Groundwater pollution in urban Dar es Salaam, Tanzania : assessing vulnerability and protection priorities

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Groundwater Pollution in Urban Dar es Salaam, Tanzania

Assessing Vulnerability and Protection Priorities

Proefschrift

ter verkrijging van de graad van doctor aan de
Technische Universiteit Eindhoven, op gezag van de
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commissie aangewezen door het College
voor Promoties in het openbaar te verdedigen
op woensdag 19 juni 2002 om 16.00 uur

door

Rubhera Rukumbuja Aloyce Mtani Mato

geboren te Bunda, Tanzania

Dit proefschrift is goedgekeurd door de promotoren:

prof.dr.ir. F.J.J.G. Janssen
en
prof.dr.ir. C.A.M.G. Cramers

Co-promotor:
prof.dr. J.H.Y. Katima (Eng.)

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“Wisdom is supreme; therefore get wisdom.
Though it costs all you have, get understanding”
(Proverbs 4:7)

Preface

Groundwater has increasingly become a major source of water supply for the city of Dar es Salaam, Tanzania. As for many large urban centres in developing countries, Dar es Salaam is multifaceted with environmental problems, which demand collective efforts to rectify. This thesis addresses the issues of groundwater pollution, focussing on assessing vulnerability and protection prioritisation. The book contributes knowledge for understanding the problems of groundwater in the city as well as a resource material for educating both decision-makers and the general public.

Many people have contributed in one way or another towards the completion of this four years research work. I wish to express my sincere gratitude to all of you. I extend my appreciation to the Dutch and Tanzania governments (through Nuffic) for sponsoring the EVEN project, which included my study programme. I wish to thank the administration of the University College of Lands & Architectural Studies (UCLAS), Dar es Salaam, Tanzania for giving me a study leave and other logistical support.

I wish to sincerely thank Prof.dr.ir. F.J.J.G. Janssen, my first supervisor and head of the Environmental Technology Group at the Eindhoven University (TUE), for his guidance and encouragement throughout my study. He took trouble to visit me during my fieldwork in Tanzania. I also extend much appreciation to retired Prof.dr.ir. C.A.M.G. Cramers, my second supervisor and head of the then Instrumental Analysis Group (SIA) at TUE for his well thought challenges. I started my studies at TUE in his group, where I was introduced to high precision analytical techniques, a knowledge that was essential for my study. I am also grateful to Prof.dr. J.H.Y. Katima (Eng.), my co-promotor and the dean of the Faculty of Mechanical, Chemical and Process Engineering, University of Dar es Salaam (UDSM), Tanzania, for his guidance and challenges. I appreciate his encouragement and logistical support given to me while in both Tanzania and The Netherlands.

I extend much thanks to Dr. Ruud Schotting of the Faculty of Civil Engineering, Delft University of Technology; dr. Hans Reijnders of RIVM, The Netherlands, and dr.ir. K.J. Ptasinski of Environmental Technology Group (TUE), for their guidance during the research as well as reading the manuscript. Their keen comments were fundamental for the completion of this work.

I would also like to give special thanks to Mr. Jovint Kamara of the Chemical and Process Engineering (CPE) laboratory, UDSM for analysis of groundwater samples. His patience and hardworking in collection and analysis of the samples is creditable. I also appreciate the assistance I received from ing. Peter J. Lipman and Roy Reinierkens of TUE during the analysis with GCMS equipment. I also give thanks to my fellow researchers at TUE in the Laboratory of Chemical Reactor Engineering (SCR), especially the Environmental Technology Group and the former Instrumental Analysis Group. I enjoyed working with you all.

There are those who contributed to this work who I would particularly wish to mention: H. Kijazi; M. Shemdoe; N. Vindi; M. Jaka; P. James; I. Chonya and Z. Ngereja. They collected raw data (especially geographical positioning of boreholes) as part of their undergraduate studies at UCLAS. Our driver, Mr. Stewart, of CPE at UDSM, is also acknowledged.

I am also grateful for the assistance obtained from the Drilling & Dam Construction Agency (DDCA) at Maji-Ubungo, Dar es Salaam for allowing me to access their borehole data. This contribution is rated significant. I give special thanks to Dr. Mohammed, the director of DDCA, for his encouragement and Mr. Lape, his assistance was great.

I cannot forget the support I received from the Bureau for International Activities (BIA) at TUE. Their encouragement and social-attention made me quickly get acclimatized into the Dutch system. I would like to mention Mr. Jan van Cranenbroek for his kindness and “ready to help” character. Mr. L.J.G.M. Robben, Mrs. L.G. van Kollenburg, Ms. K.A. Duijvesz and Patrick van Schijndel are all acknowledged.

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Last but not least, I owe much to my family. I was separated from them for many months during my study. I am indebted to the courage and patience of my wife Mary, and our dear children Azaria, Enock and Naomi. God bless you.

The prayers of my brothers and sisters in the Lord Jesus Christ made me overcome all the circumstances.

To the Living God be Glory, Honour and Might.

Rubhera RAM Mato
Eindhoven, University of Technology, The Netherlands
June 2002.

Summary

Groundwater pollution in urban areas is a growing environmental problem in the world. In developing countries, it commonly results from indiscriminate disposal of municipal (especially extensive use of on-site sanitation systems) wastes, industrial effluents, and urban agriculture. In low-income countries (like Tanzania), the situation is aggravated by rapid urbanization, which is characterized by inadequate provision of water supply, sanitation, solid waste and drainage infrastructure. In Tanzania, about 30% the whole population, and 42% of the inhabitants in major urban areas, depend on groundwater. This dependence may increase in future due to deterioration in quality of surface water sources. However, exploitation is not controlled and no adequate groundwater quality monitoring and protection mechanisms have been installed. Therefore, the impact of human activities on groundwater quality is not yet properly understood, which is a key element in sustainable use of the resource.

The Dar es Salaam City is the largest urban centre in Tanzania, with a population of about 3 million. It gets water supplies from three surface water treatment plants, on the Rivers Ruvu and Kizinga. The supply is severely inadequate and in many parts of the city is rationed. The piped water system supplies only about 50% of the demand and groundwater is the alternative source. The groundwater is used to augment piped supply and more than 36 deep boreholes drilled in the city are directly (without treatment) connected to the main water system.. However, crude practices of waste disposal are threatening the quality of the aquifers: about 90% of the inhabitants use on-site sanitation systems, industrial effluents are inadequately treated and solid wastes crudely dumped or buried in the ground. Such a situation exposes the public to serious health risks. Despite the importance of groundwater in the city, water quality and exploitation are not adequately monitored and thence, little field performance data on quality characteristics of the aquifers are known. Limited researches on the subject have been conducted and generally the groundwater database is inadequate. The little relevant information available is also fragmented making access difficulty, and hence affecting plans for groundwater management.

In light of the above-mentioned problems, a research on groundwater pollution was conducted in Dar es Salaam City from 1997 to 2001. The main objectives of the research were to establish an information system for groundwater pollution monitoring in Dar es Salaam and to develop a rapid assessment model to guide protection strategies. The specific objectives include making an inventory of groundwater pollution sources, determination of extent of aquifer pollution, assessing groundwater vulnerability and developing a protection model.

Information was gathered through desk study, fieldwork, laboratory analysis, modelling and mapping. About 29 months were spent for fieldwork in Tanzania, making inventory of pollution sources, recording borehole geographical locations (using GPS handset), groundwater sampling and analysis for chemical and biological contaminants. The GIS ArcView 3.1 software was used for geo-processing (mapping). A rapid assessment scheme, the WYVUL model (encompassing five factors: water quality, yield , vulnerability, use value of groundwater and landuse characteristics) was developed and used for groundwater protection prioritisation.

From the research, it was clear that domestic wastes, industrial effluents and leachate from solid wastes disposal sites are the major sources of groundwater pollution in Dar es Salaam City. Groundwater quality has started to degrade; more than 20%, 35% and 45% of the samples collected from boreholes failed to comply with the national standards for drinking water in chloride, nitrate and faecal coliform respectively. The total dissolved solids map shows that over 90% of the city has good freshwater, which can be used for domestic supplies. A few samples were found having elevated levels of total organic carbon (TOC), indicating organic pollution. Petroleum hydrocarbons, especially polycyclic aromatic hydrocarbons (PAHs) were identified in some groundwater samples. However, the concentrations were lower than drinking water standards in Europe and USA. It was also observed that some of the production boreholes are located in high-risk zones of petroleum hydrocarbon pollution. Presence of such substances in groundwater points to possible chemical contamination, which can be from industrial effluents or leakage from underground petroleum fuel storage facilities like the filling stations.

The groundwater vulnerability map for the city has been developed using the DRASTIC model (developed in USA). The map shows that over 50% of the city is located on a high vulnerability zone (especially areas adjacent to the coastline), meaning that the groundwater can potentially be polluted by anthropogenic activities. The well fields of Mbagala and industrial areas of Changómbe are also under the high vulnerable zone. The map indicates that the risk of groundwater pollution from human activities is high and therefore precautionary measures need to be taken before it is too late.

The WYVUL model was used to assess the groundwater protection priorities, which in turn help to target resources. The model was formulated on the aim of protecting high yield clean aquifers located in high vulnerable zones with less physical development. Using the model, the groundwater protection priority map was developed. The map shows that areas of Mbagala and Charambe wards, with high aquifer yield (located in recharge zones) and low urbanization level, have the highest priority for protection.

In addition, a groundwater management programme has been proposed. The programme includes schemes for monitoring activities. The legislative and community involvement measures also have been suggested as vital for a successful groundwater protection programme in Dar es Salaam City.

Inadequate data management is one of the problems pertaining to groundwater in Tanzania as whole. Access to data was the major obstacle encountered during this research. Among the questions that aroused in the entire period of the research were: what is the groundwater quality status? Where are the boreholes located? Where is their information stored? How was information collected? etc. It was challenging to collect the information amidst a fragmented system of data storage. However, in this research, a groundwater database, featuring both non-spatial and spatial attributes, has been established. The groundwater data have been geographically referenced using the ArcView GIS software. With database it is easy to enter or retrieve information, as well as its visualization has greatly been increased. The database also forms a framework and baseline for future monitoring and other specific groundwater management programmes.

Samenvatting

Grondwaterverontreiniging in stedelijk gebied is een groeiend milieuprobleem in de wereld. In ontwikkelingslanden wordt dit hoofdzakelijk veroorzaakt door onzorgvuldig verwijderen van huishoudelijk afval (vooral het extensieve gebruik van plaatselijke sanitaire systemen), industrieel afvalwater en stedelijke landbouw.
In arme landen (zoals Tanzania) verergert de situatie door snelle verstedelijking die gekenmerkt wordt door ontoereikende voorzieningen voor watervoorraad, sanitair, vuilafvoer en rioleringsinfrastructuur. In Tanzania is ongeveer 30% van de gehele bevolking en 42% van de inwoners van de voornaamste steden afhankelijk van grondwater. Deze afhankelijkheid kan in de toekomst toenemen als gevolg van een verslechtering in kwaliteit van open waterbronnen. De exploitatie van grondwater wordt echter niet gecontroleerd en er bestaan geen afdoende mechanismen om de kwaliteit van het grondwater te controleren en te beschermen. De invloed van de menselijke activiteiten op de kwaliteit van het grondwater wordt derhalve nog niet goed begrepen, hetgeen een belangrijk element is voor een duurzaam gebruik van de hulpbron.

Dar es Salaam is het grootste stedelijke centrum in Tanzania met een bevolking van ongeveer 3 miljoen inwoners. Het krijgt zijn watervoorziening van 3 zuiveringsinstallaties voor oppervlaktewater van de rivieren Ruvu en Kizinga. De voorziening is volledig ontoereikend en in veel stadsdelen gerantsoeneerd. Grondwater wordt gebruikt om de voorziening te vergroten; meer dan 36 diepe boorgaten in de stad zijn rechtstreeks verbonden met het waterleidingsysteem (zonder gezuiverd te zijn!). De watervoorziening d.m.v. buizen voorziet slechts in ongeveer 50% van de vraag en het alternatief is grondwater. Onzorgvuldige afvalverwijdering bedreigt echter de kwaliteit van de waterhoudende grondlagen (aquifers). Ongeveer 90% van de inwoners gebruikt plaatselijke sanitaire systemen; industrieel afvalwater wordt ontoereikend behandeld en het vaste afval wordt rechtstreeks gestort of begraven. Een dergelijke situatie stelt het publiek bloot aan ernstige gezondheidsrisico's. Ondanks het belang van grondwater in de stad wordt de kwaliteit van het water en de exploitatie daarvan niet toereikend gecontroleerd. Daarom is er weinig informatie over de kwalitatieve eigenschappen van de aquifers. Er zijn beperkte onderzoeken over dit onderwerp verricht en over het algemeen genomen is de grondwaterdatabank inadequaat. De beschikbare relevante informatie is beperkt en zó versnipperd dat de toegankelijkheid moeilijk is en als gevolg daarvan plannen voor grondwaterbeheer negatief beïnvloed worden.

Met het oog op genoemde problemen is onderzoek gedaan naar grondwatervervuiling in Dar es Salaam van 1997 tot 2001. Het belangrijkste doel van dit onderzoek was het opzetten van een informatiesysteem voor de controle van de grondwatervervuiling in Dar es Salaam en het ontwikkelen van een model, waarmee prioriteiten voor bescherming van het grondwater snel vastgesteld kunnen worden. De specifieke doeleinden omvatten het maken van een inventarisatie van vervuiling van grondwaterbronnen, het vaststellen van de verspreiding van reservoirvervuiling, het beoordelen van de kwetsbaarheid van het grondwater en het ontwikkelen van een beschermingsmodel. De informatie werd verzameld via bureaustudie, praktijk, laboratoriumanalyses, modellering en het in kaart brengen. Ongeveer 29 maanden werden praktisch besteed in Tanzania, zoals het inventariseren van vervuilingsbronnen, het registreren van geografische locaties van boorgaten (gebruikmakend van de 'GPS-handset'), het keuren en analyseren van grondwater voor chemische en biologische verontreinigingen. De GIS ArcView 3.1 software werd gebruikt voor landmetingen (in kaart brengen). Een methode om de waterkwaliteit snel vast te kunnen stellen, het zgn. WYVUL-model werd ontwikkeld en gebruikt voor grondwaterbescherming.

Uit het onderzoek is gebleken dat huishoudelijk afval, industrieel afvalwater en het lekken van vast afval op stortterreinen de belangrijkste bronnen van grondwatervervuiling in Dar es Salaam zijn. De kwaliteit van het grondwater is sterk verminderd. Monsters die van de boorgaten werden genomen, voldeden niet aan de nationale norm voor drinkwater voor colifecale bacteriën (40%), nitraat (35%) en chloor (20%). Het kaartje van de opgeloste vaste stoffen laat zien, dat meer dan 90% van de stad goed zoetwater heeft dat voor huishoudelijk gebruik geschikt is. Er werden enkele monsters gevonden die een verhoogd niveau van totale organische koolstof hadden, hetgeen duidt op organische vervuiling. Koolwaterstoffen - vooral polycyclische aromatische koolwaterstoffen (PAKs) - werden aangetroffen in enkele grondwatermonsters. De concentraties waren echter lager dan de drinkwaternormen in Europa en de VS. Er werd ook vastgesteld dat enkele werkende boorgaten in risicovolle zones geplaatst zijn, wat betreft de PAKs. De aanwezigheid van zulke stoffen in het grondwater wijzen op mogelijke chemische besmetting veroorzaakt door industrieel afvalwater of het lekken van ondergrondse brandstoftanks, zoals bij pompstations.

De kaart die de kwetsbaarheid van het grondwater voor de stad aantoont, is opgezet met behulp van het DRASTIC model (ontwikkeld in de VS). De kaart laat zien dat meer dan 50% van de stad in een zgn. hoge kwetsbaarheidszone is gelegen (vooral het gebied grenzend aan de kustlijn), hetgeen betekent dat het grondwater vervuild kan worden door menselijke activiteiten. De bronnen van Mbagala en de industriegebieden van Changómbre vallen ook binnen de zone van hoge kwetsbaarheid. De kaart laat zien dat het risico van grondwatervervuiling door mensen erg hoog is en daarom is het noodzakelijk dat preventieve maatregelen worden genomen voordat het te laat is.

Het WYVUL-model is gebruikt om de prioriteiten ter bescherming van het grondwater vast te stellen, die van nut zijn om zich te richten op de hulpbronnen. Het model werd gemaakt teneinde bescherming tot stand te brengen voor de schone aquifers met hoge wateropbrengst, die gelegen zijn in kwetsbare zones met minder fysieke ontwikkeling. Met behulp van het model werd een prioriteitskaart ontwikkeld voor bescherming van het grondwater. De kaart toont aan dat de stadsdistricten Mbagala en Charambe, met aquifers van goede opbrengst (die bovendien op natuurlijke wijze aangevuld worden) en minder verstedelijking, de hoogste prioriteit hebben wat betreft bescherming.

Vervolgens werd een grondwaterbeheerprogramma voorgesteld. Het programma omvat schema's voor controle-activiteiten. Wetgevende maatregelen en betrokkenheid van de maatschappij zijn ook gesuggereerd als zijnde noodzakelijk voor een succesvol beschermingsprogramma voor het grondwater in Dar es Salaam.

Ontoereikend data management is een van de problemen aangaande grondwater in Tanzania als geheel. Toegankelijkheid van data was het grootste struikelblok gedurende dit onderzoek. Vragen die tijdens de gehele periode van het onderzoek gesteld werden, waren o.a.: Hoe staat het met de kwaliteit van het grondwater? Waar zijn de boorgaten te vinden? Waar is de informatie hiervan opgeslagen? Hoe is deze informatie verzameld? enz. Het was een uitdaging om uit een versnipperd systeem van dataopslag de benodigde informatie te vergaren. Tijdens dit onderzoek is echter een grondwaterdatabank opgezet, die zowel niet-ruimtelijke als ruimtelijke kenmerken biedt. De grondwater data zijn geografisch na te slaan, gebruikmakend van de ArcView GIS software. Met een databank is het gemakkelijk om informatie toe te voegen en op te zoeken; ook is de visualisatie sterk toegenomen. De databank vormt ook een kader en uitgangspunt voor toekomstige controle en andere specifieke grondwatermanagement programma's.

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Chapter 1

INTRODUCTION

Abstract

Water is essential for livelihood as well as socio-economic development of any community. Consumption of contaminated water has resulted into epidemics and loss of many lives, especially in developing countries like Tanzania. Groundwater is normally a favoured source of water supplies due to its natural protection against pollution. Lack of access to safe water supplies and pollution are among the six key environmental problems stated by the Tanzania National Environmental Policy (1997), which need urgent attention. Protection of water sources, especially groundwater that is increasingly being used for both public and private water supplies in urban areas, is therefore in line with the prevailing policies in Tanzania. This chapter introduces the research on groundwater pollution conducted in Dar es Salaam City between 1997-2001. It spells out the rationale of carrying out the research, objectives, methodologies used and organisation of the thesis.

1.1 General

Water is one of The God given precious and obligatory substance for man's life. It has no substitute for our daily life. Safe and adequate provision of water to the people has been a continued aim of many countries worldwide. Diseases resulting from consumption of polluted water are enormous, and to-date claim millions of deaths, especially in developing countries. Most of the water we use is termed as fresh water, which accounts for about 6% by volume of the world's total water resources (Table 1.1). Groundwater contributes about 95% of the readily utilized fresh water of the world (Nace, 1971; Leopold, 1974). This volumetric superiority makes it undoubtedly a valuable resource for mankind. Though groundwater is a renewable resource, its residence time can be over thousands of years, meaning a very long time of replenishment – which can be several human generations (Freeze and Cherry, 1979). Many urban and rural populations in the world utilize groundwater in various ways, mainly as a public water supply and irrigation source. Unsustainable exploitation of groundwater resources has led to many problems including: declining water table, land subsidence, salt-water intrusion, deteriorated quality by pollutants, etc. The quality degradation normally arises from the different human activities on the land, such as urbanization, industrialization, agriculture, etc. in most cases pollution occurs due to poor methods of waste disposal and inappropriate handling of chemicals. Water-soluble wastes and other materials that are dumped, spilled, or stored on the surface of the land or in burial pits and lagoons can be dissolved by precipitation, irrigation waters, or liquid wastes and eventually move through the soil in the unsaturated zone to pollute the groundwater. Once contaminated, it is difficult, perhaps impossible, for the water quality to be restored. Hence, if groundwater resources are to continue to play an important role as dependable sources of water supplies, then they must be protected from increasing threats of subsurface contamination. This study is dedicated to assessing the vulnerability of groundwater to pollution and developing methods for prioritising protection plans for the city of Dar es Salaam, Tanzania.

