided transport for free to the patient to seek treatment from the nearby health facility visitation (Tindana et al., 2007).

4.5.5 Importance of knowledge

Meetings with community members and focus group discussions that were held with water-point committee members provided them with knowledge on water management. Their active involvement through interviews and field measurements (tour-guides) to provide information demonstrated the opportunity of using local community members to collect data on groundwater parameters as they also gain knowledge in the process. With support from water experts, such an approach would ensure data availability and accessibility on local hydrogeologic environment that would in turn provide a basis to start improving understanding on groundwater system (quality, water levels and local practices) leading to improved analysis on groundwater system for effective planning and management for water development in rural areas (Tindana et al., 2007; Molyneux et al., 2005; Préziosi, 1997). Through fieldwork campaigns, researchers gained knowledge from the community on various aspects that enhanced data interpretation.

4.6 Limitation of the study

Firstly, lack of previous studies in the study catchment on similar topic and approach inhibited the detailed analysis on benchmarks about water resources management especially groundwater resources. Data on hydrogeology, water level, quality and governance of groundwater were scanty and inaccessible to inform the evidence-based gap that the current study would have built on. However, the development of the hydrogeologic conceptual model for the entire catchment and for the upper catchment on contaminants coupled with field measurements provided an essential starting point for further detailed studies on water resources management especially groundwater.

Secondly, since this study followed a case study approach, results may not represent the same situation nationally, regionally and even globally. However, the research design and the approach followed to collect and analyse data, and results obtained provided useful insights on factors that limited IWRM execution. Such insights formed a justified basis for proposing the implementation of the local IWRM approach at local scale.

Thirdly, the limited available resources such as finances and time for the study limited the yearly data collection on various aspects of groundwater that would have enabled trend analysis on such water resources to inform appropriate intervention. Nevertheless, the approach and research design adopted for this study led to the generation of the data that provided the most key noteworthy insights into the science and management practices of groundwater resources in the area that need nurturing.

4.7 Summary

Chapter 4 has described the general approach used in this study in terms of research design, data collection methods, data analysis methods, ethical consideration and limitation of the study within the context of water resource management. Since chapter 1 sets the thesis for the study with its scope, objectives and research questions, the second chapter provided the prevailing situation about water resource management in Malawi to contextualise the thesis. Thereafter, chapter 3 provided the global status of water resources management highlighting the globally agreed principles of IWRM that underpin management of water resources with a focus on the status of IWRM and groundwater management globally and in Malawi. Chapters 5, 6, 7 and 8 present and discuss the evidence for the argued thesis in the present study. Details on the method used to answer each research question are provided in each chapter where objectives are fulfilled. Each chapter contains a brief introduction, relevant literature review relevant to that objective to guide discussion of the results in the pursuit of contributing knowledge in the field of groundwater management from IWRM perspective. The results presented and discussed in each chapter are generated in the Upper Limphasa River catchment and where discussion has referred to results from other studies, references are made. Each chapter ends with a summary section to highlight key results in that chapter and to notify what comes in the next chapter so that the link between chapters is provided.

Chapter 5: Local Hydrogeologic Environment

5.1 Introduction

This chapter presents and discusses results on objective 1 which aimed at developing a hydrogeologic conceptual model to show how local hydrogeologic and socioeconomic factors influence a successful execution of IWRM. The chapter describes groundwater systems in terms of flow direction by using maps, field observation and measured data on geologic, geomorphologic and hydrogeologic settings of the Upper Limphasa River catchment. To assess factors that explain the limited and unsuccessful operation of the IWRM approach, the hydrogeologic conceptual model is developed for the entire Limphasa River catchment where interactions and relationships among the physical and socioeconomic factors are conceptually shown and explained. Lastly, the chapter shows implications of the hydrogeologic conceptual model for managing water resources from the IWRM perspective. Arguments in this chapter are that i) interactions between and among physical and socioeconomic factors in the catchment need to be understood in terms of their influence on managing water resources; and ii) hydrogeologic conceptual model is important as an interactive visual tool to show interactions, flow directions of surface water and groundwater that assist in guiding the assessment, planning and executing a successful IWRM at catchment level.

Despite such a model being largely descriptive in nature, it provides a basis for numerical modelling which has the capacity to quantitatively estimate the effects of some of the interactions among physical and socioeconomic variables in the catchment (Younger, 2007). However, the conceptual model developed in this study provides scientific, pragmatic and cost effective visual presentation of the scenario on the ground which is easily understood among key stakeholders to lobby for a successful operation of the IWRM in the catchment. This chapter fulfils the first objective of the present study which aimed at developing a hydrogeologic model for the first time for the Limphasa River catchment to assess factors that explain limited and unsuccessful operation of IWRM approach. It contributes to the general objective of the current study on improving understanding of local hydrogeologic and socioeconomic factors that influence successful execution of IWRM. In this study, key stakeholders refer to water scientists, water users, water developers and water managers.

5.2 Methods used

A comprehensive approach to understanding factors that limit successful execution of IWRM was adopted using the conceptual model of local hydrogeology which was developed for the entire Limphasa River catchment showing land-based resources as well as groundwater flow direction with its associated features (Fig 5.9). Although the study did not quantify effects of human modification of landscape on quantity, quality and governance of groundwater resources, the conceptual model qualitatively illustrated implications of interactions and relationships among subsurface and surface selected parameters on IWRM implementation. In this chapter, geologic methods and field observations were largely used although remote sensing and geophysical methods which are commonly used in similar studies could have provided a more robust analysis (Todd & Mays, 2005; Health et al., 2000; Keys, 1989). However, the present analysis provides a starting point for a holistic management approach for water resources.

Geologic methods that involve interpretation of geologic data and field observation represent an important first step in groundwater studies with supplementary use of the remote sensing satellite images as one of the effective tools to enhance understanding on groundwater conditions (Health et al., 2000; Keys, 1989). Geophysical methods such as electrical resistivity and seismic refraction techniques are commonly used but they only provide indirect indications of groundwater conditions (Todd & Mays, 2005) hence their exclusion in this study. Nevertheless, a complete correct interpretation on groundwater conditions requires additional data from subsurface investigations such as aquifer characteristics which was beyond the scope of this research. But such additional data could have substantiated the observed findings in chapters 6 and 7 of this study as an initial research work. Again, such data could have strengthened the present analysis.

However, the advantage of using the geologic method is that a large area is studied rapidly and economically on a preliminary basis in relation to its potential for water development (Todd & Mays, 2005). Records such as geologic maps, topographic maps and aerial photographs are used as sources of data in addition to field observations and field measurements. Geologic history, formation of rock types, depositional events and thickness of overlying beds provide the basis to assess water-bearing formations and estimates of drilling depths (Delleur, 2007). Again, faults that may form impermeable barriers to subsurface flow usually are mapped from surface traces and landform often reveals near-surface unconsolidated formation that serve as aquifers (Delleur, 2007). In addition, using geologic methods, the relationship between geology and groundwater is well understood in terms of occurrence, movement and storage capacity. Thus, quantity and quality of groundwater can be deduced from geologic materials where such water flows and resides. However, the need to supplement geologic methods with more advanced methods such as remote sensing and geophysical explorations methods for a more accurate interpretation of groundwater system has been well studied (Todd & Mays, 2005; Delleur, 2007; Kresic, 2009) though the use of such methods was beyond the scope of the current study, hence their exclusion.

This chapter reaffirms that a thorough understanding of the hydrogeologic as well as socioeconomic environment of the study area is a key requirement to implementing a successful IWRM approach in a particular river catchment. Because of such a claim, this study through the use of maps analysed the geology, hydrogeology, landform characteristics as well as field observations on the land-based socioeconomic activities (Fig. 5.9). The assumption was that such physical factors and human modification of the landscape influence the quantity, quality and governance of the water resources thereby impacting on the management approaches of water. Literature was reviewed to provide supporting evidence on such effects in other areas of the similar environment.

To assess factors that explain limited and unsuccessful IWRM execution at catchment level, the role of geologic, hydrogeologic, geomorphologic settings were examined in terms of their influence on groundwater flow direction. The assumption was that knowledge on flow direction on both groundwater and surface water would enforce collaborative management practices between upstream and downstream dwellers. The upstream dwellers settle on the recharge areas for groundwater and sources of surface water while the downstream dwellers settle in the discharge zone of groundwater and in the flood plain of surface water. The influence of human interaction with land-based resources either in upstream or downstream areas have implications on water resources management (Section 5.5; Fig 5.9). The influence of geologic, hydrogeologic, geomorphologic settings on groundwater availability (quantity) was examined and results are presented and discussed in chapter 6 in terms of implications for IWRM.

5.3 Role of geologic setting on effective water management

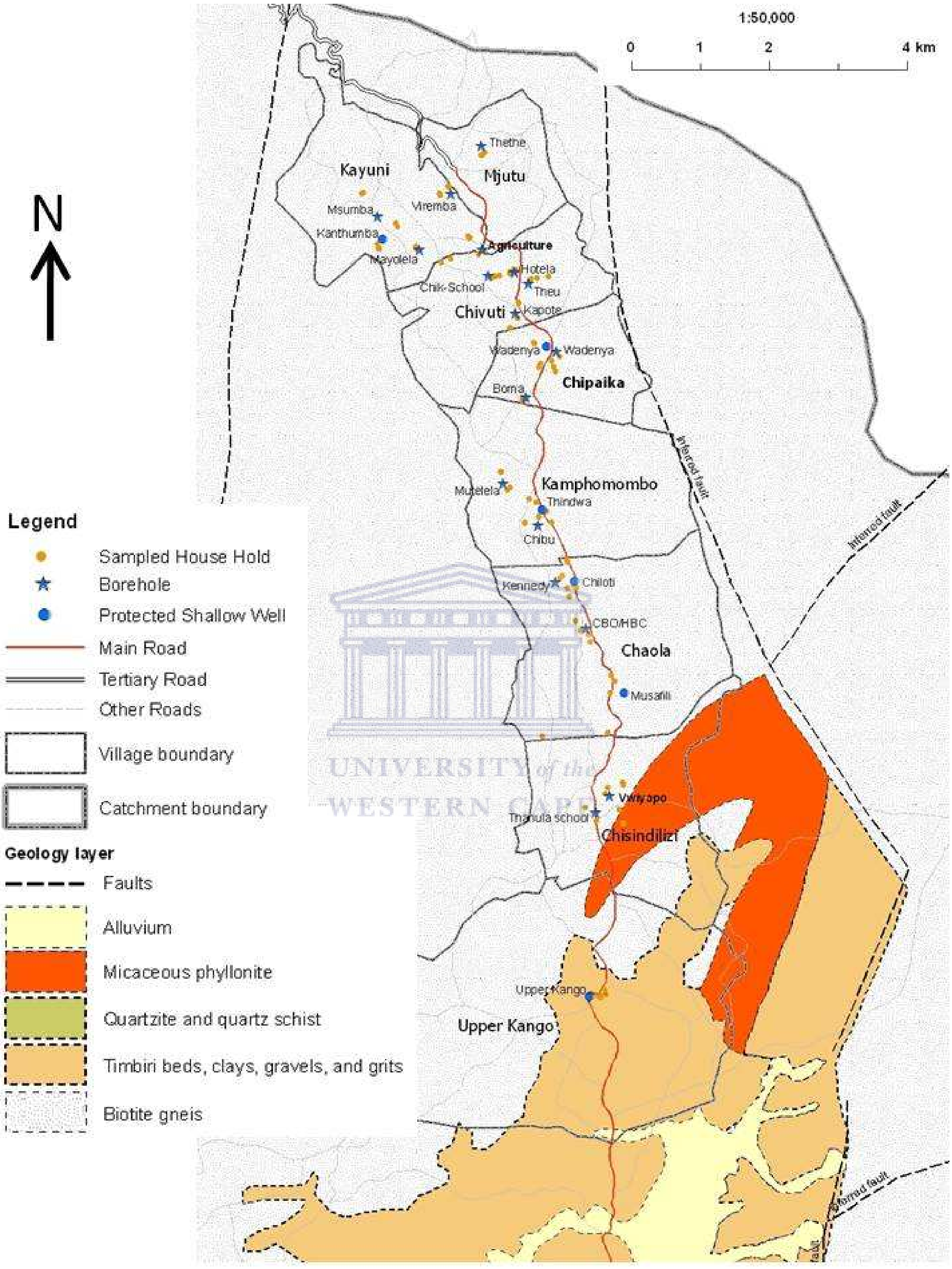


Figure 15: 5.1 The role of geologic settings on water management

5.3.1 The role of geologic setting on groundwater management

The knowledge of rock types facilitates understanding of regional and local hydrogeologic context of groundwater in catchments (Carter & Bennett, 1973). About 80% of Malawi is underlain by crystalline metamorphic and igneous rocks of Precambrian to Lower Palaeozoic age, commonly known as Basement Complex which is a tectonically stable shield area such as gneiss (GoM-UNDP, 1986). Chapter 2 has provided details on the geology of Malawi in general. Nevertheless, Carter & Bennett, (1973) re-emphasized the importance of proper knowledge on lithological and structural variations of rock types because such geologic features control the occurrences, movement, quality, availability of groundwater resources, among other factors.

Understanding geologic units in the study sites improves knowledge on pathways for the available water and contaminants in groundwater systems (Younger, 2007). Delleur (2007) advised that water management especially groundwater improves when the following geologic parameters are assessed: limits of aquifers; limits of confining units; presence of interconnections between aquifers; anisotropies in the aquifer materials and presence of discontinuities such as fractures on small scale and faults on large scale. Based on field observations, geologic maps and geologic reports by (Hopkins, 1973; Carter & Bennett, 1973), the geology of the Upper Limphasa River catchment revealed to have the following: 1) Fractures that included joints and faults (Fig. 5.1) ; 2) Fracture traces or lineaments that consisted of topographic, vegetation, soil-tonal alignments that were visible on aerial photograph (Fig. 5.2); and 3) Fracture traces that were abundant and had North-South and East-West strikes which gave rise to blocks that were throwing eastwards and westwards into the study area. Major fractures when expressed topographically are called fracture traces or lineaments (Fulton et al., 2005).

The findings on geologic settings showed that the Upper Limphasa River catchment is underlain by Basement Complex which leads to fractured hard rock aquifer with limited groundwater storage capacity. Secondly, the topographic nature and north-south strikes of the lineaments (Figs. 5.2 & 5.1) explain the north-south groundwater flow direction. Heterogeneity in basement complex is common hence generalisation is not possible. However, detailed site specific versus regional characterization need to be conducted because locating traces is important as wells drilled on fracture traces produce higher yields than those drilled off traces (Freeze & Cherry, 1979; Kresic, 2009).

5.3.2 Influence of hydrogeochemical information on groundwater management

Waters in aquifers react chemically with geologic media and several types of such chemical reactions are common in aquifers including sorption, chelation, complexation, ion exchange, precipitation /dissolution and hydrolysis (Delleur, 2007). Details on each type of these reactions are beyond the scope of this study. However, understanding the characterization of hydrogeochemical properties of the aquifer materials is important when assessing the quality of groundwater for different purposes including drinking (Younger, 2007). On the basis of field measurements that were used to collect data on the physicochemical parameters of groundwater, the Piper Graphical Diagram as a classification methods was used to i) identify dominant types of groundwater, ii) characterise chemical composition in groundwater and iii) analyse and interpret groundwater flow systems (Weight, 2008; Younger, 2007, Todd & Mays, 2005;). The analysis showed that groundwater flow direction in the Upper Limphasa River catchment was north-south direction (Chapter 7, Section 7.3.1; Fig. 7.1).

5.4 Role of geomorphology on successful water management

5.4.1 Estimating direction of groundwater flows with geomorphologic features

Features of geomorphology such as topography provide a plausible indicator of estimated direction of groundwater flows in aquifers in addition to influencing groundwater availability through the recharge process (Younger, 2007; Todd & Mays, 2005). The Upper Limphasa River catchment in Fig. 5.2 is slanting north-south direction and is situated in the mountainous area with altitude that ranges from 586 m to 1122 m above sea level (asl). To the north of the study area there is a highland that separates Ruvuo River and Limphasa River catchments. The watershed starts slightly above from Kayuni Village (1122 m asl) and Mjutu Village (1103 m asl) (Fig.5.2) passing through Viremba Borehole (X: 627136; Y: 8741198) to Manje Hills. To the south lies a lowland area, the Limphasa valley known as Limphasa Dambo is located in the south shortly after Upper Kango Village (586 m asl) (Fig.5.2). The Kandoli and Kaning'ina Mountains are located in the east and west respectively (Fig.5.2). Several spurs and v-valleys exist within the study area (Fig.5.2). From the description of the study area based on Fig. 5.2 and field observations, it can be deduced that the local groundwater flows in the aquifers of Upper Limphasa River catchment follow the north-south direction. The methodology used in this study is similar to the one used by De Vries & Simmers (2002) when they assessed groundwater flow pattern in Botswana between the Kalahari sands and adjoining Precambrian hard rock area showed to have been influenced by geomorphologic features. The Upper Limphasa River catchment is also underlain by basement complex of the Precambrian to lower Palaeozoic hard rock making deductions in this study rational. Toth (1963) demonstrated the impact of topography on local and regional groundwater flow paths where it was concluded that understanding the role of geomorphology contributes to a better grasp of groundwater flow systems.

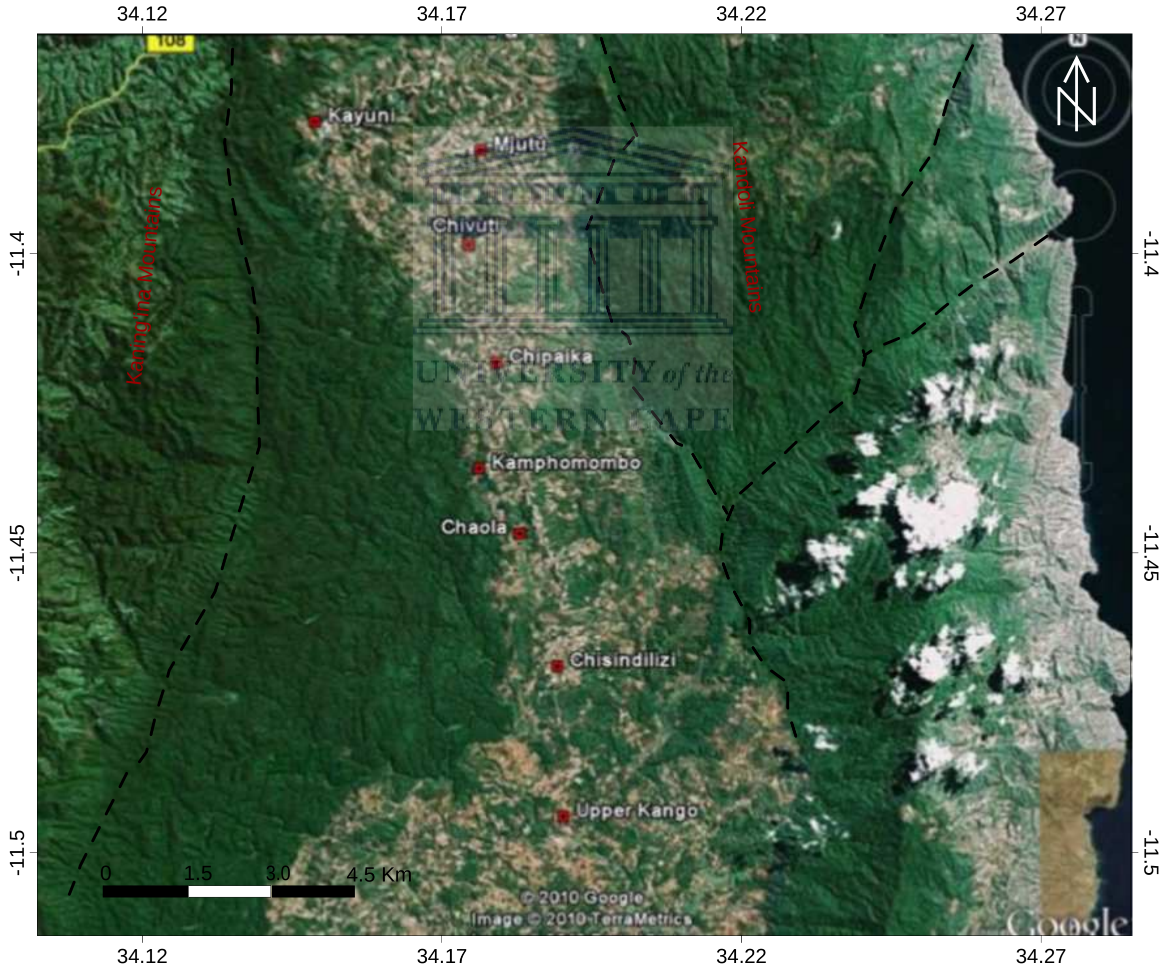


Figure 16: 5.2 The Influence of geomorphologic features on groundwater flow system

5.4.2 Influence of potentiometric surface information on groundwater flow path

Knowledge on elevation of potentiometric surface improves understanding on the direction of groundwater flow in the catchment. Such information facilitates the understanding on whether or not the aquifer system is unconfined, confined or perched. Elevation of groundwater potentiomentric surface is assessed by measuring depth to groundwater at several locations, calculating elevation of groundwater at each location and then interpolating contours of groundwater elevation for the study area. The aim is to obtain potentiometric surface information for the uppermost aquifer or underlying aquifer that could be interconnected or not connected with the uppermost aquifer and could be impacted by a release from potential source (Delleur, 2007).

Although depths to groundwater were not measured, field measurements and field observations showed that elevation data for water sources ranged from 599 m to 1093 m above sea level for protected shallow well at Upper Kango and borehole at Mayolela respectively. The depths for protected shallow wells ranged from 3.0m to 55 m and for boreholes it ranged from 40 m to72 m. For slope, the percentage ranged from 8-53% with protected shallow wells being located at steeper slope of 35-53% while borehole had a slope of 8-35% and only one borehole at Mayolela had a slope of 38%. The land form characteristics have the potential to explain local groundwater flow direction thereby providing a crude qualitative indicator on potentiometric surface information in the study catchment. Details of these statistics are presented in Table 7.4.

The alternative approach is to understand the depth of water table in unconfined and confined aquifer systems. For example, Wu (2005) reported that as the depth to groundwater increases, the potential for rainfall to percolate to the saturated zone decreases suggesting that recharge to groundwater is expected to be less if the water table is deep and higher when water tables are shallow. This implies that when the water table is shallow, infiltration reaches the saturated zone fairly fast for the individual rainfall event to correspond to isolated infiltration events with small time lag (Wu (2005). Based on field measurements data presented in Table 7.4 and the conceptual model of recharge process (Fig.6.1), results appeared rational in showing that the Upper Limphasa River catchment has two aquifer systems, the shallow and the deeper system (Fig.6.1). Calculations showed that the average depth for the shallow aquifer system where protected shallow dug well abstracted water was 3.8 m whereas the deeper system for boreholes was 53m (Table 7.4). Although these results are not conclusive, but useful insights are provided on water flows in terms of which aquifer system is more prone to contamination than the other; and which aquifer system receives and loses water quicker than the other in rainy or dry season (Fig.6.1). That information is required for sharing with key stakeholders for lobbying the implementation of management practices that require collaborative efforts among such stakeholders.

5.5 Influence of landscape-human modifications on water management

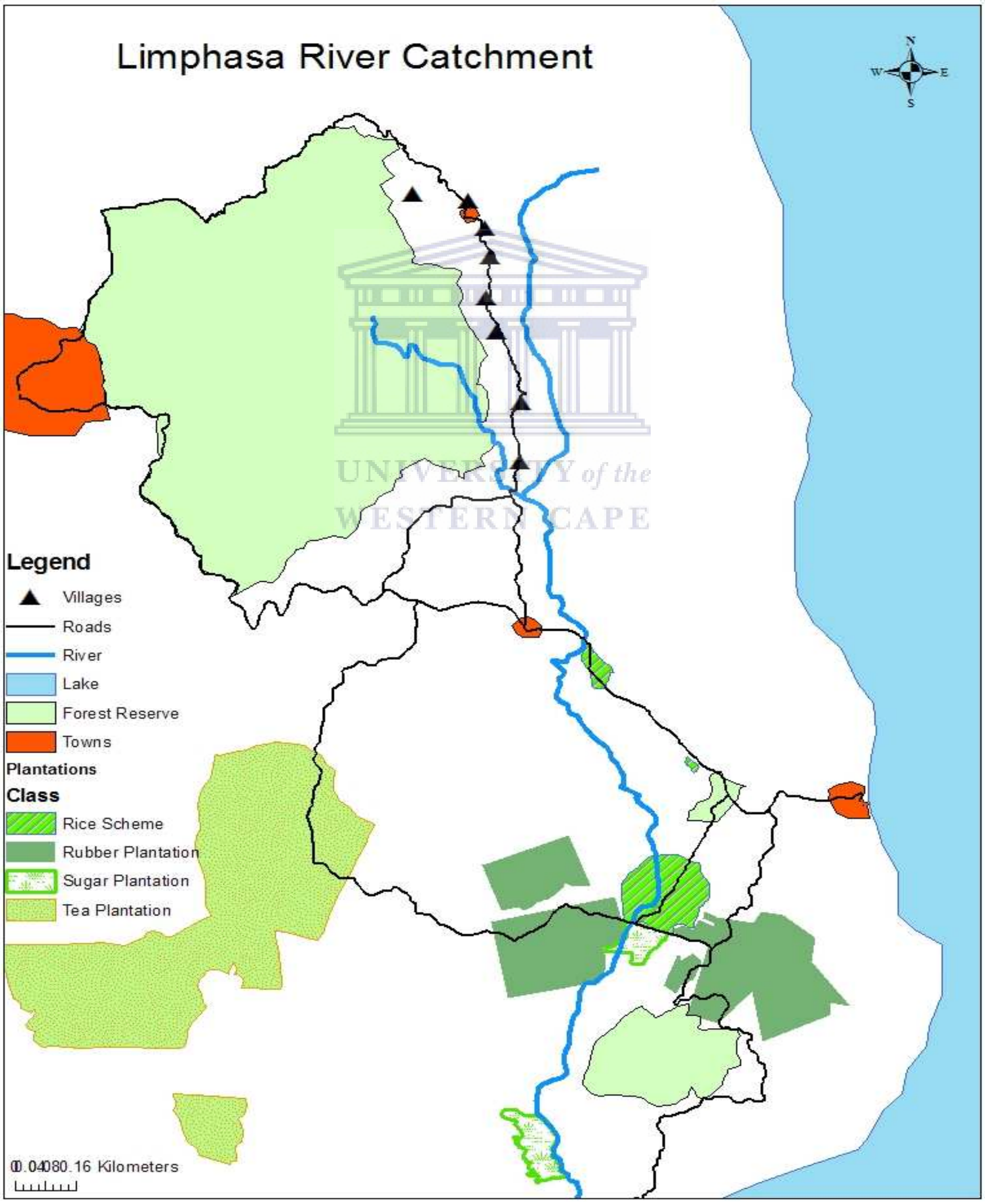


Figure 17: 5.3 Land-based socioeconomic activities the entire Limphasa River catchment

Fig 5.3 showed that major land-based socioeconomic activities were located in the Lower Limphasa River Catchment. In the Upper Limphasa River catchment, only subsistence farming was observed where gardens for cassava, maize, bananas and coffee existed (Fig.5.4). Chemical fertilizers and herbicides in crops were not reported and physicochemical analysis on water samples in chapter 7 confirmed such reports. For example, concentration for nitrate values ranged 0.0-0.90 mg/l (Table.7.1) although the study area was densely vegetative (Fig. 5. 2). However, hill tops were observed to have been cleared for maize growing where hydrocensus results showed that maize was used as a cash crop at household levels. Thus, the Upper Limphasa River catchment which is the recharge region for groundwater and headstream for surface water had fewer land-based activities for potential pollution effects compared to Lower Limphasa catchment (Fig.5.3). This observation has implications for managing the quantity and quality of waters flowing downstream to service agricultural activities and the ecosystem.

Figure 18: 5.4 Subsistence agricultural activities in Upper Limphasa River Catchment

Fig 5.3 showed that the major land-based activities such as commercial agricultural activities were practiced in the Lower Limphasa River catchment as follows: i) Limphasa Rice Scheme and ii) Limphasa Sugar Plantation were operating in the Limphasa Valley also known as Limphasa Dambo whereas iii) Vizara Rubber Plantation and iv) Kawalazi Tea Plantation were operating adjacent to the Limphasa Valley. The present study, using field observations, focused on water use, waste disposal, chemical application and land clearing for these plantations. The discussion focused on implications for water management and how benefits from such plantations were being shared with communities where such plantations operate and communities in the Upper Limphasa catchment who are expected to protect i) recharge areas for groundwater feeding surface waters and ii) headstreams as sources of surface water for such water to be used in plantations located in the Lower Limphasa River catchment.

Field observations showed that plantations located in the Lower Limphasa River catchment depend on water from Limphasa River and its tributaries such as Luwawa, Mwambazi, Lwazi, Liskaska, Limambaza, Nkhwali, Lilezi, Banga, Kalwe and Ling'winya Rivers. Headwater for these tributaries provides sources of freshwater which is being used to support commercial agricultural activities in the Lower Limphasa River catchment as the conceptual model has shown in Fig 5.9. Therefore, mismanaging headstreams of these tributaries has implications on quantity (flows) and quality of waters in the Limphasa River leading to potential negative effects on the agro-business activities that depend on such water for their operations (Figs. 5.5 ; 5.6).

Figure 19: 5.5 Water diversions (water use) for irrigation in Limphasa Sugar Plantation

Figure 20: 5.6 Water diversions (water use) for irrigation in Limphasa Rice Scheme

Field observations showed that for irrigation purposes, water was being diverted from Limphasa River to small channels (Fig. 5.5 & Fig. 5.6) in addition to abstracting water into storage tanks (Fig. 5.7) for use in processing activities in factories on each plantation. Such diversions have the potential to affect water flows and levels in Limphasa River. When key staff officers for water management in each plantation were asked the amount of water they abstract from Limphasa River against the amount they actually use per day in their respective factories, they failed to provide statistics on water withdrawal and water use in the factories. Such lack of data has negative effects on managing water in the catchment but confirms the need to assess factors that explain the limited and unsuccessful operation of IWRM at catchment as this thesis argues.

Figure 21: 5.7 Water storage tank at Vizara Rubber Plantation Factory (water use)

Figure 22: 5.8 Waste water disposal ponds for Vizara Rubber Plantation Factory

On managing waste-water from the processing activities in the agricultural-based factories in these plantations, the study showed that plantations had waste ponds and landfills where generated wastes were kept to decompose on their own. For example,

Fig. 5.8 showed waste water disposal ponds for Vizara Rubber Plantation where wastes from were disposed off. The advantage of waste water ponds is that they form artificial recharge preferential points for groundwater thereby increasing the quantity of groundwater for future abstractions. But if such wastes contain toxic materials, the ponds become preferential pathways of contaminants for groundwater pollution whose remediation would be costly (Kresic, 2009). The present study did not assess the quality of the observed waste water in ponds as such a task was beyond the study design. Yet, observations made in this study provide useful insights for future research activities.

Field observations showed that there is potential to contaminate the quality of groundwater and surface water in the Lower Limphasa River catchment because of the chemicals being applied in the plantations. For example, interviews with key staff officers working in these plantations revealed that fertilizers, herbicides and pesticides were applied but their effects on the environment including water had not been comprehensively assessed. It was further reported that Ametryn and monosodium methanearsonate chemicals were used to remove weeds in sugar plantation. Such chemicals are toxic to human, wildlife and aquatic life in addition to having the potential of polluting the groundwater resources during their leaching process (LISUCO, 2011). Yet, the chemicals have been in use since the plantation started.

Therefore, the observed differences between the Upper and Lower Limphasa River catchments suggest that strategies to managing water resources from catchment perspective are needed. Such strategies would enable cooperation and coordination among upstream and downstream dwellers in managing their waters. The IWRM approach provides such a solution but factors that would facilitate its operation need to be assessed as the current study argues. Hence, the development and use of the hydrologic conceptual model for the Limphasa River catchment highlighted interactions that require consideration for a successful implementation of the IWRM approach.

5.6 Hydrogeologic setting and hydrogeologic conceptual model

5.6.1 The role of hydrogeologic setting in water management

The description on the basic aquifer system and hydrogeological boundary of the aquifer system for the Upper Limphasa River catchment are provided from the water management perspective using the geological map with structures contours (Hopkins, 1973). From the geologic map (Figs 5.1 & 5.2), three hydrogeologic boundaries of aquifer were identified and described below, namely, lithology, faults and drainage system: a) Lithology controls flow occurrence due to the impedence or presence of impermeable layers. Flows discharge at contact zones with interbeds and lithological boundaries (Wu, 2005); b) a regional fault is normally a structural boundary as well as a hydrogeological boundary. Most of the regional faults are impermeable boundaries but fault branches are tensile faults which are excellent infiltration path flows; c) a drainage system or watershed is usually a groundwater recharge boundary, but groundwater recharge can be obtained from vicinity catchments through fracture networks. Usually, primary and secondary catchment boundaries are related to structures or are some of the hydrodynamic boundaries (Wu, 2005). Rivers are active hydrogeologic boundary as discharge areas and sources of recharge (Kresic, 2009).

Although results on lithology in this study were elusive, the faults system (Fig.5.1) and drainage system (Fig.5.2) were conspicuous for a plausible discussion on the implication for water resources management especially groundwater resource. For example, although it was not established whether or not that the faults in Upper Limphasa River catchment were barriers but inferred faults are usually regional faults which are impermeable hydrogeologic boundaries (Wu, 2005). Hence, the faults to the west and east of the study area (Figs 5.1 & 5.2) form hydrogeologic boundaries for the groundwater flow in the Upper Limphasa River catchment and the analysis from the geologic map (Hopkins, 1973) showed that both faults throw toward the study area.

This impermeable nature of faults suggests that no water will come in the study area beyond such faults. This has two implications for managing water resources in the area as follow: i) contaminants observed in groundwater sources are generated within the study area and therefore if stakeholders agree to implement practices that protect groundwater from contaminants, groundwater quality would improve significantly. In this case the faults provide an opportunity for collaborative efforts among stakeholders to implement a successful IWRM approach in the Upper Limphasa catchment; ii) If the recharge pattern decreases due to increased reduction in the rainfall pattern (Fig. 6.2 & 6.3) as effects of climate variability intensify, it means that the study area will experience reduced groundwater storage capacity. Since the study area is underlain by basement complex aquifer with limited storage capacity, the impermeable nature of the existing faults is likely to exacerbate groundwater availability for domestic and productive use. Therefore, such knowledge when shared with water stakeholders will facilitate the execution of the IWRM approach to ensure that their waters are managed and utilized sustainably to meet their domestic as well as livelihood needs.

In addition to Figure 5.2, chapter 6 has described the Upper Limphasa River catchment as a recharge area because of its drainage system. However, several factors have been highlighted in Chapter 6 that affect the recharge process in the study area including the topography, dense vegetation cover, among others. Although (Wu, 2005) advised that groundwater recharge can be obtained from vicinity catchments through fracture networks despite establishing that the study area has fractured rock aquifer system, the analysis on fracture networks was beyond the scope of the present study. Nevertheless, the presence of many perennial streams and main rivers of Luwawa and Mwambazi to west and east respectively (Fig 6.6), agrees with the description of Wu, (2005) that rivers are active hydrogeologic boundary as discharge areas and sources of recharge. Wu's description refers to the concept of groundwater/surface interaction which was not the scope of this present study but opens focus for future research work.

In this research, aquifer systems were not categorised into either independent or regional systems as Kresic (2009) suggests. An independent aquifer system usually occurs locally but regional aquifer systems are always complex and synthetically produced and different aquifer systems may connect to each other through faults or leakage layers (Kresic, 2009; Wu, 2005). This study found i) that the study area has a fractured rock aquifer system; ii) no hot springs in the Upper Limphasa suggests existence of local groundwater flow system with probable deeper regional groundwater flow system; Hot springs were observed in Lweya River catchment (Fig.6.6); iii) the presence of faults which control groundwater flow dynamics and iv) the topographic nature of the study area suggest groundwater flowing north-south direction. However, analysis on geological structures and presence of hot springs in the middle and adjacent catchment were beyond the current study but they provided insights for future study.

Figure 23: 5.9 Hydrogeologic conceptual model for the entire Limphasa River Catchment

5.6.2 Hydrogeologic conceptual model for water management

A conceptual model is a simplified representation of the hydrologic system whereas a hydrogeologic conceptual model (HCM) is physical in nature and it describes the hydrologic connectivity between recharge areas, hydraulic properties and geology that controls the way in which water is added, stored, transmitted and discharged through the system (Anderson & Woessner, 1992; White, 2003). Due to variability in the land use and the hydrologic complexity in the Limphasa River catchment, the HCM considered the integration of surface water and groundwater to i) account for the physical exchange of water and ii) identify the processes that influence sources (recharge) and sinks (water use) within the catchment. This simplification is necessary because a) a complete accounting of water is not possible (Todd & Mays, 2005) and b) traditionally, most hydrologic systems are not analysed holistically as single entity but as parts of the system in a fragmented manner (White, 2003). Thus, HCM aligns the philosophy of IWRM which is the theoretical and conceptual framework of the present study.

Results from Fig. 5.9 and Figs. 1 & 2, showed that Limphasa River catchment (LRC) consists of two settings, namely, i) a forested weathered bedrock in the upland and ii) alluvial bedrock in valley with agricultural land use as dominating activities particularly rice and sugarcane farming. From Fig.5.9, the LRC can be described by the process of precipitation, runoff, infiltration and stream flow that are common to the hydrology of the weathered bedrock upland and in the alluvial bedrock valley (Kresic, 2009). Precipitation, infiltration and runoff from the upland provide groundwater recharge and stream flow respectively for use in Limphasa valley's agricultural activities (Fig. 5.3).

To conceptualize the hydrology of the LRC, the relationship between precipitation and runoff are explained from a water-balance perspective where the mechanics of how a catchment responds to a precipitation event and how stream flow is generated are understood (Todd & Mays, 2005). This description was applicable in the LRC where the geology, topography, land use and vegetation are variable in the area (Fig. 5.9; Fig. 5.1 & Fig 5.2). Fulton et al., (2005) identified components in their study basin similar to Limphasa River catchment as follows: a) overland runoff, subsurface storm flow and groundwater flow which are described in the context of the LRC. For example, Fulton et al., (2005) understand overland runoff as a product of infiltration excess associated with a rainfall event where its intensity exceeds the infiltration capacity of the soil; alternatively, they defined it as the saturation excess where the soil above the water table or perched surface becomes completely saturated and any additional precipitation produces runoff. In humid regions such as the Limphasa River catchment where vegetation protects the soil from compact and dispersion from precipitation, overland runoff created by infiltration excess is rare but overland runoff created by saturation excess is common (Freeze & Cherry, 1979). Overland runoff created by saturation excess is called variable source-area contribution (VSAc) which was applicable to Limphasa River catchment where the rate of interflow entering a saturated area from upslope exceeded its capacity to be transmitted and the excess storm flow returned to the surface as runoff. Field observations revealed this type of overland runoff in the upslopes (hill sides) of Kandoli and Kaning’ina Mountains.

Although the qualitative analysis of VSAc provided a scientific merit to enhance understanding the importance of using the conceptual model as a planning tool for IWRM operation among stakeholders, this study did not quantify the VSAs overland runoff which could have provided a robust interpretation of the results. However, the following are the parameters that are usually considered when calculating VSAc: a) rainfall intensity and duration; b) unsaturated zone thickness; c) available water-storage capacity; d) depth to bedrock; e) soil hydraulic properties; f) water-table or perched-water depth and g) hydrology of the upland in various sub-basins (Fulton et al., 2005). Nevertheless, the qualitative approach used in this study was useful, practical and simple to understand because the process associated with stream flow generation which is produced by overland runoff and subsurface storm flow can be complex and different for different sub-catchments within one river catchment (Weight, 2008; Nonner, 2006).

The upland ridge of Kandoli and Kaning’ina Mountains (Fig. 5.9) form the physical and hydrologic boundaries along the eastern and western margins of the Upper Limphasa River catchment (Figs 5.2 & 5.9) and the entire Limphasa River catchment. The configuration of the water table surface beneath these mountains suggests that they act as groundwater divide in addition to indicating the groundwater flow direction in the catchment. Since these mountains are at significant distances from groundwater abstraction points (boreholes and Protected shall wells) in Fig. 5.1, the location and orientation of the groundwater divides are fixed and can be conceptualized as no-flow boundaries. Precipitation on bedrock upland is first intercepted by the forest canopy and evapotranspiration then becomes direct runoff or infiltrates to become subsurface interflow or groundwater recharge (Fig. 5.1; Fig.5.2; Fig.5.9). Upland areas are adjacent to stream banks, near converging topography and at bottom of hill slopes (Fig. 5.2). Subsurface water becomes groundwater recharge when it enters the saturated zone at water table. The water-bearing rocks beneath the upland are generalized as a fracture-dominated aquifer and these aquifers are least productive. Most groundwater recharge in these aquifers occurs in the rainy season i.e. from November to April in Malawi and November to May in Limphasa catchment. Generally, Fig. 5.9 showed that groundwater in upland moves down slopes through fractures in the bedrock, from areas of high hydraulic head (hill tops) to areas of low hydraulic head (Limphas valley).

Fig. 5.9 shows that bedrock valley of Limphasa River catchment (LRC) is formed on less resistant bedrock of alluvial, gravel and sand and rocks than the upland. The valley is linked hydrologically to the adjacent upland by runoff and groundwater discharge from upland providing large amount of stream flow and recharging the valley. Hydrologic boundaries of the Limphasa River catchment with the bedrock valley are more difficult to delineate than in the upland. Fulton et al. (2005) explained that in humid areas, conceptually within the extended groundwater basin, groundwater contributes to water budget of the basin but streams transmit water to basin. For example, the surface water lost as infiltration or runoff to streams becomes groundwater. In other words, groundwater discharges into streams and streams recharge groundwater (Fig. 5.9). This results in conceptualizing the bedrock valley as a no-flow boundary at depth of active groundwater flow as shown by depth that permeability has been enhanced by weathering depth of weathering zone in bedrock (Fulton et al., 2005).

However, some studies (Weight, 2008; Younger, 2007) have suggested that in such a situation, numerical models of the hydrologic system are needed to simulate the dynamics of groundwater-surface water interaction in the bedrock valley. The main reasons being that groundwater flow within the fractured rock aquifer such as Limphasa River catchment is altered by structural geologic features such as faults and secondary permeability features such as joints, sinkholes and enlarged fractures (Figs. 5.1; 5.2).

These features may change any conceptualization of groundwater movement by adding anisotropy (preferential direction of flow) parallel to the strike of the bedrock aquifers or valley alignment (Fulton et al., 2005; Todd & Mays, 2005). Nevertheless, from the holistic management views as advanced by the IWRM philosophy, the conceptual model developed in this study for the Limphasa River catchment for the first time contributes significantly towards providing practical and visual planning tools for making realistic decisions in the catchment. The implications of such a tool for operating a wider and successful IWRM approach are highlighted below in section 5.7.

5.7 Implication of conceptual model on managing water resources

The implication of the hydrogeologic conceptual model of the Limphasa River catchment is discussed in the context of integrated water resources management (IWRM) in terms of assessing physical and socioeconomic factors that thwart its wider and successful implementation at catchment level. In general, IWRM renounces politics, the traditional fragmented and sectoral approaches to water. It makes a clear distinction between resource management and water service delivery functions. However, Kresic (2009) reports that IWRM itself is a political process because it deals with reallocation of water, allocation of financial resources and the implementation of environmental goals. These aspects require political decisions and such political context affects political will and political feasibility of IWRM operation successfully. In agreement with Kresic’s (2009) observation in Orange County Water District in California of the United States of America, Colvin et al. (2006) who drew lessons from Nkomati River Basin in South Africa highlighted the need to establish effective water governance regime in order to implement IWRM successfully. This pertains to both management of water resources and the delivery of water services including drilling of groundwater sources for rural water supplies.

In the water community, there is a general agreement that IWRM provides the only viable way forward for a sustainable water use and management. Despite such considerable history and international acceptance of IWRM, debates are ongoing in terms of the meaning of IWRM in practice focusing on how and when IWRM can be used to achieve the practical results for the end users of water (Garcia, 2008). Despite such debates, there is agreement within the water community on the principles underlying the IWRM and the potential it holds for managing complex systems that cannot be adequately achieved through the single-sector management approach of the past (GWP, 2006; UNESCO-WWP, 2006; UN-Water, 2008). Anderson et al. (2008) highlighted the need to seek a new approach to overcome the past management regime and local IWRM is among such new approaches as the current study argues. To visualize how local IWRM would work, this investigation assessed the local physical and socioeconomic factors using the hydrogeologic conceptual model for the Lipmhasa River catchment where upland and valley water-related aspects were highlighted. The current study uses IWRM as a theoretical and conceptual framework and it is aware that there are no universal solutions for executing a successful IWRM in any catchment similar to what (Kresic, 2009) observed, but the provision of the hydrogeologic conceptual model and a case study description on local IWRM in chapter 8, provides a starting point towards a successful IWRM implementation.

The study showed that groundwater system in terms of flow dynamics (flow direction) in the Limphasa River catchment was influenced by the geologic settings, geomorphologic settings, hydrogeologic settings and human modification of the landscape through agricultural based activities in the catchment. These findings have implications on managing water resources in the catchment. However, one of the challenges that affect the successful implementation of IWRM is to balance between the needs of i) ecosystem and ii) growing population with their associated socio-economic development activities and environmental integrity respectively as observed in the Limpasa River catchment. Kresic, (2009) observed that the shared dependence on water by both ecosystem and human needs make it natural that ecosystem needs to be given full attention within the IWRM framework. Alongside that view, human population suffering from poverty, hunger, ill-health and lack of safe drinking water and sanitation require to improve their human livelihoods system to achieve the UN MDG set goals (UNICEF&WHO, 2012, MDHS, 2010; Malawi-MDG, 2010, UN-Malawi, 2010. All these closely water related aspects need to be considered when implementing the IWRM at catchment level, which is difficult.

From the results presented in this chapter, one of the key implications for implementing a successful IWRM is for key stakeholders to realize that balancing and trade-offs are necessary in order to sustain the life support system of both human population and the ecosystem. For example, agreeing with Anderson et al., (2008) that implementing a successful IWRM requires a balance between the policy and institutional support and community level projects that have small-scale tangible results at community level. The developed hydrogeologic conceptual model implies that implementing a successful IWRM at catchment level, entails satisfying the needs of local communities. As communities participate in managing the water that they consume, they monitor activities that minimize negative effects on the environment which sustain such water. Since the hydrogeological model addresses the water aspects in uplands and valleys, it implies that the successful IWRM requires building a secure hydro-solidarity between upstream and downstream dwellers to manage societal and ecosystem needs in a sustainable manner. That approach requires IWRM to build in benefit sharing mechanisms and conflict management aspects that would ensure that the upstream and downstream dwellers cooperate and co-exist for the benefit of each other (Haas, 2009).

The findings on the role of geologic settings, geomorphologic settings and hydrogeologic settings and hydrogeologic model presented in this chapter 5 indicate that a successful implementation of IWRM in Limphasa catchment and beyond would require creating public awareness on groundwater resources among the general public and key stakeholders (water scientists, water developers, water users and water managers) in particular. Such civic education would focus on the importance of groundwater and its invisible role in the river catchment such as Limphasa and the role of groundwater in the hydrologic cycle as a whole. One of the effective ways to create such awareness on the role of groundwater is to use hydrogeologic conceptual model for broader understanding on complexities of water management in the area. This would be similar to what Kresic (2009) described as one of the best examples of implementing IWRM in Orange County Water District in California, USA where different management practices were allowed to be implemented to facilitate achieving the philosophy of IWRM. Chevalking et al. (2008) observed that catchments showing positive IWRM implementation have been using different strategies to create basic understanding of the resource. Such strategies include: 1) maps prepared based on field observation and measured data that show delineation of groundwater protection; 2) pictures to show uses of water in the catchment; 3) flow diagrams to show interaction and relationships of water with other aspects including water flows in the catchment; 4) plays during celebration days and engaging members of parliament, district assembly officers and local leaders with petitions to support the management of water resources (Chevalking et al., 2008). The provision of hydrogeologic conceptual model and analyses on the role of geologic, geomorphologic and hydrogeologic settings in one step towards achieving the IWRM in practice as Chevalking et al. (2008) observed.

The benefit sharing concept has gained increased attention as a tool for integrated water resources management (Gupta & van der Zaag, 2007). One of the underlying ethical principles for benefit sharing is that projects such as plantations observed in the Limphasa River catchment (Fig 5.3; Fig.5.9) generate significant economic profits which can be justifiably shared with local communities that are either affected by such projects or are involved in managing water resources being used in such projects. The concept of benefit sharing comes from the growing recognition that before water allocation takes place, upstream and downstream water users need to identify and agree on benefits derived from water uses and the manner in which these benefits should be shared so as to improve their livelihoods and reduce potential future conflicts and therefore achieve social, economic and environmental sustainability (Haas, 2009).

The results from Fig.5.3 and Fig.5.9 showed the feasibility as well as complexity of incorporating the benefit sharing concept in the implementation of integrated water resources management. Meetings with selected key officers from plantations, community local leaders and government officers in the catchment showed their values and concerns about water use with associated management practices. Yet, they did not indicate the existence of basic agreements or mechanisms of sharing benefits between the local communities and plantation owners from revenue of plantations. Again, they did not indicate any existence of cooperation between the upstream and downstream dwellers about water use and water management despite the hydrogeologic model (Fig.5.9) showing the relationship between upstream and downstream. Although the present study was not about benefit sharing, the analysis on local hydrogeologic and socioeconomic factors in the Limphasa River catchment with the use of hydrologic conceptual model provides an explanation on factors that need to be understood for a successful IWRM implementation. The model provided the platform for effective multistakeholder dialogue to facilitate defining a viable approach that has practical and ethical orientation in building on and reinforcing the roles of existing local institutions, local government departments and non-governmental organisations for managing water resources holistically. It revealed the need to execute benefit sharing concepts which has potential to reduce unforeseen future conflicts between upstream and downstream dwellers and also between local communities and plantation owners in the catchment.

Although the model has provided the general understanding of how hydrological processes operate between uplands and in the valleys, the available knowledge is not adequate for accurate predictions of effects of land-based activities either in upland or valleys on the quality and quantity of water resources in the Limphasa River catchment. For instance, quantifying effects of human modifications of land resources on quantity and quality of water was beyond the scope of the present study. Groundwater and surface water flow relationships and dynamics within and between Upper and Lower Limphasa River catchments remain unknown and the knowledge available is inadequate for accurately predicting these relationships along within and between the sub-catchments. Therefore, using results in Fig. 5.3 and Fig.5.9, which provided visual location of land-based activities, a precautionary approach should be followed where activities that are likely to have negative effects on the quantity or quality of groundwater and surface water are being implemented. In this way, the precautionary approach is appropriate because it complements IWRM execution.

5.8 Summary

Assessment of physical and socioeconomic factors using visual tools such as maps, photos and conceptual model is significant because it shows variables that have the potential to impede or facilitate operation of the IWRM approach at catchment level. There are several methods to quantify the studied variables. However, providing the qualitative results using maps, photos and conceptual model is one step towards numerical estimates of the desired variables that provide quantitative assessment. But considerable judgment and the selection of policies have influence on the management of the resources including water. Although rules exist to guide implementation of water management policies in countries such as Malawi, alternative approaches such as local

IWRM also exist which give significantly different results and are therefore worthy scaling up to facilitate the IWRM implementation which is the argument for this thesis.

The research acknowledges the science of uncertainties on some variables in the study period which might have affected the robust analysis of the results. Nevertheless, the following key findings emerged: 1) The Upper Limphasa River catchment has fractured rock aquifer with limited permeability and storage capacity hence holistic effective management of such water is imperative for sustainable utilization. 2) The topographic nature and north-south strikes of the lineaments explain the north-south flow direction of groundwater in the catchment. 3) The drainage system observed in the Kandoli and Kaning'ina Mountains to the east and west of the Upper Limphasa River catchment respectively (Fig. 5.1; Fig.5.2) forms a groundwater recharge boundary. 4) The regional faults in the same mountains (Fig. 5.1; Fig.5.2) are both structural boundaries as well as hydrogeologic boundaries and they control flow direction of the groundwater. 5) The study showed that major land-based activities such as commercial agricultural activities were practised in Lower Limphasa catchment while in Upper Limphasa catchment only subsistence farming existed. This knowledge and visualization from the map (Fig. 5.3) and conceptual model (Fig.5.9) show the role of physical factors in controlling groundwater flow direction in the catchment. This insight facilitates the understanding on why the upland and lowland need to be managed holistically as being advocated by the IWRM approach. 6) The hydrogeologic conceptual model showed that the forested weathered bedrock in the upland forms no-flow boundary and groundwater divide. It also controls the flow direction downwards while the alluvial bedrock in the Limphasa bedrock valley indicated no-flow boundary at the depth of active groundwater flow.

These findings entail that for a successful IWRM to be implemented, the following three aspects should be considered: First, key stakeholders need to realize that balancing and trade-offs are necessary to sustain the life support system for human population and the ecosystem. Secondly, creating public awareness on groundwater resources and water resources in general among the general public and key stakeholders should be a continual process. This is because often water resources managers and decision makers have little background in hydrogeology. Therefore, such officers possess limited understanding of processes that are induced by pumping groundwater from aquifer and implication on groundwater quantity and quality when human settlements exist on recharge zones. Thirdly, the conceptual model revealed the need for establishing basic agreements and mechanisms for sharing the cooperative gains from the proceeds of plantation activities. Such agreements and mechanisms should be between i) upstream and downstream dwellers and ii) local communities surrounding the plantations and plantations' owners. Such arrangements should be based on ethical consideration of plantations' owners to communities where such agro-businesses operate in addition to considering developing the surrounding communities sustainably. Where quantifiable information is scarce from the model, then management of water resources should be based on the principles of a precautionary approach which complements the successful implementation of the IWRM approach at both catchment level and beyond.

The next chapter assesses the availability, demand and use of groundwater resources in the study. It focuses on assessing factors that explain the limited and unsuccessful implementation of IWRM and provides the practical methodology on data generation for effective management of water resources at household and catchment levels.

Chapter 6: Groundwater availability, demand and use

6.1 Introduction

Chapter 5 has described the groundwater system using the conceptual model approach with a focus on physical factors that govern the flow, availability, quality and governance of water resources. Water management practices have been discussed highlighting barriers and opportunities for IWRM implementation. This chapter has two objectives: i) to identify potential factors that explain the availability of groundwater using the conceptual model of recharge process and ii) to demonstrate a methodology for generating data on groundwater demand/abstraction and use in unmetered rural areas to showcase one of the essential approaches for systematic data collection to ensure the availability and accessibility of data on groundwater for water assessment purposes.

This thesis argues that for IWRM to be successfully implemented; a) factors that affect groundwater availability must be understood to guide methods for estimating such quantity because the available knowledge is inadequate to provide accurate estimates of temporal and spatial groundwater availability; b) statistics on demand (abstraction) and use of groundwater must be available to inform water allocation in catchments. Globally, such statistics are not available (Healy, 2010) and yet global statistics originate from country statistics which also come from statistics from catchments. This explains the significance of the approach proposed in this study; and c) procedure to generate such statistics must be shown to provide leeway for further refinement on such methods. The current common methods in water demand and use rely on modeling approaches (Falkenmark & Vorosmarty, 2005; Gleick, 1996; Falkenmark & Widstrand, 1992) with limited measured data. The use of the field measurement approach is envisaged useful in generating observation data for validating models on water demand and use. Such generated knowledge needs to be shared with scientists, users, providers and managers of water resources to facilitate a successful IWRM implementation.

6.2 The Approach that was followed

Objective 2 of this study is to demonstrate data generation on groundwater demand and use in unmetered rural areas. This approach provides a practical method for effective management of groundwater. To achieve this objective, factors that influence groundwater availability need to be explained to contextualise the demand and use of such water. Best management practices require that recharge estimates methods be matched to the conceptual models of the recharge process at individual sites to ensure that assumptions underlying the techniques are consistent with the conceptual model (Healy, 2010). This informed the development of a conceptual model of the recharge process for the Upper Limphasa River Catchment. The model helped to identify a) prominent potential factors for recharge mechanism, b) potential recharge areas, c) provide insights to guide selection of data collection methods for recharge estimates. Although conceptual models are not perfect, they provide basis for further improvement as more data are collected, analysed and interpreted resulting in using the alternative methods (Fisher & Healy, 2008). Despite the model's weakness to provide quantified groundwater recharge, its strength to provide qualitative information on recharge in terms of identifying areas of high and low recharge zones was one of the main reasons it was chosen in this study because it contributed to factors that explain water availability.

Globally, groundwater is a significant source of fresh water; however, comprehensive statistics are not available on groundwater abstraction (demand) and use (Healy, 2010). This scenario informed the basis to demonstrate generation of such statistics using unmetered rural areas, Upper Limphasa River catchment as a case study. Global estimates show that 1.5 billion people rely on groundwater for drinking (Clarke et al., 1996). The demand and use for groundwater has been increasing and shows no sign of abating for scientists to calculate the available amount of groundwater and how groundwater system gets replenished (Molden, 2007). One of such methods is to estimate the groundwater recharge i.e. the rate at which aquifer waters is replenished. Quantification of natural rates of groundwater recharge is vital for efficient management of groundwater but its difficulty has led to the common use of estimates (Simmers, 1990). This study provides qualitative estimates on expected groundwater availability using field observations on various factors for a successful IWRM implementation.

Recharge is one of the most important components of groundwater studies and the least understood aspect because recharge rates vary widely in space and time hence the most difficult aspect to measure (Fisher & Healy, 2008). Recharge is defined as the downward flow of water reaching the water table, adding to groundwater storage

(Freeze & Cherry, 1979; Lerner et al., 1990). The norm is to present recharge either as i) a volumetric flow (Volume per unit time such as L3/T i.e. m3/d), ii or as a flux (Volume per unit surface area per unit time such as L/T i.e. mm/yr. However, Healy (2010) recommends presenting recharge as a percentage of precipitation which this study would have used if data were available. Four types of recharge, namely, diffuse, focused, preferential and episodic exist as reported by Xu & Beekman (2003). Details on methods of recharge estimates are beyond the scope of this study but such details exist in Xu & Beekman (2003). The focus of this study is to identify factors that lead to having a particular type of recharge and implications of such recharge type on groundwater availability and contamination as per conceptual model.

Improved understanding on the recharge process and the potential factors that influence it is vital. For example, ASTM (2008) report that the rate, timing and location of recharge are crucial in groundwater contamination and water supply studies because i) the likelihood for contamination moving into water table increases as the rate of recharge increases and ii) areas of high recharge are often associated with areas of aquifer vulnerability to contamination. Therefore, location of subsurface facilities such as hand-dug wells, toilets, waste disposal sites are often selected based on the knowledge of relative rates of recharge in the area.

6.3 Overview on methods to estimate water availability, demand and use

Methods have been developed to quantitatively assess the availability, demand and use of water resources. Selecting suitable parameters for such methods has been a complex issue due to decisions that consider policy and scientific factors for agreements (Brown & Matlock, 2011). IWRM emerges as a unifying approach to bring these two aspects for solution so that water resources are managed in a coordinated manner for sustainable utilization (Hooper, 2006). This chapter argues that a qualitative approach for assessing factors that explain availability of groundwater as an example is a starting point to bring scientists, policy makers (managers) and users together for discussion on managing water resources in a coordinated manner. It presents results on assessing groundwater availability; demonstrates on how data on groundwater demand and use are generated at household level in unmetered rural areas; and estimates determinants for such demand and use using regressions analysis. Finally, the chapter discusses the application and implication of such results for managing groundwater resources and for lobbying the execution of a successful IWRM at catchment level. To contextualise the motivation on the need for feasible procedure on water availability, demand and use in this chapter, an overview of the existing methodologies for assessing water availability, demand and use is provided to stress the strengths and weaknesses and thereof need for improvement.

6.3.1 Existing approaches for computing water availability, demand and use

For water availability, the Falkenmark indicator is the most widely used measure of water availability where countries are surveyed and water usage per person in each economy is calculated. The index threshold of between 1700 m^3 and 1000 m^3 per capita per year is used as the threshold between water abundant and water scarcity countries (Falkenmark, 1989). Individual usage is the basis for the Falkenmark indicator and the index is designed to be used in water assessment at national level where data is readily available. Using Falkenmark's benchmark, Malawi can be described as a water stressed country with 1528 m^3 per capita per year while the neighbouring countries had 10095 m^3 (Zambia), 11814 m^3 (Mozambique) and 2591 m^3 (Tanzania) per capita per year while Kenya, Zimbambwe and South Africa with strong economic activities had 985 m^3, 1584 m^3, 1154 m^3 per capita per year respectively (FAO-AQUASTAT, 2002). The Falkenmark index is easy to understand but the use of national annual averages tends to obscure important information at smaller scales and under-measure the impact of smaller population (Rijsberman, 2006). This observation informed the need for a methodology to address this aspect as shown in this study.

Gleick (1996) developed a method to measure water demand for basic human needs where it was proposed that to meet the human basic needs; a total demand of 50 litres of water per person per day is required. The 50 litres composed of 5 litres, 20 litres, 15 litres, and 10 litres per person per day are required for drinking, sanitation, bathing and food preparation respectively. This benchmark indicator was regardless of factors that affect such demand (Gleick, 1996). In Malawi, the recommended water requirement is 36 litres per person per day (GoM, 2005; Baumann & Danert, 2008).

Both Falkenmark's and Gleick's benchmark indicators of 1,000 m^3 per capita per year and 50 litres per person per day as a standard have been accepted by the World Bank

(Falkenmark & Widstrand, 1992). Therefore, international organisations, researchers and water providers are recommended to adopt these indicators as new threshold for water availability in a country and water demand per person per day to meet basic human needs (Brown & Matlock, 2011). In Malawi, the total available water resource per capita of 1528 m^3 per capita per year is above the lower limit of Falkenmark indicator of 1,000 m^3per capita per year. However, the recommended water demand of 36 litres per person per day is below the international standard of 50 litres per person per day. Results from this study compared the water demand in the Upper Limphasa River Catchment with the Malawi values as well as the international standard.

The absence of systematic data on groundwater demand and use as one of the major problem in managing water resources has already been reported (Molden, 2007; Healy 2010; Brown & Matlock, 2011). For example, Vorosmarty et al. (2005) support the widely cited threshold of the Falkenmark indicator and hesitate to recommend using the model by Yang et al. (2003) which does not include information on groundwater due to lack of systematic data. The current study aimed to contribute this aspect by proving the methodology on how such data on groundwater can be generated systematically to ensure effective management of water resources including groundwater resources.

6.3.2 The emerging approaches for water availability, demand and use

The emerging methods for estimating water availability, demand and use argue that the former approaches were based on fixed human water requirements and national scale orientated thereby neglecting the local scale i.e. the catchment level (Rijsberman, 2006). Therefore, water resources indices were developed which considered catchment parameters in their computations. For example, Raskin et al. (1997) developed water resources vulnerability index also known as WTA ratio. These indices are ratios of total annual withdrawals for human use to available (renewable) water resources. The country is considered water scarce if withdrawals are between 20% and 40% of annual water supply (Alcamo et al., 2000). For instance, the index of local relative water use which is used to assess the availability of freshwater in a particular catchment, its computation equals the water use in each segment of a catchment (upper, middle or lower) divide by the river corridor discharge. Water use refers to total water withdrawals for domestic (D), industrial (I) and agricultural (A) sectors and river discharge corridor refers to all local discharges in that segment of the catchment (Vorosmarty et al., 2005). A similar approach for basin specific called watershed sustainability index was developed by Chavez & Alipaz (2007) who suggested hydrology, environment, life and policy as parameters for their model. McNulty et al., (2010) developed the water supply stress model to quantitatively assess the relative availability of water supply and demand at watershed level. The model is similar to WTA ratio by Raskin et al., (1997). The use of both models depends on availability of information specific to river catchments which are scarce in many regions (Brown & Matlock, 2011) hence the limitation to apply such models. This justifies the assumption for the current study to provide a method of generating data on water demand and use at catchment levels which can be used in such models especially in rural areas.

The International Water Management Institute (IWMI) used the similar water scarcity assessment approach as described in the preceding paragraph but focused on the global scale. The IWMI (2008) assessment considered the portion of renewable freshwater resources available for human requirements with respect to the main supply. Countries, globally, were divided into two categories: i) physically water scarce and ii) economically water scarce (IWMI, 2008). The physically water scarce countries refer to a situation when 75% of river flows in that area are withdrawn for agriculture, industry and domestic purposes. Molden (2007) highlights indicators for physically water scarce situation as environmental degradation, diminishing groundwater levels and water allocations that support some sectors over others. However, economically water scarce countries refer to countries that have adequate renewable water resources with less than 25% of water from rivers withdrawn for human purposes, but they lack improvements in existing water infrastructure to make such resources available for human use (Seckler et al., 1998; Molden, 2007; IWMI, 2008; Brown & Matlock, 2011).

The main research problem being addressed in this study is the mismanagement of water resources in Malawi, hence, investigating factors that need to be understood to explain the quantity, quality and governance of water resource for effective management of such resources. Largely, Malawi suffers from the economically water scarce problem but not necessarily physical water scarce although the country is water stressed according to Falkenmark's classification. This informed the current study to use the IWRM approach as a theoretical framework. GWP (2000) emphatically stated that since water sustains all life, effective management of water resources demands a holistic approach that links social and economic development with the protection of natural ecosystems, hence the use of the IWRM approach with its principles in this study. The observed limited application of this approach informed to assess its implication on catchment basis so that alternatives can suggested on how to successfully implement it.

6.3.3 Alternative methodologies for water availability, demand and use

The methodologies described in the above paragraphs aim at producing estimates on availability, demand and use of water resources. However, no one method seems to be adequate for estimating water availability, demand and use hence, the need for alternative approaches. The initial water availability threshold of between 1,000m^3 and 1,700 m^3 per capita per year developed by Falkenmark in 1989 was an important foundation on which water consumption demands were built. Recognising that water consumption varies among social sectors due to climate variability, technological use and cultural variables led Gleick and Falkenmark (1996) to further develop the water demand threshold of 50 litres per person per day which was adopted by the World bank as a standard threshold providing a yardstick for countries.

The observed continued increase in domestic water withdrawals and demands with the associated damage caused by water consumption led to recognising the importance of assessing water flows necessary for ecological quality and sustainability (Sullivan, 2002, Asheen, 2003; Vorosmarty et al., 2005; Chaves & Alipaz, 2007; Pfister et al., 2009). To measure water availability, demand and use in a holistic manner including all the socio-economic, ecological and industrial factors, Hoekstra et al. (2003) suggested the water footprint method. However, Ridoutt et al., (2009) cautioned that the water footprint method needs to be improved first before using it so that a standardized model is created to allow comparisons between areas, products and other parameters. This situation explains the ongoing search for methods that can be used to generate data and estimate water availability, demand and use in a more agreeable manner. The first step is to provide a method on how to generate data for such methods which is the thesis for the current study because such estimates require measured or observed data which can then be used in modelling processes and the provided method can be refined with time.

The review presented in this section has shown that the need for alternative methods that exist to measure the availability, demand and use of water resources. However, the procedure to generate such measured data is not provided in the above methodologies. The current study aimed at providing that procedure to produce measured data that can be used in such models. Despite the uncertainties associated with scientific methods in general and with the proposed method on generating data on availability, demand and use in the current study, the systematic procedure provided is a major step towards a more informed procedural assessment approach on data generation and its implication for managing water in coordinated manner in the catchment mainly in unmetered areas.

6.4 Groundwater availability using conceptual model of recharge process

This section presents results on factors that explain the availability of groundwater. The conceptual model has been used to show where, when and why recharge occurs. The aim is to improve understanding on factors that control groundwater availability in order to shed light on factors that need to be understood and assessed to facilitate a successful implementation of the IWRM approach as per objective set in chapter one.

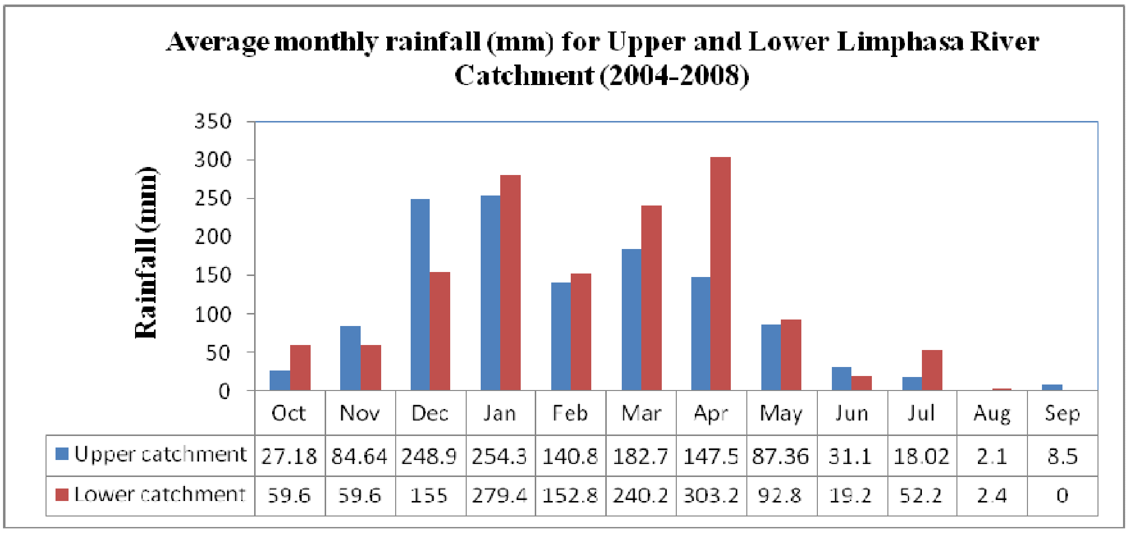
6.4.1 Conceptual model of recharge process for groundwater availability

The conceptual model of recharge process (Fig.6.1) shows how a) precipitation, b) soil and geology, c) topography, d) hydrology, e) land cover and land use including settlement pattern influence groundwater availability in the study villages. Chapter 5 referred to Fig 6.1 to show how a-d factors influence groundwater flow system while chapter 7 referred to Fig.61 to show how a-d factors influence groundwater quality. Shallow aquifers where protected shallow hand-dug wells (PSWs) abstract water and deep aquifers where boreholes abstract water are shown in Fig.6.1. Location of human settlements and pit-latrines in relation to drinking water sources are shown (Fig.6.1). Pathways for potential contaminants to groundwater quality are shown (Fig.6.1). Precipitation, mountains, fault zones, topography, land cover and use, geology types are shown (Fig.6.1) and explained in relation to the recharge process in section 6.4.2.

Figure 24: 6.1 Conceptual model of recharge process in Upper Limphasa River Catchment

6.4.2 Potential physical factors that influence groundwater availability

a) Climate is one of the potential factors that influence groundwater availability. Healy (2010) outlines four climatic regions in relation to recharge, namely, i) Arid climates with annual precipitation of less than 250 mm which are likely to experience episodic and preferential recharge, ii) semi-arid climates with precipitation rates of between 250 and 500 mm/yr which are likely to have episodic and preferential recharge, iii) sub-humid climates with annual precipitation rates that range from 500 to 1000 mm/yr are likely to experience focussed and diffuse recharge, iv) humid climates with annual precipitation rates that exceed 1000 mm/yr, generally diffuse recharge dominates although focussed and preferential recharge is considered the norm (Fig6.1). Largely, Malawi experiences sub-humid climates although some districts experience humid climates (FAO, 2008). Among the climatic variables, precipitation is the major sources of natural recharge hence the focus on rainfall data for this study area. For instance, Lorenz & Delin (2009) reported the effects of precipitation on recharge process when temporal variability (yearly and seasonal) frequency, duration and intensity of precipitation events are considered. The two authors summarised that the area experience more recharge when precipitation rates exceed evapotranspiration rate to enable drainage to occur. Healy (2010), in agreement reported that in humid region recharge occurs at any time of the year in response to intense rains leading to total precipitation for the day to exceed the daily evapotranspiration rate.



	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
🟦 Upper catchment	27.18	84.64	248.9	254.3	140.8	182.7	147.5	87.36	31.1	18.02	2.1	8.5
🟥 Lower catchment	59.6	59.6	155	279.4	152.8	240.2	303.2	92.8	19.2	52.2	2.4	0

Figure 25: 6.2 Average monthly rainfall (mm) for Upper and Lower Limphasa Catchment

Fig. 6.2 is a combination of the rainfall figures for Upper and Lower Limphasa River catchment which are approximately 30-40 km apart (Fig 5. 3 and Fig 5.9). From Fig. 6.2 one can deduce that while the average monthly rainfall varies slightly from Upper to Lower Limpahasa River catchment for each month, the seasonal trend is constant suggesting the yearly monthly rainfall pattern in the catchment. Limphasa River catchment receives more rainfall in summer (rainy season) than winter (cool-dry season). The rainy season (October to April/May) is yearly wet and the cool-dry season (June-September) has lower monthly rainfall. This low rainfall situation is made worse by the incidence of strong south-easterly winds (locally known as Chiperoni winds) which cause high evaporation rates. Generally, Nkhatabay district where the study catchment is situated receives rains almost throughout the year. However, to assess the long-term trend of rainfall which is essential for groundwater recharge interpretation among other factors, it is more accurate to use rainfall figures as far back as possible which this study did not collect. This weakness makes the information in Figs. 6.2 & 6.1 proxy of rainfall pattern in Limphasa River catchment and implication for groundwater recharge in that sense remains qualitative. The Upper Limphasa catchment is located in warm tropical climate region and in Nkhatabay District which experience a total annual rainfall of over 2,000 mm (GoM, 2008). These field results confirmed that the Upper Limphasa catchment receives more rains almost throughout the year (Fig.6.2). Such results indicate good groundwater recharge pattern holding other factors constant.

Although this study is not about methods to estimate recharge rates, basic understanding on the relationship between rainfall and recharge is essential. For example, Beekman et al. (2007) showed improved estimation of recharge and flows in aquifers for assessing the relationship between rainfall and recharge. However, from the IWRM perspective, the importance of the results from Upper Limphasa catchment on rainfall pattern indicates the months that had more rainfall and more replenishment to aquifers in the area. This observation agrees with Beekman & Xu (2003) who concluded that understanding climatic changes such as rainfall pattern especially in some parts of Southern African countries improves knowledge among water scientists and managers in terms of whether or not replenishments of aquifers are more or lesser during particular rainy seasons or thereafter. Therefore, it can be inferred that Fig.6.2 showed that yearly more rains are received from December to May and thus aquifers are replenished more during that period. While this interpretation is not conclusive, such results provide useful insights on practices for managing water resources in the area.

b) Soils and geology: The relationship between soils and recharge is that recharge is more likely to occur in areas that have coarse-grained and high permeability soils as opposed to areas of fine grained and low permeability soils. For example, Robinson et al. (2008) showed that coarse grained soils have a relatively high permeability and are capable of transmitting water rapidly. The presence of these soils promotes recharge because water can quickly infiltrate and drain through the root zone before being extracted by plant roots. Apart from soil characteristics, geology of the subsurface controls the recharge process (Fig.6.1). For example, if the rate of discharge from aquifer is less than the rate of recharge due to the nature of subsurface geology, water storage within the aquifer increases. Robinson et al. (2008) found that aquifer storage when it reaches a maximum point; additional recharge is not accepted regardless of the amount of precipitation. The authors concluded that apart from precipitation and soil features, subsurface geology needs to be understood in terms of the recharge process.

The dominate geology and its implications on groundwater system has been described in chapter 5. The key aspect of this section is to show the potential relationship of characteristics of soils and subsurface geology to the recharge process (Fig.6.1), hence, the need to understand groundwater availability for water assessment among scientists and water managers for suitable management practice. The dominant geology for the area is hard rock Biotite gneiss (Fig. 6.3 & Fig. 6.1) forming basement complex aquifer which has limited aquifer storage capacity suggesting that the additional recharge from more rainfall is not accepted (Robinson et al., 2008; Fig. 6.1). This possibly explains the presence of many perennial streams (Fig. 6.6) that were observed as groundwater discharge indicating the process of groundwater - surface in the study area.

The dominant soils sandy-clays (chapter 2) with top geology being sands and gravels (Fig.6.1) with coarse grains will lead to high permeability and capability to transmit water rapidly to aquifer but the deeper basement complex geology (Fig.6.1) in this area will not change the limited aquifer storage capacity. Yet, such knowledge is essential for IWRM practice among water scientists, users and managers for sustainable use.

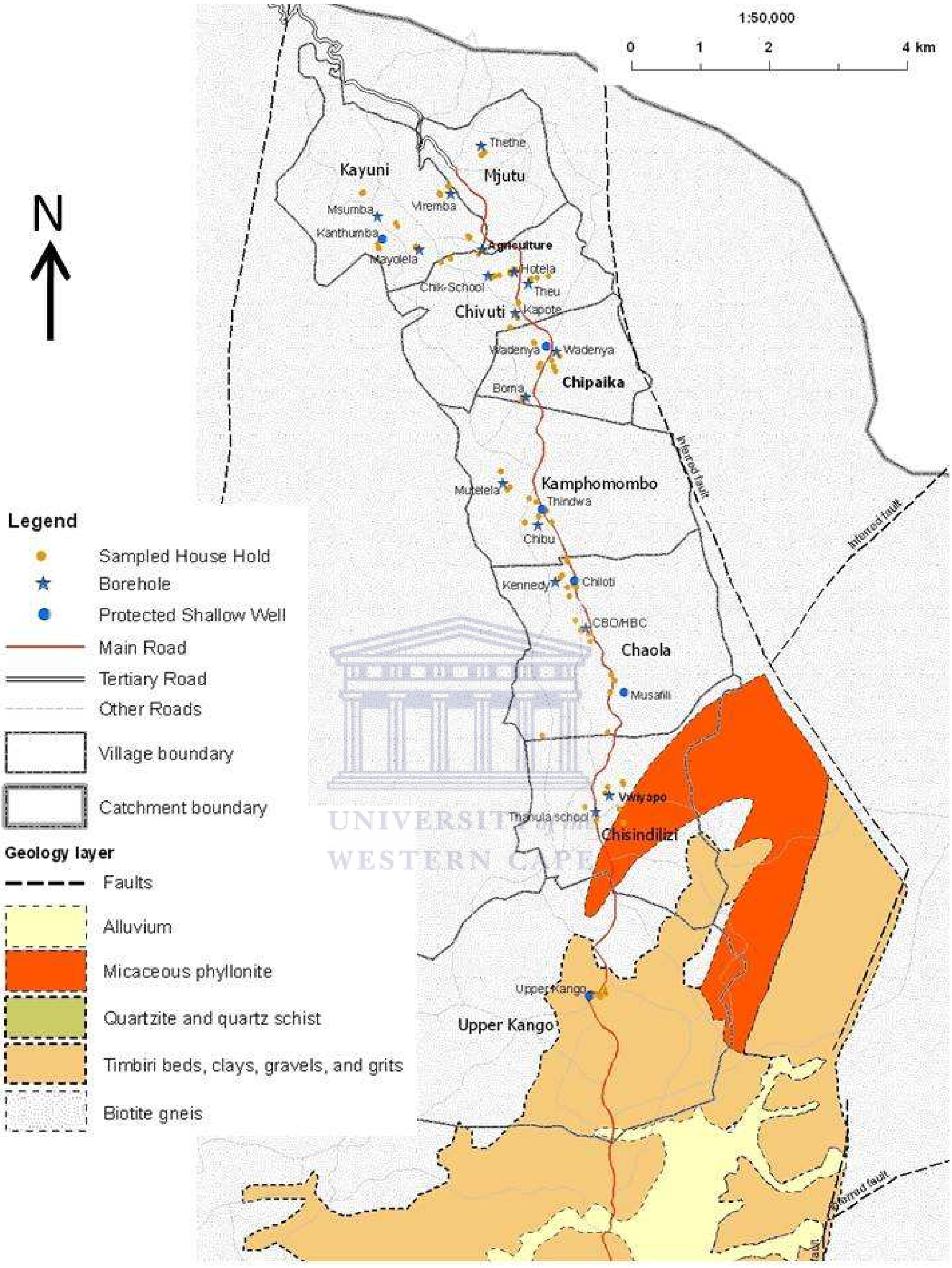


Figure 26: 6.3 How dominant geologic features influence groundwater availability

c) On topography, Stonestrom & Harrill (2007) empirically concluded that land-surface topography plays an important role in the recharge process of different types. Of importance, the authors showed that steep slopes tend to have low infiltration rates and high runoff rates hence lead to low recharge rates. They concluded that local relief, orientation/slope aspect and altitude of mountain ranges are additional topographical factors that influence the recharge process. In line with the results of these two authors, this study used satellite images (Fig. 6.4) to show the nature of topographic feature in the area. The study used observation methods to produce photos (Fig. 6.5) that revealed different topographic features that could be associated with recharge process in the area.