Table 1: Water Balance of the World (Nace, 1971)

Parameter	Surface area (km^2) x 10^6	Volume (km^3) x 10^6	Volume (%)	Equivalent depth (m)*	Residence Time
Oceans and seas	361	1370	94	2500	~4000 years
Lakes and reservoirs	1.55	0.13	<0.01	0.25	~10 years
Swamps	<0.1	<0.01	<0.01	0.007	1-10 years
River channels	<0.1	<0.01	<0.01	0.003	~2 weeks
Soil moisture	130	0.07	<0.01	0.13	2 weeks - 10 years
Groundwater	130	60	4	120	2 weeks - 10,000 years
Icecaps and glaciers	17.8	30	2	60	10 - 100 years
Atmospheric water	504	0.01	<0.01	0.025	~10 days
Biospheric water	<0.1	<0.01	<0.01	0.001	~1 week

*Depth computed assuming uniform distribution of water over the entire surface of the earth

1.2 Tanzania: Location and Key Environmental Problems

Tanzania is located on the Indian Ocean coast, and is among the three countries within the East African region, others being Kenya and Uganda. It harbours the African continent’s land peak of Kilimanjaro mountain, and the famous Serengeti National park including the Ngorongoro Crater (Figure 1-1). The country has a population exceeding 30 million and a geographical area of about 945,000 km^2, of which 6.5% is water bodies. There are over 120 tribal languages, united by a common tongue, “Swahili”. Economically, agriculture (mostly peasantry type) is the backbone, others being mining and industrial sectors.

Like many developing countries, Tanzania is facing diverse environmental problems, some of which are growing in severity day by day. According to Section 11 of the National Environment Policy (1997), the country has identified six key environmental problems that need urgent attention. These are:

- Land degradation;
- Lack of accessible good quality water for inhabitants;
- Environmental pollution;
- Loss of wildlife habitats and biodiversity;
- Deterioration of aquatic systems; and
- Deforestation;

Generally, poverty, rapid increase in population and urbanization magnify the trends of some of problems. Section 13 of the Environmental Policy (1997) recognizes particular causes for increased environmental degradation in Tanzania, as it states:

> "The reasons for the current deteriorating state of the national environment, include: inadequate land and water management at various management levels; inadequate financial and human resources; the inequitable terms of international trade; the particular vulnerable nature of some of the local environments; rapid growth of rural and urban population and inadequate institutional coordination. These factors together are creating undue pressures on natural resources systems. Other important factors include inadequate monitoring and information systems, inadequate capacity to implement programmes, inadequate involvement of major stakeholders (e.g. local communities, Non-Governmental Organisations, the Private sector) in addressing environmental problems, inadequate integration of conservation measures in the planning and development programmes"

Though Tanzania is generally considered to be a well-watered country having good rainfall, many rivers and lakes and huge groundwater deposits, the water supply coverage is only 54.2% and 42% for urban and rural areas, respectively (Ishengoma, 1998; Mato *et al*., 1998). This fact is supported by Section 12 (b) of the National Environmental Policy (1997); which states:

> "Despite considerable national effort, over half the people in towns and in the countryside do not have access to good quality water for washing, cooking, drinking and bathing".

Both surface water and groundwater are used for public water supplies as further explained in this thesis. However, the water sources are increasingly being polluted by indiscriminate disposal of wastes and at times irrational agricultural practices (such as untimely and over use of agrochemicals). The problems are magnified in urban centres where there are large populations and concentration of anthropogenic activities like industries that are accompanied with huge waste generations. The urban centres in Tanzania are characterised by inadequate infrastructure, especially facilities for proper collection and disposal of wastes. Some of these waste substances are finally transported to water sources, where they can be attenuated but sometimes accumulated. Since continuous monitoring mechanisms of water sources are generally not in place, the accumulation rates of these waste substances (some are toxic in nature) are not well understood (Kongola et al., 1999).

Notes: K- Kilimanjaro mountain; S- Serengeti National Park; N- Ngorongoro Crater

Figure 1-1: Location Map of Tanzania

Of great concern is the presence of micro-organic substances like polycyclic aromatic hydrocarbons (PAHs), pesticides etc, which are increasingly being produced from developmental activities as well as from daily urban life. The overall impact of this situation is that more and more people, of present and future generations, may be exposed to serious health risks. The National Environmental Policy (1997) again underscores this fact as mentioned in Section 12 (c), which states:

"Pollution in towns and the countryside is affecting the health of many people, and has lowered the productivity of the environment"

Despite the possibility of pollution, there is a growing demand for groundwater, and in some urban areas is the only available source of water. The other reasons for urbanites to use groundwater is that the surface water sources (especially in urban centres) have been degraded due to exposure to pollution (as further elaborated in Chapter 2). The threat of contaminated groundwater resource is mostly felt in Dar es Salaam City, the largest urban setting in the country. One should recognise that any postponement in properly addressing the problems of groundwater pollution reduces the scope of feasible solutions and the time for implementation, whilst increasing the required funds that may be needed for cleaning or remediation measures. Due to the time lag between surface contamination and its occurrence in the groundwater, even regions still enjoying satisfactory groundwater quality must be concerned with the consequences of land-use on the soil and water. A rational well-planned groundwater quality management programme, therefore, is required in the earliest stages of urban development.

Against the foresaid background, the need for developing appropriate urban groundwater management strategies becomes very essential for Tanzania, and especially Dar es Salaam City. This study addresses these issues of groundwater pollution in reflection to the second and third key environmental problems in Tanzania (i.e. lack of accessible, good quality water for both urban and rural inhabitants and environmental pollution), for the City of Dar es Salaam.

1.3 Groundwater Pollution Research in Dar es Salaam: The EVEN Project

Dar es Salaam is the largest urban centre in Tanzania, with a population of about 3 million and harbouring about 80% of the industries and over 50% of the total urban dwellers in Tanzania. The water supply is severely inadequate and in many parts of the city rationed. Groundwater is used to augment both public and private supplies. Wastes are crudely being disposed of on land, thus jeopardizing the quality of the groundwater resource and its future dependence for potable water supplies. Despite the importance of groundwater in the city, its quality and exploitation are not consistently monitored, and general information databases, and their access is lacking. This situation hampers any effort to assess the resource and formulation of plans for future aquifer protection. The situation in Dar es Salaam City is further dealt with in Chapters 3, 4 and 5.

The existing potential pollution of groundwater resource in Dar es Salaam led to the formulation and implementation of this research project, under the “Capacity Building in Environmental Engineering at the University of Dar es Salaam” project, abbreviated as “EVEN Project”. The project was undertaken from 1997 to 2001, between the Centre for Environmental Technology of the Eindhoven University of Technology (The Netherlands) and the Department of Chemical and Process Engineering of the University of Dar es Salaam (Tanzania). The

Government of Tanzania and the Dutch Government (through Nuffic) jointly sponsored it.

1.4 Objectives, Methodologies and Scope of this Thesis

The main objectives of the research were to establish an information system for groundwater pollution monitoring in Dar es Salaam and to develop a rapid assessment model to guide identification of priority areas for protection. The specific objectives include making an inventory of groundwater pollution sources, determination of extent of aquifer pollution, assessing groundwater vulnerability and developing a protection priority model.

The main methologies used to carry out this research included: desk study, fieldwork, laboratory analysis, modelling and mapping. About 29 months were spent on fieldwork in Tanzania, making an inventory of pollution sources, recording borehole geographical locations (using GPS handset), groundwater sampling and analysis for chemical and biological contaminants. The GIS ArcView (version 3.1) software was used for mapping work. A rapid assessment method was used to develop a groundwater protection priority model for Dar es Salaam City.

The research was limited within the geographical areas, especially the built –up portion of Dar es Salaam City, where basic hydrogeological data could be obtained.

1.5 Structure of the Thesis

This thesis consists of eight chapters. Chapter 2 describes the problem of groundwater pollution urban areas, worldwide and in Tanzania. It gives an account, accompanied with evidences on escalating groundwater problems resulting from the urbanization processes. Chapter 3 deals with groundwater pollution sources in Dar es Salaam City. The chapter discusses the various ways in which the city’s groundwater resource is being threatened from degradation by anthropogenic activities. It also gives estimates of pollution loads transferred to the groundwater. Chapter 4 narrates on the quantity and quality issues of groundwater in Dar es Salaam. It contains the basic hydrogeological data analysis as well as description of the quality investigations made during the research. The results of the investigations are also presented in parameter specific maps. Chapter 5 is devoted to groundwater data and information management. It explains how the databases (both non-spatial and spatial) were established and used. The borehole location map (with proper geographical reference) is one of the important features of this chapter. Chapter 6 is dedicated to groundwater vulnerability assessment, a concept that is still being developed. It gives overview of groundwater modelling and the evolution of the vulnerability assessment. A peculiar output of this chapter is the Dar es Salaam groundwater vulnerability map, which delineates areas to their relative degree of potential to pollution. Chapter 7 deals with identification of micro-organic pollutants (especially petroleum hydrocarbons) and mapping of the major sources. Chapter 8 is devoted to the development of groundwater management strategy for Dar es Salaam City. A new model, acronymic WYVUL model, formulated for assisting in the identification of priority areas for groundwater protection in Dar es Salaam is explained in this chapter. A map containing the prioritised areas for protection is one of the major contributions of the research that is presented in this chapter.

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Chapter 2

GROUNDWATER IN URBAN AREAS

Abstract

Groundwater pollution in urban areas is a worldwide growing environmental problem and now has become a topical issue. Many major cities and small towns in the world depend on groundwater for water supplies, mainly because of its abundance, stable quality and also because it is inexpensive to exploit. However, the urbanization process threatens the groundwater quality and already there are increasingly reported cases in literature on aquifer deterioration in urban areas. The urban population in Tanzania is growing at 6.8% per annum and this does not match with provision of basic infrastructure like water supply, sanitation and waste management. More than 30% of the Tanzania inhabitants depend on groundwater either directly or indirectly. About 45.8% of the urban population without access to piped water supplies uses groundwater as inexpensive alternative source. Analysis done in the 10 designated cities and municipalities in Tanzania have shown that 17.8% of the demand is being abstracted from groundwater through public works. The study estimated that 43% of the actual water consumed by inhabitants in these towns are from groundwater. It was also revealed that 50% of the deficit of demand-supply in the major urban towns is abstracted from groundwater. Despite its importance, groundwater is being threatened by the rapid urbanization experienced in the towns. The main sources of groundwater pollution are indiscriminate disposal of domestic and industrial waste, which are principal components of urbanization process. For example, over 90% of the urban population uses traditional latrines, without lining to contain the waste mass in the ground. Measurements of groundwater quality in the city of Dar es Salaam indicate deteriorating aquifers. For instance, more than 40% of the groundwater samples analysed in Dar es Salaam do not comply with the Tanzania standards. Thus, Tanzania faces a challenge to protect groundwater resources amidst rapid urbanizing human settlements, of which failure can lead to escalating costs for provision of drinking water in cities and decreased public health conditions. This chapter explores the roles of groundwater and impacts that accrue from urbanization process in Tanzania.

2.1 Introduction

Water is an indispensable resource for man's life. The global demand for fresh water doubles every 20 years (Foster, 1999). This growing demand is putting enormous pressure on water resources. Since many of the surface water sources have been degraded or depleted, due to exposure to pollution, changes in climates and over-exploitation, much pressure is being exerted on the groundwater sources. Groundwater is well suited for this purpose because of its wide distribution, dependability, inexpensiveness, and it usually requires little or no treatment before use.

Groundwater can be defined as subsurface water that occurs in voids and permeable geological formations. It accounts for about 97% (excluding permanently frozen water) of the Earth's useable freshwater resource (Canter, *et al.*, 1987, Leopold, 1974). It plays an important role in maintaining soil moisture, stream flow and wetlands. Over half the world's population depends on groundwater for drinking water supplies. In the U.K., for example, about 30% of the public water supplies are derived from groundwater, in the U.S.A. about 50%, Denmark 99% (Tebbutt, 1992), and in Germany 70% (Trauth and Xanthopoulos, 1997). In Tanzania, 30% of the population is directly depending on groundwater (Materu, 1996).

Groundwater, however, is vulnerable to pollution and over-exploitation. The pollution commonly results from human activities, where chemicals, susceptible to percolation, are stored and spread on or beneath the land surface. It has become increasingly evident that inadequately controlled groundwater exploitation and indiscriminate disposal of wastes to the ground widely result in significant deterioration of groundwater quality (Foster *et al.*, 1996). This deterioration has contributed to a larger extent to escalating water supply cost, increase in water resource scarcity and growing health hazards, especially in urban areas (Morris *et al.*, 1997). Lam *et al.*, (1994), reported, that in the state of California U.S.A, the contamination of many aquifers with industrial and agricultural chemicals made water from these aquifers unsuitable for drinking purposes, making it necessary to import water from the Sacramento-San Joaquin Delta and other uncontaminated sources. These are some of the existing challenges of abstracting groundwater for the town dwellers within the urban environment. Therefore, a balance and understanding between urbanization process and groundwater protection strategies need to be developed. Otherwise, the contamination of groundwater in urban areas would remain a growing public health hazard, especially in developing countries where both financial and technological resources, needed to clean polluted aquifers, are scarce.

This chapter gives an account on the status of groundwater pollution in urban areas worldwide as well as evaluating the impacts of urbanization process on groundwater resources in Tanzania.

2.2 Status of Groundwater in Urban Areas

On one hand, there are inhabitants of the cities in the world today who depend on groundwater for public water supplies. On the other hand, it is increasingly reported that aquifers in urban areas are deteriorated (Chilton, 1999). The urbanization process cannot be separated from water supply, sanitation and drainage infrastructure. In many lower-income urban centres in developing nations (like Tanzania), these key infrastructure facilities, normally come later in the urbanization process. Major observed impacts of urbanization include increase in peak runoffs (caused by increased urban fringe impermeability), deterioration in quality of both surface and groundwater resources, and changes in frequency and volume of groundwater recharge (Foster, 1999; Morris *et al.*, 1996, 1997; Lindh, 1983). The major impacts of urbanization process upon groundwater resources have been summarized by Foster (1999, 2001) and are shown in Table 2-1.

Groundwater contamination is essentially caused by diffuse pollution from nitrogen compounds (normally nitrate but sometimes ammonium), rising levels of salinity (essentially sodium and chloride) and elevated concentrations of dissolved organic carbon (Foster, 1999). Widespread but patchy groundwater contamination due to petroleum and chlorinated hydrocarbons and related synthetic organic compounds, and on a more localized basis by pathogenic bacteria and viruses, are also arising phenomena. In many countries groundwater pollution issues have concentrated on the identification and/or quantification of major ions, salinity and microbiological quality (Foster *et al*, 1994; Melloul and Colin, 1991; Mailu, 1997; Nkotagu, 1996; Tole, 1997). The major ions include calcium, (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), potassium (K^{+}), hydrogen carbonates (HCO_3^{-}), sulphates (SO_4^{2-}), chlorides (Cl^{-}), and nitrate (NO_3^{-}) (Melloul and Colin, 1991). With recent technological advancement in water analysis, trace elements (e.g. arsenics) and organic micro-pollutants (e.g. PAH, dioxins etc) are also being analysed (Soniassy *et al.*, 1994).

On one hand, the experience of groundwater quality deterioration in urban areas is now enormous. For example, Nazari *et al* (1993) reported high levels of chlorinated hydrocarbon solvents (CHS), especially in trichloroethene, 1,1,1-trichloroethane, tetrachloromethane (carbon tetrachloride), trichloromethane and tetrachloroethene, in the city of Coventry (U.K.). In another study, Ramesh and Purvaja (1995) reported elevated levels of heavy metals (Cd, Co, Cr; Cu; Mn; Ni; Pb; Zn) in Madras City. Over-abstraction and erratic waste disposal practices were the causes of groundwater contamination. However, Trauth and Xanthopoulos (1997) observed deteriorating standard of groundwater quality in intensively used areas in Germany, such as agricultural, trade or industrial areas and urban areas, and that only about 24% of the pumped groundwater would meet the drinking water standard. Another observation by Abdrakhmanov (1998) showed that concentrations of bicarbonate, nitrates and petroleum products are in the range of 15-300 mg/l in boreholes (15-20m deep) located in residential and industrial areas in Ufa City, Russia.

Table 2-1: Summary of impacts of urbanization processes on groundwater (Foster, 1999)

Process	Effect on Subsurface Infiltration			Quality Implications	
	Rates	Area	Time Base	Scale	Contaminant Group
A: Modifications to natural systems					
• Surface impermeabilization and Drainage					
-stormwater soakaways	Increase	Extensive	Intermittent	Negative	Cl, HC, DOC
-mains drainage	Reduction	Extensive	Continuous	None	None
-surface water canalisation	Reduction	Linear	Variable	None	None
• Irrigation of Amenity Areas	Increase	Restricted	Seasonal	Variable	N, Cl, DOC
B: Introduction of water service network					
• Mains water supply leakage	Increase	Extensive	Continuous	Positive	None
• Sanitation System Installation					
-in-situ sanitation	Major increase	Extensive	Continuous	Negative	N, FP
-mains sewerage	Some increase	Extensive	Continuous	Negative	N, FP, DOC
C: Uncontrolled aquifer exploitation					
• Falling water table	Some increase	Extensive	Continuous	Potentially positive	
• Induced downward leakage	Minor increase	Extensive	Continuous	Negative, causes pollution of deep aquifers with persistent contamination	

Cl	Chloride and salinity generally	DOC	Dissolved Organic Carbon
N	Nitrogen compounds (nitrate or ammonium)	FP	Faecal Pathogenic
HC	Hydrocarbon fuels		

In Nicosia City, Cyprus, Michaelidou *et al* (1995), using a GC/FID instrument, conclusively proved that effluents from a dye factory were responsible for the pollution of at least 11 boreholes in the vicinity. Similarly, Blarasin *et al*. (1999) reported pollution of groundwater in which 60% of the groundwater samples taken from drinking wells in Rio Cuarto City (Argentine) were found to be bacteriologic ally contaminated (total coliform, 3-1100 MPN/100 ml) and hence not suitable for human consumption. The same authors reported that, concentrations of total dissolved solids (TDS), nitrate, and chloride ranged between 623-1200 mg/l, 2-50 mg/l and 16-85 mg/l respectively, which indicated a slowly degrading aquifer.

On the other hand, the groundwater resource exploitation has also been an issue of concern. The most common quality impact of inadequately controlled aquifer exploitation, particularly in coastal situations, is the intrusion of saline water. Another one is the contamination of deeper (semi-confined) aquifers, where they are below a shallow poor quality phreatic aquifer affected by anthropogenic pollution and/or saline intrusion. This occurs as a result of inadequate well construction, leading to direct vertical seepage and/or pump-induced vertical leakage, with penetration of more mobile and persistent contaminant species. Evidence has been accumulating since the 1980s of widespread draw down of piezometric surface by 20-50 m or more of various Asian megacities, as a result of heavy exploitation of alluvial aquifers. Both of aforementioned side effects are quite widely observed (Foster and Lawrence, 1996; Foster, 1999). Cities like Bangkok (Thailand), Jakarta (Indonesia), and Manila (Philippines) have severely suffered from uncontrolled aquifer exploitation to the extent of substituting the water supply by long distance import of surface water (Munasinghe, 1990; Schmidt et al., 1990; Foster and Lawrence, 1996). Although the city of Dhaka (Bangladesh), groundwater remains the sole source of water supply, still the control over exploitation is reported to be inadequate (Foster, 1999).

Worldwide, it is increasingly questionable to tap groundwater at densely populated areas for domestic supply and sensitive industries (such as food and beverage preparations) due to pollution threats. Because of the previously mentioned problems, a good groundwater management practice is needed. In Tanzania, there is very little field performance data on quality characteristics of the aquifers. Limited researches on the subject have been conducted and generally the groundwater database is inadequate. The little relevant information available is also fragmented making access difficult, and hence, affecting plans for future aquifer protection. In these lines, a collaborative research on groundwater pollution was conducted in 1997-2001, between Technical University Eindhoven, the Netherlands and the University of Dar es Salaam (Chemical & Processing Engineering Department), Tanzania.

2.3 Urbanization and its Impact on Water Resources

Urban areas include suburban (or periurban) and central city complexes. Worldwide, urban population growths have been accelerating phenomena throughout the 20th century (Foster, 1999). A peculiar characteristic of rapid urbanization is, however, observed in many African urban areas. While the Africa's total urban population growth was estimated at 14.2% in 1950, it rose to 35.2% in 1990 and over 41.5% by 2000 year (Mwapilinda, 1998). The causes of urban population growth are rural-urban migration and natural causes; the former is strong in Africa and is principally driven by opportunities for employment (UNEP, 2000).