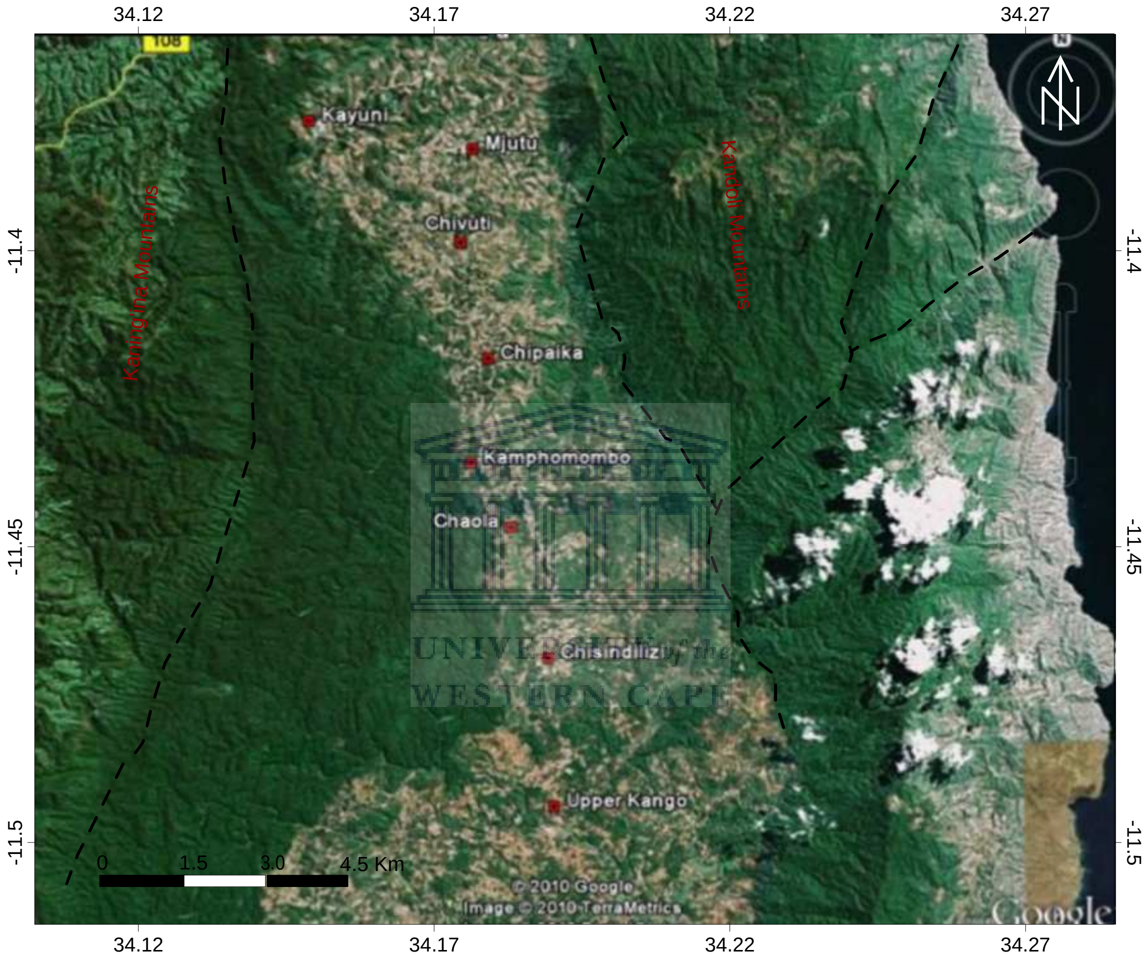


Figure 27: 6.4 influences of topography, land-cover and land-use on recharge process

Characteristics of topography, soils and subsurface geology show how groundwater becomes surface water (perennial streams in Fig. 6.6; Fig.6.1; Fig. 6.4). These are crucial as a starting point to understand groundwater-surface water interaction among scientists, developers, users and managers from the IWRM perspective. This study did not focus on groundwater-surface water interaction concept, but such knowledge in groundwater management is crucial to show factors that limit IWRM operation and to provide insights that would bring stakeholders together to facilitate successful IWRM.

Figure 28: 6.5 Influences of settlements, vegetation and land-use on recharge process

Results showed that although the study area is situated between two mountain ranges, Kandoli to the east and Kaning’ina to the west (Fig. 6.4), the area is neither a valley nor a flat land but an undulating plain. This suggests that the entire Upper Limphasa River catchment is a recharge area. In addition, although the study area experiences diffuse recharge as expected in the humid climatic region, the presence of fault line zones (Fig. 6.3) and fish and cassava soaking ponds (Fig. 6.5) indicates occurrence of preferential and focused recharge types. Such being the case, the recharge rate is expected to be high due to flux from such sites (Healy, 2008). However, the presence of gullies in steep slopes (Fig. 6.5), the dense tree coverage of the entire area (Fig.6.5) and the practice of settling on hilltops (Fig. 6.5) reverse the expected high recharge estimates. Though these findings are not conclusive, they provide i) useful insights on factors that control groundwater availability and ii) the basis to urge the prompt implementation of IWRM. Water scientists, users and managers need to share such knowledge as a starting point for robust water assessment, planning and management in a coordinated manner.

d) The hydrology of the study area as a factor for groundwater recharge has been shown in the conceptual model of the recharge process which considers both surface water and groundwater flow systems and the associated linkages (Fig. 6.1). The study observed that generally, streams in the catchment were many and were perennial in nature receiving groundwater discharge (gaining streams) (Fig. 6.6) and protected shallow wells were observed to be located at discharging sites (Fig. 6.7). The study found that fewer streams during the dry months of September to November had no flowing water and were described as losing streams suggesting that such streams provide recharge to groundwater. This study did not focus on hot springs but the presence of such hot springs in the middle Limphasa River catchment (Fig. 6.6) despite most of them being outside the catchment points to the need for expanding the scope of the current study on groundwater management in future research activities.

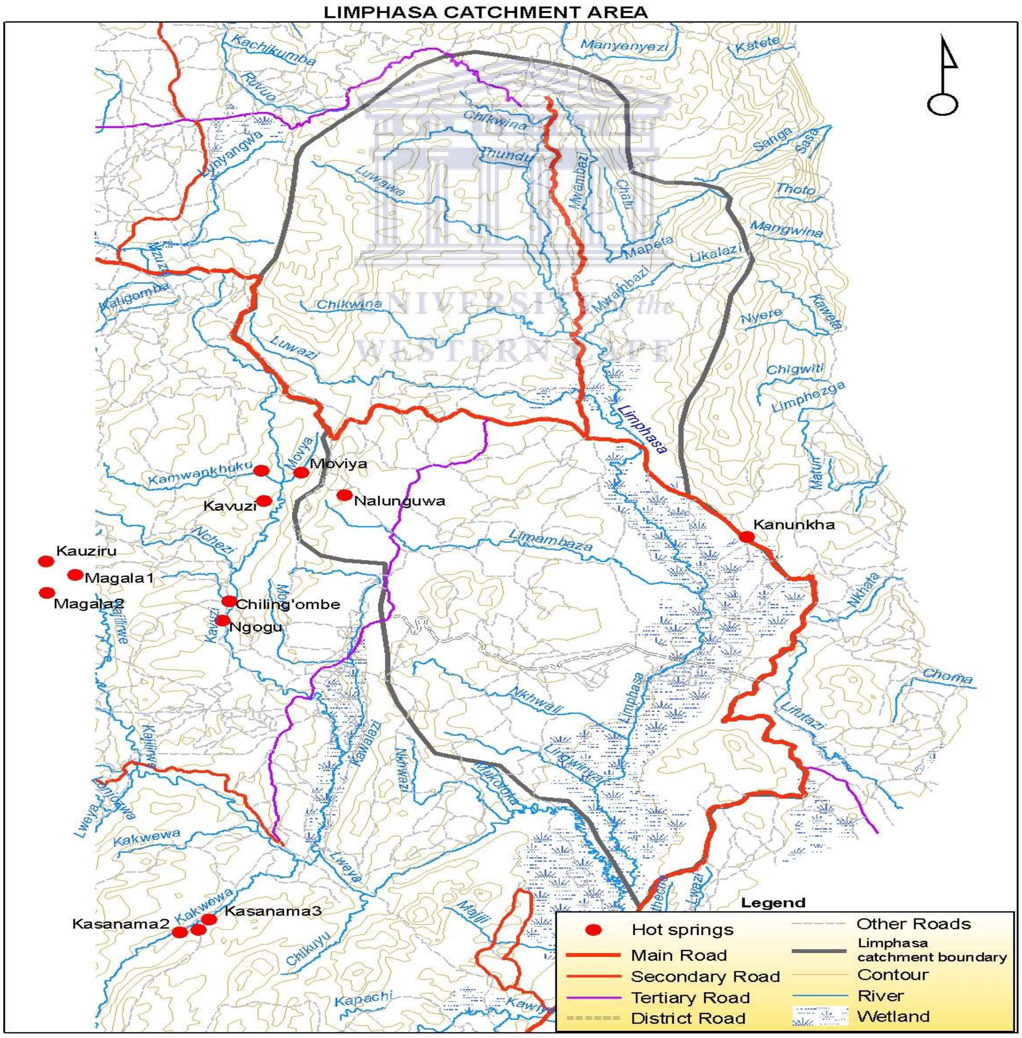


Figure 29: 6.6 Influence of groundwater on availability of network of streams

From the rainfall pattern described in section 6.4.3, recharge in Upper Limphasa River catchment is expected to be high but seasonal because of wetting fronts moving through the unsaturated zone which slow with depth and multiple fronts combines to become indistinguishable from each other (Robinson et al., (2008). Locating wells in such sites were said to be cost effective to most water developers (Mdhluli et al., 2009). However, this study showed that such groundwater sources do not provide safe drinking water (Fig. 6.7 from Kango protected shallow well). Pritchard et al. (2009) found similar results on drinking water from such sources in southern Malawi. This means that such sources are counterproductive to achieving the MDG goal on halving the number of people accessing potable by 2015. This study in chapter 7 has suggested the need for a new reflection by scientists, providers and managers of groundwater PSWs as sources for safe drinking water. Although several studies (Firth et al., 2010; Nath et al., 2006) have shown effectiveness of chlorine on similar water in other places, the existing chlorination methods in this study area have proved not effective due various reasons as discussed in chapter 7, agreeing with Tumwine (2005). Chapter 7 has shown how the use of such sources explains vulnerability of communities to ill human health.

E.coli presence in drinking water from PSWs located at groundwater discharge points

Figure 30: 6.7 Influences of sites for PSWs on groundwater contamination

e) **On Land cover and land-use**, recent studies (Leblanc et al., 2008 & Brunner et al., 2007) have shown that vegetation and land-use as factors have great influence on the recharge process. The authors state that types and densities of vegetation control patterns of evapotranspiration and abstraction rates. They confirmed that a vegetated land surface showed a higher rate of evapotranspiration than a none-vegetated land surface under similar conditions thereby explaining the less water available for recharging groundwater. They continued to argue that tree roots abstract water from deeper depth than shallow-rooted crops and that tree canopies intercept more rainfall. Their observations suggest that more dense forested areas reduce recharge rate while increasing discharge rate through tree-root abstraction and tree-canopy interception.

Field observations showed that the Upper Limphasa River catchment is largely covered with dense Brachystegia woodland followed by the Montane grasslands with forest remnants and semi-evergreen woodland (Fig. 6.9). The agricultural activities are subsistence farming which is dominated by perennial cassava and banana food crop with some maize gardens (Fig. 6.8 & Fig. 6.9). The type of vegetation cover in this study area suggests the expected low recharge rate, hence less groundwater availability. However, the understanding of the influence of such features on water availability among water scientists, water developers, water users and water managers at catchment level has positive potential influence on bringing them together for a successful IWRM implementation for sustainable utilisation of their water in the area.

Figure 31: 6.8 Relationships between land-cover/use with groundwater availability

The assessment by Leblanc et al., (2008) has shown that this type of vegetation contributes to reduction on the groundwater recharge process. It can be said that the study area is expected to have reduced recharge to groundwater hence less groundwater availability. Although the assessment by Leblanc et al., (2008) meets theoretical principles of scientific explanation, the reality is not that straightforward. For instance, the influence of vegetation is seasonal, decay roots/shrinking roots provide preferential recharge flow paths that speed up recharge rate and farming practices where ridges are made provide focused recharge areas that enhances recharge rates (Brunner et al., 2007). Field observations showed ponds and ridges in the gardens which form focussed recharge areas (Fig. 6.5 & Fig. 6.8). Such revelation forms the starting point of discussion with all villages in Fig 6.9 on how groundwater can be contaminated despite being available throughout the year. The ponds and ridges accelerate more water into the aquifer but such water might be contaminated with contaminants present in the ponds and ridges. In addition to cassava soaking/fish ponds and ridges in crop gardens, the geological method in Chapter 5 and Fig. 6.3 showed that the study area has fault zones that provide preferential recharge area. Fig. 6.4 & Fig.6.1 has shown that the entire study area is a recharge area because it is a highland with undulating plains.

Results have shown that the Upper Limphasa River catchment is a recharge area. Thus, managing water resources in such an area from the IWRM perspective is essential for upstream and downstream dwellers to utilise such waters sustainably for their socioeconomic growth and to maintain environmental integrity that sustains such waters. However, Todd and Mays (2005) suggested the use of remote sensing methods to consolidate results from field observation methods for better information on surface characteristics such as vegetation type, leaf area index and land use type that help interpret recharge mechanisms for visual understanding by all water stakeholders. Such stakeholders have varied knowledge, skills and experience about water aspects hence the need to start with field observation methods in a qualitative manner to gain consensus about the scientific knowledge that needs to be understood among all stakeholders for a coordinated management of water resources at the catchment level.

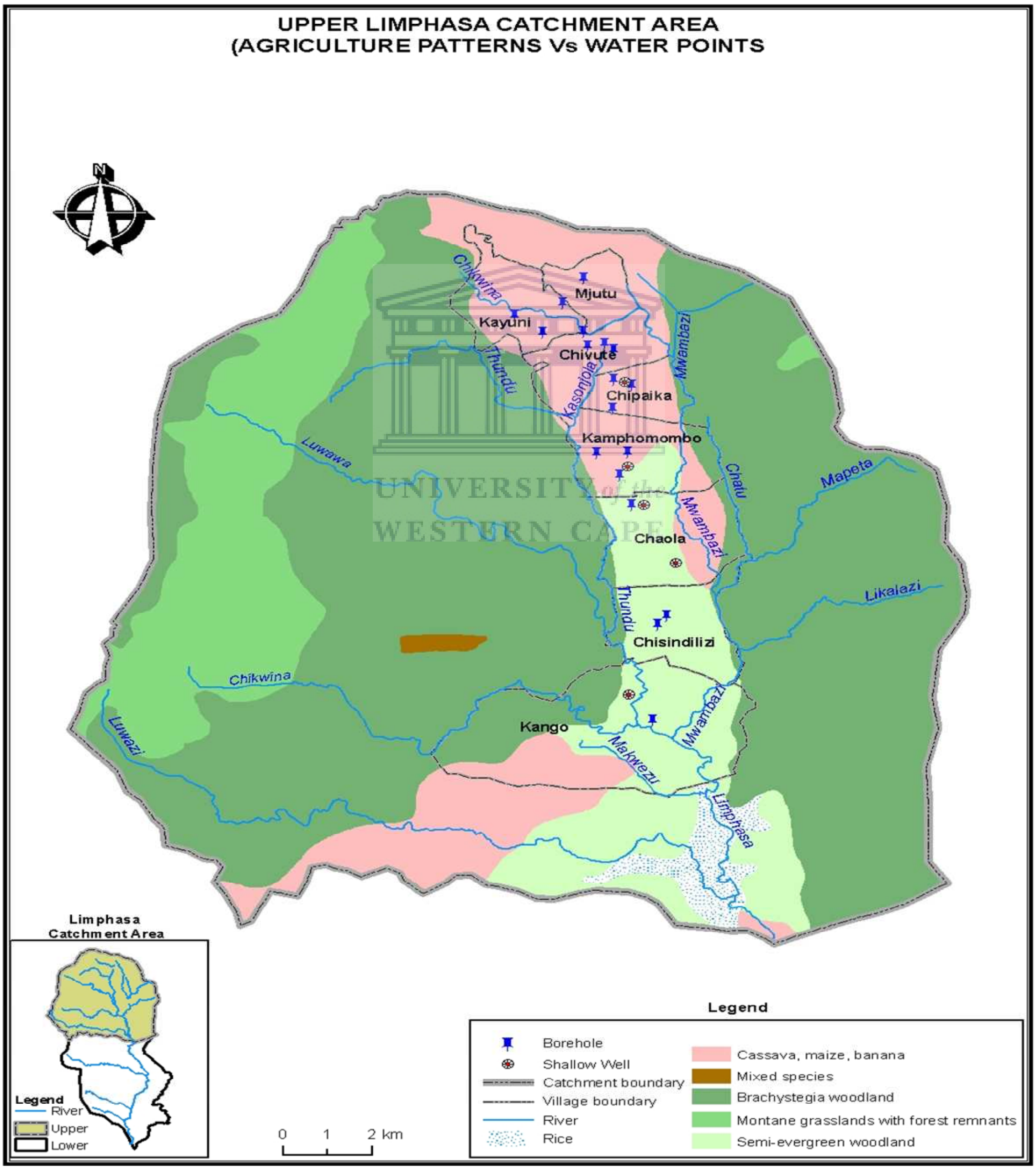


Figure 32: 6.9 Relationships between vegetation and land-use with recharge process

6.5 Procedure to generate data on domestic groundwater demand and use

This section demonstrates the procedure that was followed to generate statistics on demand and use of groundwater for domestic purposes at household levels in unmetered rural areas for effective management of water resources. The argument is that effective management of water resources such as groundwater should be based on quantitative understanding of water demand and use at household level in the catchment in terms of how statistics/data were generated. This section 6.5 provides parameters that were used to compute such statistics (6.5.1), data collection procedure on such parameters (6.5.2) and computational procedure that was followed to generate statistics on demand and use of groundwater (6.5.3). The reason for a detailed description on the procedure that was followed to calculate such statistics was to provide leeway for further refinement so that measures to allocate and manage water are based on quantitative analysis.

6.5.1 Indentifying parameters for a computational approach

This section provides parameters that were identified and used to compute statistics on demand and use of groundwater in the Upper Limphasa River catchment. The following were the identified parameters that were specified: i) settlements (households); ii) household size; iii) type of water source; iv) proportion of users; v) measured distance of users from water sources using Malawi Government recommended distance of household from water sources as a benchmark; vi) sanitation types; vii) amount of water requirement per person per day in litres; viii) amount of water use per person per day in litres. Reasons for choosing these factors are provided below:

The number of households that were available and habitable in the catchment during the time of fieldwork and number of people per household were documented through hydrocensus. The understanding is that water demand and use depend on the number of occupants in each household which determine the amount of water required and used per day due to their associated activities. In the Upper Limphasa River Catchment, the number of households was obtained from the National Census (NSO, 2009). For validation, a local census survey was conducted during the hydrocensus period and the latter was adopted for use in this study.

The types of water sources, number of households using a particular water source and types of sanitation facilities were identified and enumerated during hydrocensus using a questionnaire. Since this study focused on groundwater sources, only boreholes (BHs) and protected shallow dug wells (PSWs) were identified and enumerated. Pit latrines and pour-flush latrines were identified and enumerated to analyse the water use in such latrines. Only households using groundwater sources were identified and enumerated to assess the amount of groundwater abstracted from the aquifer per day. The focus on groundwater sources was based on the thinking that such sources provide safe water for drinking as documented in various literature sources.

The distance from households to groundwater sources for drinking such as BHs and PSWs were measured. This was roundtrip distance in metres using measuring tapes. Those households falling with 500 metres were considered near to their water source and those beyond 500 metres were considered far from their water sources (GoM, 2005; Baumann & Danert, 2008). Measuring the distance and proportion of households near and far from water sources for drinking was used to assess the status on access to safe water source in the study catchment. GoM (2005) defines access to a safe water as the number of people with minimum quantity of 36 litres of water per capita per day within a maximum distance of 500 metres from the source. Access is measured by assuming that a borehole serves a population of 250 people while a communal standpipe serves a population of 120 with no specified figures for those that use PSWs despite recognising such sources as safe sources (GoM, 2005 & GoM, 2007).

Current literature (Healy, 2010) shows that comprehensive statistics on groundwater abstraction (demand) and use are not available, although it is estimated that more than 1.5 billion people worldwide depend on groundwater for potable water supplies. However, about 1.1 billion people fail to have access to safe drinking water sources and many of these live in rural areas (Foster et al., 2000 & MacDonald, 2005). In Sub-Saharan Africa, 300 million people lack access to safe water supplies of which about 80% live in rural areas. In Malawi, although Malawi-MDG (2010) reports that 80% have access to improved sources of water, only about 40% access safe drinking water sources (Pritchard, et al., 2007). Although improved sources are better, safe sources provide potable water for improved human health (WHO&UNICEF, 2010), hence the focus of this study on safe sources. This principle informed this study to assess the amount of water abstracted from groundwater (water demand) and the amount of water actually used (water use) at household level per person per day, per household per day and in the sub-catchment per day. Although such calculations are not comprehensive, they provide useful insights on the amount of groundwater demanded (abstracted) and used in catchments with environments that are physically and socioeconomically similar to that of Upper Limphasa River Catchment.

6.5.2 Procedure and results on generating data for domestic water demand and use

This section presents the process that was followed to generate data on each of the identified parameters and findings thereof. During hydrocensus a questionnaire was used to record the total population, total number of households and average households' size, number of water types and number of pit-latrines in each of the eight studied villages. The findings are presented in two parts i) per each village and ii) the total for the sub-catchment (Table 6.1). Two boreholes, one in Kamphomombo village (at primary school) and one in Chipaika village (at Jumbo cluster) were dysfunctional and one protected dug shallow well in Upper Kango village (Mgodi-Mtalika cluster) dried up. Although, the study focused only on groundwater sources, it was noted that the three communal stand pipes present in the study area during the fieldwork, one in Upper Kango Village and one in Chisindilizi Village were dysfunctional and the one in Mjutu Village had no chlorination in the reservoir tank and users were warned not to drink such water. No household reported the use of pour-flush toilets hence only pit-latrines in Table 6.1 are presented as the available sanitation facilities.

Table 14: 6.1 Selected parameters for calculating domestic water demand and use

Selected variables	**Results from villages in the Upper Limphasa River Catchment**								
	UKA	CHI	CHA	KAM	CHIP	CHIV	KAY	MJU	Total
Total households	42	173	99	54	109	74	38	100	689
Ave household size	6.0	5.4	5.3	5.9	6.0	5.5	4.9	5.2	5.525
Water source (BHs)	0	2	2	2	3	3	2	3	17
Water source (PSWs)	1	0	2	1	1	0	1	0	6
Pit-latrines	33	110	76	53	88	54	26	76	516
Population	253	940	527	316	650	408	188	523	3805

UPKA=UpperKango;CHI=Chisindilizi; CHAO=Chaola;CHIP=Chapika; CHIV=Chivuti; KAY=Kayuni; MJU=Mjutu

The NSO (2009) revealed that Malawi has 12,615,298 persons in regular households with 461,862 in institutions and homeless. There were 2,869,933 households. Of these, 44% were traditional, 34% were semi-permanent and 22% were permanent reflecting the rural nature of the country. The average household size for Malawi was 4.6 with variation of 5.2, 4.7 and 4.4 for the Northern, Central and Southern provinces respectively (NSO, 2009). Results for the study area showed that the average household size was 5.5 with 689 habitable households and a population of 3805 (Table 6.1).

To generate statistics on domestic water demand and use at household level in the Upper Limphasa River catchment, the following procedure was followed: Water demand in this study referred to the amount of water abstracted from groundwater sources and carried to respective households per day (Wallingford, 2003; Healy, 2010; Molden, 2007). Water withdrawers carry their water largely in plastic pails (Fig. 6.10). To compute water demand, the water in water collectors' containers was poured in 20-litre calibrated plastic bucket and readings were recorded. This was done for all sampled households. To measure the actual water use, the unused water from the previous collection was measured in the 20-litre calibrated plastic bucket. The recorded amount of unused water was subtracted from the water collected water (demand). The difference was the water that was actually used. We computed for these three categories, namely, water abstracted (water demand), water actually used (water use) and the unused water (left over water or excess water) and entered the statistics into SPSS software for computation. The computations were at three levels: a) water demand per person per day, water demand per household per day and water demand per sub-catchment per day; b) water use per person per day, water use per household per day and water use per sub-catchment per day; c) water unused per person per day, water unused per household per day and water unused per sub-catchment per day (Table 6.2).

To simplify the process, the average water demand, water use and water unused per day per household was crucial to be computed. After computing that figure, when divided by the average household size, it gave us the water demand or water use or water unused per person per day and when that number was multiplied by the total number of households in the study area, it gave us the water demand, water use and water unused per sub-catchment per day Table 6.2). Such results were compared with the methodology that Wallingford (2003) proposed to calculate water demand and water use for sub-catchments as applied in River Kadzi sub-catchment in northern Zimbabwe. For comparative analysis the Wallingford approach has been applied in this study and results in section 6.5.3 (Table 6.3) show no major difference but his method is cumbersome. However, the implication of the procedure and the generated statistics are discussed in terms of their importance to improve calibrating models that estimate water demand and use especially groundwater resources at catchment scale.

Table 15: 6.2 Average rural domestic water demand and use in litres per day

Domestic Water categories	Person per day (litres)	Household per day (litres)	Sub-catchment per day (litres)
Water demand	21.2	116.91	80,550.99
Water use	16.8	92.55	63,766.95
Water unused	4.4	24.36	16,784.04

NB: Average household size was 5.525 and total households were 689 (Table 6.1)

Figure 33: 6.10 Collecting drinking water from sources using plastic containers to HHs

6.5.3 Computing rural domestic water demand and use

Direct and indirect methods are the two main methods used to assess water demand and use for domestic purposes in rural areas at catchment level. Direct methods use socio-economic surveys and participatory techniques by involving relevant stakeholders to estimate the current and future water demand and use. The focus is to predict the future trend based on the present pattern. The basis for promoting direct method approaches is supply-driven projects, where water is simply delivered to communities with little or no involvement of community members (Alcock, 1986). Direct methods are primarily designed for detailed planning of rural water supply schemes such as feasibility and design studies which are typical of the engineering approach to water development (Webster, 1999). This study used the IWRM approach whereby involving community members to manage their water was considered essential for sustainability (institutional principle of IWRM). Thus, the direct method was considered unsuitable for this study.

In this research, the indirect methods were used to compute the quantity of water consumed from population levels and then estimate demand levels in terms of per capita consumption. Alcock (1986) observed that in general, estimating rural water demand and use is difficult because of: i) many of the rural water supply systems are unmetered, ii) data concerning domestic water demand and use are often expensive to generate and time consuming to collect and iii) the level of service provided by the water supply system is often unknown. This observation was the basis of the current study which focuses on demonstrating a methodology of generating data on demand and use of water in unmetered rural areas. For effective management of water resources at catchment level, indirect methods are the most appropriate for establishing the total rural domestic water demand and use (Turton et al., 2001). This approach considers the total households in the study area, the average households size, the proportion of the households that are located below and above the national set maximum distance from water sources and the amount of water required and used per person per day in that catchment. The computation from such an approach provides the total rural domestic water demand and use for either the entire catchment or the sub-catchment. Such information when shared among scientists, developers, users and managers of water resources has the potential to manage water effectively from the IWRM perspective.

Since the current study focused at assessing factors that explain the limited implementation of IWRM using groundwater management as a case study, indirect methods were used to generate statistics on rural domestic groundwater demand and use in the Upper Limphasa River Catchment. The aim was to demonstrate the feasibility of such methods as an entry point for lobbying the successful excution of the IWRM approach. Kgathi (1998) cautions that the accuracy of a demand assessment is a tradeoff between the budget needed for an accurate demand assessment and the predicted usefulness of the results obtained from such an assessment. Based on Kgathi’ thoughts, the computational procedure with associated statistics presented on the Upper Limphasa River catchment below provides useful insights and platform towards implementing successful IWRM principles where water managers, water users, water developers and water scientists would use such findings as a starting point in their collaborative efforts.

Wallingford (2003) suggested applying an indirect method to calculate rural domestic water demand and use for the effective management of water resources at the catchment level. To apply the suggested formulae presented below, the number of water users above and below the maximum set standard by Malawi was added to the factors used to compute domestic water demand and use in section 6.5.1. That proportion of users per specified water source versus distance from their households was established through the hydrocensus where respondents were interviewed on the number of people accessing water sources and the associated reasons for such access. This was followed by field observation to validate the reported responses. Distances from sampled households to water sources were measured using measuring tapes (Figure 6.13).

In Malawi, one groundwater source serves 250 people and the required maximum distance from the water source to a household is 500 metres (GoM, 2005; Baumann & Danert, 2008). The principle in access to safe water is that the distance from the household to water sources influences the amount of water demanded and used at household level which has implications on improving human health and their productive livelihoods. Wallingford, (2003) in differentiating water use and water demand, stated that although the two have different conceptual meanings, in reality, water demand refers to water consumption or water that is abstracted or withdrawn from its source while water use refers to the actual use of water after being abstracted from the source. He gave an example that within rural parts of southern Africa, theoretical water demand considerably exceeds the actual water consumption. As operational definitions in this study, water demand refers to water withdrawals or water abstracted from groundwater sources and water use refers to actual water consumption at household levels.

Applying Wallingford (2003) indirect method to this study, findings indicated that 63% of households were located within 500 m from water sources and such households were using pit latrine for sanitation. The averages of water demand and use per person per day in those households were 21.2 and 16.8 litres respectively (Table 6.3). The averages of water demand and use per household per day were 116.91 and 92.55 litres respectively (Table 6.3). The Malawi Government recommends 36 litres per person per day while the international standard recommends 50 litres per person per day (Baumann & Danert, 2008; Gleick, 1996).This study assessed the compliance to both guidelines as a starting point for water allocation in the instrument principles of the IWRM approach.

Table 16: 6.3 Water demand, use and unused in litres with distance from sources

	HHs <500m from water source (63%)			HHs >500m from water source (37%)		
	Demand	Use	Unused	Demand	Use	Unused
Per Person	21.2	16.4	4.7	21.1	17.3	3.8
Per HH	117.0	90.8	26.2	116.8	95.6	21.2
At SC level	6,786.0	5,266.4	1,519.6	3,971.2	3,250.4	7,20.8

The computational approach that was adopted for calculating the total rural domestic water demand and use for the Upper Limphasa River catchment using the indirect method as suggested by Wallingford (2003) gave the following results:

a) Water demand = Water demand for households that are located more than 500 m away from a groundwater source x number of households x average households size x water demand per capita = 0.37 x 689 x 5.5 x 21.1= **29,584.6265 litres per day** plus water demand for households that are located less more than 500 m away from a groundwater source x number of households x average households size x water demand per capita = 0.63 x 689 x 5.5 x 21.2 = **50,612.562 litres per day.** Therefore, the total rural domestic water demand for the Upper Limphasa River catchment is estimated at **80,197.1885 litres per day.**

b) Water use = Water use for households that are located more than 500 m away from a groundwater source x number of households x average household size x water use per capita = 0.37 x 689 x 5.5 x 17.3 = **24,256.5895 litres per day** plus water use for households that are located less than 500 m away from a groundwater source x number of households x average household size x water use per capita = 0.63 x 689 x 5.5 x 16.4 = **39,153.114 litres per day**. Thus, the total rural domestic water use for the Upper Limphasa River catchment is estimated at **63,409.7035 litres per day.**

c) Unused withdrawn water = Unused withdrawn water for households located more than 500 m from a water source = 0.37 x 689 x 5.5 x 3.8 = **5,328.037 litres per day** plus unused withdrawn water for households located less than 500 m from a water source = 0.63 x 689 x 5.5 x 4.7= **11,220.7095 litres per day.** Therefore, the total rural domestic unused withdrawn water for the Upper Limphasa River catchment is estimated at **16, 548.7465 litres per day.**

From the procedure provide above on how computational procedure in the indirect method are conducted, this study provided a simplified version of such an indirect method by focusing on fewer parameters, namely, water demand, water use, total households and household size. The computation with such fewer parameters yielded similar results (Table 6.4). In this way, our proposed approach was cost effective and pragmatic to implement. It is also modern based on scientific principles of systematic field measurements accompanied with statistical analyses using the IBM SPSS software version 19 with robust quality control tests before analyses (section 6.6.3.2). With such fewer computational steps, the proposed approach is deemed acceptable socially and politically among water stakeholders, namely, water researchers, water users, water providers and water mangers. In that way, our approach provided one step towards facilitating a successful IWRM implementation as it forms a platform to discuss and implement collaborative efforts among stakeholders in the catchment.

Table 17: 6.4 Comparative results from our method and that of Wallingford (2003)

Results when Wallingford (2003) approach was applied on our data set (litres)						
	HHs <500m from water source (63%)			HHs >500m from water source (37%)		
Categories	Demand	Use	Unused	Demand	Use	Unused
Per Person	21.2	16.4	4.7	21.1	17.3	3.8
Per HH	117.0	90.8	26.2	116.8	95.6	21.2
Sub-catch	50,612.6	39,153.1	11,220.7	29,584.6	24,256.6	5,328.0

Results when the proposed approach in this study was applied on our data set (litres)			
Categories	Water demand	Water use	Unused water
Per person	21.2	16.8	4.4
Per HH	116.91	92.55	24.36
Sub-catch	80,550.99	63,766.95	16,784.04

HH= Household; Sub-catch= Sub-catchment. All calculations in the table are per day(daily basis)

Agreeing with our proposed approach, Wallingford (2003) reported that methodologies to assist planners and managers to assess availability of water resources in catchments exist, although methods to generate data for such methods are scarce. However, little is available to assist in assessing water demand and use especially domestic water demand and use in rural unmetered environments. Hence, the current study aimed at contributing to narrow such a gap by demonstrating the application of the available indirect method with observation field data and modified its computational procedure. The modified approach has shown how rural domestic water demand and use can be computed with fewer parameters but producing similar results to indirect methods (Table 6.4).

Table 18: 6.5 Monthly and yearly water demand, use and unused in Upper Limphasa

Water consumption per time in litres (day, month, year in litres)	Categories of water consumers (water in litres)		
	Per person	Per household	Per sub-catchment
Water demand per day	21.20	116.91	80,550.99
Water demand per month	636.00	3,507.30	2,416,529.70
Water demand per year	7,632.00	42,087.60	28,998,356.40
Water use per day	16.80	92.55	63,766.95
Water use per month	504.00	2,776.50	1,913,008.50
Water use per year	6,048.00	33,318.00	22,956,102.00
Water unused per day	4.40	24.36	16,784.04
Water unused per month	132.00	730.80	503,521.20
Water unused per year	1,584.00	8,769.60	6,042,254.40

Table 6.5 shows that although statistics for water demand, use and unused per person, per household and per sub-catchment per day are relatively small, such statistics are huge when analyses are conducted on monthly and yearly basis. The Upper Limphasa River catchment being a sub-catchment, such statistics provide significant key insights on how much groundwater is abstracted, used and abstracted but not used at sub-catchment level. Such revelation is important in the context of increasing population with their associated demand for water to meet their livelihoods activities and also with the increasing effects of climate variability/change on water resources especially on groundwater resources. These insights justify the need for managing water resources including groundwater from the IWRM perspective for sustainable utilization.

To strengthen the above argument, regression model in SPSS software using water demand, use and unused as dependent variables could have been used to correlate with population, and climate change factors (average temperature and rainfall) as independent variables. This could have assessed the direction and magnitude of climate variability effects on water demand and use. The results would have helped to suggest effective adaptation measures at local level so that people’s livelihoods are not seriously affected by effects of climate variability. Unfortunately, there were no adequate temperature and rainfall data for the Upper Limphasa River catchment that would have enabled such calculations. Nevertheless, this study has revealed the need to have such database to enable assessing detailed daily, monthly and yearly water consumptions pattern at sub-catchment level. Mohamed & Al-Mualla (2010) used SPSS software to calculate water demand and actual water consumption in United Arab Emirate and found that such calculations provide bases for forecasting scenarios on water demand and use in the water supply sector. This research suggests further studies on water demand, use and unused at household and catchment levels for detailed analysis using the data generation procedure provided in this study.

6.6 Assessing determinants for demand and use using regression analysis

To estimate factors that determine rural domestic water demand and use at household level, a traditional water demand model was used using regression analysis.

6.6.1 Description of how data was collected for regression analysis

Hydrocensus was conducted where the household questionnaire which consisted of five parts was used to assess the factors that influence groundwater demand and use at household level in Upper Limphasa River catchment. The first part of the questionnaire dealt with institutional management of groundwater in terms of collaboration among water developers, water users and water funders/managers; the second part focused on water policy and water laws in terms of awareness, implementation and enforcement; the third part dealt with water demand and use in terms of asking the amount of water withdrawn/abstracted/collected (water demand) from the groundwater sources for each sampled household and the amount of water used at each sampled household. Both the reported water demand and use were then measured in litres using the calibrated 20/litre plastic pails. Questions on factors that influence such demand and use were also asked from the same sampled households as explained in chapter 4. Part four of the questionnaire consisted of questions on the respondents' perceptions of the water quality from groundwater sources. The last part addressed with demographic, educational and settlement pattern aspects of respondents in the sampled households. The regression analysis was used to estimate the significant factors that influence the groundwater demand and use from the reported responses.

6.6.2 Determining factors in computational procedure of regression analysis

Our dependent variable for water demand is the amount of water (litres) carried home per day by household members divided by the total number of individuals in the household (water demand per capita per day). For water use, the only difference is the amount of water actually used per individual per household per day and the rest remain the same. We have used the Multiple Regression Analysis Model (MRAM) as a traditional water demand model in which our dependent variable is hypothesized to be a function of the following independent variables:

Table 19: 6.6 Explanations on expected signs and direction on independent variables

Variables	Explanation on expected sign and direction in the regression model
HH SIZE	Households with more people were expected to demand & use more water.
EDU	Households with formal education were expected to demand & use more water.
PWOMEN	Households with more women than men were expected to draw (demand) & use more water since water collection is the duty of women in this area. Results showed that (98.9%) were women collecting water from sources.
SRELIABILITY	The source that produced water all year round was expected to attract more users. Availability of water at source all year round was expected to result in high demand hence frequent use meaning more water withdrawn.
GWQUALITY	HHs that perceived good quality of water from source were expected to have high demand and high use of such waters.
DISTANCE	Households located more than 500 metres round trip from groundwater sources, are expected to demand less water and use less water because long distance leads to low demand and low water usage at household level. In Malawi maximum distance from HH to source must be 500 metres.
WPCOMMITTEE	Presence of water point committee indicated active community involvement in managing water demand and use to ensure sustainable utilization.
REGULATIONS	Number of respondents who showed awareness of water laws implied possibility of complying to such laws when water point committee members enforce them.
EFFECTIVE USE	Number of people using source indicated effective use of the source when compared with recommended users per source (Government of Malawi 2005 recommended that 250 people should use one groundwater source).

From Table 6.6, first, households with more people **(household size**) were hypothesized to use more water per capita because activities of many people require more water (Qn.45: How many people live in this household that use this water?). Secondly, we assumed that households with **formal educated members** will demand and use more water because formally educated people are expected to be more aware of health benefits of water use (Qn46: What is the educational level of members of this household? Thirdly, since more female members of households in Upper Limphasa Catchment were water collectors (Fig. 6.11), we expected that households with more female **(women)** members would demand /withdraw and use more water (Qn 47. Is water used at this household drawn by male members or females members?). The theory of consumer demand suggests that more women per household to collect water implies cheaper labour cost due to opportunity cost of labour as the value of time and distance spent on collecting water decreases, so we expect more water to be collected for households with more women.

Figure 34: 6.11 Women at water source collecting water and carrying it home

Fourthly, we anticipated that households that reported that their water source produces water throughout the year **(source reliability)** to draw and use more water than those households that reported unreliability of their water sources. (Qn49. Is the source where you draw drinking water reliable i.e. does the source produce water all year round?). Source reliability was used as an indicator of water availability in the study area because if sources produce water all year round, then the yield was assumed sustainable in the catchment as described in Chapter 5. Fifthly, households that reported that the **quality of water** from their sources was good were expected to draw and use more water than households that believed that such water was of poor quality (Qn55: Does the source where you draw drinking water produce water of good quality?).

Sixthly, on the basis of consumer theory about the **influence of distance**, we expected households located further (>500m) from water sources to use less water compared to households located <500m from water sources. Theoretically, longer distances from water sources increase in real costs (time for round trip walking and waiting time) at household levels to collect such water. **Distance** in villages were captured through household survey (Qn51: Is the source where you draw water for drinking far? i.e. more than 500meters?). To validate such responses, we actually measured such distances using measuring tapes (Fig. 6.12) from sampled households and compared results. Field measured results were utilised to avoid errors from under-reporting and over-reporting responses from questionnaires to distort the study findings.

Figure 35: 6.12 measuring distance from water sources for sampled households

Seventhly, we assumed that households that knew that **water point committees** existed in the villages were expected to draw and use water more efficiently than those that reported ignorance of such committees. Committee meetings were expected to clarify water management practices and enforce water regulations (Fig 6.13). Using the argument of Swallow et al. (2006) on local institutions one sees that adoption of behaviour is a function of intent and that intention is determined by people's attitude such as expected benefits or losses, we assessed their knowledge of water point committee in their area and how such committee works to facilitate operation and maintenance of their water sources for sustainable utilization through users contribution of money. (Qn66: Do you have a water committee for this water source?).

Eighthly, we anticipated that those who know existence of **water regulations** on use and management of water sources were expected to use water more effectively than those that reported ignorance of such laws. This is because acknowledging existence of water laws would entail expectation of enforcement and compliance with such laws thereby ensuring optimal sustainable use of water resources. (Qn64: Do you have regulations on the use and management of this water source?) Lastly, we assumed that safe sources of water attract more users, hence, those who reported that safe water sources are used effectively were expected to draw and use more water from such sources than those who reported **ineffective use** of safe sources. (Qn60: By observing number of users, do you think people in this village use safe water sources effectively i.e. do many people use safe sources?)

Figure 36: 6.13 Water-point committee meetings at water sources

6.6.3 Findings on factors for water demand and use using regression analysis

This section presents results on the multiple regression analysis where SPSS software version 19 was used for computation. First, using the coefficients, the correlation matrix shows direction and magnitude of the correlation between the dependent and independent variables for both demand and use (6.6.3.1). The best and significant predictors of demand and use of water at household in unmetered rural area were provided. Second, to ensure quality control on regression analysis model, tests of multicollinearity to check redundant variables, linearity to check outliers and normality to check normal distribution of population sample are presented (6.6.3.2). Thirdly, the full model output on multiple regression analysis showing determinants of water demand and use at household level is presented (6.6.3.3). A brief discussion on the theoretical basis for using hierarchical multiple regression analysis is provided (6.6.3.4).

6.6.3.1 The correlation matrix for estimation of the regression model

To check the best and significant predictor of water demand and use at household level in unmetered rural areas, Table 6.7 showed that household size was the best predictor of both water demand and water use while education variables were only significant in water demand and not water use. Predictions of dependent variables (water demand and water use) were accomplished by the following equations:

$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + ... + b_9X_9$ (Equation 1: domestic water demand)

$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + \dots + b_9X_9$ (Equation 2: domestic water use)

Where Y = Dependent variable; b_0 = constant/intercept; b = coefficient; $X_1 \ldots X_9$ = Independent variables (HHS, EDU, PWOM, SREA, GWQU, DIST, WPCO, REGU, EUSE)

Table 20: 6.7 Estimating determinants of rural domestic water demand and use

Independent variables	Domestic Water demand		Domestic Water use	
	Coefficient	Significance	Coefficient	Significance
Household size (HHS)	0.330	**0.002****	0.409	**0.000*****
Education (EDU)	0.212	**0.042***	0.153	0.134
Proportion of women (PWOM)	-0.066	0.517	-0.079	0.432
Source reliability (SREA)	0.156	0.146	0.080	0.448
Groundwater quality (GWQU)	-0.034	0.746	0.039	0.708
Distance from source (DIST)	0.103	0.330	0.147	0.158
Water point committee (WPCO)	0.123	0.284	0.104	0.356
Regulations on water (REGU)	-0.018	0.879	-0.096	0.406
Effective use of water (EUSE)	0.099	0.342	0.030	0.774

***Low Significance; **Medium significance; *** High significance at 5% level.**

The variable HHS, the number of persons per household (household size), had the expected positive sign and was the only explanatory variable which was significant at 5% level in both demand and use models (Table 6.7). EDU variable was only significant in the demand model but not in the water use model. The rest of the variables were not statistically significant at 5% level although they had expected positive signs except PWOM, REGU in both models and GWQU in demand model. These results showed that some variables that explain water demand and use in rural areas were not captured in the current model which agrees with the observation by Mu et al., (1990) in Kenya.

6.6.3.2 Quality control on the regression analysis

Our regression model could have suffered from multicollinearity problems because of the nature of the independent variables that were used to characterise household responses. If explanatory variables are not orthogonal, one might be a proxy for another (Mu et al., 1990). To solve the problem of multicollinearity, we calculated correlational coefficient matrix (Table 6.8) for the independent variables as one of the techniques for testing the presence of multicollineariy. Results showed that the data sets that were used for this study did not yield the problem of multicollinearity (Table 6.8) meaning there was no situation where the correlation of two independent variables was 1 or -1.

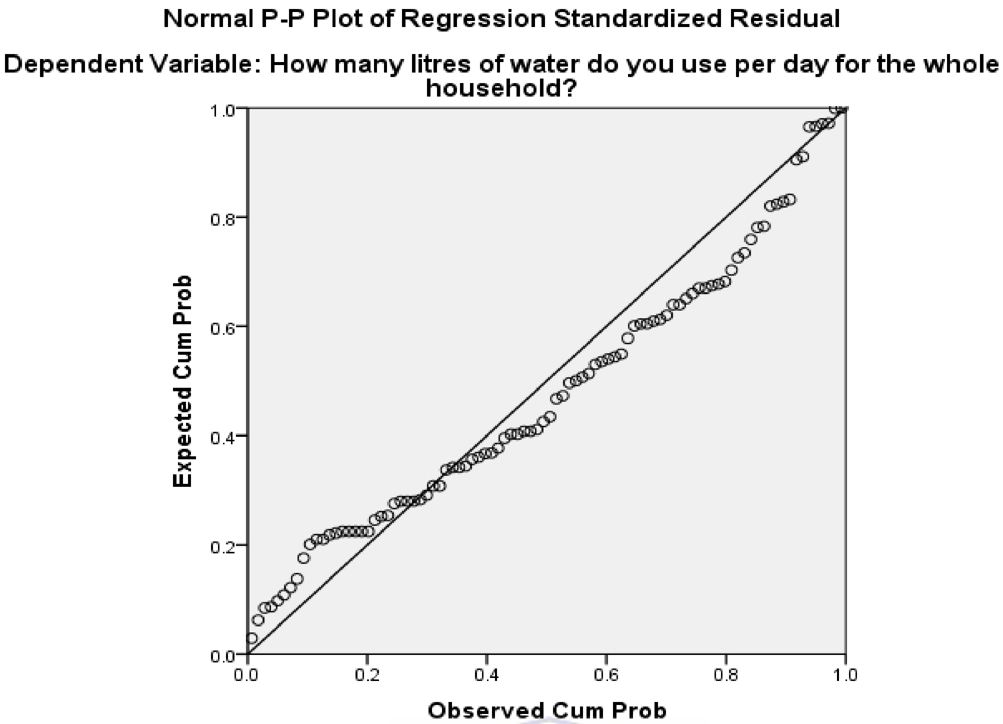
Table 21: 6.8 Correlation coefficient matrix for multicollinearity

	HHSI	EDUC	PWOM	SREA	GWQU	DIST	WPCO	REGU	EUSE
HHSI	1.00								
EDUC	0.020	1.00							
PWOM	0.074	-0.020	1.00						
SREA	0.140	-0.005	0.209	1.00					
GWQU	0.055	0.046	-0.040	-0.121	1.00				
DIST	-0.060	0.261	0.030	-0.013	0.011	1.00			
WPCO	-0.129	0.088	0.008	0.141	-0.009	0.210	1.00		
REGU	0.079	0.042	-0.026	-0.032	-0.275	-0.060	-0.425	1.00	
EUSE	-0.109	-0.008	-0.120	-0.238	-0.012	-0.099	-0.009	-0.115	1.00

In this study it was assumed that the relationships between dependent variables (water demand and water use) with independent variables (HHS, EDU, PWOM, SREA, GWQU, DIST, WPCO, REGU, EUSE) were linear. To test that assumption of linearity, a scatter plot was used. Results in the normal P-P plot of regression standardized residual (Fig 6.14) confirmed the linear relationship between the two dependent variables and the independent variables (predictors).

The sample population was assumed to have followed Gaussian (normal) distribution. The multiple regression computation assumed the same. That normality assumption of the sample population was tested using the histograms. Results confirmed that indeed the sample population followed Gaussian distribution pattern i.e. the sample for both dependent variables were distributed normally as displayed by the two histograms (Fig. 6.15) with mean = 2.34E-16, Standard deviation=0.949 and N=92. The three tests provided the confidence in the interpretation of computational output from multiple regression analyses using SPSS software (Statistical Package for Social Scientists).

In summary, to ensure quality control of the regression analysis, tests on assumptions of multicollinearity, linearity and normality were conducted and results showed no violation to such assumptions (Table 6.8; Fig. 6.14 & Fig.6.15) suggesting that results from regression analysis model were reliable and valid for appropriate interpretation.



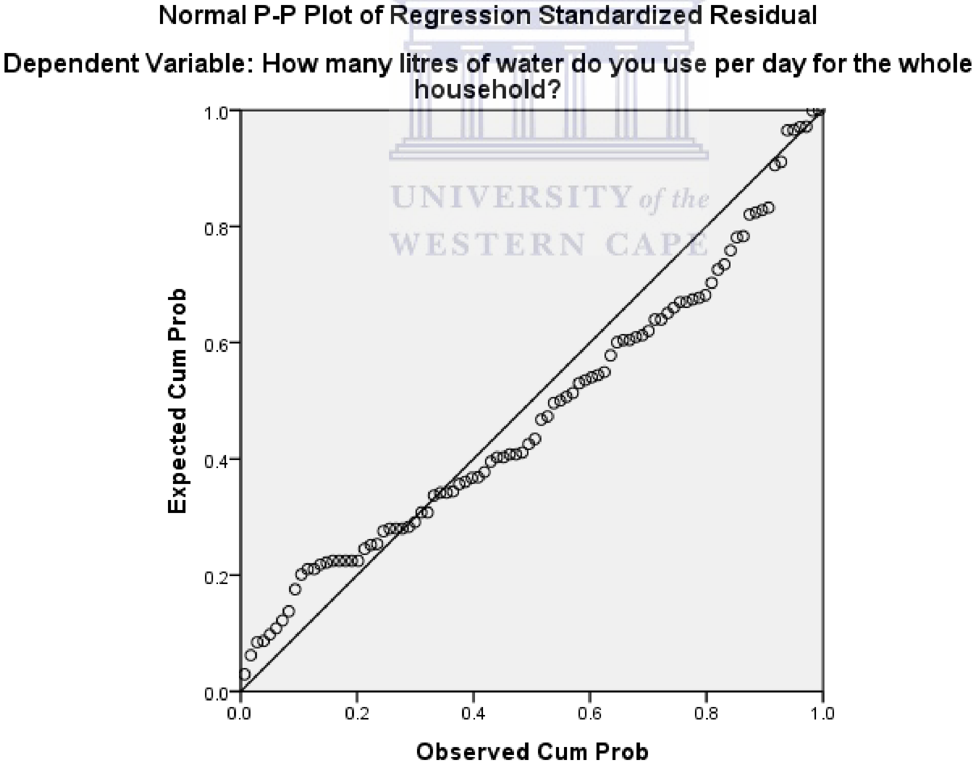


Figure 37: Results from testing linearity assumption for regression analysis

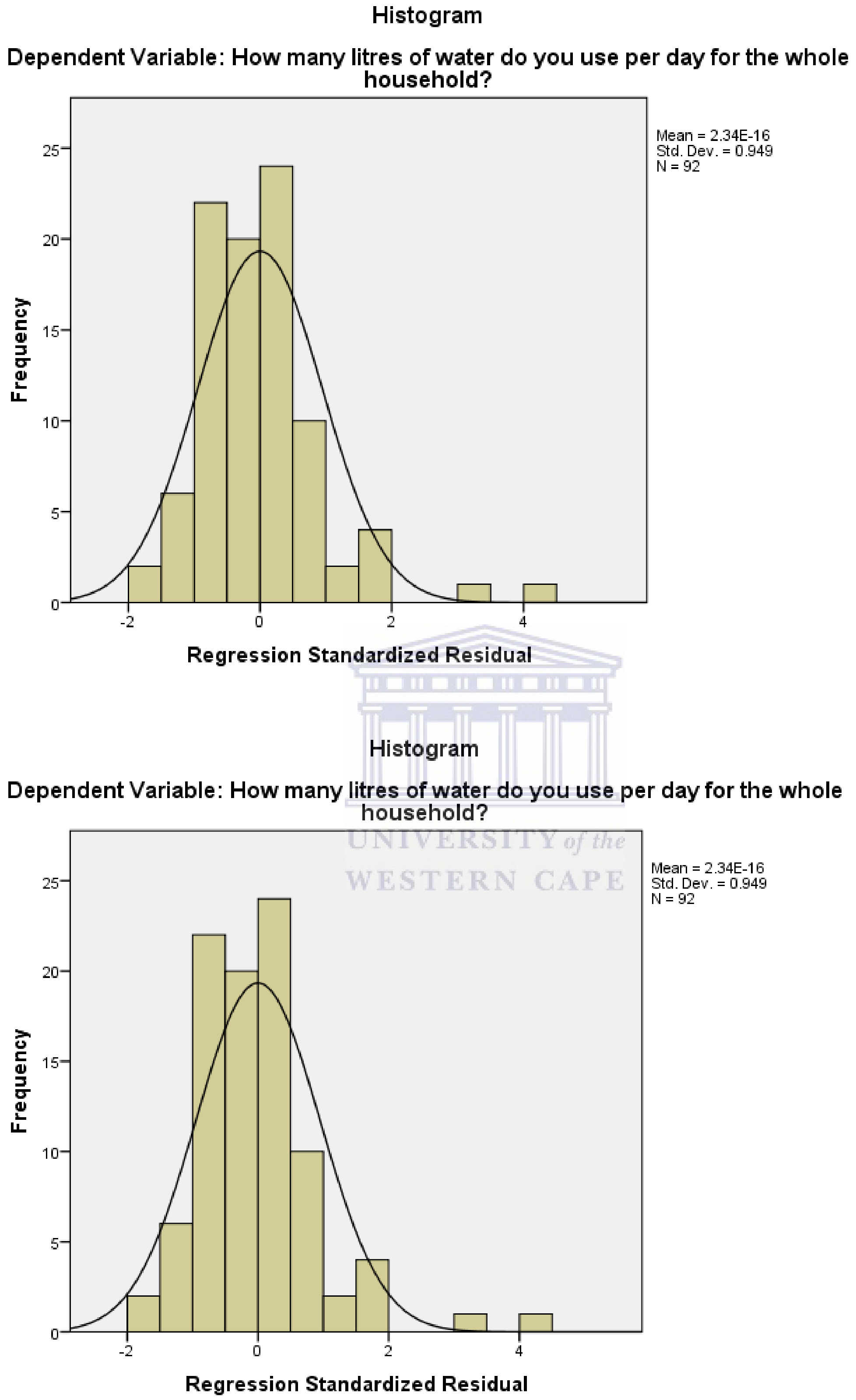


Figure 38: 6.15 Results from testing normality assumption for regression analysis

6.6.3.3 Multiple regression analysis results on water demand and use determinants

The multiple regression analysis showed that the full model was statistically significant at 5% level i.e. **0.020** for water demand model and **0.008** for water use model (Table 6.9). However, only 12% and 15% of factors in the model explain the demand and use of water at household level respectively in rural unmetered areas as shown by the values for adjusted R squared (Table 6.9). The standard error of estimate column provides a rough clue on the outcome of the Adjusted R squared. Hastie et al., (2001) observed that such low adjusted R squared are usually due to a small number of variables being predicted while Dobson (1990) argued such results partly show that theoretical planning on predictors for dependent variables were weak during research design while Darlington (1990) believed that variance of some predictors result in the small observed R Squared. Agreeing with Dobson (1990) and Darling (1990), our stand suggests improving selection of parameters during research design as we acknowledge the science of uncertainty when interpreting results of a model (Good & Hardin, 2009).

Table 22: 6.9 Regression analysis results on determinants of water demand and use

					Change statistics				
Model	R	R^2	Adjusted R^2	Standard error of estimate	R^2 Change	F Change	df1	df2	Sig. F Change
1.Demand	0.45	0.21	0.12	58.02	0.21	2.36	9	82	0.020
2. Use	0.48	0.23	0.15	46.52	0.23	2.71	9	82	0.008

Predictors: HHS; EDU, PWOM, SREA; GWQU; DIST; WPCO; REGU; EUSE
Dependent variables: water demand and water use (amount of water in litres)

6.6.3.4 Theoretical implication when using multiple regression analysis

Two arguments exist on the use of multiple regression analysis. First, the hierarchical regression argues that theory should drive the choice for statistical model and the decision of specifying variables for prediction should be determined by the theoretical principles (Kutner et al., 2004). The opposing views of stepwise regression (forward and backward) argue that the data need drive the choice of variables when the statistical procedure is allowed to select predictor variables to enter in the regression equation. In this study, the hierarchical regression was adopted because of theoretical principles. However, several forward and backwards procedures were applied to the model which produced different outputs. Stepwise gave no guarantee that outputs from forward and backward processes would converge on single regression model when combined which confirmed results by other scholars (Darlington, 1990; Anderson, 1984; Cleveland, 1983). Therefore, the full model was selected and applied in this study although it was expected that the accuracy of prediction would be weakened due to variances (error) within the data sets which generally affect regression procedure. The greater the error in the regression procedure, the greater the shrinkage of the value of R squared which is common to prediction models such as regression (Good & Hardin, 2009). However, regression models remain powerful methods to analyse multivariate data and this is the reason why in this study we opted for the use of the multiple regression method (Freedman, 2005). In this study, the theory based on our research question informed the choice to use multiple regression and assumptions were cross-validated for better interpretation (Chiang, 2003). But the reality on the science of uncertainty might have weakened our interpretation.

6.7 Implication of results for IWRM implementation in a river catchment

This section discusses results in terms of implication to facilitate a successful IWRM implementation at catchment level. The discussion shows how results support the study objective and the assumptions on water availability, demand and use as set in chapter one. In general, this section highlights the importance and meaning of the results and the implication for water management at catchment level from the IWRM perspective.

Table 23: 6.10 An overview of availability, withdrawal and use of water in Africa in km^3

Selected countries in Africa by region	Water availability per person per year (m^3)	Total water withdrawal per person per year m^3	Water withdrawal per person per year (%)	Total water use per country per year km^3	Groundwater availability (storage) km^3
1.Malawi	1,528	77.23	5.0	0.97	269
2.Tanzania	2,591	144.2	5.6	5.18	5250
3.Zambia	10,095	158.6	1.5	1.74	3950
4.Zimbabwe	1,584	513.6	32.4	4.21	2010
5.Mozambique	11,814	38.64	0.3	0.74	6290
6. Congo Dem. Rep	25,183	11.55	0.1	0.64	38300
7. Angola	14,009	42.24	0.3	0.64	17100
8. Botswana	9,345	109.5	1.2	0.19	17700
9. Namibia	10,211	158.0	1.5	0.30	77.20
10 South Africa	1,154	270.6	23.4	12.50	17400
1. Kenya (East 4)	985	72.44	7.4	2.74	8840
2. Uganda	2,833	12.66	4.5	0.33	339
3. Ethiopia	1,749	80.48	4.6	5.56	12700
4. Somalia	1,538	377.6	24.6	3.30	12300
1. Chad (Central 4)	5,453	40.63	0.8	0.37	46000
2. Cameroon	19,192	57.7	0.3	0.96	1560
3.Central-Africa Rep	38,849	17.17	0.0	0.10	4240

4. Congo Republic	275,679	14.47	0.0	0.10	6730
1. Ghana (west 4)	2,756	47.96	1.7	0.98	1400
2. Nigeria	2,514	78.67	3.1	10.31	11800
3. Mali	8,810	594.5	6.8	6.55	27100
4. Cote d'Ivore	5,058	77.95	1.5	1.41	241
1.Egypt (North 4)	859	937.0	109.1	68.3	55200
2.Libya	113	776.8	687.4	4.33	99500
3.Algeria	478	196.0	41.0	6.16	91100
4. Tunisia	482	296.2	61.5	2.85	7580

Source: FAO-AQUASTAT, 2002; FAO-AQUASTAT, 2005; MacDonald et al., 2012

6.7.1 General water availability

Malawi is known for water abundance (FAO, 2008: GoM, 2008c), but the water barrier differentiation indicator that was proposed by Falkenmark in 1989 showed that Malawi is a water stressed country with 1,528 m^3 per person per year (Table 6.10). The Falkenmark indicator states that countries are categorised water abundant (no stress) if there is more than 1,700 m^3 per person per year, water stressed when there is 1,000 to 1,700 m^3 per person per year and water scarcity when there is 500-1,000 m^3 per person per year and absolute water scarcity when there is less than 500 m^3 per person per year. In addition to the physically water stressed condition, globally, Malawi suffers from economic water scarce meaning that there is adequate renewable water resources in the country with less than 25% of water from rivers withdrawn for human purposes, but Malawi lacks improvements in existing water infrastructure to make such resources available for human use as per description by (IWMI, 2008; Brown & Matlock, 2011).

These results presented in Table 6.10 appeared reasonable and consistent with studies by Brown Falkenmark, 1989 & IWMI, 2008). However, the method used to obtain the best value for each country requires refinement as observed by Brown & Matlock, (2011). While this is probably the only way to obtain accurate results on water availability, a further limitation is that such results mostly reflect national scale situation (Rijsberman, 2006). However, results in Table 6.10 above can be used to compare countries within the SADC region and across Africa as a continent.

The results above supported the study objective and assumptions set in chapter one of this thesis on the problem of water resources in Malawi to show that Malawi is becoming both physically and economically a water scarce country although economic water scarce situation is leading. Such a situation provides a strong basis to implement a successful IWRM approach where water stakeholders manage such water resources in a coordinated manner following the principles of IWRM which calls for protection of water resources through active stakeholder involvement. These results have implication for advocating for IWRM implement in Malawi.

6.7.2 Groundwater availability

The study area, the Upper Limphasa River catchment, is located in a district which experiences a total annual rainfall of over 2,000 mm (GoM, 2008). Although this research has not confirmed this amount of rainfall for the study area, field results showed that the study area received rainfall almost throughout the year for the five years (2004-2008) which were analysed (Fig. 6.2) suggesting higher recharge rates to groundwater. The analysis on the effects of climate variability on groundwater was not the scope of this study. But decline in rainfall pattern reported for Malawi (FAO, 2008) implies reduced recharge pattern to groundwater storage including in aquifers in the study area. In addition, the dominant geology for the study area was described as Biotite gneiss (Fig. 6.3) which is the hard rock forming basement complex aquifer. This type of geology is responsible for the limited aquifer storage capacity suggesting that the area experiences low groundwater storage (Robinson et al., 2008) and being basement aquifer extracting such limited groundwater is complex due to uncertainty on the connectivity of the water channels in such geology (Chilton, 1982; Foster, 1983).

The results further showed that the study area was largely covered with dense Brachystegia woodland followed by the Montane grasslands with forest remnants and semi-evergreen woodland (Fig. 6.8 & Fig. 6.9). The type of vegetation cover in the study area and subsistence type of agricultural system suggested the expected low recharge rate, hence less groundwater availability. These results were consistent with results by Kresic, (2009), Leblanc et al., (2008) & Brunner et al., (2007) who found that vegetation cover and land-use are factors that have great influence on recharge process in similar environments. This information needs to be shared among key stakeholders for designing and implementing collaborative intervention to sustain water in the area.

Results on the qualitative approach to estimate groundwater availability using factors that influence such availability provided a sufficient and realistic basis for implementing a successful IWRM approach. By way of illustration, Beekman & Xu (2003) advised that understanding climatic changes such as rainfall pattern especially in some parts of Southern African countries improves knowledge among water scientists and managers in terms of whether or not replenishments of aquifers are more or less during particular rainy seasons or thereafter. However, in Africa, methods to provide quantitative information on groundwater resources are fewer and groundwater availability is often omitted in assessing freshwater availability (MacDonald et al., 2012). Although MacDonald et al. (2012) estimated that groundwater availability for Malawi was 269 km^3, they also noted that all that volume is not available for abstraction. Their observation agreed with various scholars on the difficulty of abstracting seemingly available groundwater resources due to different and complex hydrogeologic settings, geologic settings, technology among other factors especially in hard rock aquifers (Xu & Braune, 2010; Adelana & MacDonald, 2008).

Furthermore, MacDonald et al. (2012) reported that weathered Precambrian basement rock aquifers have the least storage capacity, which is highly significant because it is considerably more than the volume abstracted annually using community boreholes. This study was executed in hard rock fractured aquifer (Fig. 6.3), where groundwater availability is considered limited. Such a limited availability of groundwater condition revealed by qualitative assessment in this study was consistent with the quantitative approach by MacDonald et al., (2012). Such low groundwater storage is associated with abstraction difficulties. In this research, the analysis on water availability provided a benchmark for implementing efforts that could ensure sustainable utilization of such groundwater. Therefore, the IWRM framework using groundwater management as a case study provides an opportunity on how to manage such waters.

Since methods to provide quantitative data on groundwater availability continue to be scarce (MacDonald et al., 2012), then our qualitative approach for assessing groundwater availability as used in this study was probably the only way to obtain accurate results on providing a crude estimate on groundwater availability for effective water management. Although the approach is qualitative, it uses scientific principles and provides explanations that seem easily understood by all stakeholders actively participating in the IWRM implementation process in environments similar to our study area and beyond. Above all, the understanding among water stakeholders on the influence of the factors that explain groundwater availability at catchment level has positive potential influence on bringing all the stakeholders together for a successful IWRM implementation. Such collaborative efforts provide the basis to implement and monitor practices that ensures effective management of the water resource for sustainable utilisation of the same resource in the catchment.

6.7.3 Rural domestic water demand and use

Results on calculation of water demand and use per person per day, per household per day and per sub-catchment in an unmetered rural area appeared realistic and practical as provided in Tables 6.2 & 6.5. However, the method used to obtain the amount of water withdrawn (demand) and used at each sampled household was rather time-consuming because it required actually measuring the amount of water from each households' containers into our research calibrated 20-litre plastic bucket and visiting each sampled household early in the morning before that household started drawing fresh water for that new day. Thereafter, all the recorded values from field notebooks on water demand and use for each household were separately entered into SPSS for analysis to obtain average water demand and use. Then the average figure was multiplied by the total number of the households to find water demand and use for the sub-catchment and then divided that average household figure by household size to find water demand and use per person per day. This was done separately for demand and use. Despite being time-consuming, the approach was probably the only way to obtain accurate results which were similar to those obtained when using the Wallingford (2003) approach (Table 6.4). A drawback on our approach is that it can be used only in unmetered rural areas on the assumption that no taps and pipes are connected in households. Thus, with such fewer computational steps compared to those of Wallingford (2003), the proposed approach provided one step towards facilitating a successful IWRM implementation as it forms a platform to discuss and implement collaborative efforts among stakeholders.

Results in Tables 6.2, 6.4 and 6.5 have shown that the water demand per day in the Upper Limphasa River catchment was as follows: a) 80,550.99 litres for the sub-catchment, b) 116.91 litres per household and c) 21.2 litres per person respectively. For actual water per day in the same sub-catchment results were as follows: a) 63,766.95

litres, b) 92.55 litres per household and c) 16.8 per person. The results showed that more water was abstracted than actually used. However, these results were compared with recommended figures for water demand per person per day in Malawi at national level which is 36 litres per person per day; it was found that the water demand in Upper Limphasa River catchment was lower than the national recommended figures. Although such figures were small on daily basis, applying monthly and yearly analyses, results showed huge amount of groundwater abstracted, used and unused (Table 6.5).

Water demand per person per country in m^3 (Total water withdrawal/demand) was compared in ten SADC countries and four countries from East, Central, West and North Africa respectively presented in Table 6.10. The analysis showed that although Malawi is a water stressed country with 1,528 m^3 per person per year, it abstracted 77.23 m^3 of water per person per year which was more (5%) water than many of the countries presented in Table 6.9 in Africa. When total water use by country in km^3 for agricultural, industrials, municipal and domestic purposes was compared among the selected countries in Africa (Table 6.10), figures for Malawi were low ($0.97km^3$). However, water withdrawal/use for Malawi in 2005 was 80.6%, 14.7% and 4.7 for agricultural, domestic and industrial sectors respectively. The low usage of water at national level reflects low socioeconomic development of the country as revealed in Table 6.10 that poorer countries used less water than richer countries. Despite the low usage, Malawi was estimated to have $17.28km^3$ per year (FAO-AQUASTAT, 2005). With a total population of 13,077,160 (NSO,2009), Malawi is described as water stressed country because $17.28km^3/13,077,160 = 1,321m^3$ per capita per year which is below index thresholds of $1,700\text{-}1,000m^3$ per capita per year (Falkenmark, 1989). The results on low water usage in Malawi were consistent with various literature review results in chapter 2, including the assessment results by Molden (2007), which showed that relative richer countries use more water than poorer countries.

On factors that affect demand and use of water, results showed that number of persons per household (household size) influence both demand and use while education was only significant in the demand model but not in the water use model. These results are consistent with various studies which revealed that population is the main drive for demand and use on water. Although the influence of weather (seasonality) on water demand and use was not tested, results would have shown that a declining rainfall pattern as in Fig. 6.2 has effect on water demand and use (Table 6.5). These statistics provide useful insights and platform towards lobbying execution of a successful IWRM approach in Malawi where water managers, water users, water developers and water scientists would use such findings as a starting point in their collaborative efforts.

6.7.4 Return flow versus water security of the unused water for IWRM

An analysis of the unused withdrawn water in the Upper Limphasa River catchment showed that 4.4 litres per person per day, 24.36 per household per day and 16,784.04 litres in the sub-catchment per day were abstracted from groundwater sources but were not actually utilised (Table 6.2 & 6.5). From the procedure that was followed, these results appeared rational as field measured data. However, the method used to obtain such results was as time-consuming for water demand and water use as described in section 6.7.3. Nevertheless, it was probably the only way to obtain such statistics more accurately than predictions. But such procedure can be applicable in many unmetered rural areas of similar environment to the Upper Limphasa River catchment.

The implication of such unused water can be viewed in terms of the return flow concept as well as water security concept as a buffer. RDA (2007) reported on the existence of quick and delayed return flow based on the land characteristics in the catchment. They showed the irrigated water returning to streams and canals by surface runoff and groundwater discharge. Kim et al. (2009) modeled the irrigation return flow and showed that the simulation model results were in agreement with the field observation data. Our study revealed that the unused water from the source has the potential to return back to the water system either surface or groundwater depending on the hydrological and hydrogeological setting where such water will be deposited. From that perspective, the environment is considered receiving some water for its survival regardless of the amount of water. However, Kim et al. (2009) cautioned that without estimating the recaptured and reused return flow, and accurate quantitative assessment is not possible. However, our results provide an insight on the possible assessment of return flow for environmental integrity in the catchment under different hydrological and water management conditions (FAO-AQUASTAT, 2009 & 2010).

The unused water from our study suggests that water security in the catchment is robust. Three factors explain such a situation, 1) the level of water available in the area was observed to be sufficient (Fig. 6.7), 2) socioeconomic activities in the areas were largely subsistence and 3) the average monthly rainfall pattern (Fig.6.2) for the area was adequate. For effective management of such water, these results imply that livelihood productive activities at small levels such as vegetable gardens, brick making, livestock rearing, among others, can be initiated to effectively utilize the recorded unused water at each household. In addition, the water security condition implies that the system has a buffering effect to sustain the ecosystem. These insights were consistent with those of (Grey & Sadoff, 2007; Bakker, 2009) on implications of water security.

6.8 Summary

This chapter has fulfilled the objective on water availability, demand and use. The detailed summary on this chapter is provided in section 6.7 where implications for IWRM implementation drew on the provided key results in the same section. In this chapter factors that explain availability, demand and use for groundwater have been explored. By using the conceptual model of recharge process and physical factors for recharge, the research has shown how groundwater availability can be assessed qualitatively to improve the understanding among the key water stakeholders that involved in assessing, developing, using and managing water resources in the catchment and beyond. This study has shown that Malawi is physically water stressed as well as economically water scarce country. Therefore, lobbying for the implementation of a successful local IWRM approach is the most viable and rational option to sustain utilization of such waters under the existing factors that impede its success.

The present investigation vindicated that the use of the proposed approach on calculation water demand and use in unmetered rural environment, though time-consuming provides a basis for providing systematic data that can inform a quantitative understanding among key water stakeholders for implementing IWRM at catchment level. The detailed statistical computation used in this study and discussion on its strengths and weaknesses provides enlightenment on interpreting results from such method thereby proving opportunities for further researchers to refine the methodology. The systematic computational procedure provided is a major step towards a more informed procedural assessment approach on data generation and its implication for managing water in a coordinated manner in the catchment mainly in unmetered areas.

As a showcase study, findings from the Upper Limphasa River Catchment demonstrated procedures that were followed to calculate statistics on demand and use of rural domestic water at household level. Such results highlighted evidence-based guide on how to implement local IWRM in an adaptive way as a starting point for the successful IWRM implementation to ensure improved human health and productive livelihoods in rural areas of similar environments. The assessment on determinants of demand and use of such waters contributed to a comprehensive assessment of factors that explain the limited implementation of the IWRM approach. The assumption is that generation of statistical estimates contributes towards a successful implementation of the IWRM approach through appropriate planning. To make audacious statements on the use of local IWRM which feeds into successful IWRM, statistics need to be provided on aspects of IWRM principles that are observed being practised in communities. Such quantitative assessment forms the basis for evidence on the needed confidence for the contribution of local IWRM towards effective management of water resources. Nevertheless, applications of the IWRM principles need to consider differences in physical and socioeconomic conditions of various catchments, countries and geographic areas (Brown & Matlock, 2011). The next chapter assess the quality of groundwater.

Chapter 7: Assessment of Groundwater Quality

7.1 Introduction

This chapter presents and discusses results on the influence of physicochemical, microbial, socioeconomic factors and site characteristics on groundwater quality in the Upper Limphasa River Catchment. It aims to demonstrate different methodologies that can be used to assess factors that explain groundwater quality in resource poor areas. The chapter argues that to facilitate implementation of IWRM, factors that explain quality of water resources need to be identified and assessed using different methods that are modern, pragmatic, cost effective, based on scientific principles but also acceptable socially and politically among stakeholders. To achieve the study objective, physicochemical and bacteriological concentration levels were assessed to ascertain compliance of such water to the 2008-World Health Organization (WHO) guidelines and 2005-Malawi Bureau of Standards (MBS) for domestic uses; groundwater types in the study aquifer were charcterised; and sanitary risk factors alongside risk-to-health and proxy water quality parameters were assessed. Using various methods, the influence of physical and socioeconomic and factors on quality of groundwater were discussed. Risks of using groundwater sources to improve human health as a responsive initiative to meeting MDG on access to potable water as well as executing IWRM for sustainable utilization were highlighted with suggested solutions.

This chapter addresses the third objective of the study, which was to assess groundwater quality for drinking from sources and selected households in order to detect its determinants using RADWQ (**R**apid **A**ssessment for **D**rinking **W**ater **Q**uality) and model methods. It is assumed that improved knowledge on groundwater contaminants helps to develop practical measures to protect groundwater for drinking as one way of best management practices within the IWRM paradigm. To fulfil the third objective of the study, three questions were answered: i) What methods can be used to assess groundwater contaminants (quality) to protect groundwater for drinking? ii) How reliable are groundwater sources to supply potable water in rural communities? iii) What are the major physical (physical, chemical, biological and site characteristics) and socioeconomic determinants that explain the quality of groundwater in the study area?

The department of water development in Malawi is responsible for water development and monitoring. Although standards and guidelines on development of drinking water and its quality exist, enforcing them remains a challenge for various reasons. Procedures followed to develop or supply groundwater for drinking are assumed to be adequate to safeguard the quality. The microbial, physical and chemical factors that have the potential to affect the natural quality of groundwater are not routinely monitored country-wide (GoM, 2008). From the IWRM perspective, assessing concentration levels of pathogenic bacteria and selected physicochemical constituents in groundwater sources for drinking provide a basis for lobbying a coordinated management approach among water scientists, developers, users and managers. Showing sanitary-risk-factors to such water sources and risk-to-health of households that draw drinking water from such sources will facilitate users' involvement in source protection measures for their water and will caution water developers on locating water sources in safer places. This preventive approach is both sustainable and cost effective.

Pathogenic microorganisms responsible for causing disease in humans include bacteria, viruses and parasites. This study focused on pathogenic bacteria as a group without categorising them into i) *Vibrio cholerae*, the agent of cholera; ii) *Salmonella spp.*, which cause typhoid, paratyphoid fever and gastroenteritis; and iii) *Shigella spp.*, which cause dysentery and enteric fever (WHO, 2008). Methods to provide definitive quantitative pathogenic bacteria are expensive, complex and they contain errors or uncertainties (Thomas, 2011). So, this study used a qualitative approach whereby concentration levels of total coliform and *E.coli* bacteria were used as indicators of microbial water quality. Total coliforms have no sanitary implications and hence were excluded from the analyses whereas *Escherichia coli (E.coli)* which belongs to the feacal coliform group strongly indicates faecal pollution of human origin and hence was analysed and discussed in detail (WHO & UNICEF, 2010).

Physical and chemical parameters were also assessed on the basis of their potential to negatively affect human health when consumed either below or above regulated standards (WHO, 2008 & MBS, 2005). Standard methods for field and laboratory assessments according to APHA (1995) and Weaver et al. (2007) were adopted to analyse the physicochemical parameters. These parameters were used to assess groundwater in terms of i) its quality for suitable domestic uses, ii) its natural characteristics and iii) classifying its water types in the study area (Young, 2007).

7.2 Methods used

Different methods were used to collect and analyse data on physicochemical, microbiological (bacteriological), hydrogeological (site characteristics) and socioeconomic factors that explain the quality of groundwater for domestic use. To collect such data, field observations, field measurements, records review and interviews were used. To assess groundwater quality, the hydrogeochemical analysis model (HAM) was used i) to ascertain suitability of groundwater sources for domestic uses and ii) to characterise groundwater types and their dominant chemical composition, graphical methods such as piper diagram were used. Statistical methods such as correlation analyses were used to establish the relationship between potential sources of contamination and detected pathogenic bacteria in groundwater. Colorimetric methods were used to test effectiveness of chlorinating drinking water in sampled households.

To assess vulnerability of groundwater sources from potential sources of contaminants, the DRASTIC (**D**epth to water, **R**echarge rate, **A**quifer geology, **S**oil type, **T**opography (slope), **I**mpact of vadose zone, hydraulic **C**onductivity) approach was applied using a combination of field measurements and previously-created geologic and pedologic maps as recommended by WHO & UNICEF (2010) level two assessment within RADWQ methods. Table 7.6 presents explanatory results on the DRASTIC approach. For example, the rating associated with the depth-to-water of the water source was 9 for the PSWs and 1 for boreholes (BHs). In principle, depth to water implies a greater chance for contaminant attenuation as the depth to water increases due to longer travel times and more contact with potential sorbents (Aller et al., 1987; Xu & Braune, 2010).

To assess the quality of groundwater for drinking, RADWQ (**R**apid **A**ssessment of **D**rinking **W**ater **Q**uality) methods were used whose analyses focused on overall compliance of groundwater quality to 2008-WHO and 2005-MBS, sanitary risk factors to water sources, risk-to-health of the sampled households and analysis of proxy parameters. Results that considered strengths and weaknesses of the RADWQ approach have been discussed alongside results obtained in eight countries, namely, China, Nicaragua, Nigeria, Ethiopia, Jordan, Tajikistan, Bangladesh and Sierra Leone (Ince et al., 2010; Tadesse et al., 2010; Aldana, 2010; Properzi, 2010 & Thomas, 2011) that used the same approach in assessing quality of groundwater for drinking from sources and households. Rapid assessments of water quality provide useful baseline information on safety by using different statistical techniques to triangulate results for validity (WHO&UNICEF, 2010). Detailed methods on RADWQ are provided in Howard et al., (2003) and were modified for use in this study.

Water samples were taken from 17 production boreholes (BHs), six protected shallow wells (PSWs) and 90 sampled households in the eight-village study area (Fig 7.6). For each water source, one cluster of households that was closest to and the other farthest from the source were also selected for water sampling. Within each selected cluster, two households were randomly sampled. In total, 92 households were targeted in the study area, i.e., four households per water source. Two households were not included due to their inaccessibility. Chapter four provided details on sample size and sampling design.

Before sampling, water from BHs and PSWs was repeatedly pumped and measured for temperature, specific conductance and pH using an Oakton® multi-parameter probe. Water samples were collected only when all the readings stabilized. Electrical conductivity (EC) measurements were converted to total dissolved solids (TDS in mg/l) values by multiplying the EC value (in mS/cm) by a factor of 6.4 (Weaver et al., 2007). Household water was sampled using the same utensils that the residents used to access their stored water. The pH, specific conductance and temperature were measured in the household water using an Oakton® multi-parameter probe (Nielsen & Nielsen, 2007).

All water was tested for contamination by total coliform and *E. coli* bacteria. Bacteria analyses were performed with 3M Petrifilms® ChromoCult Coliform Agar together with a membrane-filtration unit and portable incubators. Analysis with the Petrifilms® was done in one of two ways. In case of the samples that were suspected to be highly contaminated, 1ml of sample water was applied directly to the agar film. When a lower level of contamination was suspected, 100ml of sample water was passed through a 0.47-mm filter paper using sterile membrane-filtration unit. After filtration, the filter paper was placed within the agar film which had been pre-wet with 1ml of sterile water.

Subsequently, the Petrifilms® were incubated at 35°C for 24 hours and the colonies were counted with blue colonies indicating *E. coli* bacteria and red colonies indicating total coliforms. Bacterial concentrations were recorded as colony forming units per 100 ml of water (CFU/100 ml). The number of counted colonies for the 1-ml samples was multiplied by 100 to maintain consistency of units for concentrations. All bacteria analyses were performed in duplicate; the reported bacteria concentrations represent the average of the two analyses. In sampled households which reported that they treated their drinking water, the sampled water was tested for chlorine and turbidity levels using colorimetric methods with a chlorine photometer and turbidity meter, respectively.