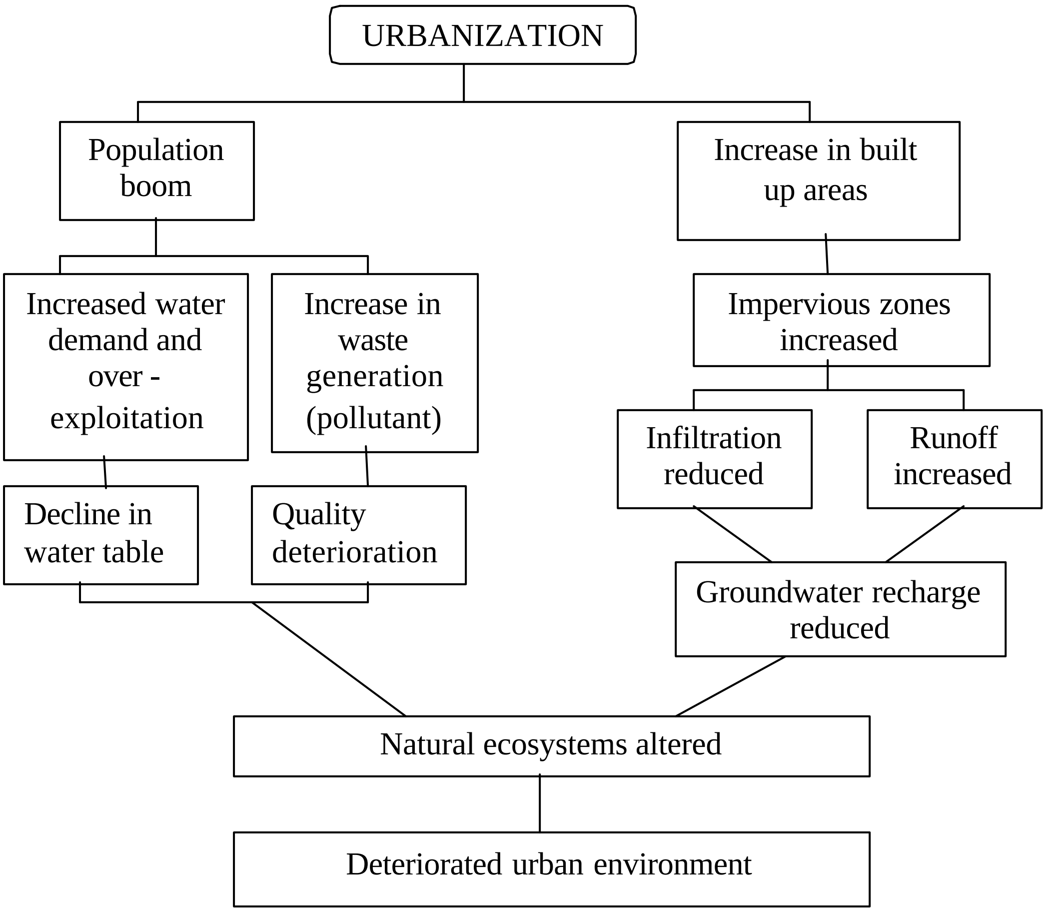

Figure 2-1: Conceptual model depicting the impact of urbanization process on hydrological regime and urban environment quality (after Suresh, 1999)

Unlike trends in developed countries, urbanization in Africa has occurred without a corresponding substantial growth of urban economy especially to support infrastructure delivery. It has been also reported in literature that urbanization in Africa is accompanied by concentration of population and economy in single large cities e.g. Dar es Salaam for Tanzania; Nairobi for Kenya; Lusaka for Zambia; Lagos for Nigeria etc (UNCHS, 1987, 1996; Mwapilinda, 1998). It also has been projected that about 50.5% of the urban population in Africa will reside in small towns of less than 1 million people by 2025 year (UNCHS, 1987). However, the process of urbanization on the African continent has resulted into negative responses including growing poverty, shortage of shelter (resulting into emergence of squatter areas) and shortage of basic services and infrastructure (e.g. water supply, sanitation, solid waste facilities etc). These factors have contributed to increased crimes in cities and environmental degradation episodes (groundwater pollution inclusive). The horizontal extensions of cities, which are necessary for absorbing new migrants, greatly reduce the efficacy of existing infrastructure. Rapid urbanization has been shown to have a profound effect on groundwater recharge and marked impact on groundwater quality. Figure 2-1 depicts the impact of urbanization process upon the quality of urban environment. The scale of implications for security and safety of developing city water supplies is of paramount importance. The urbanization process and its implications to groundwater resources in Tanzania are explained in the forthcoming sections.

2.4 Urbanization Process in Tanzania

Tanzania is a country with an estimated population of more than 30 million, of which between-20-30% live in urban areas. The urbanization process has similar trends to the rest of the African continent (Kironde, 2000). The average urban population is growing at 6.8% per annum dictated by the rural-urban migration (Ministry of Lands and Human Settlement, 2000). Table 2-2 and Figure 2-2 show population increases and growth rates in the major urban centers in Tanzania for the period 1948-1988. The comparison of populations based on the estimates for 2001 are shown in Figure 2-2. There are two urban centers with city status (Dar es Salaam and Mwanza) and eight municipalities (Morogoro, Iringa, Tanga, Arusha, Tabora, Mbeya, Moshi and Dodoma). Four towns (Dar es Salaam, Mwanza, Dodoma and Mbeya) have populations estimates exceeding 0.5 million. Statistics show that among the 10 major urban centers, Mbeya has the highest growth rate (1948-2001 estimates) of 10.4% per annum, while Tabora has the least, 5.2%. These major towns have populations exceeding 7.0 million (about 20% of the current Tanzania population), of which 50% are in Dar es Salaam.

The rapid urbanization has inevitably increased pressure on the infrastructure and services, much of which has not been properly maintained or expanded to cope with the rapid urban growth. In addition to these, there has been inadequate shelter delivery to cater for the urban population, a situation that has led to extensive development of squatter or unplanned areas accounting to about 60-70% of urban population (Ministry of Lands and Human Settlement, 2000; Mainguet, 1991; Kironde, 2000). The rapid urbanization has constrained the economy to the extent of paralyzing the physical and social infrastructure. The common phenomena in Tanzanian urban areas include inadequate safe drinking water, poor sanitation, uncollected solid wastes, over-crowding and generally degraded urban environment.

Table 2-2: Population trends in selected urban areas in Tanzania

Urban Centre	1948 Population	1967 Population	1978 Population	1988 Population
Tabora	9,756	51,044	85,490	93,504
Iringa	5,759	21,773	57,328	84,860
Moshi	8,049	26,870	52,075	96,838
Morogoro	5,420	16,754	41,101	117,760
Tanga	20,604	61,233	102,555	187,155
Arusha	5,431	32,367	55,359	134,708
Mbeya	3,069	12,234	74,852	152,844
Dodoma	9,524	23,634	45,805	203,813
Mwanza	11,254	34,977	110,238	223,013
Dare Salaam	74,729	292,692	738,716	1,360,850

Sources for raw data: Bureau of Statistics, Planning Commission (1967, 1978 and 1988), Population Census Reports, Dar es Salaam.

Ministry of Lands and Human Settlements Development (2000), National Human Settlements Development Policy, Dar es Salaam

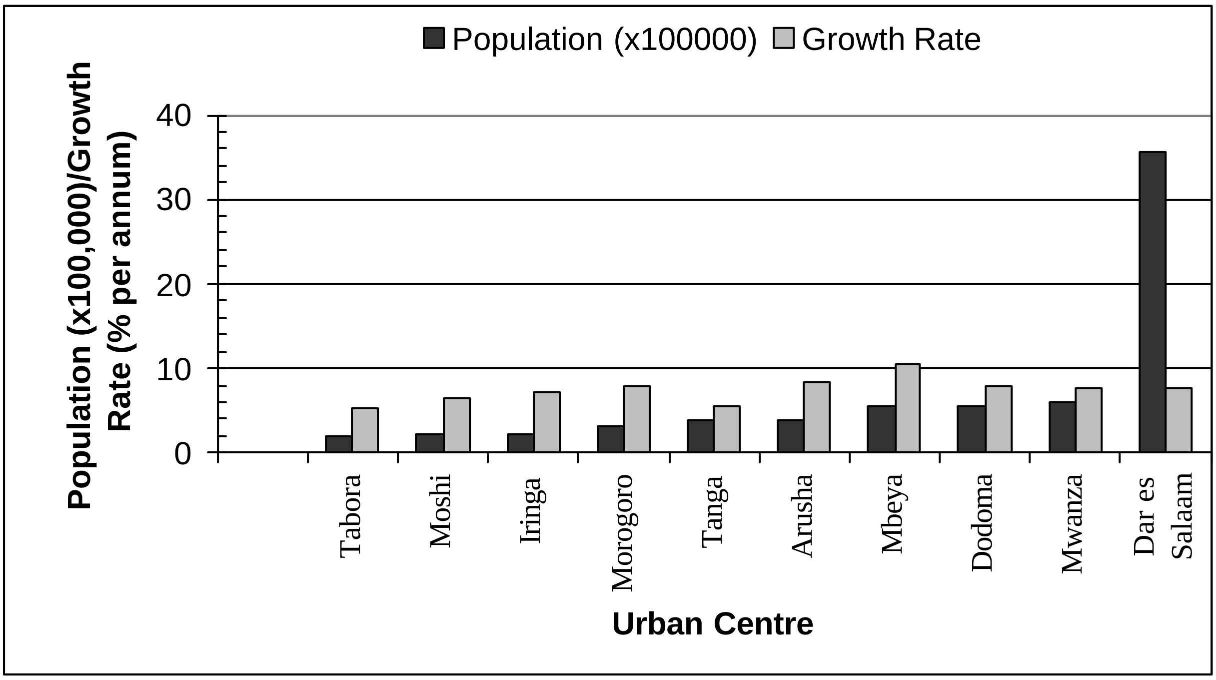

Figure 2-2: Population estimates of the major urban centers in Tanzania (2001)

2.5 Groundwater Resources in Tanzania

The occurrence of groundwater is largely influenced by geological conditions. Hydrogeologically about 75% of Tanzania (Kongola *et al.*, 1999) is underlain by crystalline basement complex rocks of variable composition and ages, but predominantly Precambrian, which form the basement aquifers (for example the Pangani and Makutopora basins). Other aquifer types include karroo (found in

Tanga), coastal sedimentary formation of limestone and sandstone (e.g. Dar es Salaam), and the alluvial sedimentary sequence, which mostly include clay, silt, sand and gravel, and volcanic materials (e.g. Kahe -Pangani basin). The groundwater potential of every type of aquifer differs much from place to place or basin-wise. The recharge is mostly by direct rainwater infiltration. Preferential recharge is from high intensity rainfall and through fractures. The country is divided into nine drainage basins (Figure 2-3).

Figure 2-3: Main drainage basins in Tanzania (Cited in Rweyemamu, 1999)

Quantification of the groundwater resources of the country has not yet been possible because of lack of requisite data. However, some efforts have been done in assessing groundwater resources in Rufiji and Pangani River Basins, where systematic and basin-wise attempts to evaluate the groundwater resources potential have started. (Kongola *et al.*, 1999). Groundwater development has concentrated mainly on shallow wells for domestic purposes over a wide part of the country (mainly rural areas). They are also commonly used in the periurban fringes where there is no distribution network and places with unreliable supply. Groundwater is the main source of water supply in municipalities like Dodoma, Arusha, Shinyanga, Moshi and Singida. Many other urban areas exploit groundwater to augment supply from surface water sources, as illustrated in the forthcoming section. The boreholes are mainly found in urban settings, some are over 100 m deep. There are over 5000 recorded deep boreholes drilled both as exploratory and production wells throughout the country in nine drainage basins as indicated in the Table 2-3.

Table 2-3: Drainage basins and distribution of recorded boreholes in Tanzania (Kongola *et al*., 1999)

Name of basin	Number of boreholes drilled	Boreholes with high yield (more than 900 1/h)
Pangani	325	292
Ruvu/Wami	892	522
Rufiji	440	268
Southern Coast/Ruvuma	344	188
Inland Drainage	1595	562
Lake Victoria	673	316
Lake Tanganyika	380	132
Lake Rukwa	263	128
Lake Nyasa	63	4

Most of the use of groundwater is for domestic purpose, irrigation, industrial and livestock. For example, at present 88% of groundwater extracted from the Pangani river basin is used for irrigation, 4% for industrial use and 8% for domestic use. In many urban areas groundwater and surface water are used conjunctively e.g. the City of Dar es Salaam. Throughout the country shallow wells are used for domestic water supply, i.e. hand-dug wells and improved wells. Groundwater is currently being used for irrigation purposes in sugarcane, paddy, horticulture, vegetable and flower farming (e.g. Tanzania Planting Company, TPC-Moshi, and sugar cane plantation and Kilombero sugar estates). Groundwater utilization for industrial use is more concentrated in urban areas, especially Dar es Salaam where about 80% of the industries are located. Due to inadequate water supplies many industries have opted for constructing private wells to augment surface water supply. Industries in Dar es Salaam, like Tanzania Breweries Ltd. (TBL), Tanzania Cigarette Company (TCC), Friendship Textile (Urafiki), Ubungo Farm Implements (UFI), Kibuku, Mpishi, and Tanzania Portland Cement factory (TPC - Wazo Hill) etc, have private wells (Mato *et al*., 1998, Drilling and Dam Construction Agency, 2001). The list is rapidly increasing and similar trends are observed in Arusha municipality.

Generally, the natural groundwater quality in Tanzania is considered potentially good, acceptable for most use. The main problems are salinity, high fluoride concentration, hardness and corrosion. The high concentration of chloride (salinity) in groundwater is the main problem especially in the coastal and central regions of the country (like Singida, Shinyanga, Lindi and Mtwara), where there is a high evaporation rate and poor drainage. In Lindi and Mtwara regions, high carbon dioxide in groundwater has been reported (Kongola *et al.*, 1999), which causes groundwater to be corrosive. High fluoride concentrations are common problems in the areas surrounding the Rift valley system (e.g. Kilimanjaro, Arusha, Singida and parts of Shinyanga regions) Materu, 1996; Mato *et al.*, 2000). High iron content in groundwater has been observed in Mtwara and Kagera regions (Kongola *et al.*, 1999). Nitrate levels of more than 100 mg/l have been reported in the Makutopora basin, Dodoma and Singida town (Nkotagu, 1996; Kongola *et al.*, 1999). Figure 2-4, shows the general groundwater quality in Tanzania.

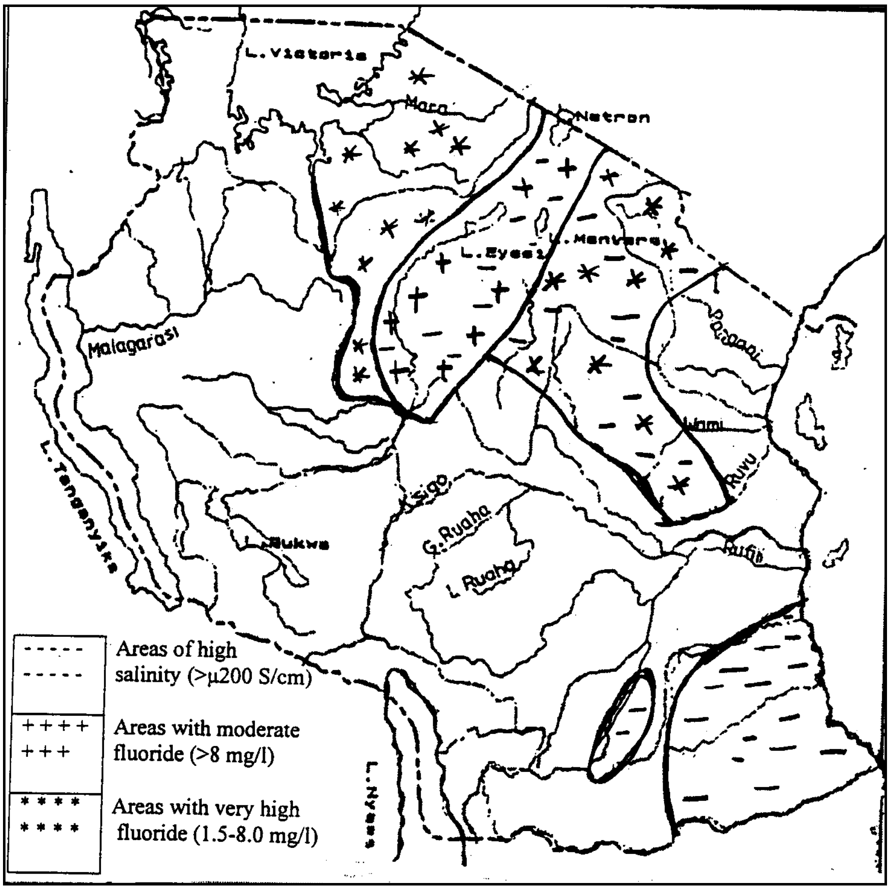

Figure 2-4: General groundwater quality in Tanzania (Cited in Rweyemamu, 1999)

However, the different human activities in both rural and urban areas are threatening the natural quality of groundwater resources. The situation is more alarming in urban areas, which are growing at a fairly fast rate as indicated in Figure 2-2. The potential sources of groundwater pollution include domestic and industrial wastewater, leaching of leachate from solid waste dumpsites and mining tailings, storm water and poor agricultural practices. These are dealt with in more detail in Chapter 3.

The current problems facing groundwater resources exploration and exploitation for urban dwellers in the country include:

- Deteriorating quality (i.e. aquifer degradation);
- Overexploitation (in some cases e.g. parts of Makutopora basin supplying Dodoma Municipality are showing declining water levels);
- Decrease of yields in boreholes (e.g. some of boreholes in Sanawari area, operated by the Arusha Urban Water and Sanitation Authority;
- Poor workmanship during construction of boreholes which leads to caving in of boreholes and opening up deeper aquifers to pollution sources;
- No established safe distances between human activities and positions of boreholes;
- Inadequate public awareness on the importance and potential sources of pollution of groundwater resources;
- Inadequate institutional arrangement to regulate groundwater resources;
- Role of private sector in ground water development and management not yet well recognized;
- Lack of Data: Data is scattered, fragmented and usually incomplete;
- Lack of groundwater monitoring networks;
- Lack of groundwater resources management plan;

2.6 Status of Water Provision in Tanzania Urban Areas

The water supply coverage in Tanzania is estimated at 54.2% and 42% for urban and rural areas, respectively (Ishengoma, 1998; Mato *et al.*, 1998)). There are more than 62 registered urban centres, with a total estimated water demand of 912,300 m^3/day while the supply is only 494,300 m^3/day (Ishengoma, 1998). Inadequate water supply in urban areas (i.e. supply does not meet the demand) and frequent interruptions, force people to go for alternative sources, some of which may be inferior in quality. For this reason, groundwater has normally been an alternative, providing an easy and cheap water source. The practice is always to drill a borehole within one's compound, where he has legal permit of ownership regardless of the surrounding land-use.

The major constraints associated with urban water supply in Tanzania have been reported by Ishengoma (1998) include:

- Insufficient funding: Funds for operation and maintenance and network expansion are not always available as a result water supply facilities become poorly looked at, a situation which accelerates deterioration.
- Low tariff and poor billing: The water authorities claim that water charges are very low to enable recoup money needed for running the systems. In addition only few customers are billed basically due to poor records. Illegal water

connections have also been an issue of concern for the urban water authorities especially Dar es Salaam.

- Water leakages: Most of the urban water supply distribution systems are heavily leaking primarily due to old age. Leakages are estimated to reach 50% in some urban centres.
- Inadequate working tools and equipment: Water authorities do not have sufficient funds to purchase enough tools and equipment for daily operation and maintenance of water schemes. This contributes to poor outputs by the workers and therefore reduced system efficiency.
- Inadequate metering: In all urban centres, bulk water consumption and production is estimated because there are no installed meters for this purpose. This affects planning as it is not known exactly how much water is produced and consequently becomes difficult to estimate the revenue that can be actually accrue from the water service.
- Limited production and distribution capacity: Inadequate pumping facilities, conveyance, storage and distribution capabilities hamper the ability to meet water demand from the rapid population increase within urban centres.

Detailed water demand-supply analysis was made for 10 urban centres designated as cities and municipalities (Dar es Salaam, Mwanza, Dodoma, Mbeya, Arusha, Tanga, Morogoro, Moshi, Iringa and Tabora). The findings are summarized in Table 2-5, Table 2-6 and Figure 2-5, Figure 2-6, Figure 2-7, Figure 2-8 and Figure 2-9. Estimations on water supply and demand in municipalities have been done basing on available data collected during the research.