Water was also analyzed for various elements including the following major ions: HCO_3^-, CO_3^{2-}, NO_3^-, PO_4^{3-}, Cl^-, F^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, K+ and Na^+ and some trace metals including Al, As, Cd, Pb, Se and Zn. Water samples were collected according to standard procedures (Weaver et al., 2007; APHA, 1995). Ion analyses were performed by Bemlab (Pty) Ltd - Assay Laboratory in Stellenbosch, South Africa. Major and trace analyte concentrations were determined using an ICP-OES auto analyzer program as a standard method for the examination of water. A tritration analysis method was utilized to analyze HCO_3^- and CO_3^{2-} in triplicate and the mean of the results used (APHA, 1995). Bacteria and ion concentrations were compared to specified guidelines of 2008-WHO and MBS-2005 to provide insights on 1) the general status of groundwater quality in the study area and 2) how such drinking water compares to the MBS defined water quality.

To conduct risk-to-health and sanitary-risk-factors analyses, the study used sanitary inspection technique within the RADWQ methods (WHO&UNICEF, 2010). Each water source was evaluated in terms of its distance from the potential sources of bacterial contamination such as latrines, animal corrals and streams. The physical condition of each water source was also assessed to determine the potential risk of contamination from poor construction, condition or siting. Each source was assigned a risk factor score calculated based on answers to a series of 10 yes-or-no questions that dealt with the proximity of the water source to the potential sources of contamination, the existence and condition of a proper fence and cement apron and the condition of the hand pump (Howard et al., 2003). Each positive answer indicated an increased threat of contamination. The risk factor score was the number of yes answers associated with the

10 questions to assess sanitary-risk factors for groundwater contamination (WHO & UNICEF, 2010).

7.3 Influence of physicochemical factors on groundwater management

The assumption has been that the natural filtration of rocks and soils protects groundwater from pathogenic contamination, hence good quality for drinking. Findings in this study and other studies (Xu & Usher, 2006) have demystified this generalized belief for all groundwater sources. In addition, little is known of the groundwater chemistry in Malawi (GoM, 2008) and Africa in general (Xu & Usher, 2006). This is due to variability of chemistry of the water as it is largely determined by the geochemical process that occurs as recharge infiltrates the ground and reacts with rock-forming minerals. In some environments, harmful concentration of elements occurs, posing threats to human health. This section describes concentration levels of selected physicochemical elements in groundwater sources. It also explores the threats of such concentration levels to human health by assessing compliance of such levels with 2008-WHO guidelines and national standards for Malawi (MBS, 2005) on drinking water.

7.3.1 Hydrochemical characterisation of groundwater in the study area

Although various hydrochemical facies were observed, Ca-HCO_3 and Mg-Ca-HCO_3 water types were dominant. This classification shows that the study area has shallow fresh groundwater in aquifers, which is largely controlled by rainfall and silicate weathering with minor contribution from carbonate weathering. Using the calculated total dissolved solids (TDS) to classify groundwater types, results testified that aquifers in the study area have young infiltrating fresh water with less than 1,000ppm TDS. The Upper Limphasa River catchment is located in relatively high areas of 600-1300m above sea level (Fig.6.5), which are generally recharge areas, results from this study were consistent with the principles of recharge process (Younger, 2007). In addition, these results agree with findings and conclusions by Healy (2010) in several of his case studies on parameters used to classify recently recharged waters in the aquifers.

The pattern in dominant hydrochemical facies (Fig. 7.1) suggests that as groundwater travels through recharge areas towards discharge zones, it may have evolved through Ca-Mg and HCO_3-Cl to Ca-HCO_3 and Mg-Ca-HCO3. This pattern implies that groundwater chemistries are changed by cation exchange reaction as well as simple mixing in certain proportions (Appelo & Postma, 1999). Typical classification of hydrochemical facies for the groundwater of the Upper Limphasa River catchment is shown in the Piper Diagram (Fig. 7.1) where major ions of sodium, potassium, calcium, magnesium, chloride, bicarbonate and sulphate are plotted to show ionic composition in groundwater in percentages. Since the study has shown that groundwater in the Upper Limphasa River catchment is shallow and fresh, the need to implement best management practices through IWRM to protect such water from contamination seems the priority. Where the full IWRM approach is delaying to be implemented, practising the local IWRM at community level (per water point source) has more potential benefits cumulatively within the catchment. Common understanding among scientists, water providers/developers, users and managers on how water types in aquifers are classified is one of the key entry points to lobby for funding and implementation of IWRM. In addition, such knowledge when shared among stakeholders who deal with water resources is deemed to facilitate efforts that minimise activities that have the potential to contaminate groundwater aquifers. In this way, this study shows the usefulness of characterising hydrochemistry of groundwater to enhance the need for groundwater protection among stakeholders collaboratively.

7.3.2 Assessing quality of groundwater supplies for domestic use

The section presents results on overall compliance of chemical and physical parameters of groundwater to provide a guide on how to assess the quality of groundwater supplies for domestic use. Concentration levels of physicochemical parameters in groundwater per source were assessed to ascertain their suitability for health (drinking) and aesthetic (drinking). The assessment was qualitatively classified as good, marginal, poor or unacceptable basing on the hydrogeological analysis model (HAM) software classification system (Kan & Xu, 1999). To ascertain the quality of groundwater suitable for human consumption, field results were compared to WHO guidelines and Malawi national standards (WHO, 2008 & MBS, 2005) for compliance.

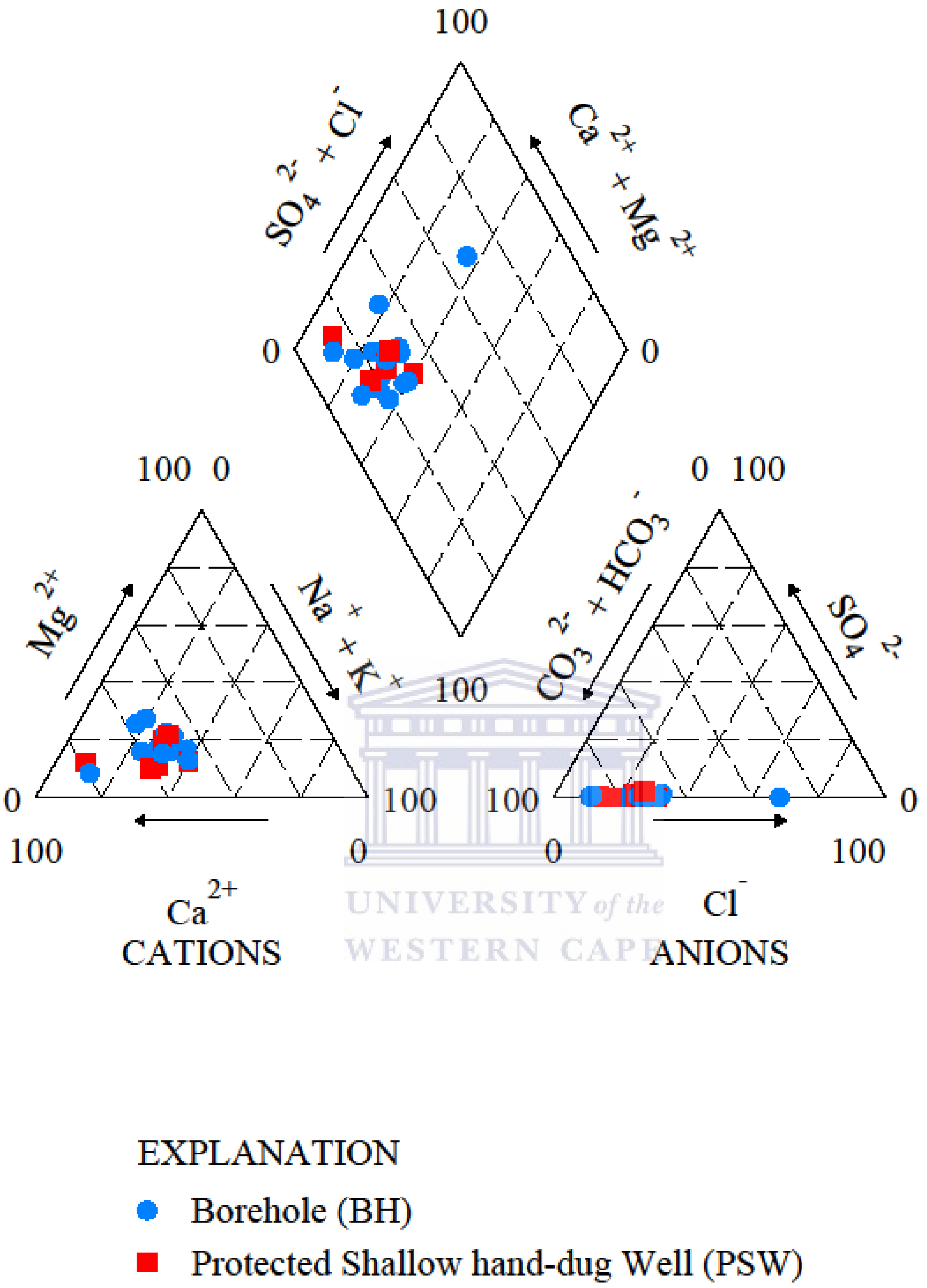


Figure 39: 7.1 Piper diagram for classifying groundwater types (BH and PSW)

In addition to compliance, such knowledge on physicochemical characteristics was envisaged essential for the correct interpretation of i) changes in temperatures of groundwater, ii) acidity and alkalinity in groundwater using pH as the most common proxy, iii) TDS estimates in shallow versus deep aquifers as proxy for salinity, iv) TDs estimates in aquifers of highlands versus lowlands as proxy of recent recharged groundwater, v) TDS in aquifers of humid areas versus those in temperate region as proxy of excessive evapotranspiration, vi) implications of cation-anion charge balance and vii) other components (Young, 2007).

Results have shown that none of the sampled BHs or PSWs had physical and chemical concentrations levels of health concern when compared with 2008-WHO guidelines and 2005-MBS (Table 7.1; detailed results in appendix). TDS concentrations were generally acceptable being < 1000 mg/l in 21 of the 23 sources agreeing with Young (2007) that aquifers in the study were shallow, had fresh water, recently recharged, less mineralised and located in highlands of a tropical humid area. The importance of such results informs the basis for collaborative efforts among stakeholders to implement interventions that protect such water being polluted. Water from 18 of the 23 sources had a pH less than 6.5 being slightly acidic, agreeing with results by Pritchard et al. (2010) who concluded that typical pH values of water sources in developing countries including Malawi fell between 5.5 and 8.0. The pH values in this study ranged between 5.84 and 7.09 with an average of 6.32 reflecting the siliceous nature of the underlying rocks as found by (GoM, 2008) in his case studies. Such results provide opportunities to study household water storage practices to reduce storage containers from corroding.

Table 24: 7.1 Physicochemical compliance of groundwater sources to WHO and MBS

Parameters	Min	Max	Ave	WHO[1] Values	MBS[2] Stds	Violation[3] (%)	Compl. (%)
Arsenic(mg/l)	0	0	0	0.05	0.05	0	100
Fluoride(mg/l)	0.40	1.33	0.75	1.5	2.0	0	100
Nitrate (mg/l)	0	0.90	0.17	45	100	0	100
Selenium(mg/l)	0	25	2.5	0.01	0.01	13	87
Iron (mg/l)	0.15	1.98	0.47	0.3	1.0	9	91
Copper(mg/l)	0.008	0.144	0.040	15	2.0	0	100
pH	5.84	7.09	6.32	6.5-8.5	6.5-8.5	83	17
Conductivity (TDS mg/l)	501.12	1077.76	715	1000	1000	9	91

Min=Minimum; Max=Maximum; Ave=Average; [1]World Health Organisation suggestive values; [2]Malawi Bureau of Standards, MBS (MBS, 2005) [3]Fraction of water samples outside limits set by MBS

Table 7.1 above shows the overall physicochemical compliance of groundwater sources in the Upper Limphasa catchment with WHO suggestive values and values for Malawi standards. Both chemicals of direct health concern (arsenic, fluoride and nitrate) and physicochemical parameters of indirect health concern (Copper 100%, pH 17%, Selenium 87%, Iron 91% and Conductivity (TDS) 91% pose no threat to human health in the studied groundwater sources. The low pH compliance did not pose threat to human health as people store their drinking water in clay pots and plastics containers which do not corrode. Generally, groundwater sources produce fresh water despite the none compliance for TDS in Musafili PSW (1078 mg/l) and Kennedy BH (1011 mg/l) water sources (Fig. 6.5). Despite these good results for drinking water sources in the study area, human health is at risk for those who drink from unimproved water sources (MDHS, 2010) because RADWQ methods are not recommended to assess such sources.

7.4 Influence of microbiological factors on groundwater management

Assessing microbial factors that explain the quality of groundwater remains a vital aspect in groundwater protection studies. This section presents results on the use of indicator bacteria to i) protect groundwater for public health improvement; ii) predict contamination levels in water sources; iii) assess risks posed by water sources and iv) evaluate risks of water sources as an effective monitoring tool in groundwater management. Sanitary inspection techniques were used to provide long-term perspectives on risks of future microbial contamination. The other analytical RADWQ methods that were used included statistical, colorimetric and DRASTIC methods.

7.4.1 Assessing sanitary risk factors using sanitary inspection techniques

Sanitary inspections are visual assessments of infrastructure and environments surrounding water supply sources focussing on condition, devices and practices in the water supply system that pose threats to drinking water quality thus to human health (Howard et al., 2003). A semi-quantitative standardized approach that uses ten logical questions with yes and no response and scoring system (risk scores) is the norm in sanitary inspection studies to determine the sanitary risk factor per source type (WHO&UNIFEC 2010). Sanitary inspection complements a snapshot of water quality analysis for robust conclusions and provides a long-term perspective on risks of future microbiological contaminants. In this study, questions with response frequency of more than 60% are bolded and shaded to highlight the high sanitary risk factors (Table 7.2).

Table 25: 7.2 Sanitary risk factors for groundwater sources (Boreholes)

Boreholes			
	Specific diagnostic information for assessment (Sanitary risk inspection questions)	**Number of “Yes” responses**	**Response frequency (%)**
1.	Is there a latrine within10m of the borehole?	2	12
2.	Is there a latrine uphill of the borehole within 100m?	**12**	**71**
3.	Is there any other source of pollution within 10 m of the borehole? (animal breeding, animals kraals, waste pits, graveyards, cultivation, roads, industry)	**12**	**71**
4.	Is the drainage faulty, allowing water pool within 3m of the boreholes?	9	53
5.	Is the drainage channel cracked, broken or need cleaning?	9	53
6.	Is apron less than 2m in diameter around the top of borehole?	**14**	**82**
7.	Does split water collect in the apron area/cement floor?	**12**	**71**
8.	Are there cracks or damages in the apron area/cement floor?	7	41
9.	Is hand pump loose at the point of attachment to the apron?	2	12
10.	Is the fence faulty or missing?	**17**	**100**
Total number of samples		17	
Note that risk score: 9-10Very high; 6-8=High; 3-5=Medium; 0-3 Low			

The major sanitary risk factors identified in the study were a) for boreholes: i) latrine uphill boreholes, ii) other sources of pollution, iii) size of apron and iv) collection of water in the apron and lack of fence and b) for protected shallow (dug) wells: included those four factors for boreholes plus i) faulty drainage, ii) cracked drainage channel and iii) loose hand pump (Tables 7.2 & 7.3). These findings indicate that the major causes of sanitary risks can be categorised into three: a) hazardous factors or poor site selection and failure to minimize sanitary risks. For example, latrines located uphill water sources and sources of pollution nearby water source; b) Pathways factors or poor workmanship or lack of maintenance. For example, cracks, faulty drainage apron and c) Indirect factors or poor sanitary conditions. For example, lack of fencing. These findings though not conclusive, provide useful insights on how assessing factors that explain groundwater quality can facilitate IWRM implementation whereby scientists, water developers from private and government departments, water users in communities and water managers can protect groundwater sources for drinking from contaminating sources in a coordinated manner within a catchment based on such assessments.

Table 26: 7.3 Sanitary risk factors for groundwater sources (PSWs)

Protected Shallow hand-dug well (PSWs)			
	Specific diagnostic information for assessment (Sanitary risk inspection questions)	**Number of “Yes” responses**	**Response frequency (%)**
1.	Is there a latrine within10m of the protected shallow well?	1	17
2.	Is there a latrine uphill of the protected shallow well within 100m?	**4**	**67**
3.	Is there any other source of pollution within 10 m of the protected shallow well? (animal breeding, animals kraals, waste pits, graveyards, cultivation, roads, industry)	**5**	**83**
4.	Is the drainage faulty, allowing water pool within 3m of the protected shallow well?	**6**	**100**
5.	Is the drainage channel cracked, broken or need cleaning?	**5**	**83**
6.	Is apron less than 2m in diameter around the top of the protected shallow well?	0	0
7.	Does split water collect in the apron area/cement floor?	**4**	**67**
8.	Are there cracks or damages in the apron area/cement floor?	3	50
9.	Is hand pump loose at the point of attachment to the apron?	**4**	**67**
10.	Is the fence faulty or missing?	**6**	**100**
Total number of samples		6	
Risk score: 9-10Very high; 6-8=High; 3-5=Medium; 0-3 Low			

The sanitary inspection technique was applied at each water source to assess potential sources of *E. coli* contamination including hazardous factors such as pit latrines, pathways factors such as cracked aprons and indirect factors such as absence of fences (Howard et al., 2003). Each water source was evaluated in terms of its distance from potential sources of bacterial contamination, namely, latrines, animal corrals and streams in terms of hazardous factors. The physical condition of each water source was also assessed to determine the potential risk of contamination from poor construction, condition or siting. Each source was assigned a risk factor score calculated based on answers to a series of 10 yes-or-no questions that dealt with the proximity of the water source to potential sources of contamination, the existence and condition of a proper fence and cement apron and the condition of the hand pump as shown in Tables 7.2 and 7.3. Each positive answer indicated an increased threat of contamination.

The risk factor score for each water source was the number of yes answers associated with the 10 questions (Table 7.4). Each water source was assigned a Risk Factor Score (0 to 10 with 10 indicating conditions most prone to contamination) taking into account its hazard, pathways and indirect factors (Howard et al., 2003). Results showed that risk factor scores for the 23 water sources ranged from 1 (Viremba BH) to 9 (Agriculture

BH) and averaged 5.8 (Table 7.4). However, there was no significant relationship between risk factor scores and the degree of microbial contamination (Table 7.4). These findings influenced application of alternative methods to investigate controlling factors.

Table 27: 7.4 Influences of site characteristics on groundwater contamination

Type of water source	E.coli levels	Distance to pollution source (m)	Depth of water source	Slope %	Conductivity (mS/cm) i.e. TDS	Risk Score (10)
Thanula School BH	0	100	48	8	842.24	4
Vwiyapo BH	0	57	66	8	602.88	6
CBO BH	0	75	40	8	646.40	5
Kennedy BH	0	65	43	8	1011.20	8
Chibu BH	0.5	180	48	8	760.32	6
Mutelela BH	0	95	48	35	798.72	5
Mutelela BH	0	89	48	8	798.72	6
Boma BH	0	30	60	8	744.96	4
Wadenya BH	0.5	35	60	35	704.00	8
Kapote-BH	0	95	45	8	768.64	7
Theu BH (toilet 1)	0	65	46	35	570.88	8
Theu BH (toilet 2)	0	76	46	35	570.88	8
Theu BH (corral)	0	38	46	35	570.88	7
Hotela BH (toilet 1	0	45	48	22	569.60	5
Hotela BH(toilet 2)	0	30	48	22	569.60	6
Chikwina School BH	0	43	42	8	548.48	3
Agriculture BH	0	30	51	8	809.60	9
Mayolela-BH	0.5	30	72	8	567.68	8
Msumba-BH	0	120	72	38	765.44	7
Viremba BH	0	121	48	8	732.16	1
Thethe-BH	0	113	72	8	663.04	6
Kango-PSW (graveyard)	240	120	5.5	35	598.40	8
Kango-PSW (toilet)	240	10	5.5	35	598.40	8
Musafili-PSW	63	210	4.5	35	1077.76	3
Chiloti-PSW	2.5	78	3.5	35	551.04	5
Thindwa-PSW	18	90	3.0	53	921.60	7
Wadenya-PSW	0.5	110	3.0	53	501.12	6
Kanthumba-PSW	1	151	3.0	53	685.44	5

Results from bacteriological analyses of water from BHs and PSWs showed that of the 23 water sources that were sampled (17 BHs and 6 PSWs), total coliform concentrations ranged from 0 to 50 CFU/100 ml in BHs and 0 to 3700 CFU/100 ml in PSWs. Since total/environmental coliforms do not reflect faecal contamination of groundwater, they were excluded from further analysis. Conversely, *E. coli* bacteria are indicators of contamination by human or other animal faeces hence their inclusion in table 7.4 for further analyses. In three of the boreholes at Chibu, Wadenya and Mayolela had an *E. coli* concentration of 0.5 CFU/100 ml respectively (Table 7.4). Other than these three instances, no *E. coli* were detected in water from boreholes (Table 7.4). This analysis made BH complying 100% for WHO guidelines and MBS standards (Table7.7). In the study area, counts as low as 1 CFU/100 ml implied user error in the field and not indication of contamination of groundwater resources. Conversely, *E. coli* concentrations in the six PSWs ranged from 0 to 240 CFU/100 ml (Table 7.4) and four of the wells had concentrations that indicated sewage contamination (Tables 7.8 & 7.9).

The hypothesis that PSWs were more contaminated than BHs was statistically assessed with a Student t-test. A summary of all statistical t-tests in the appendix showed that parametric t-tests provided weak evidence of significant difference in concentration levels of bacteria. However, basing on a nonparametric t-test, PSWs were significantly more contaminated with E. *coli* bacteria than boreholes (p-value = 6.2×10^{-6}) (Table 7.10). Analyses of relationships between contamination levels and site characteristics such as depths of BHs and PSWs; distance to potential sources of contamination such as latrines include slopes percentages and risk scores are provided in Tables 7.4. Results suggest, that in, general depth explains the difference in microbial contamination levels between BHs and PWSs. However, the observed microbial contaminations were not significantly related to either depths of water source although depths for PSWs were shallower (3.0 to 5.5m) than for BHs (42 to 72m) Table 7.4. In terms of location, latrines were usually located downhill from villages, but uphill of the water sources (Fig. 7.2). However, results yielded no significant relationship between the distance from latrines or corrals and the degree of contamination. Nevertheless, the water source (Kango PSW) with the highest measured *E. coli* concentration (240 CFU/100 ml) was also the water source that was nearest to a latrine (10m) (Table 7.4) and the only water source located in alluvial local aquifer in the study area (Fig 7.6) suggesting that further hydrogeologic assessments on aquifer vulnerability using various tools are required.

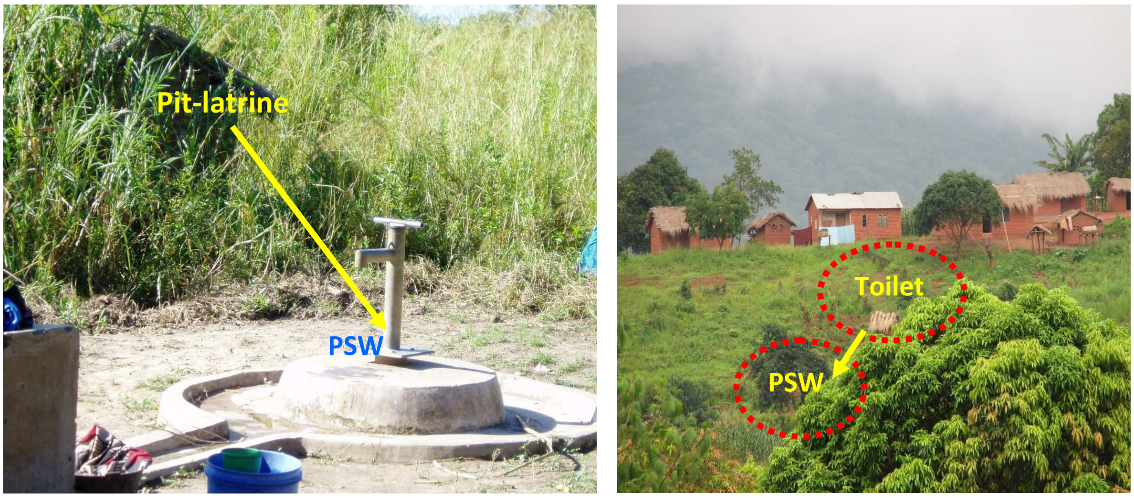


Figure 40: 7.2 Influences of on-site sanitation on quality drinking water sources

Comparatively, PSWs were located in low-lying wet areas than BHs (Figs. 7.3 & 7.4). The mixing of surface water and groundwater in such areas are unavoidable. The groundwater in PSWs appeared to exist under direct influence of the surface water (Fig. 7.3). The slopes to PSWs were steeper (35-53%) than BHs (8-35%) (Table7.4). The location of PSWs in low-lying areas or closer to surface waters is associated with large differences in bacterial concentrations between PSWs and BHs. Possibly, locations of PSWs explain the presence of pathogenic bacteria in PSWs. However, differences on conditions of sanitary seals and plain casing in BHs and PSWs were not assessed. Nevertheless, field measurements and observations made about site characteristics (Table 7.4) provide revelations for implementing best management practices on water development in rural areas to protect groundwater from contamination.

Figure 41:7.3 Protected shallow wells located in low-lying wet areas (35-53% slope)

Figure 42: 7.4 Boreholes located on high dry areas with 8% slope

In addition to the difference in slopes between BHs and PSWs, field observations on undulating topographic nature in the study area helped to visualize sources of contaminants to water sources (Fig. 7.2), difficult to access safe water and location of households not served with safe water sources (Fig. 7.5). Such supporting evidence agreed with Rajkumar & Xu (2010) who reported that the greater the hydraulic gradient towards the water source, the higher the risk of water point contamination. These field observations provided insights on potential factors for groundwater contamination observed in some water sources. The observation on terrain also indirectly explain the difficulty to access some safe sources and to be provided with safe sources as some households are located in a difficult terrain in the mountain forest (Fig. 7.5).

Figure 43: 7.5 Topographic outlook a hindrance for water access and provision

7.4.2 Establishing proxy parameters using statistical correction methods

The aim in analysing proxy parameters was two-fold: 1) to statistically ascertain the groundwater source type with high risks and 2) to determine the proxy indicator to explain the source of the identified contamination in groundwater sources from the selected and analysed water-quality parameters. Therefore, to test for differences between populations (groundwater sources), Student's t-tests (Snedecor & Cochran, 1980) were used according to the convention of Freedman et al. (1998), where $p \leq 0.05$ were considered statistically significant, providing moderate evidence against the null hypothesis, and $p \leq 0.01$ were considered highly significant, providing strong evidence against the null hypothesis. By extension, p-values between 0.05 and 0.1 were assumed to provide weak evidence against the null hypothesis. Most comparisons were performed using nonparametric methods (Wonnacott & Wonnacott, 1985) free of all assumptions regarding the distributions of the parameter values. Nonparametric methods, based on the relative ranks of the data rather than their absolute values, are preferred when the data exhibit non-normal distributions and there are large differences in variances among populations. With nonparametric analyses, p-values are approximate but satisfactory (Wonnacott & Wonnacott, 1985).

In addition to statistical significance, Spearman rank correlation analysis was used to determine possible relationships between contamination levels in water sources, the selected water quality parameters and site characteristics similar to the approach used by Conboy & Goss (2000). Such correlation analysis was thought to be potentially useful for identifying sources of contaminants in groundwater sources by showing the strength and direction of the relationship so that risks of such sources could be evaluated.

T-tests were used to compare the mean concentrations from these two populations (17 BHs and 6 PSWs) to determine significant difference. Statistical results showed weak or no evidence of difference with the parametric tests despite the great differences in the mean total coliform and *E. coli* concentrations. This lack of proof was due to the high variances associated with concentrations in PSWs, which ranged from 0 to 3700 CFU/100 ml for total coliform and 0 to 240 CFU/100 ml for *E. coli*. Therefore, nonparametric tests were used and Spearman rank correlation analyses were performed although the data were sampled from a population that followed approximately Gaussian distribution (Corder & Foreman, 2009). Nonparametric tests such as Kruskal-Wallis and Mann-Whitney U-tests show no loss of power in comparison to parametric tests (WHO&UNICEF, 2010). However, precision is lost for wider inferences of analyses because of small sample size and absence of priori assumptions (Larry, 2007).

Nevertheless, such analyses are robust because they 1) are not affected by outlier values, 2) probability statements obtained from most nonparametric statistics are exact probabilities, regardless of the shape of the population distribution from which the random sample was drawn, 3) are applicable where less is known, 4) analyses are performed in Microsoft Excel requiring no sophisticated software hence cost-effective (Corder & Foreman, 2009; Larry, 2007 & Gibbons et al., 2003). This statistical analytical technique was suitable for the RADWQ method which has a snapshot nature that does not justify using more complicated analysis (WHO&UNICEF, 2010).

Selected water-quality parameters were examined to determine if one parameter could be used as a proxy indicator for the other. The following parameters were analysed for correlations: 1) Faecal contamination (E.coli) versus Turbidity; 2) Faecal contamination (E.coli) versus Site characteristics such as depths of water source (Depths), distance from water source to nearby pollution source (Distance), slope percentage from pollution source to water source (Slope %) and 3) Conductivity (TDS) versus Nitrate (NO_3), Fluoride (F), Arsenic (As) and Iron (Fe). The correlation was used to measure the strength and direction of the association between variables in a linear manner where R = +1, -1 and 0 to show positive, negative and zero correlation respectively. Site characteristics such as placements of water sources in relation to potential sources of contaminants were assessed. It was hypothesized that the placement of latrines in relation to depths of water sources, slope to water source, distance to water sources could explain some of the bacterial-concentration variability. If so, the relationships might help to establish proper management practices on locating water sources to reduce their vulnerability from potential sources of contaminants. For these analyses, ranked data were also used. Correlations with a p-value ≤ 0.05 were considered to be statistically significant. Results showed that no statistical significance existed between concentration levels of *E.coli* in water sources and site characteristics (Table 7.4).

The Spearman rank correlation coefficient results in (Table 7.5) provide the overall relationship between i) faecal contamination (*E.Coli*) and physical factors (conductivity and turbidity), ii) faecal contamination (*E.Coli*) and site characteristics and iii) conductivity and selected chemical parameters in both groundwater source presented. The correlation between chemical parameters and conductivity (Total dissolved solids=TDS) which is a proxy of salinity (salts) in drinking water are presented. The concentration of chemical parameters varied depending on hydrogeologic and environmental conditions as discussed by Tadesse et al. (2010). Generally, there was little or no correction between the selected water quality parameters. However, there was a positive correlation in both BHs (r = 0.280) and PSWs (r = 0.926) between *E.coli* and depth of water source. The strongest positive correlation coefficient (r = 0.926) was for *E.coli* and depth of protected shallow wells and for conductivity and nitrate (r = 0.587) in protected shallow wells. However, regardless of high *E.coli* present in PWSs, nitrate was below detection levels, possibly due to abundance of vegetation in the area (Fig. 7.5) or presence of low oxygen in groundwater sources. The correlation between conductivity and arsenic was not possible to establish because all water samples had arsenic concentration levels below detection (zero mg/l).

Table 28: 7.5 Analysis of proxy parameters using statistical correlation method

Source Type	Correlation Coefficient, r								
	E.Coli versus Cond. & Turbidity		E.Coli versus Site characteristics			Conductivity versus chemical parameters			
	Cond.	Turbidity	Depth	Dist.	Slope%	NO_3	F	As	Fe
BHs	-0.136	0.076	0.280	0.091	0.074	-.0.038	0.220	-	0.064
PSWs	-0.365	-0.179	**0.926**	-0.377	-0.554	**0.587**	-0.485	-	-0.305

Cond. = Conductivity; Dist. = Distance from pollution sources

7.4.3 Assessing vulnerability of groundwater sources using ADRASTIC method

The RADWQ method allows the use of DRASTIC (**D**epth to water, **R**echarge rate, **A**quifer geology, **S**oil type, **T**opography (slope), **I**mpact of vadose zone, hydraulic **C**onductivity) techniques to assess vulnerability of groundwater sources from potential sources of contaminants where sanitary inspection techniques fail (WHO&UNICEF, (2010). The DRASTIC approach by Aller et al. (1987) is a widely-used approach for assessing aquifer vulnerability to contamination. It was used in this study to consider factors that were not possible for sanitary inspection tools. DRASTIC offers a rough management tool in lieu of more detailed hydrogeologic investigation. It focuses on hydrogeologic factors that increase the potential for contaminants to reach a given BH or PSW including depths of water sources, the recharge rate, aquifer geology and hydraulic conductivity, soil type, surface slope, and vadose zone properties. Depths of water sources were estimated from records that water-point committees kept during the development of water sources. The net recharge of the area was approximated basing on

Malawi government reports (GoM-UNDP, 1986). Features of soil were assessed on the basis of soil maps of the study area. Area geology and impact of vadose zone were estimated on the basis of a geologic map by Kim & Hamm (1999). Aquifer hydraulic conductivity was estimated on the basis of data from a study by Yu et al. (1992).

Table 29: 7.6 Assessing groundwater vulnerability to contaminants: DRASTIC analysis

Factors/variables	Weight	Range of values	Rating values	Data source
1. Depth to water (m) for PSWs	5	5-15	9	Field data from study area
Depth to water (m) for BHs	5	100+	1	Field data from study area
2. Net recharge (% of mm)	4	2-4	3	Malawi Government (2006)
3. Aquifer media (gneiss)	3	3-5	5	Study area geologic map and Kim and Hamm (1999)
4. Soil type (lithosols)	2	−	6	Study area soil map
5. Topographic slope, PSWs (%)	1	4-11	5	Study area slope map
Topographic slope, BHs (%)	1	0-4	9	
6. Impact of vadose zone	5	2-6	4	Study area geologic map
7. Hydraulic conductivity of aquifer material	3	4-8	4	Study area geologic map and Yu et al (1992)

The results showed that the most predominant soils in the study area were lithosols, which are shallow and stony soils formed from granite and gneiss rocks (GoM, 2008). These soils consist of imperfectly weathered rock fragments and mostly sandy and gravel with low runoff potential. The DRASTIC system of Aller et al. (1987) gives this soil group a ranking of 6. Rahman (2008) cautions that in addition to the soil type considered here, soil cover which was not included in the analysis also influences the surface and downward movement of contaminants thereby contaminating the aquifer through the recharge process as demonstrated on the conceptual model in chapter 6.

Using geologic maps (Fig. 7.6), the study illustrated that the major aquifers are basement and alluvial aquifers occuring in gneiss (mainly biotite gneiss) in most parts of the study area followed by micaceous phyllonite and Timbiri beds, along with clays, gravels and grits in the extreme south. Yu et al., (1992) reported that typical hydraulic conductivities for these units, depending on the degree of weathering is about 4.6 x 10^{-5} to 3.2 x 10^{-4} m/s for the granite, 1 x 10^{-4} to 4.6 x 10^{-4} m/s for the gneiss and schist and about 1x 10^{-3} m/s for the alluvium. Borrowing from the work of Yu et al. (1992) on hydraulic conductivities in basement and alluvial aquifers, similar to the study area, values for hydraulic conductivity was assigned a rating of 4 with a weight 3 on the DRASTIC model. Aquifer media (gneiss) was given a rating of 5 and a weight of 3; the impact of vadose was given a rating of 5 with a weight of 4. Net recharge from the report (GoM-UNDP, 1986) was given a rating of 4 with a weight of 3.

An assessment based on these estimations demonstrates that these factors are no threat to groundwater contamination. Theoretically, factors with high scores on the DRASTIC scale as shown in Table 7.6 would highlight significant variables that can explain contamination in groundwater sources in the study area. Practically, such factors rarely work in isolation but in combination with knowledge on local hydrogeology, fieldwork data and contaminants status in the study area (Roberts et al., 2001; Kim & Hamm, 1999). DRASTIC being an intensive data method, these results are tentative but provide a significant entry point for robust analysis. However, to manage groundwater resources for sustainable utilisation, local hydrogeologic factors need to be understood in terms of their influence on water-types in such aquifers that can explain the expected water quality. In addition, knowledge on general geology of the study area helps in the hydrogeologic and environmental (catchment) assessment on source and resource directed measures with their associated risks to ensure sustainable resource utilisation.

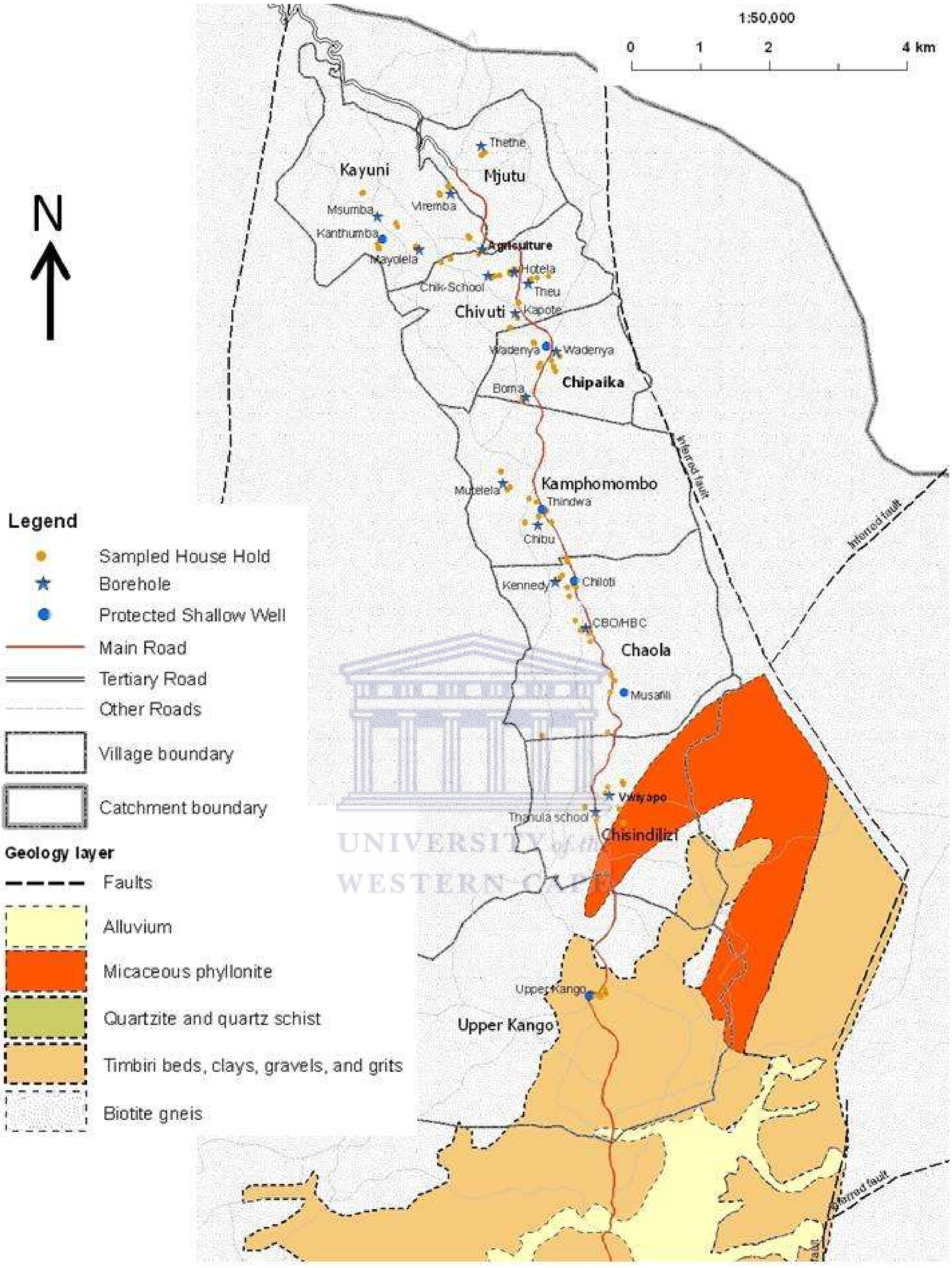


Figure 44: 7.6 All study water sources were located in hard rock geology except one

7.4.4 Analysing risks of groundwater sources to human health

Most diarrhoea-causing pathogens are present in faecal matter, hence, the need to analyze water for indicator species that are also present in faecal matter. The most commonly used indicator species are coliform bacteria, which include a wide range of bacteria such as environmental /total coliforms. However, not all coliforms are faecal in origin, so the presence of total coliforms in water is not a good indicator of poor water quality. Coliforms that come from faecal matter can tolerate higher temperatures, hence called thermotolerant /feacal coliforms (Thomas, 2011). These are more closely associated with faecal pollution. The most acceptable indicator species and specific indicator of faecal contamination is *Escherichia coli* (*E. coli*) (Thomas, 2011).