Table 2-5: Urban water demand and delivery levels in major urban centres in Tanzania

Urban Centre	Water Source	Water Demand (m^3/day)	Supply Level (m^3/day)	Per capita consumption (l/cap.day)	% Supply (m^3/day)
Tabora	Igembe & Kazima Dams	28,222	10,375	155	36.8
Iringa	River Ruaha	16,000	8,500	80	53.1
Moshi	Groundwater	20,000	19,500	90	97.5
Morogoro	Mindu dam	30,000	19,000	95	63.3
Tanga	Sigi River	40,000	25,000	110	62.5
Arusha	Groundwater	42,647	35,000	110	82.1
Mbeya	Ground & surface	30,000	18,000	55	60.0
Dodoma	Ground & dam	37,500	24,000	70	64.0
Mwanza	L. Victoria	70,000	42,000	120	58.3
Dar es Salaam	Rivers Ruvu & Kizinga	410,000	304,000	100	74.1

Source for raw data: Ishengoma, 1998 and Msimbira, 1999

Table 2-6: Summary of status of groundwater exploitation major towns in Tanzania (2001)

Component	Status	Comments
Total population	6.9 Million	
Average water consumption	100 l/cap.day	
Total water demand	6.7 x 10^5 m^3/day	
Total present supply from public water works	4.7 x 10^5 m^3/day	2.0 x 10^5 m^3/day deficit
Overall level of service	70%	
Supply excluding leakage losses	3.29 x 10^5 m^3/day	Leakages assumed 30% of the supply
Actual level of service	49%	3.38 Million people
Actual amount from alternative sources	3.41 x 10^5 m^3/day	Demand for 3.52 Million people
Groundwater abstracted by public water works	120.2 x 10^5 m^3/day	17.8% of the overall supply (1.2 Million people served)
Estimated actual amounts of groundwater sources provided as alternative source	1.7 x 10^5 m^3/day	50% of the deficit between demand and actual supply
Estimated total amount of groundwater being abstracted	2.9 x 10^5 m^3/day	42% of the demand (2.9 Million people)
Total Demand supplied by groundwater sources	42%	

Note: Basing on old age of the distribution systems and consistency in supply, the following percentages of the demand that are provided by groundwater sources, have been assumed: 50, 20, 2, 30, 30, 18, 20,36, 20,25 for Tabora, Iringa, Moshi, Morogoro, Tanga, Arusha, Mbeya, Dodoma, Mwanza, and Dar es Salaam respectively.

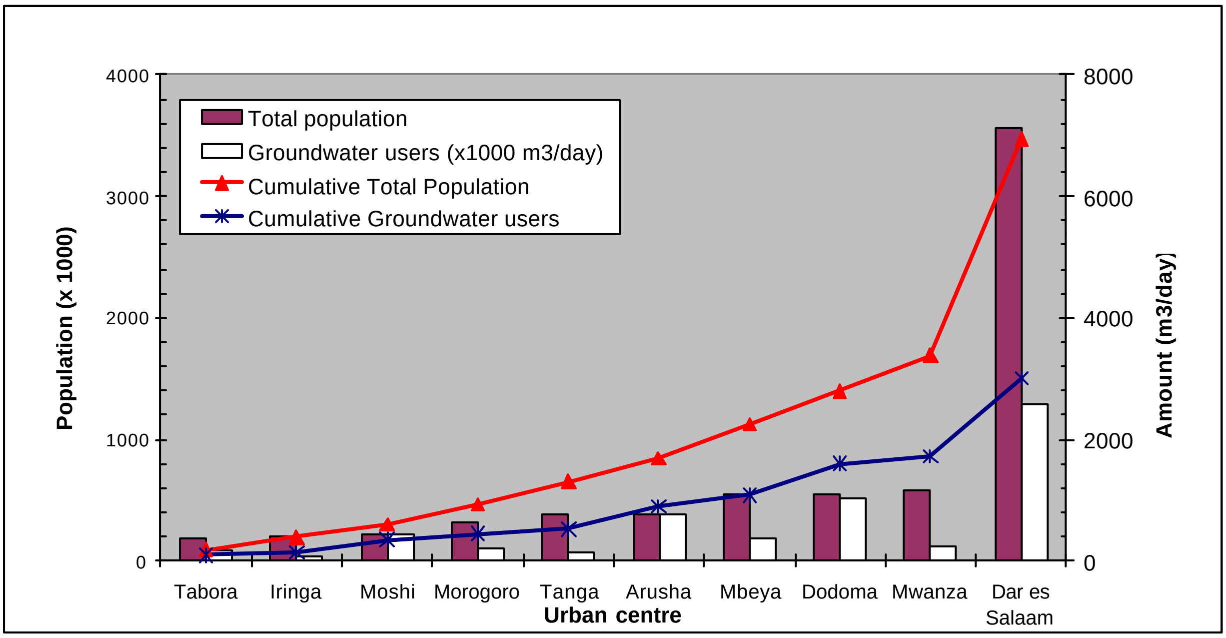

Figure 2-5: Water demand-supply characteristics in major towns in Tanzania

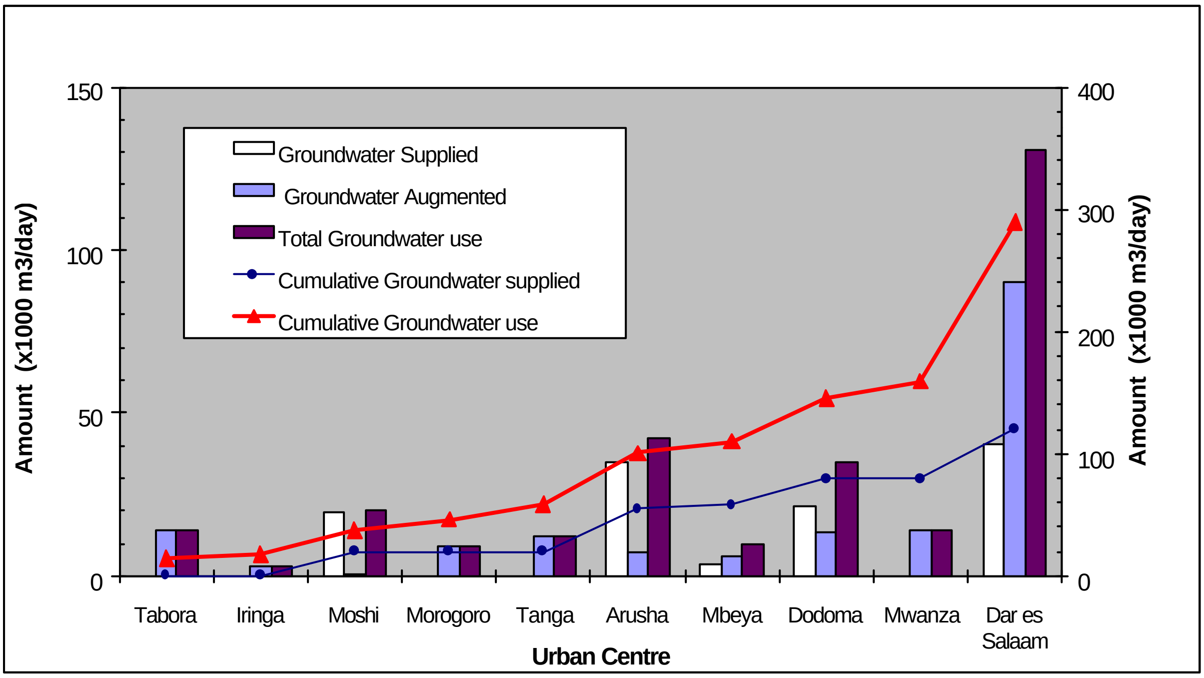

Figure 2-6: Groundwater utilization rate in major towns in Tanzania

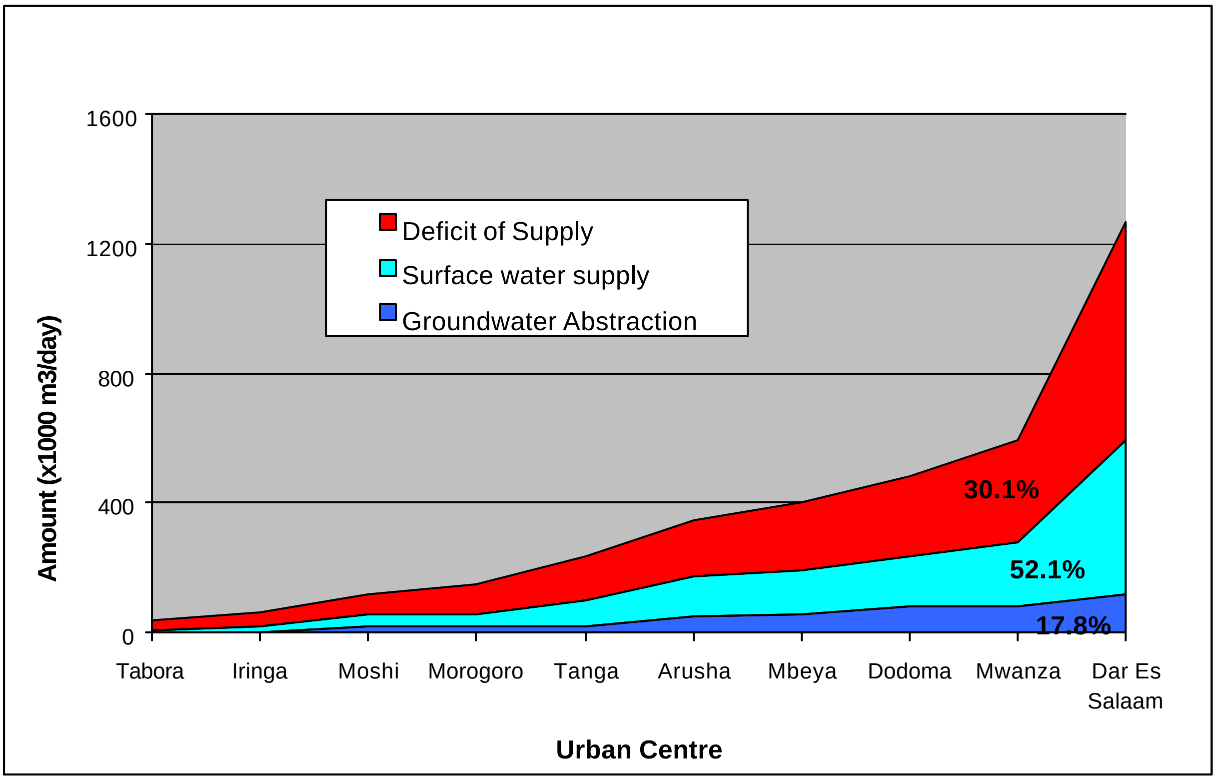

Figure 2-7: The role of groundwater resource in major urban areas in Tanzania

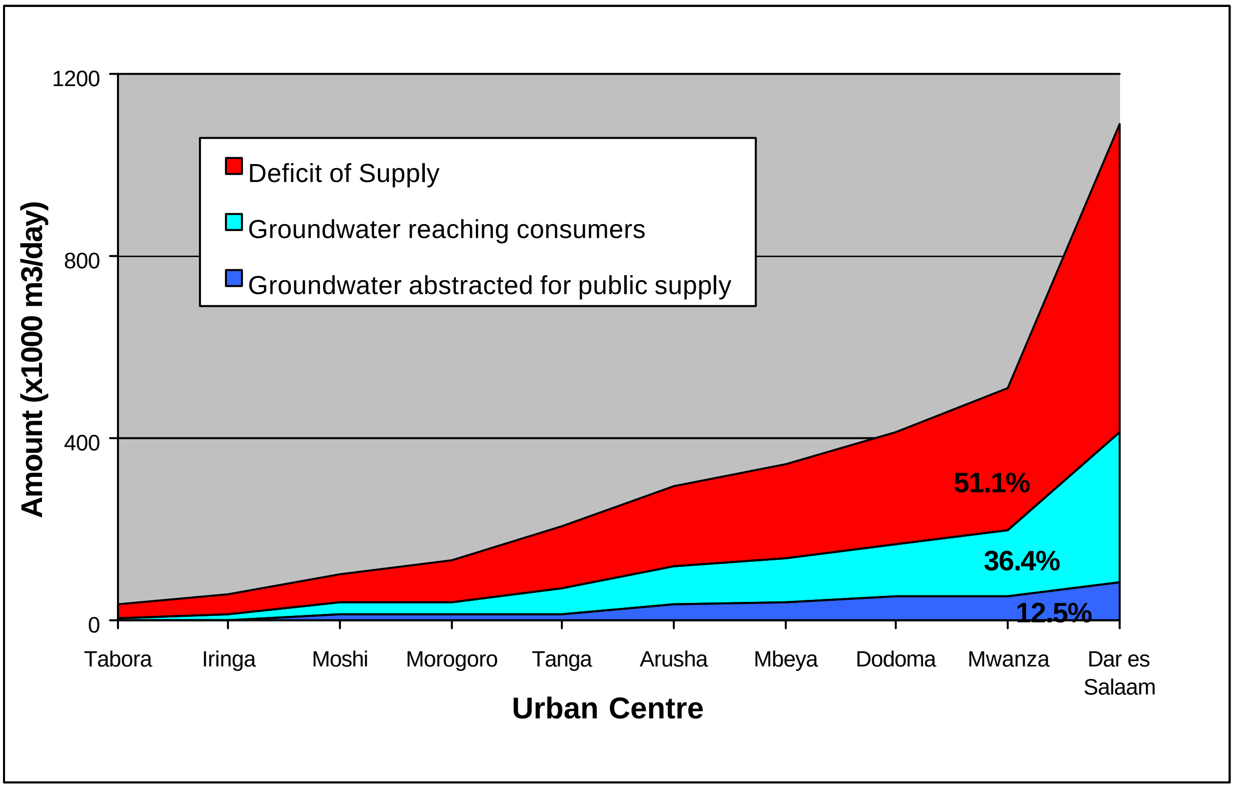

Figure 2-8: Actual amounts of groundwater reaching consumers in major towns in Tanzania

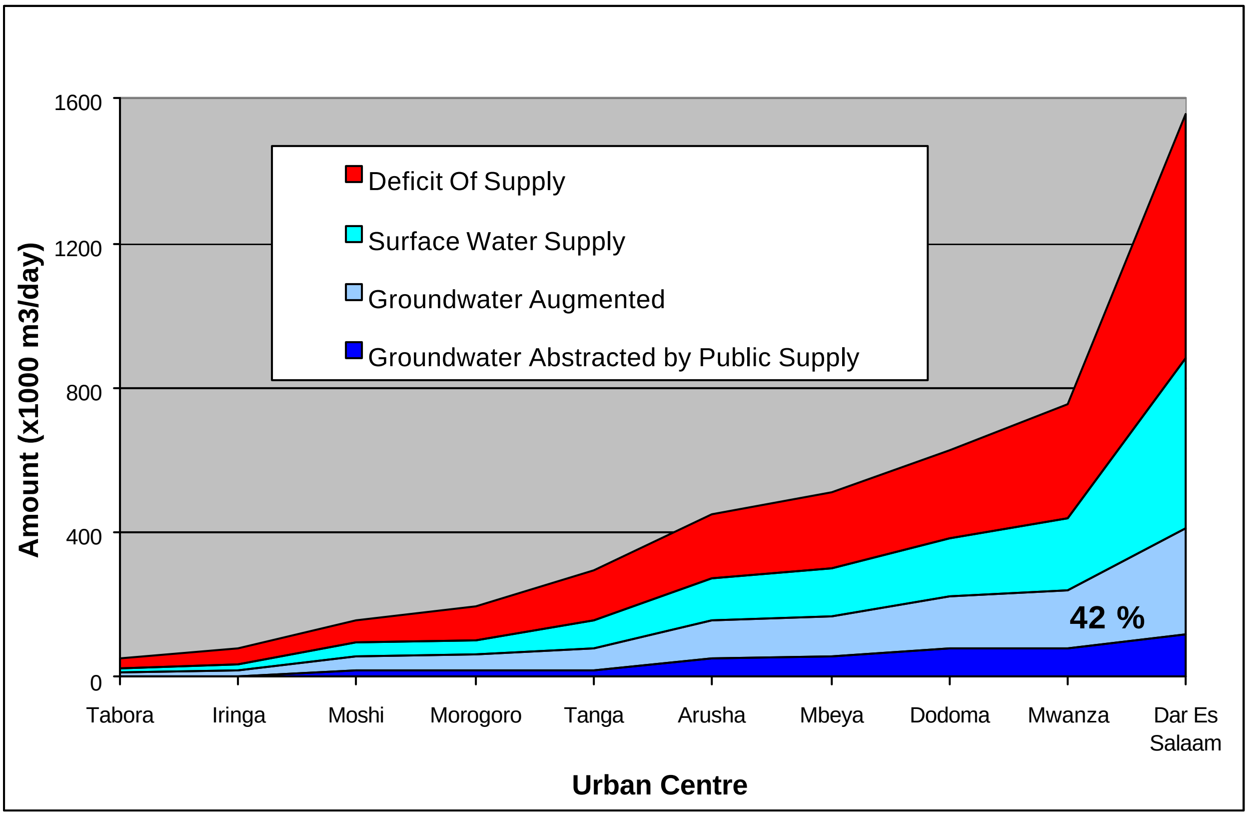

Figure 2-9: Actual groundwater abstracted for various uses in major towns in Tanzania

2.7 Groundwater Pollution in Tanzania Urban Areas

The question of urban pollution, which arises from different activities, has not been adequately addressed in Tanzania. However, many of the urban activities (such as sanitation and solid waste disposal) are linked to groundwater pollution. Urban residential districts without or with incomplete coverage by sewerage, seepage from on-site sanitation systems such as pit latrines and septic tanks, probably present the most widespread and serious diffuse pollution sources. The immediate concern is a risk of direct migration of pathogenic microbes to underlying aquifers and neighbouring groundwater sources.

The main source of groundwater pollution, in Tanzania, is sewage handling (treatment and/or disposal) since over 90% of the population use pit latrines and septic tanks for sanitation (Chaggu, *et al* 1994). In towns like Dar es Salaam, Mwanza, Arusha, Tanga the degradation of groundwater quality is exacerbated by industrialization and rapid urbanization (Baya, *et al.*, 1996; Mato, *et al.*, 2000; Kironde, 2000). Wastes emanating from the residential areas as well as industries are crudely disposed of to land, streams, lakes, or sea without prior treatment. Nine municipalities have sewerage systems, serving only about 12% of the urban population.

Probably the most serious source of groundwater pollution in urban areas in Tanzania can result from industrial activities. About 80% of industries in Tanzania are located in urban areas and over 50% of these are found in large towns, mainly Dar es Salaam (Sheya and Nyamusika, 1996). Typical industries found in the city of Dar es Salaam are shown in Table 2-7. However, many of these industries were established without adequate environmental attention, as a result they have been operating without waste treatment facilities, some for more than 40 years. The wastes from the industries are disposed of inland rivers, depressions, pits, or on land. Industrial effluents have been reported to pollute rivers like Msimbazi in Dar es Salaam, Karanga in Moshi, Mwirongo in Mwanza, and Themi in Arusha (Division of Environment, 1994; 1997). A few industries discharge raw effluents into sewers, which have resulted to malfunctioning of the municipal waste stabilisation ponds (Kayombo, *et al.*, 1998). Serious threats also arise from small-scale industries, which are accompanied by large waste production, are rapidly mushrooming. These activities normally are less monitored and to a larger extent considered to cause less pollution, although their collective impacts may be immense. Moreover, qualitative and quantitative evaluations of groundwater contamination from industrial sources have not been done, although it is speculated that the problem does exist. Chapter 3 gives quantitative estimates of the groundwater contamination from different sources.

Another potential for of groundwater pollution arises from the indiscriminate disposal of solid wastes. Most of the urban inhabitants (60-70%) live in unplanned (squatter) areas, where there are little or no infrastructure services for waste collection (National Environment Management Council, 1995; Ministry of Lands and Human Settlement, 2000). Due to increased urban population, the quantities of solid wastes to be collected and transported for disposal have also increased tremendously in recent years (Yhdego, 1995). For example, the solid waste generated in Dar es Salaam, doubled from 1090 tonnes/day in 1988 to 2000 tonnes/day in 1995 (Kaseva and Gupta, 1995). About 5-10% of the urban population receive regular solid waste collection services in most cases confined to few areas, usually the urban centres and high-income neighbourhoods (Mato, 1997; Lussuga and Yhdego, 1997). The uncollected waste (90-95%) is mainly buried at generation sites, many of them less than 1.0m below ground level, hence becoming a diffuse source of pollution. The collected wastes are disposed of crudely at "dumpsites" where there are no safe means of handling leachate. Dumpsites like Njiro in Arusha, Duga in Tanga, Vingunguti in Dar es Salaam are posing serious groundwater pollution (Mato, 1999; Baya *et al.*, 1996). It is worth noting that, no any urban centre in Tanzania has a safe solid waste disposal facility. Even the implementation of the Urban Sector Rehabilitation Programme (USRP, a World Bank funded project), did not result in the construction of an environmentally sound solid waste disposal facilities.