Table 7.7 below shows overall compliance of *E.Coli* by water source type with WHO and MBS values. The compliance of *E.Coli* in BH water was 100% suggesting that water from borehole source has low risk and free from bacteriological contamination compared to water from protected shallow wells which showed 0% compliance to both WHO and MBS values. Both WHO and MBS state that *E. coli* should not be detected in any 100ml sample for all water sources meant for drinking (WHO, 2008 & MBS, 2005).

Table 30: 7.7 Compliance of *E.coli* with WHO and MBS values by source type

Area (Villages)	**Boreholes**			**Protected shallow (dug) wells**		
	E. Coli			E. Coli		
	N	Compliance with WHO (%)	Compliance with MBS (%)	N	Compliance with WHO (%)	Compliance with MBS (%)
Upper Kango	0	NA	NA	1	0	0
Chisindilizi	2	100	100	0	NA	NA
Chaola	2	100	100	2	0	0
Kamphomombo	2	100	100	1	0	0
Chipaika	3	100	100	1	0	0
Chivuti	3	100	100	0	NA	NA
Kayuni	2	100	100	1	0	0
Mjutu	3	100	100	0	NA	NA
Total samples	**17**			**6**		

N= Number of samples; WHO guidelines/suggestive values; MBS regulatory values

A combined analysis of sanitary inspection and water quality data was used to assign a relative measure risk of groundwater sources to human health. Estimates of long-term risks of microbiological contamination (sanitary inspection) were combined with current data on *E.coli* levels in drinking water sources to derive a risk-to-health matrix (Table 7.8). After cross-referencing the *E.coli* counts with the corresponding inspection risk scores, the risk-to-health analysis was classified as very low, low, medium and high by water source type (Tables 7.8 & 7.9). Using this approach, borehole water showed that 1, 6, 9 and 1 sources had very low, low, medium and high risks respectively while in protected shallow wells, 1, 1 and 4 sources had low, medium and high risks respectively (Table 7.9).

Table 31: 7.8 Risks of groundwater sources to human health

Sanitary inspection score %	**Boreholes**				**Protected shallow (dug) wells**			
(Risk score %)	*E.coli* count (cfu/100ml)				*E.coli* count (cfu/100ml)			
	<1	1-10	11-100	>100	<1	1-10	11-100	>100
0-2 (0-20)	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
3-5 (30-50)	**6**	**0**	**0**	**0**	**1**	**1**	**0**	**0**
6-8 (60-80)	**9**	**0**	**0**	**0**	**0**	**1**	**2**	**1**
9-10 (90-100)	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	Total samples = 17				**Total samples = 6**			

Legend: Risk-to-health category

Very low	**Low**	**Medium**	**High**

Table 32: 7.9 Overall risk-to-health classifications by groundwater supply source

Risk category	**Boreholes**		**Protected shallow (dug) wells**	
	No of samples	Proportion (%)	No of samples	Proportion (%)
Very low	1	5.9	0	0
Low	6	35.3	1	16.7
Medium	9	52.9	1	16.7
High	1	5.9	4	66.7
	Total samples = 17		Total samples = 6	

The overall risk-to-health classification revealed that protected shallow wells were more risky sources to supply potable water than boreholes in terms of bacteriological contamination. Table 7.9 above shows how the ranked water sources would help to set priorities for individual interventions and support the rational decision making in terms of revising current practices for groundwater development especially in rural areas.

7.5 How socioeconomic factors influence groundwater management

This section presents results on factors that explain quality of groundwater for drinking from the socioeconomic perspective. The argument was that management of drinking water depends on how people collect, transport, store and treat such water at household levels. Such household practices in relation to bacterial contamination levels were assessed. To fulfill this objective, i) quality of water from sources and sampled households were compared; ii) storage practices at each sampled household were studied and iii) effectiveness of home water treatment was evaluated in relation to the overall analysis of household risks to human health due to such practices at homes.

7.5.1 A comparative analysis on the quality of household water with source water

WHO&UNICEF (2010) re-emphasised that as water is being transported from the source to households and stored in containers, recontamination of drinking water occurs and assessing such aspect has been recognised as an important public health concern requiring assessment. This suggests that in order to implement effective interventions that protect drinking water from contamination, assessing the quality of water within households and in sources is important. Therefore, this study conducted a comparative analysis on the quality of groundwater sources (boreholes and protected shallow wells) with households that drew their drinking water from such sources.

To test the effects of water collection, transport and storage on the quality of water, the bacteria concentrations at each source were compared with those in the households that obtained water from that source. For each water source, the concentrations found within the households using that source were averaged. Therefore, there were 46 observations: 23 represented the sources and 23 represented the average of the households associated with each of those sources. Only households that provided no water treatment were used in this analysis so that just the effects of post-collection could be evaluated. Nonparametric t-tests were applied using the relative ranks of the 46 observations to detect significant differences between the mean ranks of the water sources versus the household averages. Both total coliforms (p-value = 0.0042) and *E. coli* (p-value = 7.8×10^{-7}) concentrations were higher, on average, in the households than at the source indicating that there was bacterial contamination associated with the methods used to collect, transport and/or store the water in the home (Table 7.10).

A paired t-test was used to compare bacteria concentrations at the borehole sources with the average concentrations in the households using those boreholes. There were 17 paired observations, one for each of the boreholes. The paired t-tests indicated no significant difference with respect to total coliform, but as with the nonparametric test, *E. coli* concentrations were significantly higher in the households (mean = 0.088 CFU/100 ml) than at boreholes (mean = 14.5 CFU/100 ml) (p-value = 1.1x10^{-4}) (Table 7.10). Data from protected shallow wells and households using the protected shallow wells showed large and uneven variances, enabling the use of non-parametric tests to compare bacterial concentrations in Table 7.10 (Corder & Foreman, 2009).

Table 33: 7.10 Statistical analyses on groundwater sources and HH-stored water

Comparison	Statistical method	Mean 1	Mean 2	p-Value
BH[1] vs. PSW[2], *E. coli*	NP, equal variances	BH rank[3] = 9.2	PSW rank = 20	**6.2E-06**[4]
HH with no treatment vs. their source. Total coliform. BHs and PSWs combined	NP, equal variances	Source rank = 18	Household rank = 29	**0.0042**
HH with no treatment vs. their source. *E. coli*. BHs and PSWs combined	NP, equal variances	Source rank = 15	Household rank = 32	**7.8x10^{-7}**
HH with no treatment vs. their source. *E. coli*. BHs only	Paired, parametric	Source mean = 0.088 CFU/100 ml	Household mean = 14 CFU/100 ml	**1.1x10^{-4}**
HH with no water treatment vs. those with treatment using averages from each of 6 sources. *E. coli*	NP, equal variances	Treated household rank = 4.0	Untreated household rank = 9.0	**0.0049**
HH with no water treatment vs. those with treatment. All HH. Total coliforms	NP, equal variances	Treated HH rank = 31	Untreated HH rank = 45	0.075
HH with no water treatment vs. those with treatment. All households. *E. coli*	NP, equal variances	Treated household rank = 25	Untreated household rank = 46	**0.011**

HH=Households; NP=Nonparametric; BHs-Boreholes; PSWs=Protected Shallow Wells

7.5.2 Storage practices of drinking water in household containers

WHO (2007) reports that safer household water storage would be a suitable intervention to prevent contamination of domestic water and thereby accelerating progress towards meeting the MDG target 10 in situations where families have access to sufficient quantities of good quality of drinking water. The report emphasises that containers with narrow openings are appropriate safe storage facilities at household for drinking water. In this study storage practices (containers) in all the sampled households were studied to assess the influence of household water management on human health. Results showed that total colilform bacteria were detected in water from 57 of the households with their concentrations ranging from 1 to 67,000 CFU/100 ml (i.e., 670 CFU in a 1-ml sample) and averaged 5150 CFU/100 ml for households with detections. In general, *E. coli* bacteria were detected in 60 of the 90 sampled households with concentrations ranging from 1 to 14,500 CFU/100 ml and averaged 300 CFU/100 ml for households with detections. More revealing was that, *E. coli* bacteria were detected in 50 of the 66 households that obtained their water from boreholes despite the general lack of *E. coli* detections in water from boreholes (Tables 7.4; 7.8 & 7.9) confirming that household storage practices decline the quality of drinking water from safer groundwater sources.

For each of the 23 water sources, water were sampled in four households (for 21 of the sources) or three households (for 2 of the sources) obtaining their water from that source (Table 7.11). Types of containers used to store drinking-water were also studied. Results indicated that village residents typically collected and carried the water from each source in 20-l plastic buckets (Fig. 7.5). Of the 90 sampled households, 45 stored their water in clay pots, 44 in plastic containers and one in metal pots (Fig. 7.7). Although, 14% of the studied households left containers uncovered where they kept drinking water, 86% of them covered their containers where drinking water was stored.

Findings regarding the concentrations of inorganic solutes in this study agree with results by Pritchard et al. (2007; 2009; 2010) who concluded that the quality of drinking water from groundwater sources both boreholes and shallow wells in terms of physicochemical status in Malawi are within acceptable limits as set by both WHO and MBS. However, the pH of most of the sampled water was < 6.5 outside the MBS and WHO recommended limits with a violation fraction of 83% (Table 7.1). Cantor et al. (2000) and Hoko (2005) discussed the potential negative effects of low pH values on drinking water when stored in metal containers. The low pH values can lead to health concerns associated with corrosion of the metal containers. Fortunately, 99% of the sampled households keep their drinking water in none corrosive materials (ceramic pots = 45%) and plastic containers =44%), eliminating risks associated with corrosion in drinking water. These findings have wider application to households in this study area and also areas with similar geology. There is a need to encourage communities in such areas to keeping their drinking water in ceramic or plastic containers through educational and health promotion campaigns especially among women who are central in water collection as advocated by IWRM (Table 7.12).

Figure 45: 7.7 Common practices of storing drinking water at household level

These results suggest that the majority of households are practising safer household storage methods which need reinforcements although others are still at risk. UNICEF & WHO (2012) recommend education and promotional messages to target positive practices that are affordable and easy to use. However, such positive practices will be effective if they could be used correctly, consistently and sustainably so that the number of households with increased sanitary risk due to household practices decreases. The call for sustainable use of such practices implies IWRM implementation on household water management to achieve widespread and long terms success. Managing household water for improved human health has effect on IWRM implementation. Assessing factors that can affect such quality of such water requires coordinated approach. This can enable education sector to promote educational messages about water management. In this way, the overall risk-to-human health due to household practices will decline.

7.5.3 Effects of point-of-use treatment on quality of water stored in the households

Water from some sources has good quality needing no or little treatment while other sources may produce unsuitable water for domestic use such as drinking unless such water first receives treatment to improve its quality (Ince et al., 2010). Water treatment is often impractical in rural areas because such treatments require skilled supervision and constant buying. Therefore, it is common to select sources that can be protected against contamination such as boreholes and protected shallow dug wells. However, efforts to implement preventative measures are needed to protect groundwater sources coming into contact with potentially polluting materials (Tadesse et al., 2010).

Results from the hydrocensus of this study showed that only 11% (10 of 90) sampled households) treat their drinking water by adding Waterguard® which is another form of chlorine. The effectiveness of such treatment was tested using colorimetric analyses to detect levels of free chlorine residuals in stored drinking water. Reasons for the observed low chlorine usage were explored to conduct risk-to-health analysis. First free chlorine residuals were compared to 2009-WHO recommended values. Secondly, *E.coli* concentrations of the treated water from 10 households were compared to 80 households that were not treating water. The comparative analysis was performed to reduce bias on the basis of differences between water sources. Comparisons were performed among two sets of households that collected water from the same source but one set treated the water and the other set did not. For each water source, households with treatment and those without treatment were averaged. This allowed paired t-tests for bacterial concentrations of treated versus untreated water with each pair associated with a different water source. Only water from six water sources was used both by households that treated their water and those that did not (Tables 7.7 & 7.11).

Table 7.10 illustrated that the mean bacteria concentrations of the untreated water (7540 CFU/100 ml for total coliform and 74 CFU/100 ml for E. coli) were higher than the mean concentrations of the treated water (5.5 CFU/100 ml for total coliform and 4.0 CFU/100 ml for E. coli). However, the associated variances were so large that the differences were not significant using parametric tests. Hence, a nonparametric test was applied in which all the treated and untreated waters were combined into one data set and ranked using Mann-Whitney U-test (Corder & Foreman, 2009). Then t-tests were used to detect significant differences between the mean ranks of the treated versus the untreated water (Table 7.10). Nonparametric tests were performed for the six pairs of samples used in the parametric tests and indicated that water treatment significantly lowered *E. coli* concentrations (p-value = 0.0049) (Table7.10). The same nonparametric tests were repeated using all the households, 80 with untreated water and 10 with treated water. Results yielded only weak evidence (p-value = 0.075) that water treatment lowered the total coliform concentration, but strong evidence (p-value = 0.011) that water treatment with chlorine effectively lowered *E. coli* concentrations (Table 7.10).

Levels of free chlorine residual and turbidity in chlorinated drinking water storage is used to determine the effectiveness of household chlorination and risk-to-human health of such stored drinking water (WHO, 2009). WHO&UNICEF (2010) continue to recommend that drinking water supplies including stored drinking water should be tested for free chlorine residual because the chlorine levels directly influence microbiological quality of drinking water. It is noteworthy that, free chlorine residual less than 0.2 mg/l becomes a concern because it implies a reduced protection against microbial contamination (WHO, 2009). In this study, all the samples for the households had higher concentration levels of free chlorine higher than the 2009-WHO suggestive values of 0.2mg/l (Table 7.11). This indicated that chlorine levels in sampled households were adequate to ensure safe water at household levels. However, the levels of observed contamination in the same households were not consistent with effectiveness of the chlorine to eliminate all the *E.coli*.

Since chlorine failed to eliminate all the *E.coli*, other factors such as turbidity and temperature that were assumed to affect effectiveness of chlorine were tested. Turbidity in water is caused by suspended matter such as clay, silt, finely divided organic and inorganic matter, soluble coloured organic matter and plankton and other microscopic organisms. Turbidity can rise in drinking water if the water is inadequately treated or if sediment is re-suspended. Turbidity can also come from biofilms or corrosion products into the water storage system. High levels of turbidity can protect microorganisms from the effects of disinfection and can stimulate bacterial growth. Low turbidity minimises both the amount of chlorine required for disinfection of water and the potential for transmitting infectious diseases (Tadesse et al., 2010). Hence, this study assessed the compliance of turbidity levels in household stored drinking water with 2008-WHO guidelines and Malawi Bureau of Standards (MBS, 2005). Results showed that 4 of 10 households had water samples with a turbidity of more than 5 NTU (Nephelometric Turbidity Unit). However, there was no correlation between turbidity and concentration levels of *E.coli* levels (Table 7.5).

The results of this study confirmed that chlorination improved water quality but it did not eliminate all pathogenic bacteria. One possible explanation to this was that the correct procedure for applying chlorine to water was not strictly adhered to in terms of waiting and temperature of the water (WHO, 2009). Secondly, sampled households might have put chlorine when they heard that researchers were testing their stored drinking water. For example, except in one case, the free and total chlorine concentrations were equal to each other within the margin of error (Table 7.11). Temperatures of the stored water ranged from 22°C to 29°C and averaged 25°C. The WHO (2009) recommends that water should be at around 18°C for chlorine to effectively work after 30 minutes of being put in drinking water. The colder water needs more time for chlorine to work effectively. The equipments and the procedure of testing for turbidity and chlorine levels in household stored water are shown in figure 7.8.

Table 34: 7.11 Colorimetric tests on chlorine and turbidity levels in HH stored water

Type of water source	*Sampled HH[3] per water source*	*HH using Chlorine*	*Ave Total Chlorine (mg/l)*	*Ave Free Chlorine (mg/l)*	*Ave[4] Turbidity (NTU)*	*Ave E.coli (CFU/100ml)*
Thanula School BH[1]	4	3	0.80	0.78	5.4	18
Vwiyapo BH	4	2	7.9	7.8	1.4	2.3
Chibu BH	4	1	3.0	2.7	0.16	22
Boma BH	4	1	1.9	1.0	6.6	14
Agriculture BH	4	1	0.59	0.51	1.5	4.8
Thethe-BH	3	1	2.1	2.1	0.36	24
Thindwa PSW[2]	4	1	5.0	5.0	3.8	263

BH[1]=Borehole; PSW[2]=Protected shallow dug well; HH[3]=household; Ave[4]=Average

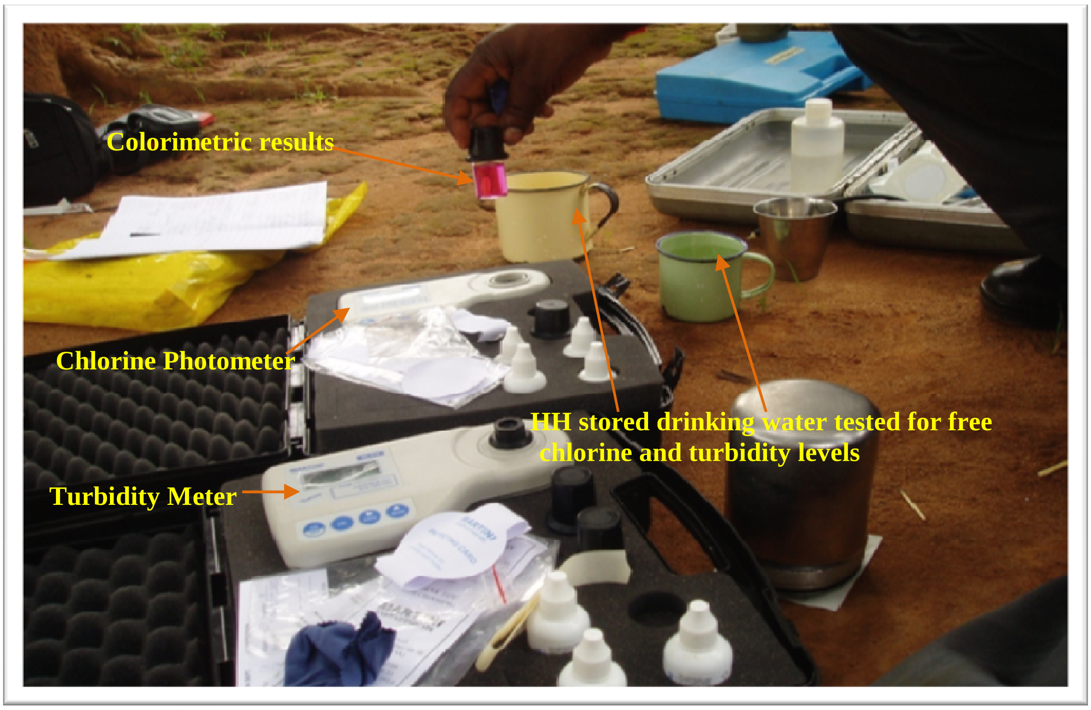


Figure 46: 7.8 Colorimetric tests on chlorine and turbidity levels in HH drinking water

7.6 Application of RADWQ methods for groundwater management

This section highlights the usefulness of using RADWQ methods to assess factors that would affect groundwater management. To fulfil that objective, the section shows the relevance and appropriateness of RADWQ methods in groundwater management and such methods could be compatible with the IWRM approach. The section ends by bringing to light some of the weaknesses of RADWQ methods that need considerations when they are being implemented in different environmental contexts of countries.

7.6.1 Relevance of RADWQ methods for groundwater management practice

The RADWQ methods are relevant in managing groundwater resources largely in terms of assessing risks of groundwater protection. RADWQ is considered one of the most recent management tools for water quality assessment. RADWQ methods are relatively new and applicable. For example, globally, RADWQ methods have been piloted in seven countries for water quality assessment. Such countries include: Nigeria, Ethiopia, Jordan, Tajikistan, India, China and Bangladesh, Sierra Leone (WHO&UNICEF, 2010; Properzi, 2010 & Thomas, 2011. RADWQ methods have both advantages and weaknesses as stated in chapter 4 of this thesis (Aldana, 2010; Ince et al., 2010; Tadesse et al., 2010; WHO&UNICEF, 2010 & Thomas, 2011).

Properzi (2010) reminds readers that that the Millennium Development Goals (MDG) on water target 10 called for monitoring in terms of coverage/use (access to water), safe water for drinking and sustainable water services. JMP (2000) reported the major breakthrough in global monitoring of access to improved drinking water sources using reports that based on households surveys (hydrocensus). Such global monitoring lacked the safety component. That lack of safety component through detailed assessment of overall compliance of microbial, chemical and aesthetic parameters of drinking water to WHO and national standards to ascertain sanitary risk factors and risk-to-health analysis for households that draw water from improved water sources gave birth to **R**apid **A**ssessment of **D**rinking **W**ater **Q**uality (RADWQ) (Schmoll, 2009). Such an approach is relevant in the water management practices where groundwater protection is one of the research themes within sustainable groundwater development for water supplies.

In terms of sampling procedure for the desired variables, RADWQ follows a multi-stage cluster sampling approach to select individual drinking water supplies and households that draw from improved sources. This approach considers spatial distribution of water sources in space which helps spatial analysis of the water being studied. This study followed such sampling design as described in chapter 4 of this thesis. The relevance of such a design is that interpretation of results from such studies becomes scale specific which is one of the important considerations in groundwater studies (Wentzel, 2009).

Since RADWQ methods deal with four types of water sources, namely, piped water supply, boreholes, protected springs and protected dug wells or protected shallow wells (PSWs) (WHO&UNICEF, 2010), it can be said that RADWQ methods largely deal with groundwater making the use of such methods more appropriate for this study. Since this research focussed on groundwater, piped water supplies were excluded and there was no identified protected spring used for drinking, therefore, only boreholes and protected shallow dug wells were studied in agreement with RADWQ methods.

7.6.2 Suitability of RADWQ methods groundwater management and IWRM

This section demonstrates five areas where the RADWQ methods are used as tools to showcase best practices in groundwater management that is compatible with the IWRM approach. The aim is show that apart from using RADWQ methods to assess factors that affect the quality of water; such methods can also be used to provide solutions on how to manage water resources in a coordinated manner for sustainable use.

Firstly, RADWQ methods through sanitary risk assessment provide a measure for operation and maintenance through sanitary risk scores for water source. For example, the findings from assessment are discussed with users and community members at time of inspection to actively involve them for solution on the observed aspects. Assessments reveal practices or factors that may cause contamination hence, community members are invited to assist monitoring such practices to protect water from being contaminated. Since ecological and institutional principles of IWRM call for protection of natural systems such as water and participation of users respectively (FAO, 2000), RADWQ methods through sanitary inspection fulfil such principles. Note that sanitary inspections focus on three categories of risks: i) hazard factors which are potential sources of faecal materials such as the presence of pit-latrine close to or uphill water sources; ii) pathways factors which are potential routes through which contaminants might enter water sources such as cracked aprons or loose handles and iii) indirect factors such as lack of fencing. These would facilitate development of pathways for animals to access the water source where they will produce faeces that may enter water sources through the cracked apron or drainage thereby contaminating water sources (Ince et al., 2010).

Secondly, RADWQ methods enable water managers to implement environmental interventions such as source protection measures to focus on controlling pollution activities within close proximity to the source (Robins et al., 2007). For instance, if statistical correlation analysis between the selected water quality parameters or site characteristics and water contamination shows positive association then public awareness meetings will be conducted to sensitise communities on human activities that lead to increased risks for the observed water contamination. The act of raising awareness among community members who are also users of such water means that decisions to protect water resources through reduced activities that threaten water quality will be taken at the lowest appropriate level (community) and such decisions are participatory in nature which is according to ecological and institutional principles of the IWRM approach as advocated in the Dublin Principles of the 1992 (FAO, 2000).

Thirdly, results from the RADWQ methods provide insights on how engineering interventions can be provided to protect water from contamination according to the ecological principle of the IWRM approach which calls for protecting water because it is a finite and vulnerable resource. Where RADWQ assessment results show that water from a particular source (s) is highly contaminated, this may suggest failures in maintenance or faulty design or that construction quality was not adequate. The solution would be to revise the design or rehabilitate the source in order to protect the water from contamination. Such decisions would involve water developers, planners and policy makers and the users in the affected community. This is participatory approach in nature according to the IWRM approach (Tadesse et al., 2010).

The fourth way in which RADWQ methods assist in managing groundwater from IWRM approach is through educational intervention (Robins et al., 2007). For example, assessment results from RADWQ methods require educating the community to improve both source maintenance and hygiene promotion. Thus, the water testing equipment and sanitary inspections as direct learning tools require emphasis. By directly involving communities in these activities, for instance, by reading results of water quality tests with communities, the potential to develop sustainable improvements is greater.

Fifthly, RADWQ methods could assist managing groundwater resource from the IWRM approach by providing the basis for monitoring water quality. For example, results from the RADWQ methods provide baseline information for building national surveillance by focusing on routine water quality monitoring programme. This activity would lead to sustainable management of the water resources being monitored as advocated by the IWRM. In this way, the RADWQ becomes an effective management tool for water resources as advocated by the IWRM in ecological principles (FAO, 2000).

7.6.3 Some limitations of RADWQ methods in groundwater management

One of the weaknesses of the RADWQ methods is the focus on improved water sources only for water quality assessment which neglects those that use unimproved water sources although this practice reflects the requirement of JMP 2000. By way of illustration, in Malawi, although 74% of households access drinking water from improved sources (48% BHs, 20% pipes and 6% PSW), 26% still use unimproved sources such as unprotected dug wells (18%) and rivers/lakes (8%) (NSO, 2009). In Nkhata Bay district where this study was conducted, 57% of households accessed improved water sources (37% BHs, 5% PSW, 15% pipes) while 43% used unimproved sources such as unprotected dug wells (27%) and rivers/lakes/ponds (16%) (NSO, 2009). Therefore, by not assessing the unimproved water sources, the risk associated with such water and risk-to-human health are underreported. This suggests that interpolation of results from RADWQ method should be cautious on overall risk-to-health of the entire population in the study area or a country. Chapter 2 has described safe and unsafe sources in Malawi.

The second weakness of the RADWQ methods is that where reliable data from the national surveillance system is scarce or does not exist, data from RADWQ assessment becomes independent and cannot be compared with national dataset (Schmoll, 2009). This means that national status on risk factors for water sources and household stored water; national risk-to-human health due to water sources and household stored water cannot be evidently stated. However, for Malawi, the National Statistics Office and the Health Demographic Surveys provide benchmarks for comparison as described in Chapter 2 of this thesis (NSO, 2009 & MDHS, 2010). Nevertheless, for managing groundwater sources, the provision of a statistical representative snapshot of drinking water quality, compliance assessments, sanitary risk assessments, risk-to-human health assessments and analyses of proxy parameters that RADWQ methods provide are adequate to implement interventions for managing water resources in a collaborative manner as required by the IWRM approach as described this chapter.

The third weakness for using RADWQ methods is the interpretation of results from RADWQ assessments by some health professionals who equate risk results to certainty. The entire method is based on risks thus results that describe risks should not be translated into certainty (WHO&UNICEF, 2010). For instance, the presence of faecal indicators in water does not confirm presence of pathogens rather it indicates that the risk of pathogens has increased because there is evidence of recent faecal contamination. This suggests that using the current indicator bacteria alone is not adequate to predict health risks especially with the knowledge that multiple pathogen microbial indicators exist. However, the use indicator bacteria remain an important aspect in protecting human health, especially in low-income countries (Properzi, 2010).

7.7 IWRM execution using groundwater management

This section demonstrates how the findings from groundwater management that uses RADWQ methods can facilitate implementation of IWRM in a catchment by reflecting on the four principles of IWRM as presented in Table 7.12 below.

Table 35: 7.12 Four summarised principles of IWRM approach

Principle 1: Freshwater is a finite and vulnerable resource, essential to sustain life, development and the environment. FAO (2000) calls this principle, the ecological principle.
Since water sustains life, effective management of water resources demands a holistic approach linking social and economic development with more on protection of natural ecosystems (environment). Effective management links land and water uses across the entire catchment or groundwater aquifer with a river basin or catchment or sub-catchment being a unit of analysis during assessments.
Principle 2: Water development and management should be based on a participatory approach involving users, planners and policy makers at all levels. FAO (2000) calls this principle, the institutional principle.
The participation approach involves raising awareness of the importance of water among policy makers and the general public. It means that decisions are taken at the lowest appropriate level with full public consultation and involvement of users in the planning and implementation of water projects.
Principle 3: Women play a central part in the provision, management and safeguarding of water. This principle is also called the institutional principle (FAO, 2000).
This pivotal role of women as providers and users of water and guardians of the living environment has been seldom reflected in institutional arrangements for the development and management of water resources. Acceptance and implementation of this principle requires positive policies to address women's specific needs and to equip and empower women to participate at all levels in water resources programmes including decision-making and implementation in ways defined by them.
Principle 4: Water has economic value in all its competing uses and should be recognised as an economic good. (FAO (2000) calls this principle, the instrument principle.
Within this principle, it is important to first recognise the basic right of all human beings to have access to clean water and sanitation at an affordable price. Past failures to recognise the economic value of water has led to wasteful and environmentally damaging uses of the resource. Managing water as an economic good is important to achieve efficient and equitable us, to encourage conservation and protection of water resources and to improve water allocation and quality.

Source: FAO, 2000

7.7.1 Influence of groundwater development on IWRM implementation

The importance of providing scientific evidence on contamination of groundwater sources for drinking in order to inform the basis for reviewing guidelines on rural water service provision cannot be overemphasized. Site characteristics as described in sections 7.4 and 7.5 were assessed to examine effects of these site characteristics on contamination of groundwater sources. Despite findings being not statistically significant, the analysis has shown that such factors have the potential to contaminate groundwater sources especially in protected shallow dug wells. According to application of precautionary and differentiated principles in groundwater protection (Xu & Reyders, 1995; Xu & Braune, 1995), these results are adequate to caution groundwater developers on appropriate sites for shallow dug wells. These principles agree with the ecological principle of IWRM presented in Table 7.12 which calls for protecting water resources because it is finite and vulnerable. In this way, results from RADWQ methods applied in groundwater management provide a guide for IWRM implementation in a catchment.

Application of the DRASTIC approach provides a well-established means of assessing the vulnerability of aquifer. According to this approach, parameters used and described in this field study should provide a measure of the risk of contamination and indicators that will provide the basis for more robust field measurements of all the DRASTIC parameters. Downscaling such an approach to a catchment level posses its own challenges especially because DRASTIC was developed for regional scale application and it is data intensive (Robins, 2010). Nevertheless, using such a technique provides an opportunity as a starting point for exploring more robust catchment fitting methodologies for groundwater contamination.

A simple vulnerability assessment scorecard technique developed by Robin et al., (2003) and applied in Mangochi, Southern Malawi is more suitable to assess effect of site characteristics on groundwater contamination. The techniques are based on DRASTIC principles but instead of being quantitative and data intensive, they are qualitative, subjective and site specific which makes them applicable at catchment or sub-catchment levels (Robins, 2010). However, scorecard also relies on data derived from a comprehensive and well-documented drilling program which was not possible in this current study due to the study’s scope as described in chapter 1 of this thesis.

Theoretically, areas with low slope tend to be more vulnerable to groundwater contamination as these are areas where water can pool for a longer period of time thereby allowing a greater infiltration and hence a greater potential for contamination migration (Rahman, 2008). The location of water sources in low-lying wet areas poses a threat of groundwater contamination partly because aquifers in such areas are likely to be in close hydraulic connection with surface water (Robins, 2010). In addition, Rahman (2008) in the Great North Indian Plain observed that PSWs that were more contaminated were located in relatively flat areas. This observation was similar to findings for this study as presented in sections 7.4 and 7.5.

Factors responsible for the contamination in groundwater sources cannot be deduced on the basis of sanitary inspection and DRASTIC methods alone. Field observations on location of groundwater sources provided useful insights that would form a basis for discussions among scientists, water developers, users and managers on where to locate water sources in relation to potential sources of contamination. This is what the institutional principle of IWRM advocates for through participatory approaches (Table 7.12). Robin et al. (2007) found that field observation about topography and slope, vegetation and land use explained detected contamination in groundwater sources at catchment level. In addition, Robin et al. (2007) demonstrated how local surface water pools after rainfall create a concentrated and prolonged zone of potential infiltration of contaminants and how cracks or fractures can offer direct and rapid pathways from groundwater to the water tables. This justifies the use of both field observation and measurement techniques to explain possible factors for the observed contamination in the studied water sources. Therefore, despite none significant results from statistical analyses, i) site characteristics are important factors that require consideration when locating PSWs and ii) participatory techniques as advocated by the IWRM approach (Table 7.12) are needed to protect groundwater from possible contaminants caused by anthropogenic activities.

7.7.2 How results from RADWQ methods lead to implementing local IWRM

Discussion on groundwater quality protection needs to be conducted in the context of set criteria about water quality with an emphasis on the hydrogeological condition where such water resides. For example, flow patterns of groundwater in the aquifer need exploration for possible demystification of general contamination in the aquifer. In this study, the groundwater flow pattern was assumed to follow the topographic structure to explain the possible presence of contaminants in the groundwater resources. The findings provided adequate preliminary evidence to caution water service providers on locating PSWs in relation to site characteristics that are likely to contaminate groundwater. The assumption on groundwater flow pattern in this study was based on basic principles of groundwater flow: i) that water moves from higher to lower hydraulic head through the most permeable parts of the geologic structure; ii) and that recharge depends on characteristics of the uppermost geologic and soil layers and on slope as described in detail in chapter 6 of this thesis.

The Upper Limphasa River catchment being a basement complex aquifer (Fig. 7.6), flow processes were assumed to take place in two scenarios: a) fractured hard rock aquifer with preferential flow pattern along faults and fractures; b) primary unconfined aquifer on top with secondary confined aquifer at the bottom. Groundwater flow pattern in fractured rock aquifer can follow lineaments such as faults (Fig. 7.6). Preferential flow along lineaments is common during recharge in this type of aquifer with almost no natural protective layer to help attenuate contamination along the faults. Although no pathogenic bacteria were detected in boreholes (Table 7.4), precautionary and differentiated principles are applicable that groundwater sources should not be sited in such lineament environment and communities should have such knowledge.

Primary unconfined aquifer has alluvium materials which usually filter contaminants coming from the surface through its particles and pore spaces acting as a natural protection layer (Xu & Braune, 2010). There is uniform recharge occurring in the unsaturated zone and contaminants travel freely down to the water table (Healy, 2010). The difference in pathogenic concentration levels in water sources in such an environment depends on the thickness of the alluvial materials to allow microbe travel to aquifer, attenuate, adsorb and filter microbes; and slope between water source and source of contaminants, among other factors (Rajkumar & Xu, 2010). MacDonald et al. (2005) found that shallow soil layers to aquifer explain high vulnerability of contamination in protected shallow wells. Findings on high levels of microbial contamination in protected shallow dug wells in Upper Limphasa catchment (Table 7.4) agree with the explanation by Xu & Braune, 2010; Healy, 2010; Rajkumar & Xu, 2010; & MacDonald, 2005). As evidence, the Upper Kango PSW being the only water point located in alluvial aquifer and having the highest concentration levels of both pathogenic bacteria alludes to the effect of slope and thin alluvium material as observed by MacDonald et al. (2005). These results provide the base for implementing ecological and institutional principles of the IWRM approach through participatory techniques to commence educational meetings with community members on protecting groundwater by reducing activities that threaten the quality of groundwater for drinking in the community. This is how results from RADWQ methods in groundwater management studies can facilitate IWRM implementation within catchment at a community level.

7.7.3 Influence of groundwater development on social vulnerability of community

Theoretically, that assumption has been that groundwater provides safe drinking water (Xu & Braune, 2010). However, results from this study agree with results of many studies in southern Malawi by Pritchard et al. (2007, 2009, 2010); in Nigeria by Ince et al. (2010); in Ethiopia by Tadesse et al. (2010); in Sierra Leone by Thomas (2011), and in the Great North Indian Plain by Rahman (2008) that some groundwater sources especially protected shallow dug wells do not provide potable water. Field measurements and water quality assessment on PSWs have revealed high levels of *E. coli* in such sources confirming the increased risks to human health. From such assessment, this study has demonstrated the risk to human health of PSWs and provided the insight on how groundwater provision for drinking using such sources makes the community vulnerable. Although such findings are not conclusive, they provide the base to start reviewing guidelines about such sources in terms of providing safe drinking water sources. Renewed reflection on PSWs as safe sources for potable water in rural areas requires commitment of key governmental agencies as managers, private-sector as water developers and communities as users on rural water and sanitation issues. This is how findings from PSWs using RADWQ methods could enable IWRM implementation.

This study concludes that scaling up PSWs so as to provide potable water to rural communities remains risky and counterproductive of the MDG target 10. Malawi-MDG (2010) shows that 81% of Malawi's population had sustainable access to improved water sources whereas the MDHS (2010) reports that 79.3% of Malawi population use improved drinking water source. Although the two assessments seem to agree, the target in MDG target 10 is not about access to improved source but access to safe sources as discussed in chapter 2 of this thesis (WHO&UNICEF, 2010 & JMP, 2000). With only 40% of the people in Malawi having access to safe drinking water (Pritchard et al., 2007), the country faces difficulties in achieving the drinking-water MDG target 10 by 2015 and using PSWs to speed up access to safe drinking water sources remains regressive as evidenced by the analysed data on PSWs in sections 7.4 and 7.5.

In addition, the analysis in section 7.5 has shown that deficiencies exist in the hygienic practices associated with collection, transport and storage of water in the studied households. Even when water at the source was free of pathogenic bacterial contamination, water tested in the households was often contaminated with *E.coli.* These findings were consistent with those found in Jordan by Properzi (2010), in Nigeria by Ince et al. (2010), in Ethiopia by Tadesse et al. (2010), in Nicaragua by Aldana (2010) and in Sierra Leone by Thomas (2011), who used the same RADWQ methods. Such contamination in the households suggests the necessity to disinfect drinking water at point-of-use which has its own limitations as described in sections 7.5. However, these findings indicate that possibly door-to-door health education campaigns might enable communities to reduce the insinuated practices to improve health benefits. Such educational intervention can effectively be carried out through participatory approaches where women who are the water collectors and household water managers could be given the central role in implementing the best practices of household water management. This complies with the third principle of IWRM as stated in Table 7.12.

7.7.4 How socio-economic conditions limit uptake of scientific solutions

This section shows the limitation of implementing the instrument principle (FAO, 2000) of the IWRM approach which encourages water management as an economic good to improve water quality, among others (Table 7.12). In this study, management of drinking water at household level was not managed as an economic good because the price of disinfectants (chlorine/ water guards) was not affordable to community members. The result was that only 10% of the sampled households applied disinfected their drinking water and this was regardless the findings that water that was tested free of pathogenic bacteria at sources were found contaminated with *E.coli* at households which drew from safe sources as described in sections 7.4 and 7.5 of this thesis.

A review by Nath et al. (2006) on hygienic practices at households showed that improving the microbial quality of household stored water at point-of-use treatment and safe storage reduces water-borne diseases in communities and households up to 50%, even in the absence of other programmes. This study revealed that use of Waterguard$^{®}$ chlorination significantly reduced contamination by *E.coli* bacteria in household stored water, and similar health benefits as observed by Nath et al. (2006) would be expected despite the fact that chlorine failed to eliminate all pathogenic bacteria in drinking water. Similar results were observed in rural south India where Firth et al. (2010) studied point-of-use treatment to decrease contamination using chlorine and found that chlorine reduced bacteria to potable level but did not eliminate them all.

Turbidity, temperature and pH were studied as crucial physical or chemical parameters that affect the effectiveness of chlorine in drinking water (WHO, 2008; 2009). Theoretically, chlorine treatment in drinking water does not effectively penetrate suspended silt and organic particles where bacteria may reside (WHO, 2008; 2009). The higher the turbidity levels, the higher the risk of gastrointestinal diseases. Turbid materials can shield pathogens thereby interfering with effectiveness of both chlorine and ultraviolet sterilization of water (WHO, 2008; 2009). For effective chlorination treatment, water should have < 30 NTU. The overall average water turbidity in sampled households was low (0.16 NTU), at which level it does not impede sterilization with chlorine. The highest average recorded turbidity was 6.6 NTU (Table 7.11). In water with temperature above 18^{o}C, chlorine should be in contact with the water for at least 30 minutes. If the water is colder then the contact time should be increased (WHO, 2009). The average temperature for water stored in sampled households was 25^{o}C. Thus, the temperature should not have had negative impacts on chlorination effectiveness. Health workers teach residents to wait for 30 minutes after pouring chlorine in their drinking water. However, investigation of the compliance to such teachings was beyond the scope of this study. Nevertheless, such educational intervention by the health workers and active involvement of community members is what IWRM approach advocates. Therefore, results from RADWQ methods in groundwater management at household level show how local IWRM can be implemented with the potential for sustainable utilization of water for their improved health when participatory approaches continue.