Table 2-7: Typical industries found in Dar es Salaam City (Haskoning and M-Konsult, 1989)

Industry Sector	Company
A. Food and Beverage	Tanzania Breweries; KIOO ltd; Tangold Products
B. Cotton Industry	Friendship textile units; Tanganyika Dyeing and Weaving Mill; Sunguratex
C. Metal Industry	ALAF Steelcast; Asbesco; Matsushita Electric Co.; Metal Products (ALAF)
D. Paper and Wood Ind.	KIBO Paper; Arusha Timber Plant
E. Shoe & Leather Ind.	Bora Shoes Company
F. Plastic Industry	Tanganyika Tegry Plastics Ltd.; Tanganyika Plastics Ind. Ltd.; Simba Plastics; Polysacks
G. Pesticide Industry	Moechst Ltd.; Twiga Chemicals; Henkel Chemicals
H. Pharmaceutical Industry.	Keko Pharmaceuticals; Mansoor Daya Chemicals; Shelys chemicals; Banco Products; Mount Carmel Rubber Ind.; Berger Paints; Robbialac

Other sources of groundwater pollution arise from agriculture, both urban and rural. The former is a growing activity in all urban areas in Tanzania, being practised by about 60% of the households. The rural farming, which occurs at the outskirts of urban centres, can have influence on urban groundwater quality. This is more apparent if the two are hydrogeologically linked, which at most is the case. However, rural agriculture in Tanzania is still peasantry (small –scale). The threat may due to inadequate use of agro-chemicals, which can result into undesirable amounts of chemicals being washed into the surface waters or the soil. Due to non-existent of groundwater quality data in almost all, urban centres in Tanzania, it is difficult to know the trends of the problems. Examples of two important urban centres are given in the coming section.

2.8 Examples of Dar es Salaam and Arusha Urban Centres

Assessment of the aquifer conditions under the urban centres of Arusha and Dar es Salaam were made by analysing available groundwater data. Table 2-8 presents a summary of results of the investigation done in Dar es Salaam City from the year 1999 to 20001. High nitrate levels and bacterial contamination were observed in boreholes located in high residential areas like Buguruni, Manzese and Mabibo. Extreme cases of nitrate concentration of up to 200 mg/l were measured in Buguruni area. The details of the groundwater quality variations are contained in Chapter 4.

Table 2-8: Range of percentage compliance to National Drinking Water Standards for groundwater samples collected from deep boreholes in Dar es Salaam, 1999-2001

Parameter	Range of percentage compliance
Nitrate	66-100
Chloride	83-100
Faecal coliform (bacterial contamination)	14-58

Table 2-9: Quality of outgoing water from Sekei central station, Arusha municipality (1994 – 2001)

Parameter	Unit	Range	Tanzania standard
pH	-	7.2 – 7.96	6.5-9.2
Turbidity (NTU)	NTU	0 – 2.0	30
Calcium (Ca^{2+})	mg/l	4.0 – 9	-
Magnesium (Mg^{2+})	mg/l	0.9 – 4.8	-
Nitrate (NO_3^-)	mg/l	6.0 – 17.6	100
Fluoride (F^-)	mg/l	3.2 – 4.9	8.0
Iron (Fe^{2+})	mg/l	0 – 0.05	3.0
Manganese (Mn^{2+})	mg/l	0 – 0.1	-
Residual chlorine	mg/l	0.2 – 1.2	-

Source of raw data: Arusha Urban Water and Sewerage Authority, 2001

In Arusha municipality there are about 15 deep boreholes (63 – 189 m) and springs located at the foot of Mt. Meru with a yield of 19.7 – 111.4 m^3/h. Groundwater abstracted from the boreholes are collected at the Sekei central station before being fed into the distribution system. Normally only chlorination is done at this station. The quality of the outgoing water is displayed in Table 2-9 from the year 1994 to 2001. The results show high concentration of fluoride, though within the Tanzanian standard. Fluoride is derived from the geological formation within the municipality. The nitrate data still indicate clean water. However, there were no data of bacterial quality of the raw water. The current rapid urbanization of the Arusha municipality and farming on the slopes of Mt. Meru may have profound effect on the quality of groundwater in few years to come, should appropriate measures be taken.

2.9 Conclusion

Groundwater pollution in urban areas is a worldwide growing environmental problem. In Tanzania, many major urban centers depend on groundwater for domestic supplies. The rapid urbanization experienced in the country can have a profound effect to the groundwater resources, both quantitatively and qualitatively. Already in some towns like Dar es Salaam City and Arusha the water quality of the aquifers have started to deteriorate. The main sources of groundwater pollution are indiscriminate disposal of domestic and industrial wastes, which are principal components of urbanization process. The existing challenge is to protect groundwater resources amidst rapid urbanizing human settlements, of which failure can lead to escalating costs for provision of drinking water in cities. The overall result can be decreased public health conditions. As it is technologically difficulty and economically expensive to treat a contaminated aquifer, groundwater protection measures must be sought before hand. Specific recommendations for Tanzanian case are detailed in Chapter 8.

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Chapter 3

DAR ES SALAAM CITY: GROUNDWATER POLLUTION SOURCES

Abstract

The natural processes of filtration, sorption and chemical and microbiological reactions normally purify the water as it percolates through the soil mass to reach the water table. The different human activities on land contaminate the water infiltrating into the soil mass, thus affecting the quality of groundwater in the aquifers. An investigation was conducted to identify the major potential sources of groundwater pollution in Dar es Salaam City, the largest urban centre in Tanzania. Domestic sewage, industrial effluents, solid waste dumpsites and petroleum products dispensing units were found as main pollution sources. The on-site sanitation systems, which are being used by about 90% of the city inhabitants, have become a diffuse source of organic and microbiological pollution of the unconfined aquifer. About 60 tonnes/day of chemical oxygen demand (COD) are transported to the groundwater through domestic sewage. Industrial effluents are partially treated or disposed of on land, in pits at production premises or to nearby watercourses. More than 2 tonnes/day of COD reach the groundwater from industrial establishments, including effluents containing hazardous components. Solid waste is crudely disposed of at Vingunguti dumpsite, a disused sand quarry. The practice severely affects the quality of groundwater, in that it injects organics and toxic substances in it. Taking into account that the water is being used within the nearby low-income neighbourhood, this practice can be considered as a health hazard. Crude disposal of solid waste in Dar es Salaam can potentially transfer about 230 and 85 tonnes/day of COD and NH_3-N respectively. The filling stations dispensing petroleum products in the city are potentially threatening the aquifers, due to the toxic nature of some of the hydrocarbons. The number of filling stations has doubled during the past five years. It was observed that more than 25% of the stations might be having leaking tanks. Generally, awareness on the environmental hazards the petroleum products have on groundwater is low with the attendants at filling stations. The inadequate disposal of waste oils also contributes to the pollution of groundwater in Dar es Salaam. More than one million litres of waste oils are generated per year in Dar es Salaam, and only about 6% is reused. The emerging urban agriculture has brought a rural-type pollution in the city, that is, pesticide pollution threats. This chapter describes the identification and

quantification of the pollutants reaching the groundwater in Dar es Salaam City.

3.1 Introduction

The subsurface environment is a complex system subject to contamination from many sources. Waste disposal and inappropriate handling of chemicals often affect groundwater quality. Water-soluble wastes and other materials, which are dumped, spilled, or stored on the surface of land or in burial pits and lagoons can be dissolved by precipitation, irrigation waters, or liquid wastes and eventually move through the soil in the unsaturated zone to pollute the groundwater. Additionally, the waste fluids disposed of in injection wells (which are mainly used in developed countries) can eventually migrate into drinking water aquifers. Groundwater can also be contaminated by agricultural activities, such as pesticides and fertilizers application on land. Excess irrigation water or annual precipitation can dissolve the applied chemicals or their degradation products and leach them into underlying groundwater. The potential for agricultural chemicals to contaminate groundwater depends on the individual properties of the chemicals, the quantities applied, and manner of application. Groundwater can also be contaminated by natural sources. As the water migrates through subsurface strata, it can dissolve heavy metals, selenium, fluorides, arsenics, radionuclides, etc from subsurface minerals.

The potential for natural and artificial chemicals to contaminate groundwater is dependent on many factors, including the following:

- Chemical and physical characteristics of the soil
- Rainfall and percolation rates
- Distance from sources of pollution
- Water solubility of the chemical
- Volatility of the chemical
- Mobility of the chemical in soil
- Resistance of the chemical to degradation
- Nature of any degradation products
- Nature of physical encapsulation of the chemical
- Amount of chemical

Because the groundwater generally moves slowly, there is little mixing and dilution of contaminants. A contaminant in a plume of groundwater may remain highly concentrated for decades as it moves from the recharge to the discharge area or to wells in its path. Some of the chemicals, which are being detected in groundwater, now may be a result of contamination, which occurred decades ago (sometimes even before existence of controls and regulations) (Kiely, 1997). Thefore, in absence of groundwater monitoring systems, the contamination of an aquifer can go on undetected over long periods of time thus exposing consumers to great health risks.

Groundwater contamination is typically categorized as either point or non-point source contamination. Point source contamination is generally localized and is caused by recognised defined sources such as industries, underground gasoline tanks, on-site sanitation systems, exploding and leaking transformers, solid waste disposal sites etc. These normally cause numerous localized groundwater contaminations. Non-point discharges have no easily identified points of discharge; examples of these are storm run-off from heavily populated areas, surface and subsurface agricultural drainage from irrigated areas, percolation of pesticides applied in irrigated areas and numerous on-site sanitations. The non-point can cause contamination, which can affect the whole groundwater basin.

The natural processes of filtration, sorption, chemical and microbiological reactions, purify the water as it percolates through the soil mass to the water table. The level of treatment depends on many factors including geochemistry and geomorphology of the area, type and depth of the soil layer and the vadoze zone and the rate and the quality of water infiltrating to the water table. The quality of infiltrating water to a larger extent is influenced by human activities on land. These activities at times result into pollutants, which cannot be assimilated by the natural processes in the soil mass, thereby degrading the quality of groundwater. In this regard, the different human activities are regarded as pollution sources.

The urban centres have become major sources of diffuse pollution of groundwater, due to heterogeneous nature of human activities being carried on (Morris *et al.*, 1994). Of more concern to-date is the groundwater pollution from organic compounds (organic micro-pollutants) such as petroleum products, chlorinated hydrocarbons and other synthetic compounds (British Geological Survey 1996; Oliveira *et al* 1991; Vujasinovic, 1991) due to recalcitrant nature of some of these substances. Because groundwater quality monitoring is rare or out of existence due to high costs which are normally involved, contamination of ground water from such chemicals might have going on for many years without being noticed. Therefore, identification, quantification and predictions of concentration trends of substances in potable groundwater are activities of paramount importance in order to safeguard the public health. The clue to the expected substances in groundwater is normally given by the potential pollution sources. Thus, the identification of sources of pollution presents an essential stage in developing appropriate groundwater quality management and protection programmes.

Many activities in Dar es Salaam City contribute to pollution of groundwater resource; of major concern are municipal sewage, solid wastes and industrial effluent disposal practices. The point sources include the on-site sanitation facilities (septic tanks and pit latrines), infiltration from wastestabilization ponds, solid waste dumpsites, underground fuel storage facilities (such as petrol filling stations), industrial establishments (small and large scale) and other commercial points. The large areal distribution of on-site sanitation in the city of Dar es Salaam makes them be considered as diffuse sources of groundwater pollution. Emerging urban activities like urban agriculture (vegetable growing and chicken/pigs husbandry) also constitute to diffuse sources of pollution. This chapter introduces the Dar es Salaam City setting and existing potential sources of groundwater pollution and tries to make estimation of pollutants loads.

3.2 Dar es Salaam City

3.2.1 Location, History, Administration

The city of Dar es Salaam is located between 6°S and 7°S and has an area of about 135 km^2. The history of the city dates back to the year 1862, when it was established as a port and a trading centre to support caravan routes being opened up into the interior of the African continent by early traders. It assumed the national capital status of the then Tanganyika in 1891. Thereafter, it became a municipality in 1949 and then rose to a city status in 1961, the year when Tanganyika became an independent state. The city falls under administrative jurisdiction that divides it into three municipalities: Ilala, Temeke and Kinondoni (Figure 3-1).

3.2.2 Climate Population, and urban growth

The city of Dar es Salaam experiences a tropical coastal climate, with mean daily temperatures varying between 17 °C and 32 °C and average humidity of 67%-96%. The annual rainfall averages between 1000 mm to 14000 mm, with the wettest period being March-May. The evaporation rate is over 2104 mm per annum.

The population of the city is estimated to exceed 3 million (the largest urban population in Tanzania). This population is about 30% of the urban population in Tanzania. The growth rate is estimated at 7.2% per annum (Baruti et al., 1992). The population forecast depicted in Figure 3-2 indicates that before the year 2020, Dar es Salaam will turn to a megacity.

The city's physical growth is guided by master plans, which were prepared in 1948, 1968 and 1979. However, there is less compliance and as such a great discrepancy between master plan and actual urban growth and development can be observed (Halla, 1994). One of the outstanding features of the non-compliance is the emergence of unplanned residential areas or "squatter areas". There are more than 40 unplanned residential areas in Dar es Salaam, accommodating about 70% of the city population (Baruti et al., 1992; National Environmental Management Council, 1995; Maira, 2000). There are more than 170,000 housing units in unplanned areas compared with 50,000 in the planned areas (Baruti et al., 1992). The "squatter areas" are characterised with absent or inadequate infrastructure services. Other important land-uses in Dar es Salaam include industrial enterprises, concentrated in Chang'ombe, Nyerere Road, and Ubungo areas.

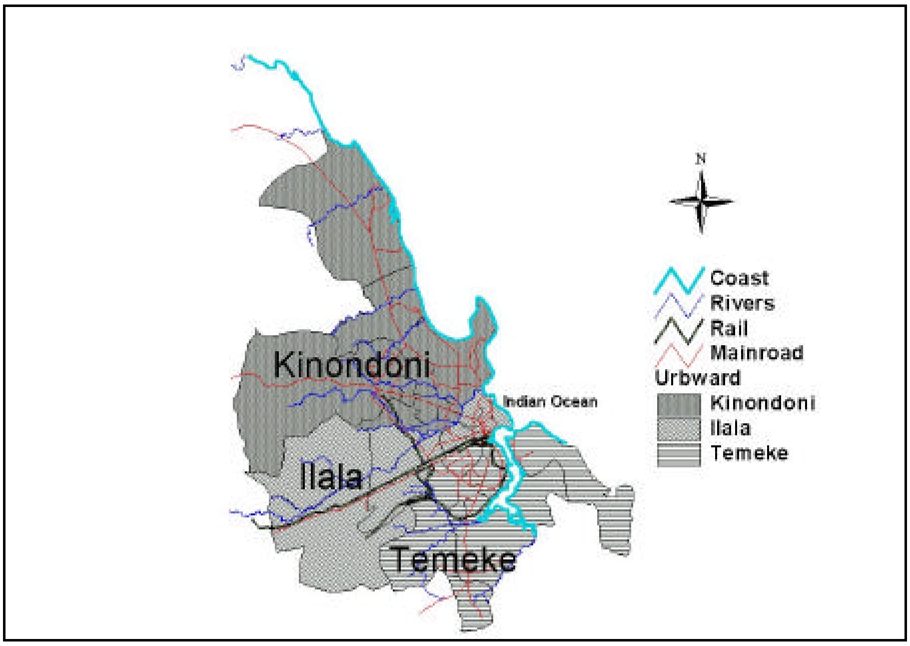

Figure 3.1: Dar es Salaam City- Administrative Map

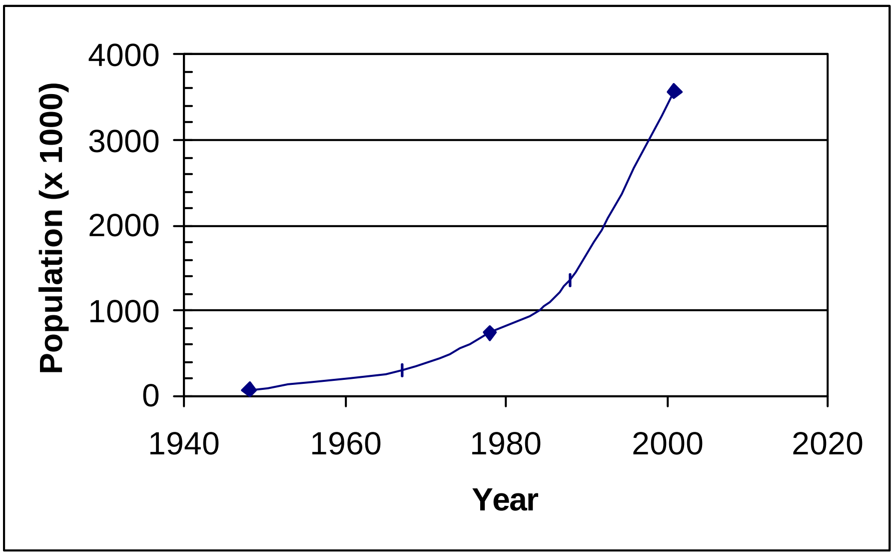

Figure 3-2: Population Trend in Dar es Salaam City

3.3 Sources of Pollution

3.3.1 Domestic liquid wastes

The safe disposal of both solid and liquid wastes is among the hot issues of many urban authorities in the world today. The magnitude of the problem increases with the population growth as well as expansion of the urban boundaries. In Tanzania over 90% of the population use on-site sewage disposal systems (pit latrines and septic tank systems) (Mato, 1999; Mgana, 1996). Less than 10% of the population are connected to sewerage system. Urban authorities with sewerage systems include Dar es Salaam, Tanga, Morogoro, Dodoma, Arusha, Mwanza, Mbeya, Tabora and Moshi. Only about 10-12% of the urban population have access to the sewerage system.

In Dar es Salaam City, domestic sewage is collected by a sewerage system that was first constructed in the 1950's. The system serves only about 12% of the residents (Baruti *et al*., 1992) and the areas covered include City centre, Kariakoo, Msasani, Mwenge, and Ubungo. The collected sewage is treated in waste stabilization ponds (WSP) before being discharged into inland rivers (except the sewer segment draining, the city centre discharges the sewage to the sea via a screen chamber and sea out-fall near Kivukoni front). There are eight WSPs out of which only three are in good physical and working condition (Kayombo, *et al*., 1998, 2000). Some of the ponds have broken embankments (Mabibo); others are totally with covered with vegetation. The ponds are used to destroy pathogenic bacteria and the ova of intestinal parasites as well as reducing dissolved biodegradable organic matter in the domestic wastes. The hot climate of Dar es Salaam provides a favourable environment for high efficiency of the ponds. Some ponds like Mabibo, Vingunguti and Msasani also receive industrial wastewater. The common layout of the WSP consists of an anaerobic pond, facultative pond followed by two maturation ponds in series (Figure 3-3). The anaerobic pond is mostly used to receive raw sewage from septic tanks or pit latrines brought to site by vacuum tankers. Malfunctioning of WSP means that raw sewage is discharged to the surface and groundwater resources. Defective embankments and lining will allow pollutants to infiltrate into the groundwater. Also non-working WSP means more sewage will be disposed of into the ground, as less septic tank and pit latrine sludge will be brought to the ponds.

The major part of the Dar es Salaam residents (about 88%) use on-site sanitation facilities encompassing pit latrines (79%) and septic tanks (9%) (Figure 3-4). The effluent from the septic tank system and pit latrines that is allowed to percolate into the soil represents a potential source of groundwater contamination. Pit latrines when full are emptied by vacuum tankers, Mapeti system (improvised pit-emptying arrangement) or by using “frog men” or simply abandon. Since the vacuum tankers services are limited and expensive, more than 80% of the people having pit latrines use “frog men”, whereby a new pit is dug adjacent the targeted one and a hole is made in the ground to connect the two pits. Connection allows the contents in the targeted pit to move to the new one. The process is repeated after every two to three years, when the pit latrine needs desludging. This method is common in “squatter areas” where accessibility is limited. As the squatter areas accommodate about 70% of the Dar es Salaam residents, one can imagine the point sources of pollution to the groundwater resource. Therefore, the on-site sanitation systems in Dar es Salaam are now considered as diffuse sources of groundwater pollution.

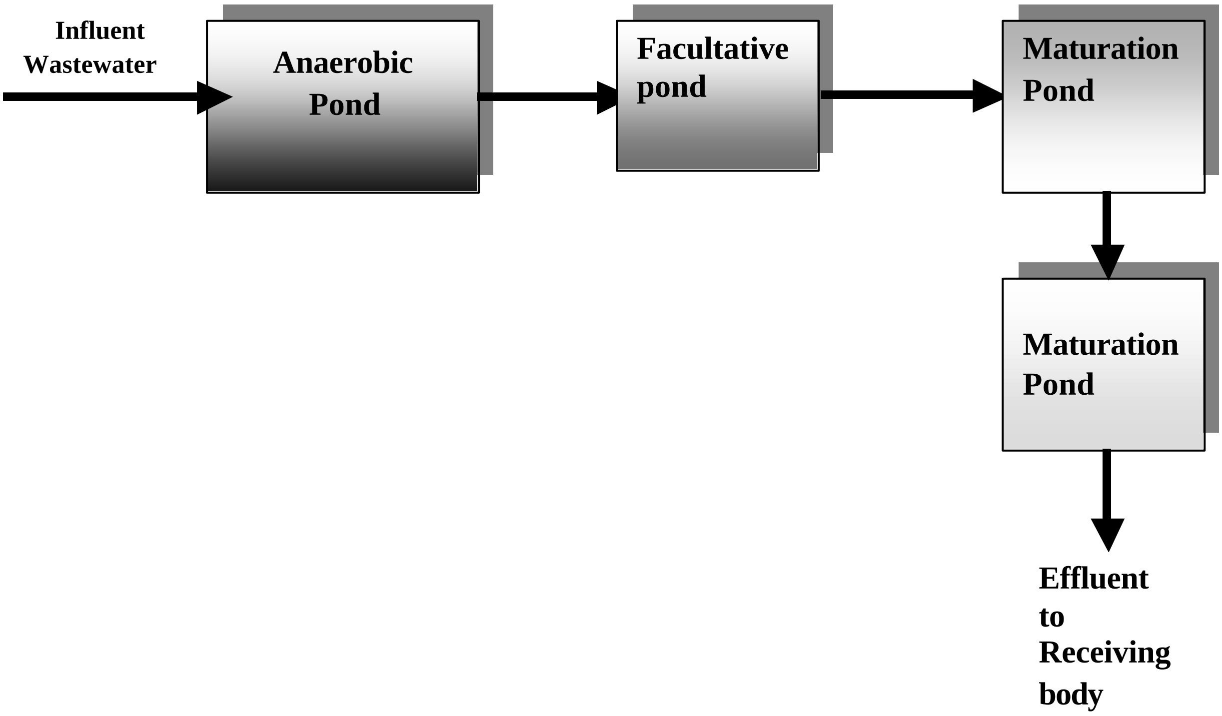

Figure 3.3: Typical wastewater treatment layout with wastestabilization pond

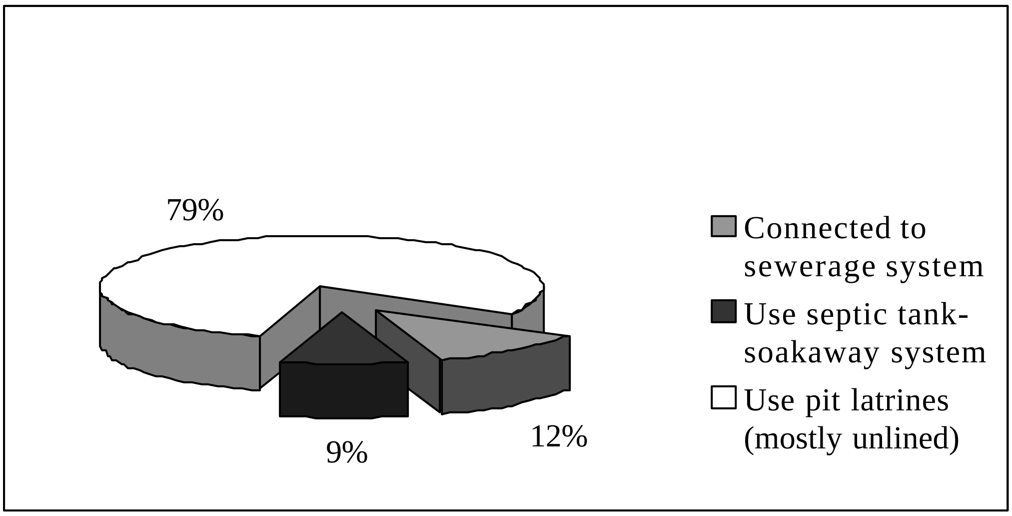

Figure 3-4: Percentage usage of sanitation systems in Dar es Salaam City

Table 3-1: Characteristics of effluent from septic tanks (Canter and Knox, 1985)

Parameter	Septic tank effluent	Concentration reaching groundwater
Suspended solids, mg/l	75	18-53
Chemical Oxygen Demand (COD), mg/l	300	57-142
5-days-Biochemical Oxygen Demand, BOD_5, mg/l	140	28-84
Ammonia-nitrogen, mg/l	40	10-18
Total phosphate	15	6-9

The characteristics of septic tank effluents and the concentrations of pollutants reaching the groundwater were estimated by Canter and Knox (1985), and are presented in Table 3-1. The figures indicate an attenuation capacity of about 40-75% in concentration of pollutants. Although septic tank systems are designed to operate without threatening groundwater resources, in many instances poor system design, improper construction and maintenance, and bad system locations have led to groundwater pollution (Canter *et al*., 1987). Excessive septic tank densities in "unplanned areas" have degraded groundwater quality with high concentrations of nitrates, bacteria and organic contaminants. In Dar es Salaam, guidelines for location and construction of the on-site disposal systems are practically not in place. In areas with a high water table (such as Sinza, Mlalakuwa, Kiwalani, Manzese, Majumbasita etc) the sewage is disposed of directly in the groundwater (i.e. below the water table line) within the pit latrine or soak-away pit of the septic tank. It is obvious that such practices lead to serious faecal and organic pollution of the unconfined aquifer, and may render the groundwater unfit for human consumption. Some researches done in Dar es Salaam have confirmed heavy faecal pollution of the unconfined aquifer (Chaggu *et al*., 1994). However, the pollution can easily reach the deep aquifers (confined) should there be fissures in the geological formation or overloading. Canter *et al*. (1987) reported that soils with high permeability could be overloaded with wastewater resulting in downward migration of organic and inorganic chemicals and microorganisms.

Haskoning and M-Konsult (1989) estimated that the amount of pollution loads emanating from different sanitation systems (Table 3-2) would reach the groundwater. The total amount crossing the water table line was estimated to be about 47,000 m^3/day (or 1.7×10^7 m^3/year) for the year 1988. Using population data, the pollution loads were extrapolated to get the expected amounts of pollutants reaching the groundwater resource (Figure 3-5). The extrapolation shows that by the year 2015, more than 60 and 20 tonnes/day of BOD_5 and total-nitrogen respectively will be reaching the aquifers (mainly unconfined). Such loading rates can have a devastating effect on groundwater quality should remedial actions not be put in place.

Table 3-2: Estimated pollution loads from different sanitation facilities reaching the groundwater resource in Dar es Salaam City, 1991. (All units in kg/day) (Haskoning and M-Konsult, 1989)

Parameter	Pit latrines	Septic tanks	Sewers-domestic	Industrial effluents	Without facility	Total
BOD_5	15,282	7,641	1,221	1,899	1,100	27,143
COD	16,131	8,068	1,289	1,994	1,161	28,643
Suspended solids	6,116	3,832	2,035	3,148	1,833	16,964
Dissolved solids	97,857	61,128	3,618	5,596	3,258	171,457
Total-N	4,829	3,018	179	276	120	8,422
Total-P	915	572	34	52	23	1,596

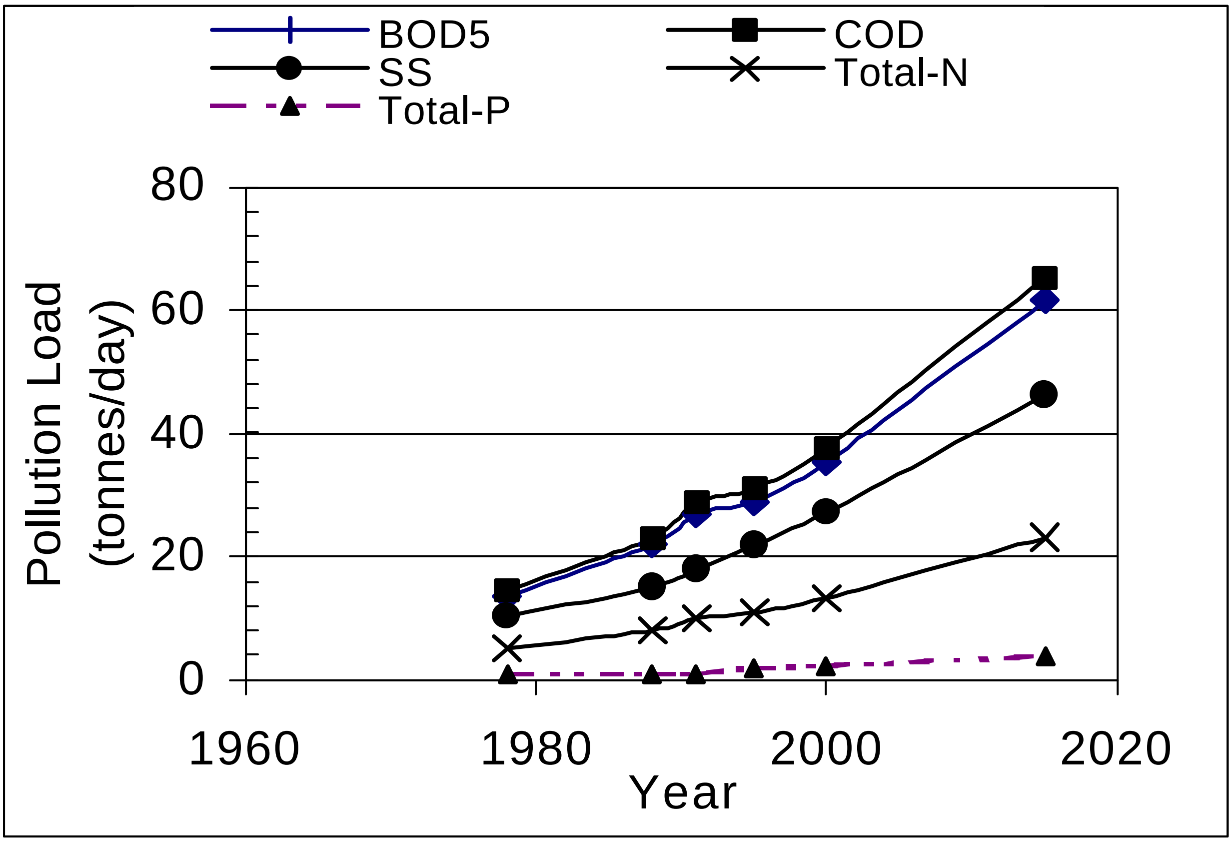

Figure 3-5: Estimates of pollution loads from domestic wastewater reaching groundwater in the Dar es Salaam City

3.3.2 Industrial point source discharges

There is a sizeable number of different natural and synthetic organic chemicals used in chemical and petrochemical industries, in the manufacture of pesticides, plastics, pharmaceuticals, cosmetics and other products that we use in everyday life. However, many of these compounds are highly toxic in such a way that exposure to very low concentrations (like pico levels) can lead to serious disorders like birth defects, genetic problems and cancer (Houzim *et al*, 1986; Blackman, 1993). Some of these substances are resistant to degradation (persistent) and their breakdown products do not always result in harmless or less harmful products. The pollution of groundwater by such chemicals can result in a serious public health threat, partly because the available aquifer cleaning technologies are complex and expensive. Also, the analyses for such chemicals are expensive and normally require sophisticated equipment. To many developing countries (like Tanzania), the only cheap solution is to make sure that detrimental levels of these chemicals do not reach the aquifers by properly managing them (e.g. by treating the effluents before final disposal). Table 3-3 shows a list of examples of industrial chemicals reaching the environment (Henry and Heinke, 1996).

Table 3-3: Examples of toxic chemicals found in industrial effluents and solid wastes (Henry and Heinke, 1996)

Type	Example	Industrial Use or Source	Probable Destination
Metals and Inorganics	Cyanides	Electroplating baths	Water
Pesticides	Chlordane	Pesticides Manufacturing	Sediments, Biota
Polychlorinated biphenyl (PCB)	PCB arochlors	Transformer coolant	Sediment, Biota
Halogenated aliphatics	Dichloromethane	Solvent	Water
	Tetrachloromethane	Solvent and degreaser	Water
	Chloroethene (vinyl chloride)	Manufacture of plastics	Water
Ethers	2-chloroethyl (vinyl ether)	Pharmaceutical wastes	Water, Sediment
Monocyclic aromatics	Ethylene benzene	Solvent	Sediment
	Toluene	Solvent	Sediment
Phenols and cresols	Phenol	Refinery waste	Water
	Pentachlorophenol	Wood preservation	Sediment, Biota
Phthalate esters	Dimethylphthalate	Cellulose acetate Manufacture	Sediment, Biota
Polyacrylic aromatics	Naphthalene	Manufacture of dyes and synthetics	Sediments, Biota
	Phenanthrene	In coal tar	Sediment, Biota
Nitrosamines	Acrylonitrile	Manufacture of plastics	Water, Sediments

Historically, the industrial development in Tanzania spans over three major parts, namely: pre-colonial, colonial and post-independence (Sheya and Mnyamusika, 1996). During the pre-colonial era only simple iron tools were used as industrial inputs to the traditional economy and there is no record of significant environmental abuse. The modern industrial development began during the colonial era when rudimentary industrial set up based on a number of medium and large-scale industries started (Sheya and Mnyamusika, 1996). These industries processed a limited range of consumer goods based on cash crops such as sisal, coffee, cotton, tea, wax and meat. Many of the industries were established after independence in which the government embarked on the policy of import substitution. Industries like fertilizer and cement production, crude oil refinery, textile mills, tanneries and many others were started. This industrial development took place without adequate environmental attention; as a result many of them came into operation without waste treatment plants. Similarly, industries had no environmentally sound plans of disposing of heterogeneous effluents and solid wastes, which were produced from the processes. Despite the large-scale industries, many small scale and informal sector processing units started after independence and have been growing since then.

Late in the 1990s, the Government of the United Republic of Tanzania decided to privatise the state owned industries and other companies. The industries were transferred to private hands in similar conditions in regard to waste management. Though the industries have not adequately controlled the effluents, the government (through the National Environment Management Council, NEMC) has been increasingly able to summon or finger point extreme pollution cases. However, information on waste handling and disposal from industries is still inadequate or non-existence. Generally, environmental management is still least considered as key issue to industries. Studies on the impact of industrial effluents (especially to water resources) have also been limited, partly due to lack of financial and technical resources.

About 80% of industries in Tanzania are located in urban areas and over 50% of these are found in large towns, especially Dar es Salaam (Mato and Kaseva, 1999). The major industrial areas in Dar es Salaam are Ubungo, Nyerere Road (the then Pugu Road), Mikocheni, and Chang'ombe. In addition, there are numerous small-scale factories scattered in the whole city, the main one being Gerezani area on the periphery of the Central Business District (CBD). Only few industries in Ubungo and Nyerere Road industrial areas are connected to the municipal sewerage system. The remaining industries mainly dispose of untreated sewage directly to surface watercourses or underground by means of soakaway pits. Although, there are specific laws on the control of pollution, their enforcement has been inadequate. Therefore, industries have been disposing of untreated effluents to land or surface watercourses for more than 35 years. The major threat is from chemical industries, which may be discharging wastewater containing high levels of persistent substances.

3.3.3 Petroleum hydrocarbons storage and transportation facilities

Both urbanization and industrialization processes are characterized by increased consumption of petroleum hydrocarbons and related compounds for energy requirements or as industrial solvents. The chemical components of petroleum and derived products are hydrocarbons, including n-alkanes, cycloalkanes and aromatic compounds. Of special environmental significance are the aromatics (e.g. benzene, toluene and polycyclic aromatic hydrocarbons (PAHs)), which form about 20% w/w, some of which are carcinogenic in nature (Connel, 1997). Mineral oils have become potential groundwater contaminants of modern civilization because of the increasing use of fossil fuels as mentioned above. Wherever mineral oil is produced, stored, transported by vehicle or pipeline or consumed there exists a potential source of oil pollution through direct seepage into the ground. Similarly, disposal of used oils is currently presenting potential pollution sources to water resources (Alloway, 1996). Other potential pathways include leakage from underground storage tanks (like filling stations) and accidental spillages (during use or transportation). Although spillage incidents may involve a small amount of oil, one should know that a litre of oil is sufficient to pollute one billion litres of clean water (Kiely, 1997).

Underground storage tanks may leak due to several reasons, the main ones being corrosion and poor operating practices (Canter *et al*., 1987). More than 300,000 releases were confirmed leaking in USA (USEPA, 1996; Kramer, 1982) and about 27,000 gas stations were suspected leaking in Brazil (Corseuil *et al*., 1998). Similar leakages of fuel tanks leading to groundwater pollution have also been reported in Zibo City, China and Taiwan (Kun *et al*., 1998; Doong *et al*., 1998). In United Kingdom, about 30% of the filling stations are said to be leaking (Alloway, 1996). Oil comprises the second major source of pollution incidents for the Scottish regulatory authority (Ellis and Chatfield, 2001). Onianwa (1995) reported increased incidences of hydrocarbon pollution in Nigerian urban environments.

All fossil oils consumed in Tanzania were imported, either as crude or finished products. The average oil imports in Tanzania were about 400,000 MT/year of crude oil and 550,000 MT/year of petroleum white products (Ministry of Energy and Minerals, 1996) as shown in Figure 3-6. The crude oil was processed by TIPPER refinery plant located in Kigamboni area, Dar es Salaam. Currently, all petroleum products are imported as white products. Moreover, huge amounts of oil are received at the Dar es Salaam harbour to be pumped into the Tanzania-Zambia pipeline (TAZAMA) or on transit to other landlocked countries like Rwanda and Burundi and Democratic Republic of Congo (the former Zaire) as well.

Some studies have been done on the issue of oil pollution in the Dar es Salaam City. Ndensamburo (1986) reported pollution of coastal waters from the wastewater generated by the TIPPER refinery plant. Nshunju (1993) reported pollution of Keko stream from wastewater emanating from the oil depots. Oil spillage by defective marine vessels, rail and road transportation, leakages from poorly maintained petroleum products storage tanks, oil spillages due to ineffective loading and unloading facilities were reported (Yhdego and Mato, 1996). Huge oil spillage occurred in 1997, when a TAZAMA bulk oil storage tank burst and released a lot of hydrocarbons onto the soil that was never recovered (which ultimately will reach the aquifers). Vindi (2000) and Jaka (2001) reported poor management of waste oils in the city of Dar es Salaam.

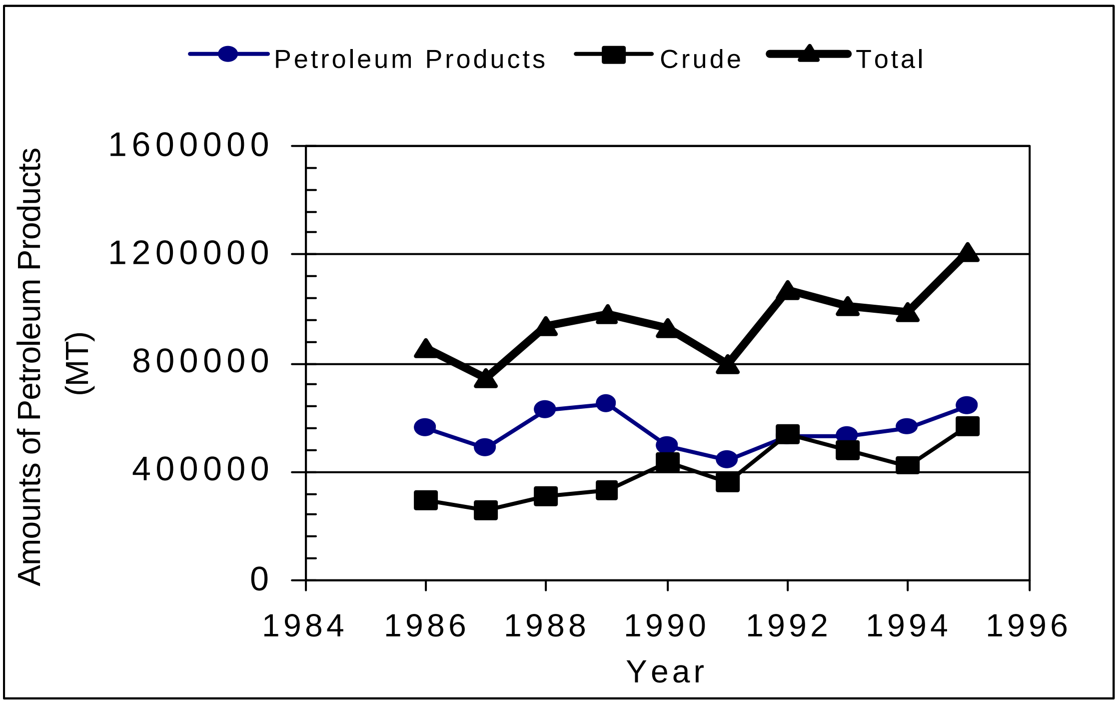

Figure 3-6: Importation of petroleum products in Tanzania (1986-95)

During this research, an investigation to identify the potential of groundwater pollution from hydrocarbons was conducted in the city of Dar es Salaam for the period 1998-2000. The investigation involved physical inspection of the facilities (mainly fuel filling stations, garages and depots) and questionnaires (to operators and/or owners). A total of 31 facilities were surveyed. It was found that oil pollution mainly resulted from petroleum products sales business, inappropriate disposal of used lube oils and poor loading and off loading procedures at depots. There are more than seven oil-marketing companies, all of them having bulk storage facilities (depots) and filling stations in the city.