The need to chlorinate drinking water from PSWs cannot be overemphasized, and yet the current rate of usage of chlorine is discouraging. The use of chlorine on water from PSWs confirms that it is at least a partially-effective solution but it remains a socio-economic unsuitable answer for the majority of rural residents. For instance, although study participants were willing to use chlorine, they could not afford to purchase it on a regular basis. The assessed income earnings of study participants through hydrocensus (chapter 8) insinuated difficulties of affordability, sustainability and feasibility of scaling up such chlorination intervention for households that draw their drinking water from PSWs. These findings on barriers to use chlorine when made available for sale were similar to what Tumwine (2005) observed among East Africa communities. This study has shown that only 10% of the sampled households used chlorine and only one household of the 23 that drew water from PSWs used chlorine effectively. The lack of widespread use of water treatment and especially the low usage among households using PSWs raises fundamental research questions regarding the ability of communities to adopt chlorination as a widespread practice. As a case study, these findings have wider implications in poverty-prone rural areas where chlorination is encouraged. These results suggest that implementing instrument principle of IWRM approach in order to manage water as economic good remains a long term goal in low income countries.

7.8 Summary

The argument for this thesis has been that factors that explain the quantity (availability, demand and use), quality (physical, chemical and microbial) and governance of groundwater need to be assessed to improve the required scientific understanding that can be shared among researchers, developers, users and managers (stakeholders) of water resources to implement IWRM for sustainable use of such water. Groundwater management in the Upper Limphasa River catchment was used as a case study. In addition, the thesis argued that methods used to assess such factors need to be demonstrated among stakeholders in terms of being modern, feasible, simple but robust, cost-effective and producing results that agree with underlying scientific principles.

This chapter has shown that the dominant water type in the aquifers of Upper Limphasa catchment was Ca-HCO_3 suggesting that the area has shallow fresh groundwater which has been recently recharged in the aquifer. The physicochemical analysis showed that none of the sampled boreholes (BHs) and protected shallow dug wells (PSWs) had physical or chemical concentration levels of health concern when such levels were compared with 2008-World Health Organisation (WHO) guidelines and 2005-Malawi Bureau of Standards (MBS). Conversely, although the compliance with 2008-WHO and 2005-MBS of *E.coli* in borehole water was 100% suggesting that water from BHs had low risk and free from bacteriological contamination, water from PSWs showed 0%

compliance with both 2008-WHO and 2005-MBS values implying high risk to human health. The overall risk to health classification showed that PSWs were risky sources to supply potable water in terms of bacteriological contamination.

In terms of source of contamination, results have not been conclusive. In general, though no significant relationship between site characteristics and contamination levels was observed in PSWs, DRASTIC and correction statistical analyses showed that depth contributed to contamination. In this regard, the strongest positive correlation coefficient ($r = 0.926$) was for *E.coli* and depth of PSWs and for DRASTIC depth to water in PSWs was rated 9. Again, results on high sanitary risk scores for water sources showed vulnerability of water quality suggesting that environmental, engineering and education interventions need to be implemented to improve future trends in water quality as authorities in water-health sectors revisit the policy on PSWs as safe sources.

When groundwater from sources and households was compared, results showed that both total coliforms (p-value = 0.0042) and *E. coli* (p-value = 7.8×10^{-7}) concentrations were higher in the households than at the source indicating that there was bacterial contamination associated with the methods that were used to collect, transport and/or store the water in the sampled households. These findings suggest continued efforts in educating the community on hygiene practices to promote good health among them. Although results showed that *E. coli* concentrations were significantly higher in the households (mean = 0.088 CFU/100 ml) than at boreholes (mean = 14.5 CFU/100 ml) (p-value = 1.1×10^{-4}) and that strong evidence (p-value = 0.011) existed that water treatment with chlorine effectively lowered *E. coli* concentrations, only 11% of households were chlorinating their drinking water, suggesting that high risk to human health in such a community exists thereby requiring further studies on such risk factors.

Although 14% of the studied households left containers uncovered where they kept their drinking water, 86% of them covered their containers. In addition, 99% of the sampled households kept their drinking water in none corrosive materials (ceramic pots = 45%) and plastic containers= 44%), eliminating risks that are associated with corrosion in containers used to store drinking water. Reinforcing such positive practice for household water management would be cost effective in terms of health promotion.

Although advantages of using the RADWQ methods in managing water resources especially groundwater have been demonstrated with examples in section 7.6, some limitations on using the same methods have been highlighted that need caution when being applied. A proper understanding on how results from RADWQ methods can be utilized in facilitating the implementation of IWRM at a local scale (community) has been provided in section 7.7 because it was thought crucial for managerial efficiency in the water sector. Unless the generated information and knowledge are assimilated and understood by water users (community), water developers/funders and water managers, the efforts applied in generating and explaining the applicability of such information and its associated benefits and methods might be a waste.

The next chapter demonstrates how local IWRM can facilitate implementation of the full IWRM in a river catchment. This is done by showing how local IWRM works as a best management practice using community groundwater management practices at community level as a case study. The entire research design is a case study approach.

Chapter 8: Local IWRM Status in Limphasa Catchment

8.1 Introduction

Application of the integrated water resources management (IWRM) principles at a community level makes a credible showcase for the role of IWRM in sustainable utilization and management of water resources especially groundwater for domestic and productive livelihood. Highlighting working aspects of IWRM principles at local scale provides direction for future revisions of IWRM strategies that are developed to guide implementation of water policy. This chapter provides the evidence for the argued thesis that local IWRM acts as a proxy for the full IWRM. Such evidence is provided through the findings on local IWRM and application of IWRM principles that focused on groundwater management for domestic use (drinking) in the Upper Limphasa River Catchment. The argument highlights the feasibility of local IWRM to facilitate the full and successful IWRM when multiple-use services (MUS) approach is considered. As a case study, the thesis demonstrates the application of IWRM principles in the Upper Limphasa River catchment in managing and utilizing the groundwater resources. Finally, this thesis shades light on the contribution of local IWRM to groundwater management as part of the IWRM approach for the sustainable utilization and management of the water resources and environmental integrity. Local IWRM refers to local-level governance, self-regulation, local solutions that uses principles of adaptive management (Wester et al., 2009; Walters, 1986; Holling, 2005; Habron, 2003).

8.2 Methods used to collect and analyse data

The hydrocensus method was used to collect data on local IWRM where questionnaire was used as an instrument. The questionnaire contained five sections, as follows: Section A: institutional arrangement where types of institutions, organisations, structures, coordination among them were investigated. Analysis focused on how such local organisations coordinate among themselves and how they adapt to government structures in the study area in the process of water development. Section B investigated whether or not local communities are aware of government policies, laws and assessments on water resources especially on groundwater. Section C focused on investigating demand for water in terms of availability, reliability, use, accessibility, regulations and gender. Section D investigated perception of local community of quality of groundwater for drinking in terms of treatment and storage practices. Finally, section E assessed the respondents. The questionnaire is provided in the appendix.

Using a questionnaire in hydrocensus methods is a common technique because results are believed to be more optimistic as they are completed by water professionals who probe respondents to give more realistic responses (FAO-AQUASTAT, 2009). However, the questionnaire technique might not be adequate to depict under-reporting or over-reporting responses by respondents. Furthermore, interpretations of questions in the questionnaire might be subjective to individual resulting in giving bias to those filling the responses. Nevertheless, the results are sufficient to highlight insights that can be verified with other methods such as field observations and field measurements.

In this study, results from the questionnaire depending on the theme were verified using field observations and field measurements as presented and discussed in chapters 5, 6 and 7 on hydrogeology, water availability, demand, use and water quality respectively. SPSS software version 19.0 was used to analyse descriptive statistics for this chapter to show the magnitude of the analysed aspects. For analytical method in this chapter, a multiple-use service (MUS) approach which advocates for the integrated manner of providing water services in rural areas was adopted. The argument for the use of MUS approach as an analytical method in groundwater for rural water supply and sanitation is that water users tend to use water resources for multiple purposes such as domestic and productive activities at and around their households (Smits et al., 2010; FAO-AQUASTAT, 2009 & 2010). Therefore, multiple-use services (MUS) approach is a suitable analytical approach for IWRM analysis at local IWRM and full IWRM levels.

The description in chapter 2 has shown that groundwater management in Malawi lacks comprehensive coordination and is highly fragmented with responsibilities distributed among different water developers. For example, different government ministries are involved in groundwater development such as Ministry of Health, Ministry of Education, Ministry of Agriculture and Department of Water Development, among others. These provide groundwater (boreholes) in health facilities, in schools, to smallholder farmers for irrigation activities in rural areas and for rural water supply and sanitation respectively (GoM, 2008c). In the NGO sector, there are various local and international organisations that are involved in groundwater development including religious organisations. This observed lack of coordination partly emanates from the fact that implementation of the IWRM water policy and strategies would require political will to release significant resources for monitoring and enforcing land-use practices (Kresic, 2009) which are rarely released to fulfil the planned activities.

That political will to release financial and human resources to the lowest level of water management at sub-catchment level is not feasible in the near future, at least in Malawi and in most developing countries. This is so because in most cases, financial resources to manage water resources are left to the local communities and private water sector such as NGOs (NBDA, 2009). These two will have to develop management plans that involve active participation of local stakeholders to minimize risks to their water supplies. Local communities will have to be aware of activities that would threaten the quantity and quality of their water resources including groundwater sources (Chevalking et al., 2008). In this case, local-level governance is essential as shown in 8.4.6 when this study assessed how such self-regulation system works in Upper Limphasa catchment.

8.3 Physical environments for local IWRM

Physical factors/environments that explain or influence groundwater availability in the Upper Limphasa River catchment have been described in chapter 6 section 6.4 with various figures (maps and photos). Such factors include a) climate, b) soils and geology, c) topography, d) water resources (hydrology) and e) land cover and land use. A brief summary is provided in this section with references made to figures in section 6.4.

Kresic (2009) and Healy (2010) categorised climatic regions into four classes in relation to groundwater availability (recharge process) as follows: Arid and semiarid climatic regions receive annual precipitation of less than 250mm and between 250mm and 500mm respectively. These regions experience episodic and preferential recharge types; whereas sub-humid and humid climatic regions receive annual precipitation rates of 500 to 1000 mm and exceed 1000 mm respectively and such areas experience, diffuse, focused and preferential recharge types. Fig. 8.1 shows that both Upper and Lower Limphasa River catchments are in humid climatic region although on average the Upper catchment receives relatively lower annual rainfall than the Lower catchment. In addition, Fig. 6.2 had shown that yearly, both catchments receive rains from October to July suggesting that aquifers are recharged almost throughout the year.

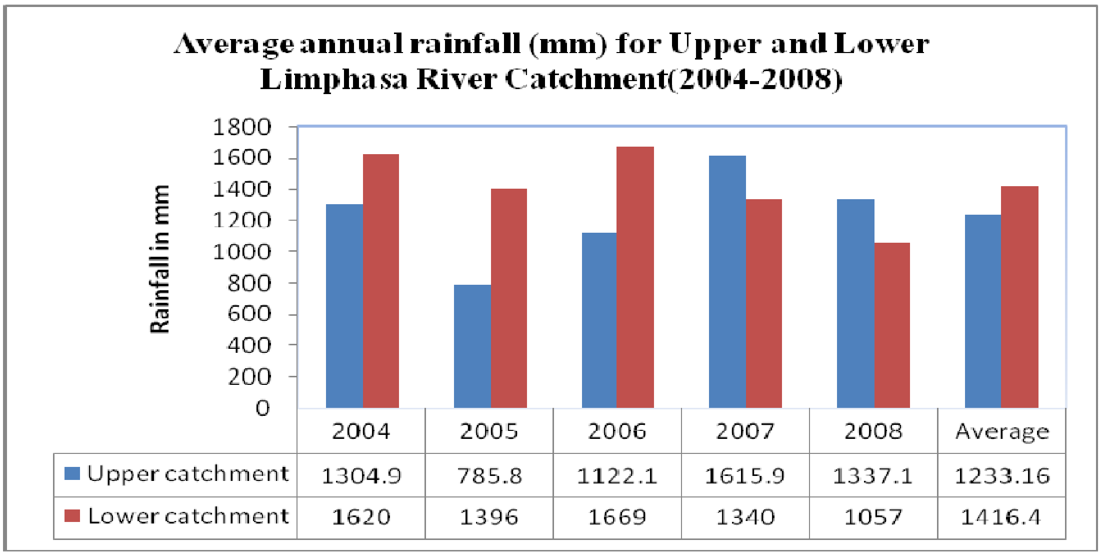


Figure 47: 8.1 Average annual rainfall(mm) for Upper and Lower Limphasa catchment

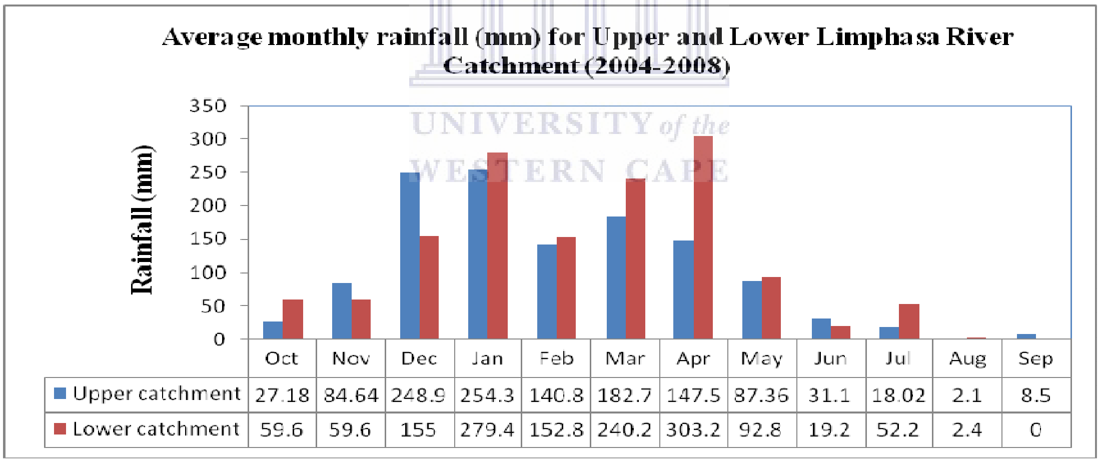


Figure 6.2 Average monthly rainfall (mm) for entire Limphasa Catchment (2004-2008)

Being in the humid climatic region as shown by Figs 8.1 and 6.2, the catchment experiences diffuse, focused and preferential types of recharge. This suggests high recharge pattern which should result in more groundwater availability in the aquifers. However, the steep topography in the Upper catchment does not facilitate high recharge pattern as it increases more runoff than infiltration. In addition, the geology that forms the fractured rock aquifers in the Upper catchment does not suggest good permeability and storage system for more groundwater in aquifers. The dense vegetative land cover types which act as groundwater abstracters do not allow high infiltration pattern for groundwater recharge. The land use pattern such as human settlement on hill tops (recharge areas) and cultivating hill slopes which accelerates runoff than facilitating infiltration negatively affect recharge process. All these factors as described in chapters 5 and 6, suggest less groundwater availability in the Upper catchment. Therefore, there is need for stakeholders in the catchment to understand how these factors influence groundwater availability so that such waters should be managed collaboratively in a coordinated manner among institutions for sustainable utilization. This chapter demonstrates how such waters are managed in the catchment using the local IWRM approach which is based on adaptive management practices.

8.4 Socioeconomic environments for local IWRM

This section describes some of the socioeconomic conditions prevailing in the Upper Limphasa River catchment in brief because details on such aspects have been presented and discussed in chapters 5, 6 and 7 in relation to management of groundwater from the IWRM perspective. In this section, where applicable, references are made to some sections in chapters 5, 6, 7 and even chapter 2 where socioeconomic factors have been already discussed. The following socioeconomic aspects are described in this section in relation to groundwater management from IWRM focusing how local IWRM operates in this study area: a) household population; b) household environment; c) education facilities and literacy levels; d) health facilities and services; e) employment challenges and opportunities and f) institutional arrangements in the upper catchment in relation to water management using local IWRM approach/local solutions.

Table 36: 8.1 Selected socioeconomic factors in Upper Limphasa catchment

Socioeconomic variables	**Studies villages in the Upper Limphasa River catchment**								
	UKA	**CHI**	**CHA**	**KAM**	**CHIP**	**CHIV**	**KAY**	**MJU**	**Total**
Total households	42	173	99	54	109	74	38	100	689
Average HH size	6.0	5.4	5.3	5.9	6.0	5.5	4.9	5.2	5.53
Water source (BH)	0	2	2	2	3	3	2	3	17
Water source (PSWs)	1	0	2	1	1	0	1	0	6
Pit-latrines	33	110	76	53	88	54	26	76	516
%Pit-latrine coverage	79	64	77	98	81	73	68	76	75
Population	253	940	527	316	650	408	188	526	3805

UKA=UpperKango; CHI=Chisindilizi; CHA=Chaola; KAM=Kamphomombo; CHIP=Chipaika; CHIV=Chivuti; KAY=Kayuni; MJU=Mjutu

8.4.1 Household population and composition

Table 8.1 above shows that the Upper Limphasa River catchment had a population of 3,805 who stayed in 689 households and the average household size was 5.5. The average household size was higher than the national average household for rural areas which was 4.7 and national average household was 4.6 (MDHS, 2010). It was important to calculate the average household size because the number of people per household has a direct bearing on the demand and use of water resources in the area. Housing characteristics reflected typical rural settings in Malawi; and 52% of sampled households had mud-floors and 54% had grass-thatched roofs. Such characteristics have direct implications on the use of i) water for mud-smearing their floor and walls and ii) vegetation for thatching their dwellings units. Of the sampled households, 91% said that they settle on hill-tops and in a nuclear/cluster pattern. When asked on reasons for settling on hill-tops, 82% cited their Tonga cultural identity which they inherited.

The analysis showed that the settlement pattern reflected the historical pattern of the Tonga tribe of settling on hill-tops to watch over the incoming Ngoni/Nguni warriors of Tshaka the Zulu from South Africa in the early 18th century (Nyaluwanga, 2008). However, such cultural identity had direct implications on groundwater quantity and quality because hill-tops are recharge zones for groundwater. Hence, such settlements create impervious surfaces resulting in increased runoff and erosion and less recharge to groundwater aquifers leading to less groundwater quantity. Again, such a settlement system means that pit-latrines are dug near their households on hill-slopes while their shallow hand-dug well (PSWs) for drinking water are constructed down-hill below pit-latrines which threatens groundwater quality. This is one of the explanations for the presence *E.coli* pathogenic bacteria detected in PSWs as discussed in chapter 7, Fig.7.2.

8.4.2 Household environment

Although this study focused on groundwater sources only as sources of drinking water supplies, other sources exist in the study area where people collect water for drinking. Such sources include rivers/streams and unprotected hand-dug wells. However, the 17 boreholes that were studied in the area were enough to supply safe drinking water to a population of 3,805 (Table 8.1) against the Malawi Government recommendation of 250 people per borehole (GoM, 2005; Baumann & Danert, 2008) which would have served 4,250 people for the 17 boreholes. Still, the terrain is the major challenge in accessing drinking sources as shown in chapter 6 Fig. 6.12 and in chapter 7, Table 7.4 & Fig. 7.5. In general, access to safe water sources was not dire although improvements are needed on the protected shallow wells as safe sources of drinking water.

Table 8.1 showed that on average pit-latrine coverage in the study area was 75%. In all villages the availability of sanitation facilities was over 60%. Results in Table 8.1 are consistent with the ones for the northern region 83.8% and Malawi 82.1% in chapter 2 (Table 2.3) in terms of high percentages of households using traditional pit-latrines. Although sanitation facilities are available for almost each household in the study area, these facilities are not improved sanitation facilities (NSO, 2009; Malawi-MDG, 2010; WHO&UNICEF, 2010). Such traditional pit-latrines form focused and preferential recharge of contaminants to groundwater sources which threatens the quality of groundwater in the catchments. Although direct sources of contaminants were not found in this study, results on assessing microbial quality of groundwater in chapter 7 have shown that water from shallow aquifers (Protected shallow wells) had *E.coli* which is an indicator of fresh feacal contaminants. *E.coli* as pathogenic bacteria are not supposed to be found in drinking water sources (WHO&UNICEF, 2010). On the basis of this information (results), an education programme could be made to create awareness on groundwater protection and contaminants. With local IWRM operating in the study where school teachers and health surveillance assistants participate, they can implement such messages in schools and health facilities effectively and monitor the compliance.

8.4.3 Education facilities and literacy levels

The study area had four primary schools as follows: i) Mwambazi in Kango Village; ii) Thanula in Chisindilizi Village; iii) Kangoyi in Kamphomombo Village; and Chikwina in Chivuti Village. Each of these schools had a functional borehole as a water supply facility except the borehole at Kangoyi primary school which was dysfunctional for three years (2008, 2009 and 2010). This was observed during the fieldwork period in the study area. The district water office was informed about the problem. The alternative source of drinking water was the nearby stream and Thindwa protected shallow well. Literacy levels in the study area was very high with 95% of the respondents had primary education and above; 95% of the sampled households had their members who attained primary education and above; and 96% of sampled household water collectors had primary education and above. Such observed literacy levels were advantageous civic education and active participation for coordination and collaboration efforts to manage groundwater from IWRM perspective among stakeholders from different institutions.

8.4.4 Health facilities and services

Field observation showed that three health facilities existed in the study area a) Thanula health mobile clinic in Chisindilizi Village; b) Kangoyi health mobile clinic in Chaola and; c) Chikwina rural health centre in Chivuti Village. Thanula and Kangoyi clinics had a Health Surveillance Assistant each while Chikwana had a Medical Assistant as the main contact person. Each of these health facilities had a health committee to oversee health issues of people in villages accessing services from such facilities. The under-five, maternal and sanitation issues were mentioned as the most services clinics offered. Existence of such health institutions was an opportunity for local IWRM, because results showed the critical role that health institutions played in creating awareness among community members on groundwater protection from contaminating sources. Sanitation facilities such as pit-latrines were among the most critical aspects that were discussed on groundwater protection for improved human health.

8.4.5 Employment challenges and opportunities

Results on Fig. 5.3 in chapter 5, section 5.5 and field observations showed that the Upper Limphasa River catchment had no plantations and industrial activities where local communities could seek employment. Apart from the civil servants who worked as teachers at the primary schools, health surveillance assistants and other extension workers for agricultural, forestry and fisheries department, job opportunities in the Upper Limphasa was a challenge. Yet, the analysis in chapter 5, section 5.7 on benefit sharing concept which is based on the ethical principles and economic emancipation of the poor, showed that opportunities for employment exist in rubber, tea, sugar and rice plantations in the Lower Limphasa. Nonetheless, basic mechanisms, negotiations and cooperation that need to be initiated, implemented and sustained between plantation owners and local communities in the entire catchment are non-existent. The benefit sharing concept when implemented has the potential to ensure sustainable management of water resources especially for the upstream land users who live and cultivate in the headwaters and who could negatively affect the quantity and quality of water for consumers downstream in the Lower Limphasa River catchment. A detailed discussion on the benefit sharing concept is provided in chapter 5, section 5.7 (Haas, 2009).

8.4.6 Institutional arrangements

This section describes the institutional arrangements from the village level within the Upper Limphasa River Catchment to the District level where the District Water Office is situated so that key findings from the Upper Limphasa River catchment on how coordination works within and among local institutions in the study villages are contextualised. Like any other district in Malawi, Nkhata Bay has a District Executive Committee (DEC) whose membership consists of all heads of government departments and NGO partners in the district. DEC is responsible for coordination, monitoring and evaluation of implemented projects in the district. Within the DEC, there is a District Coordination Team (DCT) which implements the coordination and management of projects in the districts and it meets once per month (NBDA, 2009).

Below the District level, comes the Traditional Authority (TA) level, where there are also two committees, i) Area Development Committee (ADC) which focuses on developing project proposals for the communities and mobilizing resources from communities to contribute towards such projects. At TA level, there is a technical committee called Area Executive Committee (AEC) which consists of officers from government departments such as Water monitoring Assistants, Health Surveillance Assistants, Community Development Assistants, Field Assistants, Fisheries Assistants and Teachers, among others, who reside in communities providing services to local communities on behalf of the Malawi Government. AEC also consists of NGO Officers working in communities on various funded projects. The Health and Environment Committee is part of AEC and it has a sub-committee for water and sanitation issues which links with similar committees at village level (NBDA, 2009).

In each village, there is Village Development Committee (VDC) which is responsible for identifying needs and facilitating planning and development in local communities. Apart from the VDC, each village has Village Health and Water Committee (VHWC) whose roles include managing water and sanitation issues. VHWC has 10 members with at least five women. Two of the 10 members are locally trained as technical caretakers of the water point. Villages with more than one water-point have a Water-Point Committee (WPC) whose responsibility is to manage the water point facility to ensure that it remains functional always by mobilizing resources from water-point users. The WPC also ensures that good sanitation and hygiene are maintained around the water-point area. Communities are expected to channel their requests for water facilities using the above described structure (NBDA, 2009).

This study worked more with water-point committees in each village because it aimed at assessing the management of groundwater sources focusing on how such structures are coordunated in managing groundwater at local scale (community level). The analysis used the multiple use services (MUS) approach to identify application of aspects of the IWRM principles in the management of groundwater in the Upper Limphasa River catchment. The Multiple-use analytical approach starts from recognizing the multiple-use of water as a de facto practice and seeks to manage water services with the aim of meeting people's water needs for multiple purposes (Van Koppen et al., 2006). When water is managed with this understanding, it is expected to have more impact on livelihoods and improve the sustainability of using water resources. By focusing on multiple uses which is integration, the MUS concept borrows from the principles underlying IWRM. This was the reason for choosing the MUS approach as analytical method in this study.

One of the reasons that limit successful operation of IWRM is the contradiction in water policy. For example, it recognizes the multiple uses of water at higher levels of scale under the heading of IWRM and within the same water policy there is a continued division between subsectors at operational level where water programmes are conceived and implemented (Van Koppen et al., 2009). By way of exemplifying, sector experts and line departments are all guided by their own subsector mandate and goals. Moriarty (2008) observed the common trends on how different approaches are implemented at community level regarding the use of water. The above scholars observed that water use to increase food production through irrigation follow different strategies from water use to reduce morbidity and mortality from water-borne diseases through water supply and sanitation services in the same communities. Smits et al. (2010) agreeing with Moriarty

(2008) observed that each subsector has its own set of institutions, objectives, methodologies and financing frameworks that reproduce the subsectoral focus. As a result, water service providers from subsectors fail to address people's water needs beyond the type of water use they are mandated to provide.

Local IWRM provides a solution to such a complexity at local scale where multiple uses of water are recognised. With local IWRM, through the structures or institutions that exist at local level or at community level different water providers or water users from government departments and NGO offices meet in one meeting with committees such as Village Development Committee and discuss their challenges and progress. Their suggested solutions are taken one step higher to Traditional Authority level where technical inputs from government, NGOs and community representatives (Area Development Committee) reflect on what has been discussed and agreed upon at Village Development Committees. Then after refinements, such reports are forwarded to the District level where the District Coordinating Committee meets and further refines the inputs from the Area Development Committee before the District Executive Committee adopts the report and final decision is made on the way forward.

All this participation by different stakeholders in decision-making, all this active involvement by the community members in decision-making, all this institutional involvement at different levels within the catchment is taking place without establishment of Catchment Management Agency or Catchment Management Strategies. This is how local IWRM prepares the way for a full, wider and successful IWRM if this existing and working structure could be recognised by the central government and nurtured. This showed how the institutional principle of IWRM is being applied within the local IWRM or how local IWRM applies the institutional principle of IWRM. It is the institutional arrangement which is one of the critical challenges in implementing IWRM but this study has shown that in Upper Limphasa River Catchment, local IWRM surmount such an obstacle as described in this chapter.

Note that in chapter 2, section 2.2, the administrative hierarchy from the district head office to the household level has been provided where it is said that each district in Malawi is headed by District Commissioner (DC). The district is administratively subdivided into traditional authorities (TAs) led by a Chief called Traditional Authority. These TAs are further subdivided into Group Villages led by Group Village Headmen which are further subdivided into villages led by Village Headmen then come households which are basically defined as houses whose members eat from the same pot/table. The institutional arrangement follows such a structure and this study was conducted in eights villages, namely, Upper Kango, Chisindilizi, Chaola, Kamphomombo, Chipaika, Chivuti, Kayuni and Mjuti as shown in chapter 8 Fig. 8.2 and chapter 2 Fig.2.2.

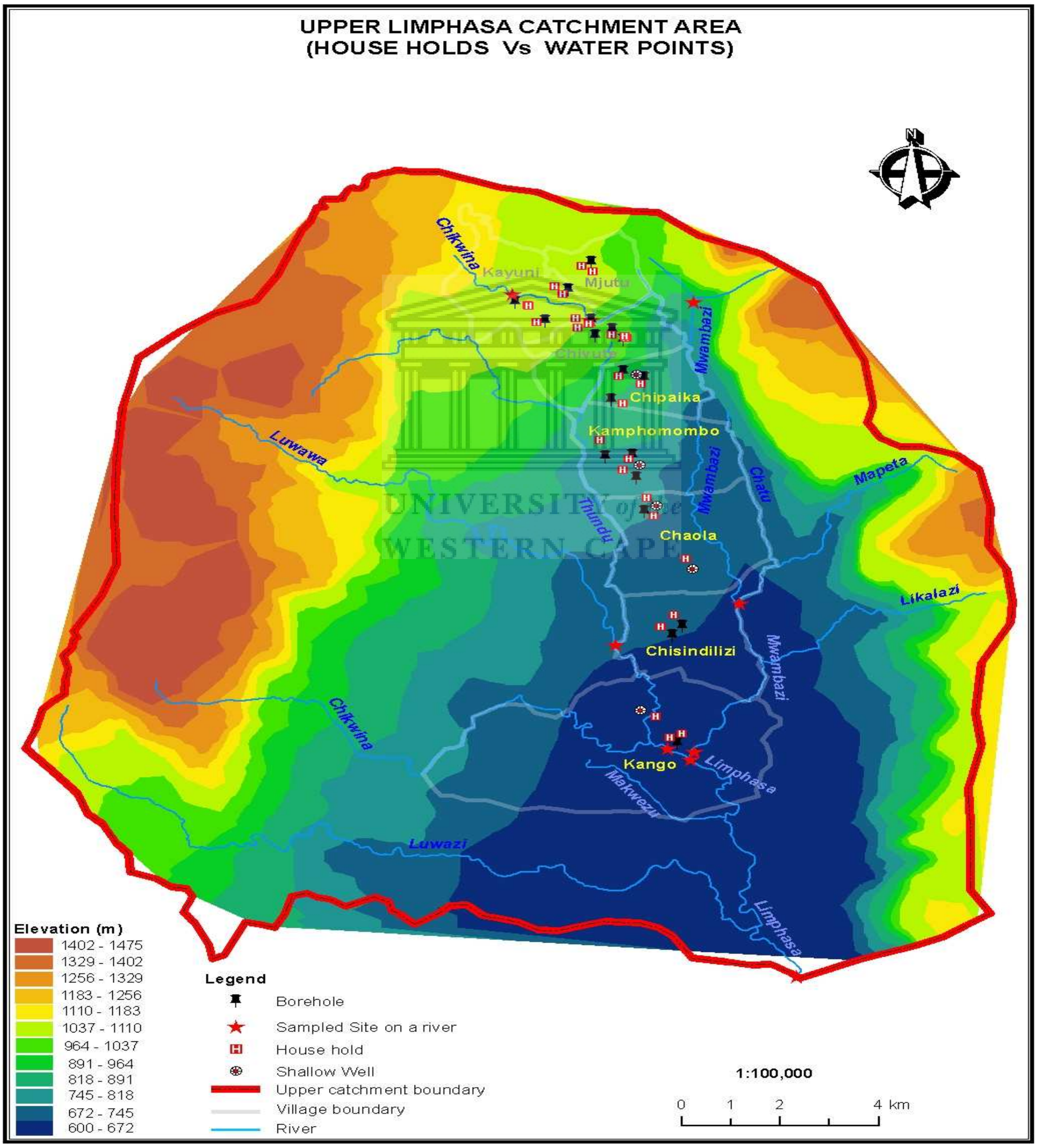


Figure 48: 8.2 Organisations of sampled households in relation their water sources

8.5 Implementing local IWRM with a focus on groundwater

Globally, IWRM has been endorsed and accepted by many international agencies and governments as a holistic approach to water resources management (Anderson et al., 2008). The IWRM concept is being increasingly accepted and integrated in planning and decision-making processes of water managers and policy-makers. The debates about the history, operational definitions and procedures are on-going. However, within the water community there is general agreement on the underlying principles and approaches that underpin the IWRM concept and the potential it holds for managing complex systems that cannot be adequately achieved through the single sector management approach of the past (Anderson et al., 2008). Molle (2008) stated that generally implementation of IWRM is difficult and Biswas (2008) observed that, absence of acceptable operational definition of IWRM in terms of issues that should be integrated makes IWRM difficult to implement.

Apart from problems with definition, Kresic (2009) observed that IWRM itself is a political process which requires political decision and such a political context affects political will and political feasibility to implement the IWRM approach. Jeffrey and Gearey (2006) argued that it is difficult to implement IWRM because it remains a theory about, an argument for and at best set of principles for, a certain approach to water resources management. This is why empirical evidence to show tangible benefits of IWRM are either missing or poorly reported in many countries. Grigg (2008) agreeing with Jeffrey & Gearey (2206), Anderson et al. (2008), Biswas (2008) and Kresic (2009) on the difficulty of implementing a successful IWRM added institutional arrangement as the other crucial obstacle and suggested improved governance as a solution. The scholar suggested that instead of implementing the full IWRM approach, it is essential and practical to focus on elements for integration which could be found in the following areas: i) policy sectors, ii) water sectors, iii) government units, iv) organizational levels, v) function of management, vi) geographic units, vii) phases of management and viii) disciplines with experts. This thesis has used institutional arrangements as some of the crucial elements as described in section 8.4.6.

To make progress in the water sector, Lankford et al. (2007) and Merrey (2008) recommended adopting an adaptive approach to managing water resources that focus on identifying and implementing practical solutions while clearly recognising the political and distributive dimensions of water governance. Since the development of IWRM for groundwater use has received scant attention with exception from the USA and Australia (Wester et al., 2009), local IWRM is suitable for groundwater management. Local IWRM refers to local-level governance or self-regulation approach to managing water resources with a community (Wester et al., 2009). Alternatively, local IWRM refers to the collective management practices of groundwater by water users at community level as an alternative or complement to state/government regulation (Steenbergen, 2006; Schlager, 2007). This is the definition used in this thesis where local IWRM has been mentioned. Leendertse et al., (2008) emphasised that implementation of IWRM requires a more progressive approach that is based on interative and learn-by-doing approach (adaptive approach) which is local IWRM. It also requires a balance between establishing enabling environments (law, policy and institutional support) and community projects that have tangible benefits for the communities. Studies in South Africa (Olifants/Doorn) and Philippines showed that IWRM is most effective when initiatives actively empower communities by involving them in projects that serve to improve their livelihoods and well-being (Anderson et al., 2008). Therefore, implementing local IWRM is one step forward, towards successful implementation of the full IWRM. Hence, it is essential in this thesis to highlight aspects of the IWRM principles that were observed working in the management of groundwater for domestic use in communities of the Upper Limphasa River Catchment.

8.6 Key findings on how Local IWRM and implication for full IWRM

This section presents key findings on local IWRM and discusses such results in terms of their positive influence to facilitate full and successful implementation of IWRM at catchment level especially in places where successful implementation and enforcement of water laws, water policies and institutional coordination encounter critical challenges for various reasons. These results have been discussed by highlighting principles of IWRM that were observed in the actions of study communities when groundwater management was being carried out using principles of adaptive management (learning-by-doing). The following IWRM principles were checked in the operation of local IWRM in the study villages: ecological, institutional, gender and instrument principles.

The interpretation of the results in this section highlights the application of IWRM principles through local IWRM and such principles resemble the elements in multiple use approach (MUS approach). Local IWRM uses the meaning and principles of adaptive management practices as described in chapter 3, section 3.5. The assumption is that an increased awareness on the role of groundwater in the hydrological cycle would result in better understanding of the resources in terms of its flow dynamics, storage mechanisms and susceptibility to pollution as described in Fig 5.9 and Fig 6.1 in chapters 5 and 6 respectively. The analysis in Figs. 5.9 and 6.1 provided the basis for the need to increase efforts to managing water resources from the IWRM perspective. Since the two conceptual models did not yield quantitative data, interpretation was based on risk-analysis which agrees with precautionary principles of environmental management as discussed in Chapter 5.7. The use of risk-analyses and precautions for education intervention to create awareness on understanding challenges and opportunities on groundwater management are based on principles of adaptive management as illustrated in chapter 3.5 (Walters, 1986; Holling, 2005; Habron, 2003). The discussion on key results such as systematic data collection by communities, women's roles in community committees, self-regulation in water management and coordination among institutions in communities reflects the use of adaptive as well best management practices in the Upper Limphasa River catchment. Local IWRM is both adaptive and best management practice. This thesis argues that such practices deserve nurturing to facilitate the full, wider and successful implementation of IWRM approach in other catchments.

8.6.1 Systematic data collection by local community without water experts

Without undermining the importance of collaborative efforts that IWRM advocates for with regard to data collection during groundwater studies, Todd and Mays (2005) provide the context as to why local community members have been sidelined in such studies. The scholars stated that groundwater management studies are usually conducted by local government agencies for various professional reasons. For example, when conducting preliminary examination to identify management possibilities to meet a defined need for a specific area, judgment by experienced personnel is required. In such a situation learning-by-doing as adaptive management calls, would be undesirable. In addition, reconnaissance studies which often utilise the available data for analysis and collect new data sets to consider possible alternatives when formulating management plans to meet a defined need for specific areas, largely rely on the cost-benefit estimates which require skilled personnel and not communities. Furthermore, feasibility studies require detailed engineering, hydrogeologic and economic analysis to professionally estimate the costs and benefits of the project to ensure that the selected project is an optimum development in terms of meeting the goals of socioeconomic development and environmental integrity. All these three elements do not require the expertise of local community members hence, their exclusion in data collection on groundwater management studies, stated Todd and Mays.

Agreeing with Todd and Mays (2005), Swallow et al. (2006) argued that initiatives that seek to foster collective action especially in the watershed need to account for the very different interests and professional needs in managing water resources. Swallow et al., (2006) concluded that collective actions between and among stakeholders on water resources are key for sustainable management in water development especially at local scale where community members are expected to manage the developed water resources when water professionals leave communities. Therefore, there is a need for local communities to be involved at all levels of water development including data collection for institutional memory among others, argued Swallow et al. (2006).

Table 37: 8.2 The calculated depths of water sources from community collected data

Village names	Names for the studied water type	GPS coordinates (location) for the studied water sources and altitude	Recorded no. of rods	Calculated depth (m)
Upper Kango		X:629151;Y:8729518; 590 m.a.s.l	18feet	5.5
Chisindilizi	Thanula Sch. BH	X:629255;Y:8732195; 669 m.a.s.l:	8	48
	Vwiyapo BH	X:629452; Y:8732450; 683 m.a.s.l	11	66
Chaola	Musafili PSW	X:629656; Y:8733926; 711 m.a.s.l	14feet	4.3
	CBO BH	X:…….; Y:…..; m.a.s.l: (missing)	6.7	40
	Chiloti PSW	X:628939; Y:8735560; 774 m.a.s.l:	11.5feet	3.5
	Kennedy BH	X:628686; Y:8735540; 801 m.a.s.l	7	43
Kamphomombo	Chibu BH	X:628402; Y:8736372; 818 m.a.s.l	8	48
	Thindwa PSW	X:628457; Y:8736604; 818 m.a.s.l	10feet	3
	Mutelela BH	X:627902; Y:8736990; 840 m.a.s.l	8	48
	Kangoyi Sch.BH	X:628440; Y:8736890; 850 m.a.s.l	7	42
Chipaika	Boma BH	X:628245; Y:8738242; 886 m.a.s.l	10	60
	Wadenya BH	X:628679; Y:8738904; 899 m.a.s.l	10	60
	Wadenya PSW	X:628524; Y:8738988; 898 m.a.s.l	10 feet	3
	Jumbo BH	X:628266; Y:8739044; 921 m.a.s.l	6.7	40
	Kapote BH	X:628097; Y:8739468; 956 m.a.s.l	7.5	45
Chivuti	Theu BH	X:628266; Y:8739896; 997 m.a.s.l	7.7	46
	Hotela BH	X:628070;Y:8740064; 1018 m.a.s.l	8	48
	Chikwina Sch.BH	X:627681;Y:8740000; 1020 m.a.s.l	7	42
Kayuni	Mayolela BH	X:626685;Y:8740390; 1093 m.a.s.l	12	72

Mjutu	Msumba BH	X: 626070Y:8740876; 1087 m.a.s.l	12	72
	Kanthumba PSW	X:…….;Y:……. m.a.s.l (missing)	10feet	3
	Agriculutre BH	X:627610;Y:8740390;1042 m.a.s.l	8.5	51
	Viremba BH	X:627136;Y:8741198; 1087 m.a.s.l	8	48
	Thethe BH	X: 627600;Y:8741908;1053 m.a.s.l	12	72

BH=Borehole; PSW = Protected Shallow hand-dug well; For PSWs figures were recorded in feet in the registers; m.a.s.l=metres above sea level; GPS gave an error margin of 8-10 metres; Calculated depth=depth of water calculated based on the figures from records/registers note that 1drilling rod=6metres.