The investigation showed that about 64% of more than 330-registered fuel filling stations in Tanzania are located in the Dar es Salaam City (Figure 3-7). There are also hundreds/thousands of oil trucks, which transport mineral oil inside and outside Tanzania (particularly Burundi, Rwanda, Congo and Zambia). Cleaning of tanks or tankers usually result in large amounts of wastewater, which are normally disposed of on land or streams. In addition, there are numerous vehicle garages in the city.

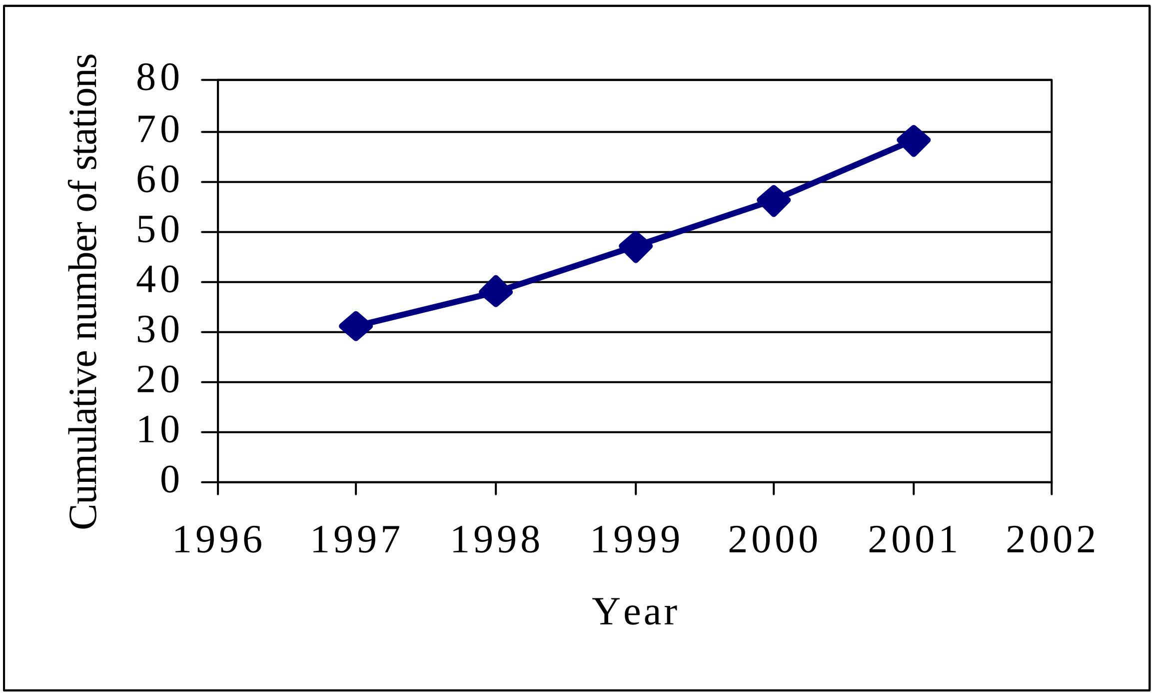

Figure 3-7: Trend of fuel filling stations installations in Dar es Salaam city (1997-2001)

The waste oils from vehicle maintenance are discharged on site (normally in ditches or other improvised facilities). Although it may be argued that the quantity of waste oil emission per garage is low, their combined discharge can be considerable .The quantity estimates of waste oil production are shown in Figure 3-8. The Ubungo thermal power plant in Dar es Salaam is another potential source of mineral oil pollution.

The following specific observations were made:

- All surveyed garages were characterized with oil spills on their working environment
- Diesel/petrol fuels were carelessly handled; for instance, employees use these products to wash their hands instead of water!
- 58% of the filling stations conduct vehicle services at their locations.
- 45% conduct their business without knowing their environmental-related obligations. 49% replied that their obligation is to plant trees around business locations. And 6% stated that the obligation is to maintain general cleanliness around the filling station and to stop oil spillage.
- 45% admitted to observe losses of fuel that are suspected to be caused by underground seepage through cracks in tank structures.
- More than 26% of the filling stations are more than 20 years old.
- 89% dispose of used oil in iron drums, 5% dispose of in open drainage channels and 6% dispose of in open drains through constructed oil separator tanks.

Individuals or builders collect a small amount of the spent oil for preserving timber.

- No filling station conducts groundwater pollution monitoring.
- The garages dispose of the waste oils in ditches or other improvised facilities

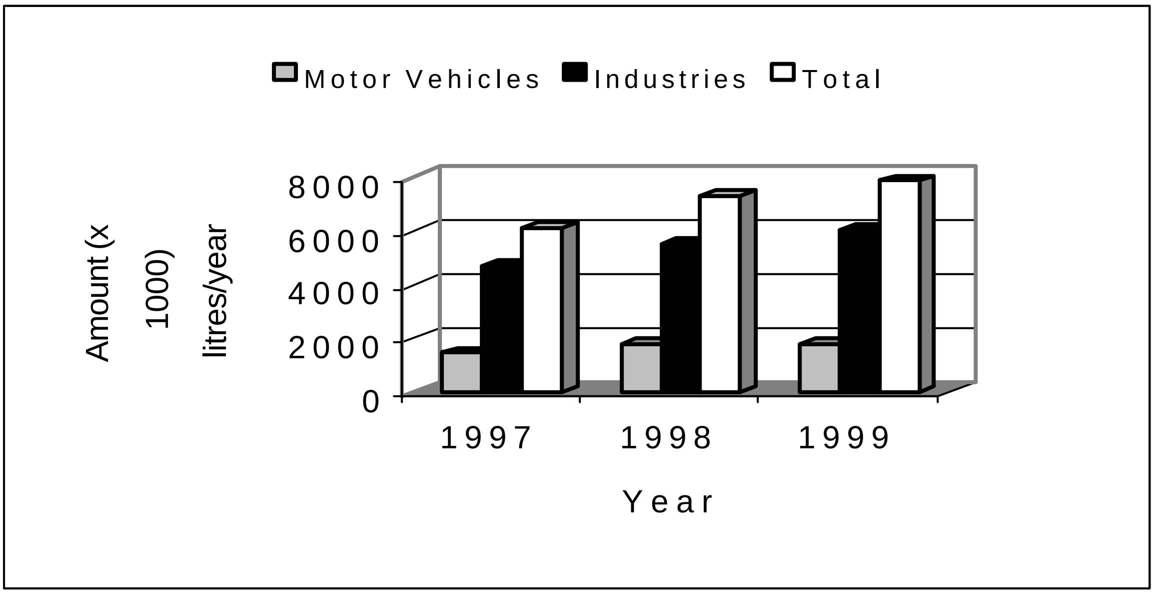

Figure 3-8: Estimates of waste oils generation in Dar es Salaam City

A few industries visited, showed that waste oils are disposed of crudely in conjunction with other effluents and some industries recover the oils and use them for heating. The rampant uses of old vehicles (normally second or third hand), some of which are characterised by incomplete fuel combustion; obviously do also contribute to the PAHs concentration in the urban atmosphere, surface waters and groundwater (the analysis for these substances are explained in Chapter 7). The total amount of waste oils production in Dar es Salaam has steadily been growing for the past five years as indicated in Figure 3-8. The figures indicate an increase of over 1000 m^3 waste oils per year, about 75% of which is contributed by the industries.

3.3.4 Solid wastes disposal

The leachate, which is the water percolating through a mass of solid waste placed (or dumped) on/under the ground, is the major threat to groundwater quality. This water normally contains high levels of dissolved substances that can irreparably degrade an aquifer if not controlled. Table 3-4 gives typical values of common pollutants in leachate. Sanitary landfill is the common technically acceptable means for municipal solid waste disposal being used by many countries.

Table 3-4:Typical leachate composition (World Bank (1986)

Parameter	Fresh wastes	Aged wastes	Domestic sewage
pH	6.2	7.5	7.5
COD (mg/l)	24,000	700	700
BOD_5 (mg/l)	13,600	70	400
TOC (mg/l)	8,000	400	240
Volatile fatty acid (mg/l)	6,000	<5	<40
Ammonia-N (mg/l)	600	260	46
Orthophosphate (mg/l)	0.7	0.5	14
Chloride (mg/l)	1,300	1,400	120
Sodium (mg/l)	960	880	100
Magnesium (mg/l)	250	130	4.5
Potassium (mg/l)	780	340	20
Calcium (mg/l)	1,820	200	110
Chromium (mg/l)	0.56	0.07	0.005
Manganese (mg/l)	26.5	1.7	0.07
Iron (mg/l)	540	10	0.03
Zinc (mg/l)	21.5	0.2	0.16

This practice involves spreading waste in thin layers, compacting its volume, and providing a daily cover to protect the environment. The waste is disposed of onto an engineered pit, with well-compacted bottom to deter leachate migration to the groundwater. The produced leachate is collected and treated before its final disposal. However, in Tanzania sanitary landfilling is advocated but the practice remains crude dumping of solid waste into the ground (Mato, 1999).

The uncollected waste (about 80%) is normally burnt or buried on-site or disposed of at unspecified locations and therefore forming another source of diffuse pollution. About 50% of the uncollected domestic solid waste (680 tonnes/day) is normally buried on-site (i.e. points of generation). Since most of the domestic solid waste is from the kitchen (see Table 3-5), they putrefy in the soil and contribute to organic pollution of the groundwater.

Table 3-5: Percentage solid waste composition forecast for Dar es Salaam City (Kaseva and Gupta, 1996)

Waste component	Percent by weight	Amount (tonnes/day)
Food/vegetable	59.8	1196
Papers	8.7	174
Metals	2.8	56
Plastics	1.9	38
Glass	0.4	8
Textiles	0.9	18
Others	25.5	510
Total	100	2000

Kiunsi (1993) and Mato and Kaseva (1999) reported that more than 122 industrial establishments in Dar es Salaam produce about 127 tonnes/day hazardous wastes, which is about 40% of the total industrial solid waste production in Dar es Salaam. The per capita hazardous waste production is estimated at 3.8 kg/year, which is about 60% of that of Japan, 17% of Denmark and 3.8% of the Netherlands (Mato and Kaseva, 1999). Most industries have no waste holding facilities other than open ground, which may result into pollution of both surface water and the groundwater resource. The collected solid waste is disposed of at the Vingunguti crude-dumping site. Mgana and Rwegasira (1993), performed a rapid baseline environmental study on the dumpsite before it was declared an official solid waste disposal facility and reported, that with the exception of relatively high levels of iron, copper and chromium the quality groundwater was good (see Table 3-6). Longdare (2000) made investigation of the groundwater quality around the Vingunguti dumpsite after operating for about seven years. The results of Longdare's investigation are shown in Table 3-7. His results indicate increased pollution in the groundwater, definitely due to the presence of the dumpsite.

Table 3-6: Groundwater quality around Vingunguti dumpsite, Dar es Salaam. (Mgana and Rwegasira, 1993)

Parameter	BH 1	BH 22	BH 17	DW 9
pH	6.24	6.42	6.26	6.87
Temperature (^{o}C)	30.5	30.2	30.6	29.8
E. Conduct. (ì S/cm)	1349	402	1239	483
Salinity (mg/l as $CaCO_3$)	0.67	0.21	0.61	0.22
Dissolved oxygen (mg/l)	2.2	5.5	2.9	5.5
Total hardness (mg/l as $CaCO_3$)	189	98	139	132
Chlorides (mg/l)	199	50	274	32
Nitrate (mg/l)	9.89	7.9	2.14	8.6
Sulphates (mg/l)	132.6	6.6	47.8	18.7
COD (mg/l)	50	90	130	160

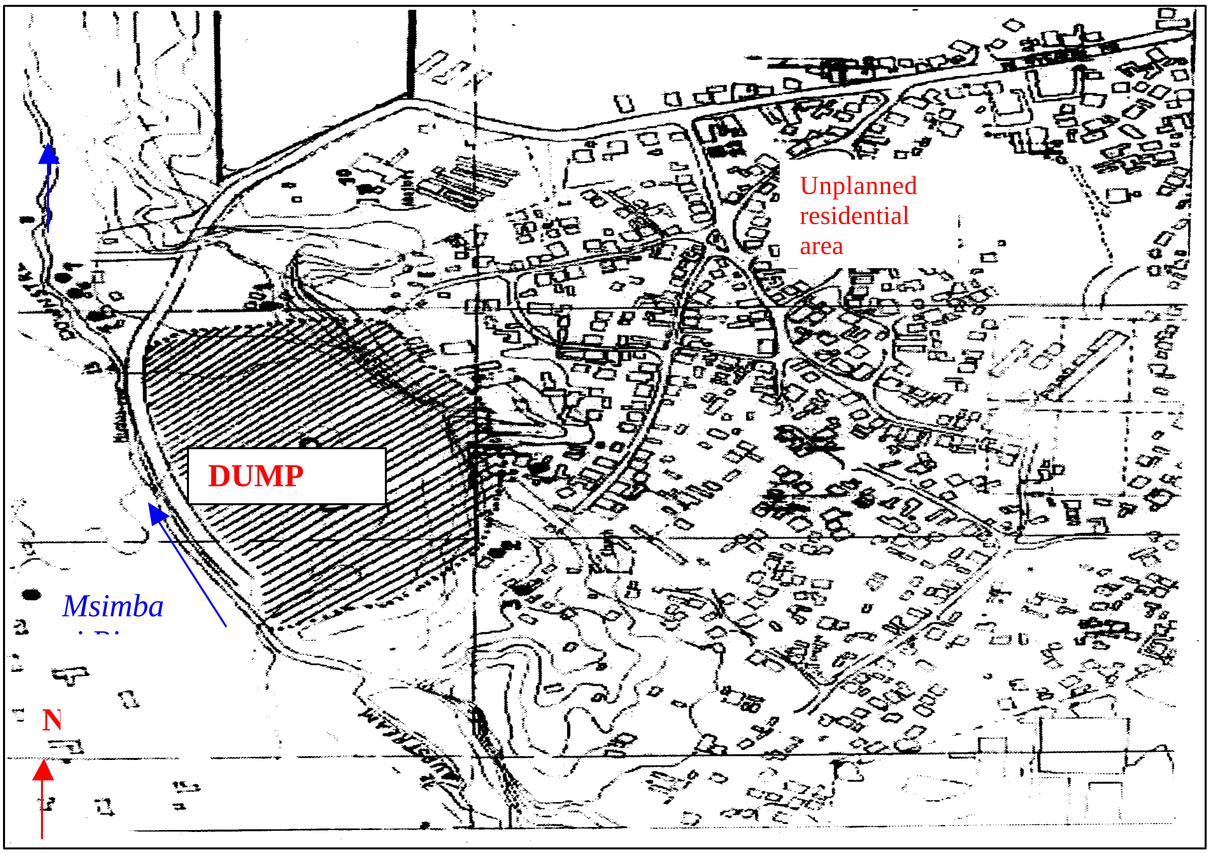

Figure 3-9: Vingunguti solid waste dumpsite in Dar es Salaam City

Table 3-7: Groundwater quality around Vingunguti area, Dar es Salaam (Longdare, 2000)

Location	Parameter (mg/l)			
	COD	SO_4^{2-}	NO_3^--N	NH_3-N
Boreholes	0-41	45.5-96.0	11.7-16.5	0.3-0.9
Dug wells	0-358	23.7-84.5	>25	0.7-1.5
Msimbazi stream (upstream)	73-106	62.9-70.4	11.5-12.9	0.7-0.8
Msimbazi stream (down stream)	249-344	92.5-152.4	14.7-19.2	1.1-1.3
Tanzania standard	6	600	25	0.5

3.3.5 Estimation of pollution loads to groundwater

The amount of pollution reaching the groundwater from solid waste disposed of above or underneath the ground depends on the volumes of leachate emanating from it. The estimation has been made for the city of Dar es Salaam basing on values given by Cooper *et al* (1996), as seen in Table 3-8. Considering the soil types of Dar es Salaam it has been assumed that 10% of the mean annual precipitation reaches the groundwater. Estimation of pollution loads to the groundwater from the dumpsites at Vingunguti, Tabata (closed), Kunduchi (proposed) and Pugu Kajiungeni (proposed) were made during this research. The results of the estimations are shown in Table 3-9. The assessment indicates that a substantial amount of pollution loads is emitted to the groundwater. More diffuse sources of leachate are from the on-site burying of solid wastes at points of generations (at homes). Estimations of leachate production from a family size of six people in both unplanned (squatter) and planned areas were made assuming waste production of 1.17 kg/cap.day and 0.33 kg/cap.day respectively (JICA, 1997) and waste bulk density of 400 kg/m^3 (see Table 3-10). It has been assumed that each household needs a total area of at least 1.5 m^2 for burying the solid waste (assuming that the maximum depth of the pit will be 1.0 m). Equations 1 and 2 have been used to calculate leachate volume and pollutant loading respectively.

$$V = i * P \text{ ……………} \textit{Equation 1},$$

where i is the percentage infiltration (taken as 10% as per Table 3-8), P is the average annual precipitation (taken as 1200 mm/year) and V is the estimated leachate production rate through the waste mass (expressed in mm/year). The pollutant loading to groundwater in tonnes/year is given by:

$$L = 10^{-6} * V * A * C \text{ ……} \textit{Equation 2}$$

where V is leachate production rate through the waste mass (expressed in mm/year); A is the area of the waste disposal point in m^2 and C is the pollutant concentration in mg/l.

Table 3-8: Estimated amount of water infiltrated to the groundwater (Cooper, *et a.* 1996)

Amount (% Annual precipitation)	Type of soil or vadoze zone
20	Very coarse texture + excessively drained to well drained soils
15	Coarse texture + well drained to moderately drained soils
10	Medium texture + moderately drained soils
5	Semi confined or fine texture + poorly drained soils
0	Confined aquifer

Table 3-9: Estimation of pollution loads to groundwater at dumpsites in Dar es Salaam

Site	Area (ha)	Pollution loads (x100, tonnes/year)			
		COD	BOD_5	TOC	NH_3-N
Tabata	6	50.4	5.0	28.8	18.7
Vingunguti	10	84.0	8.4	48.0	31.2
Kunduchi (New MECCO)	32	268.8	26.9	153.6	99.8
Pugu Kajiungeni	50	420.0	42.0	240.0	156.0

Table 3-10: Estimation of pollution loads to groundwater at household level in Dar es Salaam City

Parameter	Pollution load (kg/year)	
	Unplanned (Squatter) area	Planned Area
COD	52.1	101.6
BOD_5	5.2	10.2
TOC	29.8	58.1
NH_3-N	19.3	37.8

3.3.6 Urban agriculture

Urban agriculture, which include horticulture, fruit and vegetable growing, livestock keeping etc., is one of the fast growing informal activities in Dar es Salaam (Sawio and Sokoni, 1996). Marginal lands such as roadsides (road reserves), steep slopes, valleys and vacant lands are normally used for agricultural purposes. The common substances found in groundwater, which arise from agricultural activities, are nitrates and pesticides. In agriculture, pesticides are normally used to kill pests. The source of pollution can be point or diffuse depending on the location and area of application. More than 39 different pesticides have been identified in groundwater in USA and Canada (Kiely, 1997). In a country-wide study done by the National Environment Management Council (NEMC) in 1997/98 on obsolete pesticides and veterinary wastes, it was revealed that 41% of the pesticides were expired, 39% deteriorated and 14% remained in stores because the stock was too large beyond usage rate. Some of these chemicals include DDT that has been banned in many countries in the world. JET (1997) reported that DDT was being used for urban agriculture in Dar es Salaam City. If such persistent chemicals find way to the groundwater due to improper usage, many people can be exposed to health risks of cancer for a long period of time.