Using the argument of Swallow et al. (2006), this study conducted interviews and results in Table 8.2 showed the data which community members in the Upper Limphasa River catchment collected when water experts were developing groundwater sources for drinking in the area. Community members were actively involved in collecting sand, bricks and gravel when boreholes were being drilled. They proactively participated in the data collection process by recording the number of drilling rods in their notebooks (registers) to estimate the depth of each borehole. Although they could not report the depth of their water sources in metres during hydrocensus, they could tell the number of drilling rods that went in each of the boreholes as recorded in their notebooks. Such information was recorded in a register known as a borehole register and kept by the secretary of each water-point committee in the study area. This study used such records to estimate depths of BHs and PSWs in the area when correlating risk factors to observed microbial contamination of groundwater as discussed in chapter 7(Table 7.4).

The data collected by local community was useful for such statistical analyses because such data could neither be read on the apron of boreholes nor be accessed from government water offices with the explanation that the drilling agencies did not give such data sets to the government water offices for record keeping. In this situation, local IWRM (local-level governance with local water-point committee) proved useful in data collection and record keeping on each water facility. If this approach can be nurtured and standardized and replicated country-wide, then data on water facilities will be available and accessible for various assessments. Such a process when nurtured would enable water professionals to standardize and refine such information for uniformity.

This local IWRM in this case provides a starting point towards making data and information available on groundwater resources for assessments at catchment levels and national level. Such local water-point committee members could then be trained on how to collect data on various aspects of groundwater quantity (levels) and quality (some basic physicochemical and microbial parameters) for monitoring purposes with associated trainings. Periodic refresher courses on data collection procedures and data storage would improve the availability and accessibility of data. This type of community involvement in data collection is one step towards fulfilling the institutional principle of IWRM which calls for a participatory approach involving water users at all levels in managing water resources. This study fulfilled the objective on demonstrating how local IWRM practically implements active participation of water users in water management. As a testing exercise during fieldwork, our study trained few young men in collecting data on groundwater quality aspects (Fig. 8.3). The procedure of calibrating data collection instrument was demonstrated to them and they were given the opportunity to practise, and results showed that they were able to collect data on EC, pH and temperature (Fig. 8.3). This approach revealed that local communities are capable of participating in data collection and if such a practice could be nurtured and harnessed coupled with refresher trainings and monitoring, groundwater monitoring activities would be facilitated. Such an approach is likely to be sustainable and cost effective.

Figure 49: 8.3Training community members to collect data on water quality

8.6.2 Centrality of women's role in groundwater management

One of the principles of IWRM is the gender principle which recognises the central role of women in water management. The roles of women as water users, water collectors, users and managers at household level have been widely acknowledged in various literature GWP (2000). In this study, 84% of respondents said that there is a water committee for each water-point in the study villages and another 84% said that such water-point consists of men and women. When management positions of women in each water-point committee were verified from water-point registers (Borehole registers), results indicated that more 5 out of 10 committee members were women. This agrees with the local institutional arrangement in the study area which requires at least 5 members of each water-point committee need to be women (NBDA, 2009).

Figure 50: 8.4 Water-point committee members with large representation of women

However, the focus group discussions with such committee members which took place around water-point areas as shown in Fig.8.4 above revealed that such women had less influential roles than men in management, problems analysis and decision-making process related to water resources citing cultural belief as a reason which restricts women to be outspoken before men. Agreeing with findings from this study, GWP (2000) noted that women's active participation as decision-makers is interwoven with gender hierarchies and the roles within different cultures leading to some communities sidelining women's voices in water management. Nonetheless, the 50% involvement of women in each water-point committee in the Upper Limphasa River catchment is one step forward towards gender mainstreaming in water management. Such results revealed that the local IWRM requires maintaining and intensifying gender awareness and trainings. These results showed that the gender principle of the IWRM principles works in the local IWRM as evidenced in the Upper Limphasa River catchment.

8.6.3 Self regulations without catchment management agency

The rationale for local IWRM is same as those for full IWRM which is based on the basics that many different uses of finite water resources are interdependent as demonstrated in the hydrogeologic conceptual model in chapter 5. For example, water demand for irrigation in the Lower Limphasa catchment showed signs of increase because of the expansion of sugar and rubber plantations with the already existing rice scheme (LISUCO, 2011). While in the Upper Limphasa catchment demand for groundwater was relatively low largely due to absence of commercial farming and again only groundwater demand for households was studied (chapter 6). Polluted drainage flows from with chemicals from plantations and waste water from processing plants in addition to river diversions in the lower catchment would suggest that less freshwater to ecosystem and domestics use among implications (LISUCO, 2011).

As for the upper catchment, potential sources for groundwater contamination were observed to originate from cleaning and laundry around boreholes and engineering design or poor workmanship (Fig 8.7). Such observations indicated pathways for possible contaminants posing risks for groundwater quality (Fig.8.7). This was due to water pools that would collect around apron areas. In addition, waste water from cassava soaking ponds and fish ponds activities either around the water sources or around their homesteads would be potential sources to pollute surface waters and groundwater thereby threatening the integrity of the ecosystem. Gardening around groundwater sources for vegetables are risk factors for groundwater pollution. This would depend on types of chemicals used, available pathways for contaminants and depth of sanitary seal for each water source. If water from boreholes can be strictly used for drinking only and not for productive livelihood activities, and if the surplus borehole water that flows when people are collecting water at boreholes can be left unused and let it flow to protect the environment, it means less would be left for productive livelihoods and economic activities. This scenario would be regarded as lost opportunity for people’s improved livelihoods. It would mean that unregulated use of water is wasteful and unsustainable (Tapela, 2008).

Based on the rationale and basics of the local IWRM explained in the above paragraph, each water management water-point committee in the Upper Limphasa River catchment formulated their own regulations (self-regulations) to ensure that water resources are protected from possible contamination and are not wasted meaning water is used efficiently. The main three self-regulations that were observed were: 1) Timetable to draw water and to enforce such regulation, boreholes at water sources were locked the times that were agreed to be not for drawing water (Fig. 8.5); 2) Monthly financial contributions towards operations and maintenance (O&M) of water sources; 3) Timetable for households in each village to come and clean around their water sources. To enforce these self-regulations, members of community policing committees go round homes to caution defaulters. During hydrocensus and focus group discussions, participants reported that they had no problems with these regulations as they were agreed upon in their communities through various committees existing in the villages.

The analysis on the timetable to draw water and locking the boreholes at water sources and enforcing such regulation seemed hydrogeologically appropriate especially in the Upper Limphasa River catchment which has fractured rock aquifer which is a low yielding aquifer (chapter 5). This practice would give time for aquifer recovery for more in the well. Through this practice, the ecological principle of IWRM on protecting the finite water resources was being applied and local IWRM demonstrated it.

In addition, on regulation to ensure that each household that draws water from a water point contributes money could be said is the action in the right direction towards efficient water management in the demand-management paradigm. Interview results showed that in most cases, contributions were enforced when the borehole requires maintenance by the local technical person who is part of the water-point committee. When such contributions were requested, the money was usually not enough to meet the costs of O&M. The amount varied from one water-point committee to another, but the figures ranged from K100-K200 (about R3-6 or about 1US$) per month or per incidence. From the socioeconomic situation described in section 8.4.5, the reported high rates of defaulters could be understood. Baumann and Danert (2008) found a similar pattern when they assessed O&M situation in Malawi for groundwater rural water supplies. Although the monetary self-regulation requires refinement, results showed that communities were aware about the economic importance of water resources and were able to contribute though in small amount towards O&M of their water sources. Therefore, it can be said that elements of instrument principle of IWRM were present in the local IWRM activities although such amounts were insignificant.

On time tabling households to clean areas around water-points (Fig 8.6), the analysis showed that this was a positive way to ensure groundwater protection from possible pathways that would contaminate groundwater. Most areas around boreholes were found clean (Figs. 8.4; 8.5) expect few (Fig.8.7). This self-regulation agreed with environmental intervention requirement which focuses on protecting water sources and controlling polluting activities within close proximity to groundwater sources (WHO&UNICEF, 2010). Self regulations showed that positive practices would sustain good groundwater quality. Therefore, local IWRM was able to exhibit application of the ecological principle of IWRM which states that freshwater is a finite and vulnerable resource essential to sustain life, hence its protection (Table 3.1; FAO, (2000).

Figure 51: 8.5 Locking boreholes is one of the self-regulations

Figure 52: 8.6 Cleaning around water sources, another self-regulation

Results on self-regulations have shown that IWRM can start with local IWRM while waiting for the establishment of Catchment Management Agency. This observation agrees with (Grigg, 2008) who observed that implementing all IWRM principles at once is not expected but implementing elements of IWRM step-by-step is practical. Therefore, weaknesses in some self-regulations are part of such step-by-step process.

Although the self-regulations were successful in demonstrating their scientific validity and how local IWRM translated the principles of IWRM into practice, the analysis in this study showed that the benefits were not absolute. For example, those who could not default payment or cleaning the water-point areas shunned the use of safe water sources and resorted to using unprotected and unsafe sources of drinking water (Figs 8.8; 8.9). This was counterproductive to meeting the Millennium Development Goals on halving the number of people who lack access to safe drinking water sources. The self-regulation could unintentionally increase such number if left unchecked. Again, the designs of boreholes that provide for laundry slabs near water sources posed sanitary risks among others (Fig.8.7). Although water quality from such boreholes showed no presence of pathogenic bacteria in chapter 7, further assessments are encouraged on such engineering design in relation to risk-analysis. Nonetheless, local IWRM provided more insights on self regulations as a proxy for a successful IWRM implementation.

Figure 53: 8.7 Some of risk factors for groundwater quality (soakaways and laundry)

Figure 54: 8.8 Drinking from unsafe sources when fail to comply with self-regulations1

Results showed that households' members who fail to comply with self-regulations for various reasons voluntarily resort to using unsafe sources of drinking water, a situation which requires modifying the implementation of self-regulation (Figs.8.8 & 8.9).

Figure 55: 8.9 Drinking from unsafe sources when fail to comply with self-regulations2

8.6.4 Coordination within local IWRM work among institutions

Based on field observations and hydrocensus conducted in the eight study villages, this section presents results on how coordination among institutions worked. Results focused on three aspects: a) decentralisation; b) collaboration and; c) dialogue. The MUS analytical approach allowed the analysis on coordination to consider the practices of multiple uses of groundwater services in addition to drinking. Thus, institutions that coordinate in managing groundwater resources have been listed alongside their activities that use groundwater resources which have been briefly described.

The institutional arrangement has been described in 8.4.6 together with their expected roles and operation procedure (NBDA, 2009). In each village, the following local institutions were studied: 1) Village development committee which consisted of a chairperson and secretary of each committee in the village and each Government and NGO Officer working in the village; they meet at Village Headman (VH) place; 2) Water-point committee responsible for water management; 3) Village health committee which is responsible for managing health issues. A village which had a clinic this committee was called clinic committee; 4) School committee that oversees education issues; 5) Farmers clubs responsible for smallholder farmers; 6) Youth organisations were responsible for sports and entertainment for the young boys and girls. They were meeting in schools halls; 7) Community policing committee for security issues and summoning people to VH for meetings and offences. This study focused on assessing the working relationship among these institutions regarding water issues especially groundwater management in terms of dialogue, teamwork and decentralised democracy.

It was reported that each committee meets monthly to brainstorm on issues affecting their operations. Their agreed suggested solutions are forwarded to the Village Development Committee (VDC) which meets once every two months to consolidate the plans, progress and challenges from various committees into one report representing one village. That one report is sent to the Area Development Committee at Traditional Authority (TA) level. At TA level, all reports from various villages are consolidated into one report which goes to the district head office for endorsement or disapproval.

It is during the VDC meeting where dialogue among chairpersons and secretaries of various committees; government officers who work as Field Assistants and NGOs who work as Field Officers in the village is strengthened. It is at the VDC meetings where ideas, objectives, plans, activities, progress, challenges from different committees are discussed and the suggested solutions are agreed. The VDC meeting acts as a parliament of the village. It is at VDC level where teamwork, cooperation and tolerance among committee members and community members when carrying out their activities are encouraged. When some issues have not been agreed properly, such issues are referred back to a particular committee for improvement then it is brought back in the next seating of the VDC at the Village Headman’s meeting place. The key informants of each committee interviewed said that this decentralised democracy works better in most cases but there are inadequate financial resources to fulfil all their planned activities.

When coordination through decentralisation was assessed in the activities of local IWRM, it emerged that only community-based maintenance (CBM), Borehole (BH) maintenance services were decentralised from the ministry of water head office (central government) to district water office (local government) and community (village water committee) level (MoIWD, 2006; 2008; Nkhata et al., 2009). The Ministry of Irrigation and Water Development (MoIWD) had the following components: a) departments of i) Water resources with divisions of groundwater, surface water and water quality; ii) Water supply which deals with CBM, BH maintenance and piped water supply iii) Sanitation iv) Irrigation; b) Water resources board serving urban areas; and c) National water development projects (NWDP). NWDP implements water projects with funds from donors through Malawi Parliament as per agreement with Malawi Government.

Results from interviews showed that the Village Water-Point Committee (VWPC) controls water facilities and raises financial resources for operation and maintenance services of their water sources. The VWPC engages an area mechanics who visits each water source bi-annually and he links with the district water office (DWO) on major maintenance for assistance. In turn, the DWO assists the VWPC with trainings on CBM materials and regulates activities of NGOs. On the basis of this finding, it has been shown that there are elements of decentralization of powers to make decisions at the lowest appropriate level with involvement of water users at community level in managing their groundwater sources. In this case, it can be said that management of water services within local IWRM, fulfils the institutional principle of IWRM which states that water management should be based on participatory approach involving users and planners (GWP, 2003; GWP, 2002: GWP, 2000; FAO, 2000) where users are VWPC members and the entire community while planners are district water officers.

Interviews and field observations showed that collaboration and dialogue occurred during meetings in each sector committee when all representatives met during Village Development committee meeting at the Village Headman to consolidate reports from sector meetings. Collaboration and dialogue in this study referred to interactions and discussions among government officers (Fig 8.10), NGO officers and community members from various committees. The analysis showed that although this study largely focused on groundwater for drinking as described in chapters 6 and 7, groundwater was used for various purposes in the study area. For example, a) cold springs were diverted into fish ponds (Fig. 8.11) where a Fisheries Field Assistant from the Department of Fisheries worked with farmers in liaison with World Fish Centre to promote food security; b) cold springs were also used by communities as cassava soaking ponds (Fig 8.11) where a Field Assistant from the Ministry of Agriculture and Food Security worked with communities; c) groundwater at primary schools in the Ministry of Education (Fig. 8.12) were used by school pupils and their teachers in various ways; d) Boreholes at health clinics, groundwater was used for sanitation services in the outside toilets among others (Fig.8.13); e) boreholes in the study for rural water supply from the Department of Water Development. This analysis showed how multiple use services for groundwater was operating in the study villages thereby shedding light on how local IWRM worked with practical examples of active participation by stakeholders.

The use of adaptive management principles (learning by doing) have been supported by several scholars in the management of water resources such as (Colvin et al., 2008; Du Toit & Pollard, 2008; Walter, 1986, Holling 2005 & Habron 2003). These scholars argue that the learning-by-doing approach is interactive, progressive and flexible in nature and builds learning among those involved in the management cycle. This is what happens in the local IWRM (local-level governance). Therefore, the collaboration and dialogue demonstrated in the local IWRM in the Upper Limphasa catchment among government officers, NGO officer and community members during the Village Development Committee meetings was part of creating awareness about management of water resources. This was demonstrated when members from different committees explained their activities and how they manage the water for their activities. The commonly reported challenge among such water users was lack of suitable institutional funding arrangements for the reported activities. This challenge agrees with Braune & Xu's (2008) observation that despite the recognition in Africa that local groundwater resource plays vast strategic roles for most rural communities, systematic financial resources are not available to support local participation, investments and initiatives. Nevertheless, Van Koopen et al. (2009) observed that when various water service providers in a community collaborate and exchange their ideas, they see multiple uses as a real practice and then support communities to cooperate in the use and management of water resources (Figs. 8.11; 8.12; 8.13; 8.14). This is what was observed in this study. These results showed the application of institutional principle of IWRM in the local IWRM in villages in the Upper Limphasa River Catchment.

Figure 56: 8.10 Consulting some Malawian water officers on water management & IWRM

Figure 57: 8.11 Groundwaters (cold springs) for MUS: fish and cassava soaking ponds

Figure 58: 8.12 Groundwater use for students, teachers & school related activities

Figure 59: 8.13 Groundwater use by patients & related activities at clinics

Figure 60: 8.14 Groundwater use for MUS at household level

8.7 Summary

Institutional arrangement for local IWRM in Upper Limphasa River catchment provided conducive insights for the successful implementation of the full IWRM because from village level to district level, each committee at each level had a representation of community members (water users), NGOs officers (private sector = water developers/water providers) and government officers (water managers/planners) who implemented projects that utilized water resources. Such arrangements saw successful operation of self regulations and coordination among institutions through meetings within the Upper Limphasa River catchment. Monitoring of different activities in the studied catchment was feasible through feedback during village development committee meetings at village level, Area Development Committee and Area Executive Committee at Traditional Authority level and finally at district level during the meetings of District

Coordination Committee which feeds into District Executive Committee. All this institutional arrangement and coordination among institutions was possible in the absence of the Catchment Management Agency or Catchment Management Strategy.

From how the local IWRM operated in Upper Limphasa River catchment, it showed that implementing IWRM does not require a new super ministry to be created but rather it requires rearranging the existing structures so that people change their working practices and start considering the bigger picture that surrounds their actions. That rearrangement will then enable people to realise that their actions have implications on other people as demonstrated in chapter 5 where the hydrogeologic conceptual model showed such interrelations between upstream and downstream activities.

Literature has shown that IWRM seeks to introduce an element of decentralised democracy into how water is managed with its emphasis on stakeholder participation in decision-making process at the lowest appropriate level such as water-point committee in the case of Upper Limphasa catchment. This aspect has been demonstrated in this thesis in terms how local communities through their various committees within one village feed into one village development committee which then feeds the committees at Traditional Authority level which in turn feeds the committees at district level. In all these committee meetings, it has been shown how stakeholders actively participate in making their self-regulations, planning their activities, implementing and reviewing them from the Village Development Committee to District Executive Committee. In this case, local IWRM has shown the structures and procedures that can be used as proxy for a wider and successful implementation of the full IWRM at catchment level.

Although local IWRM happened in the absence of Catchment Management Agency in the Upper Limphasa River catchment, it does not mean that Catchment Management Agencies are not required but it means that local IWRM is a starting point for a successful IWRM. Such local IWRM also showed that when developing Catchment Management Agencies and Catchment Management Strategies judiciously, the existing and working collaborative practices in the catchment as shown in the Upper Limphasa catchment should either be acknowledged or adapted otherwise creating a totally new structure for the IWRM in areas such as Upper Limphasa would be counterproductive.

This study has shown that although IWRM brings threats to people’s power and positions such as water experts, the data collection system that were done by local communities through local IWRM provided a new insight/platform for more collaborative efforts worthy nurturing and supporting by water experts. IWRM requires that platform to be developed to allow different stakeholders with different skills, expertise, mandates, goals, funding agencies to start working together through the committees that have been described in this chapter. Working through such existing institutional arrangements described in this chapter, provided the required reform that IWRM seeks to see at all stages in the water planning and management cycle. From the limitations discussed under the self-regulation section, this study has shown or confirmed that indeed implementing all IWRM principles at once is not expected but step-by-step implementation of the IWRM principles is practical hence the justification for applying adaptive management principles as suitable practices for IWRM. This has been described in chapter three of this thesis and exemplified in this chapter.

Chapter 9: Conclusion and Recommendations

9.1 Introduction

The two main objectives of this study were to: i) assess the effects of local hydrogeologic and socioeconomic factors on IWRM implementation ii) demonstrate how local IWRM works as a proxy for wider and successful implementation of full IWRM. A case study approach was adopted using Limphasa River Catchment in Northern Malawi. The fundamental aspects in this study were that water resource managers especially groundwater for community supplies should use methods presented in this study when i) understanding groundwater systems for water planning development and management, ii) assessing groundwater sources for drinking water supplies iii) generating data on demand and use in unmetered rural areas to form the basis for planning and management of water resources, and iv) assessing operation of local IWRM and application of IWRM principles in the execution of local IWRM at community level for rolling out best water management practices in other catchments.

9.2 Conclusion and recommendation on each study objective

Although Malawi has general warm tropical climates (FAO, 2008), variations in geology, landform and socioeconomic activities are observed within the country. Such variations affect the availability, quality, demand, use and governance of water in various forms. A general understanding of how hydrological processes operate in Malawi’s hydro-climatic setting exists (GoM, 2008). However, the available knowledge is not adequate for accurate interpretations on how temporal and spatial variability of groundwater availability, quality, demand, use and governance would facilitate IWRM implementation. Scientists, users, developers and managers of water resources together needed to have a visual understanding of hydrological processes within the catchment which the hydrogeological model has provided in chapter 5 and how such factors explain the availability, demand, use, quality and governance of groundwater as shown in chapter 6, 7 and 8. However, quantifying effects of human modifications of landscapes on quantity and quality of groundwater resources has not been addressed in the chapter 5, 6 and 7. Nonetheless, the relationship among various factors provided in the two conceptual models in chapter 5 and 6 respectively have provided adequate scientific knowledge in a qualitative manner to enable scientists, users, developers and managers of groundwater resources to collaborate towards IWRM implementation.

Since IWRM promotes managing water resources in a coordinated manner among stakeholders, this study has provided the required knowledge about the availability, demand, use, quality and governance of the same resources in chapters 5, 6, 7 and 8 respectively for continuous utilization. Information on such parameters was also provided realizing that the balance between water development (supply) and water management requires such information. An improvement in the knowledge of factors that explain the availability, demand, use, quality and governance of groundwater resource also informs the basis for identifying opportunities for using water to improve productive livelihoods as well as promote environmental integrity. It can be concluded that the study has both scientific and societal value in its conception and execution.

9.2.1 Assessing local hydrogeologic and socioeconomic environments

Using visual tools such as maps, photos and hydrogeologic conceptual model, this research identified and described physical and socioeconomic factors that limit IWRM operation. This was achieved by showing the implication/influence of the explained factors on water resources management using groundwater as a case study. For example, the description on basement complex geologic setting in the study catchment revealed the reason for the limited groundwater availability in the area because such geology forms fractured rock aquifer system which has limited permeability and storage capacity. The topographic nature and north-south strikes of the lineaments explained the north-south flow direction of groundwater in the catchment. The drainage system observed in the Kandoli and Kaning'ina Mountains in the east and west of the Upper Limphasa River catchment (Fig. 5.1; Fig.5.2) formed groundwater recharge boundaries.

The regional faults in the same mountains (Fig. 5.1; Fig.5.2) formed structural boundary as well as hydrogeologic boundary and they controlled flow direction of the groundwater. The hydrogeologic conceptual model showed that the forested weathered bedrock in the upland formed no-flow boundary and groundwater divide which also controlled the flow direction downwards. On the other hand, the alluvial bedrock in the Limphasa Dambo (Valley) indicated no-flow boundary at the depth of active groundwater flow (Fig. 5.9). The study showed that major commercial farming activities in the Lower Limphasa catchment (Fig. 5.3) that would need sustainable water supply from the Upper Limphasa catchment which had only subsistence farming. It then suggested the initiation of collaborative efforts to enhance upstream-downstream cooperation for sustainable utilization and management of water, and IWRM was seen as a suitable solution. This insight from the analysis in (Fig. 5.3 & Fig. 5.9) facilitated the understanding on why the upland and lowland needed to be managed holistically as being advocated by the IWRM approach for sustainable utilization of water resources.

Therefore, the first objective of this study was fulfilled on developing and using a hydrogeologic conceptual model to explain local hydrogeologic and socioeconomic factors that limit wider and successful implementation of IWRM. The use of conceptual model to show interrelationships and interactions among variables in studies that promote IWRM is recommended. However, more data on groundwater level and pumping tests are required to characterise aquifer properties. Data on climate parameters is also required to provide spatial distribution of rainfall and groundwater/surface water flow measurements would be perfect for simulation models. These would improve the conceptual understanding of the Limphasa River Catchment. Nonetheless, the hydrogeologic conceptual model developed in this study has provided the visual decision planning and guiding tool that should be used in other catchments in addition to laying foundation for further studies and refinement of the model.

9.2.2 Proposed method on generating groundwater data on demand and use

Using different physical factors, water scarcity indices and methodologies, this study showed that Malawi is physically water stressed as well as an economic water scarce country. This novelty is against some literature that present Malawi as a water abundant country. Again, despite the high proportion (85%) of Malawians relying on groundwater resource, groundwater availability (storage in km^3) is relatively low (269 km^3 in Table 6.10) compared to other countries within SADC and Africa. Given the complexity of groundwater abstraction, the available groundwater for use is further reduced for Malawians who depend on such a resource for their domestic and productive livelihoods. Such insights provided the basis for discussing the need for IWRM.

Although daily statistics on groundwater demand (i: 21.20 litres; 116.91 litres; 80,550.99 litres), use (ii: 16.8 litres; 92.55 litres; 63,766.95 litres) and abstracted but not used (iii: 4.4; 24.36; 16,784.04 litres) were relatively low per person, per household and per sub-catchment respectively, such statistics when calculated on monthly basis (i. Demand: 636 litres; 3,507.30 litres; 2,416,529.70 litres; ii.Use:504 litres; 2,776.5 litres; 1, 913, 008.5 litres iii. Abstracted but not used: 132 litres; 730 litres; 503, 521.2); and on yearly basis (i. Demand: 7,632 litres; 42,087.6 litres; 28,998,356.4 litres; ii. Use: 6,048 litres; 33,318 litres; 22, 956, 102 litres; iii: Abstracted but not used: 1,584 litres; 8,769.6 litres; 6,042,254.4 litres) per person, per household and per sub-catchment provided huge amount of groundwater (Table 6.5). Given the limited storage capacity of fractured rock aquifer in the basement complex geology, the monthly and yearly groundwater demand and use on one hand and abstracted but not used on the other was considered enormous. With the population growth rate of 2.8 for Nkhata Bay (NSO, 2009) and the observed desire to intensify productive livelihoods activities coupled with expected negative effects of climate change, the need to implement the IWRM approach for such groundwater resource in the study catchment remains imperative and is urgently needed.

In addition to identifying and describing factors that explain the limited groundwater availability in the study catchment, the study developed a methodology for calculating groundwater demand, use and unused at both households and sub-catchment levels. This methodology provided step-by-step procedure for collecting data on groundwater demand and use as a tool that would improve availability of data on groundwater. Implications of such results for IWRM in similar environments were discussed. Despite the time-consuming procedure involved in collecting data on demand and use, the calculations are simple and interpretation of results is easily understood among various stakeholders. Therefore, such an approach is recommended for IWRM approach which requires stakeholders from various disciplines to interact and collaborate. Thus, the use of the proposed method is recommendable as its further refinement is being sought.

Therefore, the second objective of the study on demonstrating data generation procedure on groundwater demand and use in unmetered rural areas was fulfilled. However, further studies are required to model the demand and actual use of groundwater. In such studies, two data sets on average yearly water consumption and detailed monthly water consumption can be collected. SPSS software can be used to model the expected demand and actual use in 5 or more years. Independent variables could be population and climate (average temperature and rainfall for specified period). The values from demand and actual use could be compared and used as bases for forecasting scenarios. However, the methodology provided in this study provided one step forward towards data generation procedures that are needed in rural unmetered rural areas where groundwater is used for domestic and productive livelihoods multiple purposes.

9.2.3 Assessing quality of groundwater for drinking using RADWQ methods

The analysis on groundwater quality has shown that the dominant water type in the aquifers of Upper Limphasa catchment was Ca-HCO_3 suggesting that the area has shallow and fresh groundwater which has been recently recharged in the aquifer. The physicochemical analysis showed that none of the sampled boreholes (BHs) and protected shallow dug wells (PSWs) had physical or chemical concentration levels of health concern when such levels were compared with 2008-World Health Organisation (WHO) guidelines and 2005-Malawi Bureau of Standards (MBS). Conversely, although the compliance with 2008-WHO and 2005-MBS of *E.coli* in BHs water was 100% suggesting that water from BHs had low risk and free from bacteriological contamination, water from PSWs showed 0% compliance with 2008-WHO and 2005-MBS values implying high risk to human health. The overall assessment on risk to health classification showed that PSWs were risky sources to supply potable water.

Based on such findings, the analysis in this study demonstrated the feasibility of using the IWRM approach as a platform for implementing environmental and engineering interventions through education programmes to create and raise public awareness on groundwater protection. The use of different analytical methods that were applied to identify the exact sources of the observed contaminants in the PSWs proved futile. Hence, rolling-out PSWs either as improved or safe sources of drinking water requires further detailed investigations. Nonetheless, the use of modern methods in this study such as RADWQ for assessing the quality of groundwater for drinking is recommended. Therefore, the third objective of this study on assessing the quality of groundwater for drinking using RADWQ methods has been fulfilled.

9.2.4 Demonstrating how local IWRM works as proxy for the full IWRM

Despite the study area being in the humid climatic region with annual rainfall above 1,000 mm, many of the physical factors were not favourable for more availability of groundwater in the aquifers. Such observation provided a compelling evidence to lobby for a successful IWRM implementation for sustainable utilization of such waters. This study recommends the continuous operation of local IWRM as a proxy for full IWRM.

Although institutional arrangements, water laws and water policies were found problematic to facilitate a successful implementation of IWRM at national level in Malawi, this study demonstrated that local institutional arrangements, coordination, data collection efforts by local community members (active participation), self-regulation among local community committees were favourable conditions for a successful local IWRM in the Upper Limphasa River catchment. This study recommends such local participation, investment and initiatives as proxy for the full and successful IWRM beyond the study catchment. Therefore, the fourth objective of this study on demonstrating how local IWRM works as proxy for the full and successful implementation of IWRM was fulfilled. Still, this study recommends further research which should aim at improving some observed negative implications of self-regulations on community members and the limited decentralisation elements in the water sector.

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11. Appendices

Parts of this research work have been disseminated through publications and presentations as indicated below and relevant sources for the data, publishing houses and conference organisers have been dully acknowledged.

11.1 Publication: Journal article

Kanyerere TOB, Levy J, Xu Y & Saka J (2012) Assessment of microbial contamination of groundwater in upper Limphasa River catchment, located in a rural area of northern Malawi; *Water SA Vol.38 No.4;* http://dx.doi.org/10.4314/wsa.v38i4.14

11.2 Publication: Book chapters and stakeholder guide

Kanyerere TOB, Nkhata, MGM & Mkandawire T (2010) *Rural Water Supply and Sanitation in Malawi: Groundwater Context:* Chapter 16 in Sustainable Groundwater Resources In Africa: Water Supply and Sanitation Environment, UNESCO, CPR Press, The Netherlands by Y. Xu and E. Braune (Eds), 2010 ISBN: 978-0-415-87603-2 (hard book); ISBN:978-0-203-85945-2(eBook)

Xu, Y, **Kanyerere TOB,** Braune E, Nel J, Phil Hobbs P, Bradbury K, & Robin N (2010) *Best Practices for Groundwater Quality Protection* Chapter 4 in Sustainable Groundwater Resources, Water Supply and Sanitation Environment, UNESCO, CPR Press, The Netherlands by Y. Xu and E. Braune (Eds),2010 ISBN:978-0-415-87603-2 (hard book); ISBN:978-0-203-85945-2(eBook)

Braune E, Goldin J, Xu Y, Duah A, Kambinda W, Peck H, & **Kanyerere TOB** (2010) *Stakeholder Guide: Sustainable Utilization of Groundwater in Southern Africa*. UNESCO Chair on Groundwater & Integrated Water Resources Management of the Department of Earth Sciences, Faculty of Natural Sciences, University of the Western Cape, RSA

11.3 UNESCO Report

UNESCO Report on Addressing Water Quality Challenges in Africa: Groundwater contamination & water quality monitoring systems in Malawi part of a Comprehensive Groundwater Monitoring Network Design for Limphasa River Catchment for Sustainable Livelihoods through Water Resources' Protection, Southern Africa, by Thokozani Kanyerere, Yongxin Xu, Jonathan Levy & John Saka pages 15-16 in a 37 page report for UNESCO Regional Office, UN Gigiri, Nairobi, Kenya, March 2011

11.4 Conference proceedings: (Oral and poster presentations)

Kanyerere, T.O.B., J. Levy, Y. Xu & J.K. Saka (2011) Exploring innovative local technologies for managing groundwater for drinking in Upper Limphasa Catchment, Northern Malawi: A paper presented during NUFU water sciences project dissemination conference titled *Water resources under changing climate in Southern Africa*: Zomba, Malawi 12-15 September 2011

Kanyerere, T.O.B. and Y. Xu and J.K. Saka (2010) Towards a Better Understanding of Groundwater Microbial Contamination in the Upper Limphasa River Catchment, Malawi, Southern Africa, a paper submitted under Water Supply and Sanitation Theme for 11th WaterNet/WARFSA/GWP-SA Symposium, Victoria Falls, Zimbambwe, 27-29 October 2010

Kanyerere, T.O.B., Y. Xu , J. Levy & J.K. Saka (2010) *Health Implications of Groundwater Supply and Sanitation Provision in Communities: Health promotion in a given setting,* Spring School Session, School of Public Health, University of the Western Cape, Cape Town, South Africa, 8th September 2010 invited by Dr Ruth Stern through Professor Yongxin Xu

Kanyerere, T.O.B., Y. Xu, J. Levy & J.K. Saka (2010) *Health Implications of Groundwater Supply and Sanitation Provision in Communities: Policy and Practice Gap,* Being Heard in Water Policy Debates, Department of Biology and Conservation Biodiversity, University of the Western Cape, Cape Town, South Africa, 21st September 2010 invited by Dr Richard Knight through Professor Yongxin Xu

Kanyerere, T.O.B., Y. Xu & J.K. Saka (2009) Assessment Tools for Appropriate Groundwater Governance in Upper Limphasa River Catchment in Malawi, Southern Africa, a poster paper submitted for *Groundwater 2009 Conference on Groundwater-Pushing the Limits,* Somerset West, Western Province, South Africa 16-18 November 2009

Kanyerere, T.O.B., Y. Xu &J.K. Saka (2009) Groundwater Governance: Legislation and Regulations in Malawi, Southern Africa, a paper submitted under socio-economic issues relevant to groundwater in hard rock areas for *International Association of Hydrogeologists (IAH) 37th Congress Proceedings,* Hyderabad, India

Kanyerere, T.O.B., Y. Xu & J.K. Saka (2009) Aquifer Assessment Tools for Suitable Groundwater Governance in Upper Limphasa River Catchment, Malawi, Southern Africa, a paper submitted for *10th WaterNet/WARFSA/GWP-SA Symposium,* Entebe, Uganda

Kanyerere, T.O.B., B.J.W., Msika,Y. Xu, & J.K. Saka (2008) Adaptive Utilization of Water Resources for Improved Human Health in Rural Communities within Lipmhasa Catchment Area in Nkhata Bay District, Malawi, Southern Africa; *International Association of Hydrogeologists (IAH) 36th Congress Proceedings*, Toyama, Japan

11.5 Ethical clearance

This study was approved by the Senate Research Committee of the University of the Western Cape with the approval registration number 11/1/5, see attached documents for details.

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13 DEC 2010
UNIVERSITY OF THE WESTERN CAPE

The ADDRF Manager
African Population and Health Research Center
Shelter Afrique Center
Longonot Road, Upper Hill
PO Box 10787-00100
Nairobi
KENYA

Dear Sir/Madam

ETHICAL REVIEW AND SUPPORT LETTER FOR PhD STUDIES FOR THOKOZANI O.B. KANYERERE

I write to inform you that the Senate Research Committee (SR) of the University of the Western Cape received the PhD research protocol of Mr Thokozani Kanyerere on developing adaptive framework for managing groundwater for drinking to improve human health in Upper Limphasa River Catchment. The protocol covers three aspects

i. Groundwater quality (point-of-use and non-point-of-use);
ii. Groundwater security (demand, use and access); and
iii. Groundwater governance (indicators, institutions and infrastructure).

The protocol was reviewed and the following ethical aspects were clearly explained:

a. Informed consent;
b. Risks to the subjects;
c. Adequacy of protection against risks;
d. Potential benefits;
e. Importance of knowledge.

All in all the decision of the SR was that the protocol raises no ethical concern.

Apart from ethical aspects which the SR approved, the entire protocol was also reviewed for its format, logic sequence of ideas and relevance both scientifically and application (usefulness to society). Review results from the SR showed that the protocol followed good format, was logically presented and contained relevant research proposals on aspects of water resources management. The aim is to improve the quality of human life when implemented. A publication is planned from this work.

I recommend this project to you for the award of a fellowship.

Yours sincerely

Renfrew Christie

PROF RENFREW CHRISTIE
Dean: Research Development

13 December 2010

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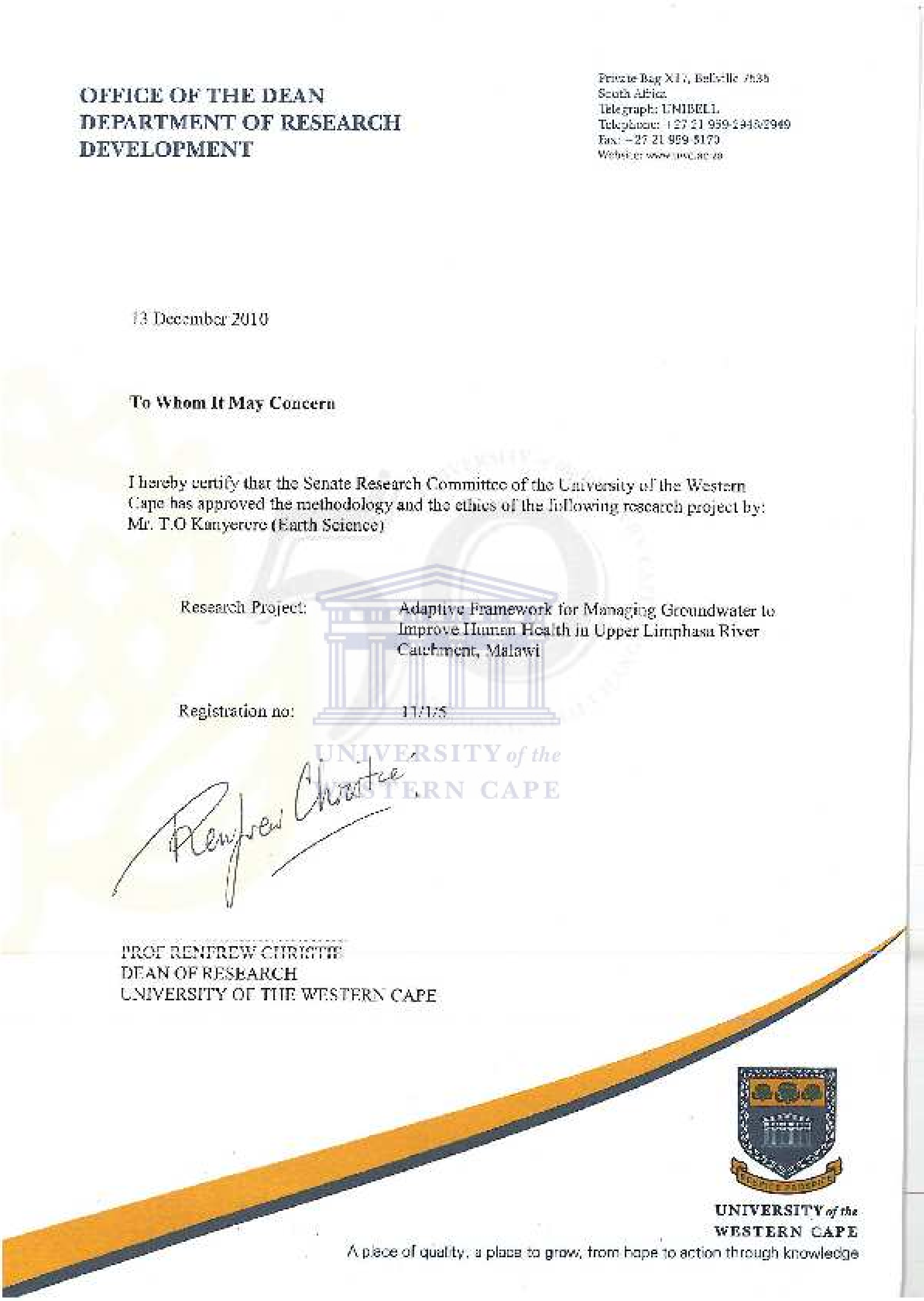

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13 December 2010

To Whom It May Concern

I hereby certify that the Senate Research Committee of the University of the Western Cape has approved the methodology and the ethics of the following research project by: Mr. T.O Kanyerere (Earth Science)

Research Project:	Adaptive Framework for Managing Groundwater to Improve Human Health in Upper Limphasa River Catchment, Malawi
Registration no:	11/1/5

Renfrew Christie

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