3.4 Conclusion

Potential groundwater pollution sources exist in Dar es Salaam City. The major pollution sources include domestic sewage from on-site sanitation, industrial effluents, leachate from solid waste dumpsites, leaking fuel filling and waste oils. It has also been revealed, that the solid waste burying practices being used at dwelling premises do significantly contribute to pollution of unconfined aquifers. The sandy soil nature and large amount of annual precipitation exacerbate the pollution plumes to reach the aquifers.

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Chapter 4

GROUNDWATER QUANTITY AND QUALITY CONSIDERATIONS

Abstract

The quantity and quality of groundwater in the urban Dar es Salaam was investigated in the period 1999-2001. Over 95% of the boreholes supplying drinking water are drilled at 20-70 m deep, a zone dominated by lower confined aquifers whose characteristics are not yet well understood. The average static water level is 11.2 m below ground level, a depth within the unconfined aquifer. Groundwater abstraction is by multiple layers including both unconfined and confined aquifer bands. About 40% of the boreholes have yields greater than 5 m^3/h. Some areas such as Mbagala have outstandingly high yield of over 20 m^3/h. Riverbanks (like Msimbazi and Kizinga valleys) seem to be predominant areas of groundwater recharge. Major groundwater quality problems have been found to be in bacterial, chloride, nitrate and organic contamination. Only about 40% of samples analysed during the investigation were within the national standards on bacterial quality of 0 faecal coliform per 100ml sample, while about 50% were observed for chlorides. Nitrate levels of up to 306 mg/l were observed and about 70% of the boreholes showed levels between 50-100 mg/l (a band between WHO guideline levels and Tanzanian limit of 100 mg/l). Elevated levels of total organic carbon (TOC) of up to 20 mg/l and chemical oxygen demand (COD) of up to 10 mg/l were observed in several samples collected from the entire Dar es Salaam area. This observation indicates that organic contamination of groundwater is taking place in the city. Apart from the point and diffuse sources of pollution, the contamination found in the boreholes might have arisen also from poor construction of boreholes, which would allow surface water inflow in the wells or tapping the water at polluted unconfined layers. It has been observed that the aquifers in the city have started to degrade, a situation that may expose many people to varying health risks. The findings also indicate that the safety of the groundwater in Dar es Salaam is questionable and therefore, treatment is needed before being supplied to consumers.

4.1 Introduction

The Dar es Salaam City receives water supplies from surface sources of Ruvu and Kizinga rivers. As summarized in Table 4-1, there are three water treatment plants namely, Upper-Ruvu, Lower-Ruvu and Mtoni, with a total installed capacity of

605,000 m^3/day (Japan International Cooperation Agency, JICA, 1991; Howard Humphreys Ltd, 1967, 1995). The plants were constructed more than 25 years ago. An overall shortage, unsatisfactory quality and uneven supply of water to the residents characterize the existing water reticulation system. The frequent interruptions in supply are caused by many reasons, ranging from power failure to pipes bursts due old age. There are more than 60,000 private and 50,000 illegal connections respectively (JICA, 1991). About 55-65%% of the water demand is domestic, 10-20% commercial, 10-15% institutional and 20-30% industrial. It is estimated that more than 22% have tap in the house (Kokusai Kogyo Co., 1997). The water system in the city is being managed and operated by the Dar es Salaam Water and Sewerage Authority (DAWASA).

Table 4-1: Surface water sources for Dar es Salaam City, 1994 (JICA, 1994)

Name of the Plant	Source	Year of Construction	Design capacity, m^3/day	Operating capacity, m^3/day
Upper Ruvu	River Ruvu	1959	210,000	82,000
Lower Ruvu	River Ruvu	1975	386,000	182,000
Mtoni	River Kizinga	1949	9,000	6,000
Total			605,000	270,000

The water demand estimations for the city are shown in Figure 4-1 and Tables 4-1 and 4-2. The estimation is based on a water consumption of 120 l/cap.day (giving a total demand of 360,000 m^3/day for the year 2000) and 35% loss in pipe network through leakages. The 2000-year, level of service was found to be only 48% and the deficit about 52%. It can be seen from the Table 4-1 that while the total output from the three water treatment plants is about 270,000 m^3/day, out of which 175,500 m^3/day actually reaches the consumer that is, less the losses). The remaining portion of 184,500 m^3/day of the demand, is obtained privately from alternative sources, mainly boreholes and shallow wells. Due to water shortage, DAWASA is augmenting the supply by exploiting groundwater through boreholes drilled within the urban environment (the surface waters in the city are considered polluted and therefore, not used as alternative source of supply).

It is further estimated that the water demand will grow to 550,000 m^3/day by the year 2015 (JICA, 1994). Assuming that no appropriate steps are taken to revamp the water treatment plants (by DAWASA or the government), and that they will maintain the same production level, the deficit of water supply would expand to 68.2% in the year 2015 (Table 4-2). The new level of service will be constricted to 31.8%.

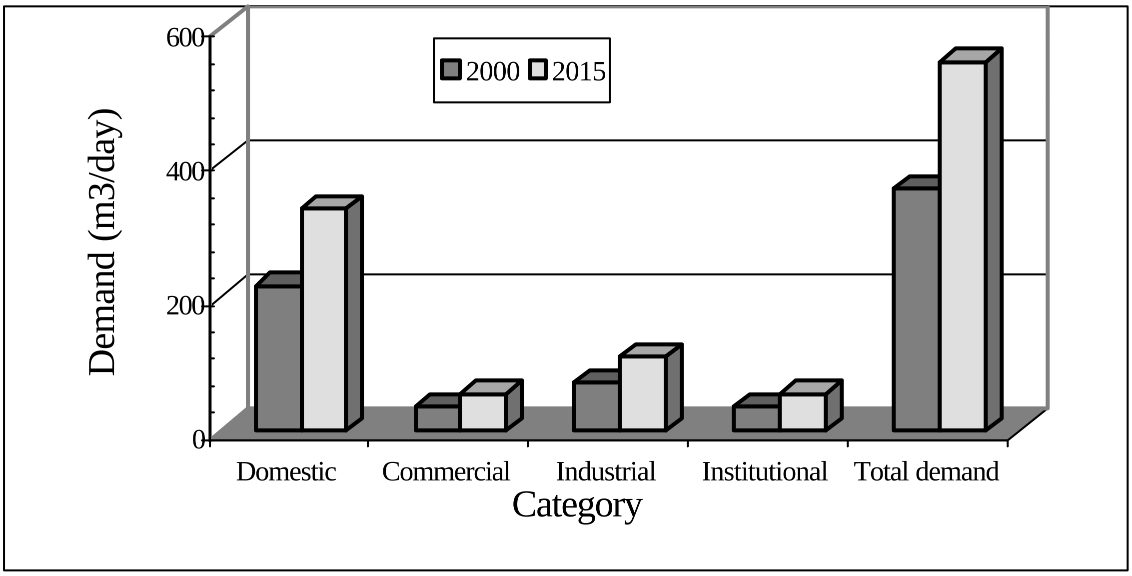

Figure 4-1: Estimation of water demand in Dar es Salaam for the years 2000 and 2015

Table 4-2: Water-demand and supply estimations for the Dar es Salaam City

Component	Year	
	2000	2015
Domestic demand (m^3/day)	216,000	330,000
Commercial demand (m^3/day)	360,00	55,000
Industrial demand (m^3/day)	72,000	110,000
Institutional demand (m^3/day)	36,000	55,000
Total demand (m^3/day)	360,000	550,000
Total supply from surface sources (m^3/day)	270,000	270,000
Leakage, 35% of supply (m^3/day)	94,500	94,500
Actual supply to consumers (m^3/day)	175,000	175,000
Deficit of demand and supply (m^3/day)	184,500	375,000
Level of service (%)	47.75	31.82
Deficit of supply (%)	52.25	68.18

(Source of raw data: JICA, 1991, 1994; Howard Humphreys 1995)

However, efforts to revamp the water supply in the city system is frustrated by financial incapability of DAWASA as compared to high level of investment that is required. DAWASA has poor capacity of revenue collection levels and generally poor working gear. The 2000 year overall amount of groundwater being privately exploited (through deep boreholes, shallow wells and open hand dug wells) for different uses was estimated at 50% of the daily demand. The assumption is that the water to cover the deficit in supply is obtained from groundwater sources, since the surface water are known to be polluted. It is thus obvious that groundwater is an important source of water supply for the city of Dar es Salaam. This chapter estimates the groundwater amounts used in the city and the quality variations (both temporal and spatial).

4.2 Groundwater Exploitation in Dar es Salaam

4.2.1 Historical development

Historically, groundwater was the main source of water supply for the Dar es Salaam residents until 1949 the time when the Mtoni Water Treatment Plant (on River Kizinga) was constructed. The first borehole (on record) was drilled in 1943 at the Temeke Diary Plant, with a depth of 30 m and a yield of 8 m^3/h (Service Plan, 1997). Few other boreholes were constructed in the period between 1943-1949. The completion of the Mtoni water scheme and further construction of Upper and Lower Ruvu Water Treatment Plants (on River Ruvu) in 1959 and 1975 respectively, made a radical shift to surface water sources. Increased water demands due to rapid urbanization and salt-water intrusion in some of the boreholes contributed greatly to the shift to surface water sources (Service Plan, 1997). From 1975 to 1997, the pace of borehole drilling remained very low except for shallow wells in areas without piped water connections. In 1997, Tanzania experienced a severe draught, causing DAWASA to set a task force "Emergency Programme" to drill extra boreholes to meet the water demand. Many of the existing boreholes in Dar es Salaam were constructed during this period. Today, there are more than 850 boreholes supplying water for drinking and industrial purposes. Since 1997, many boreholes are continually being drilled as indicated in Figure 4-2. More than 35 boreholes are connected to the main distribution system of the city (some of them are shown in Table 4-3), supplying water without any treatment (Mato *et al.*, 1998; Ministry of Water, 1997; DAWASA work files, 2000). The connected wells are 26-66 m deep with a yield ranging from 50 m^3/day to 1267 m^3/d. The actual amount being abstracted from each borehole is not known as no flow measurement meters are installed.

4.2.2 Borehole drilling

There are several drilling companies; the main ones are the Drilling & Dam Construction Agency (DDCA, Hydro Tech (T) Ltd located at Mwenge, Benwell Engineers with its office at Victoria (Merry Water building). DDCA is the biggest drilling company in Tanzania and is based in Dar es Salaam, Maji-Ubungo yard. This firm was transformed from government department (under the ministry of water) to an agency about two years ago. It, therefore, inherited all the equipment and skilled labour from the mother, the government. Others are still small companies with low capacity of manpower and equipment.

DDCA is now spearheading drilling of boreholes in the city on commercial basis. Being a business, it is largely commercially operated and in most cases demand-driven. The pace of drilling is an average of about 170 boreholes per year in the city. The boreholes are drilled at places that customers want to locate the water well, provided that the hydrogeological investigation shows that there is enough water. The company keeps the data on investigation and drilling operations.

Table 4-3: Boreholes connected to the Dar es Salaam water supply system (DDCA, 1997)

B/H	Location	Depth (m)	Yield (m3/h)	Colour (mg/l)	pH	Conductivity (μS/m)	Chloride (mg/l)
67/97	Mwananyamala Kisiwani	30	2.6	4	8.6	1550	121
56/97	Amana Hospital	50	14.4	2	7.8	1000	142
94/97	Mwananyamala P/School	36	2.1	2	8.6	1670	167
66/97	Kigogo P/School	28	12.5	-	8.5	1900	121
28/97	Ilala-Boma	30	15.2	-	8.4	940	91.6
29/97	Magomeni Garden	48	26.4	-	7.8	1000	63.2
30/97	Dar Tech.College	50	26.4	-	8.5	1350	106
22/97	Chang'ombe TTC	40	19.8	2	8.1	650	28.8
306/97	Keko Gerezani	42	14.4	10	10.5	3000	923
108/97	Mwananyamala NHC	39	52.8	4	2.4	1050	68.8
105/97	Yombo Mkangarawe	62	14.4	40	5.9	1310	380
37/97	Kinondoni P/School	30	22.6	2	8.1	1690	76.7
20/97	Nzasa II-Mbagala	48	32.7	-	7.4	250	49.7
35/97	Kiwalani CCM	28	14.1	7	7.1	1620	351
39/97	Kigogo Mwisho	33	26.4	5	7	1210	234
99/97	Mtoni P/School	42	9.3	-	6.6	1020	111
110/97	Tandika M/Yanga	58	28	4.9	6.7	1010	106

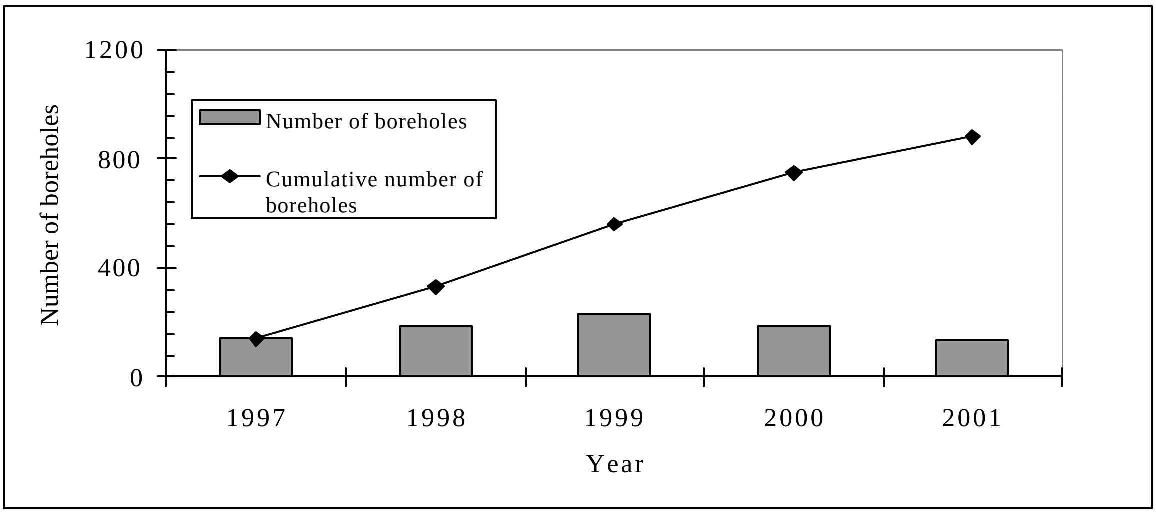

Figure 4-2: Boreholes drilled in Dar es Salaam by DDCA

No flow meters are installed during construction and therefore the actual amounts of water being abstracted from the boreholes are not known. At the moment, the company has not fully computerized its operations and therefore many of the information are kept in working flat files. The knowledge of the spatial locations of the boreholes is in drillers' minds as there is no map that have been produced. The same was observed for small drilling companies; in addition, their drilling records could neither be accessed. The details of information management concerned with the boreholes are explained in Chapter 5.

4.3 Aquifer Characteristics

4.3.1 Hydrogeological and Soil Characteristics

The typical bedrock underlying Dar es Salaam City are sandstone and limestone, whereby, the former occupies about three-quarters of the area (Msindai, 1988). The overburden consists of residual as well as transported soils. Generally, the soils vary from gravel to sands, silts and clays. The residual soils are widespread on uplands with thickness up to 5 m, while transported soils are found in the creeks with thickness up to 7 m.

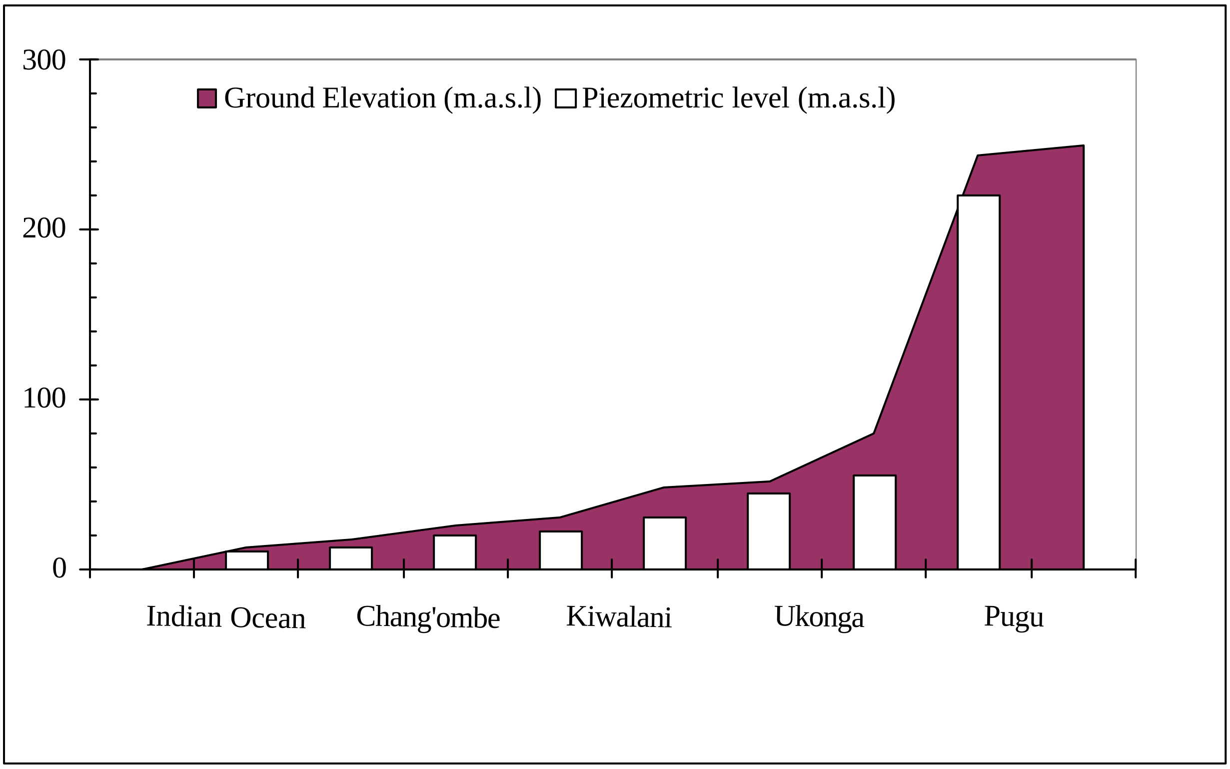

Figure 4-3: A transect showing topography and hydraulic grade line from Pugu recharge areas to the Indian

The limestone is mainly of coralliferous and is found along a narrow coastal belt. Kaolinitic sandstone consisting of fine to medium grained quartz sand and sandstone occur at the Pugu hills in the western part. The Dar es Salaam region also lies within an area that is traversed by swarms of lineaments and faults (Howard Humphrey, 1967; CBA Engineering, 1979; Msindai, 1988; and Service Pan, 1997).

There are three types of aquifer in Dar es Salaam, which include; an upper unconfined aquifer (1-15 m thick); the upper confined aquifer (most productive zone, 5-50 m thick) and multiplayer aquifer (normally separated from each other by alternating layers of clay) (Service Plan, 1997). The regional groundwater flow pattern towards the north is inferred from the general tilt of the geological blocks (Msindai, 1988). The groundwater recharge is considered to be of both distant and in-situ types. The distant recharge areas are the surrounding hills of Pugu (Kisarawe district). However, the in-situ source is considered to be the major contributor, mainly due to the sand soil nature of Dar es Salaam City. Within the alluvial sands, terrace sandstones and reefs areas, which have unconfined and to a lesser extent perched aquifer conditions, riverbank infiltration into the aquifers is possibly the predominant recharge mechanism (Msindai, 1988). The groundwater flow is considered to be towards the Indian Ocean as inferred from the piezometric heads (Figure 4-3).

4.3.2 Aquifer yield and borehole depth

The aquifer yield and drilling depth data for 472 boreholes drilled from 1997 to 2001 in Dar es Salaam (Drilling and Dam Construction Agency, DDCA, 2001) were statistically characterised. Table 4-4 summarizes the results of statistical computations. The mean for static water level is 11.2 m, suggesting that the groundwater is found in the unconfined aquifer in most of the places in the city. It has also been observed that over 95% of the boreholes are drilled between 20-70m deep (Figure 4-4). Msindai (1988) reported similar observation. Correlating the drilling depth with the yield data, it can be seen that the production aquifers are in the 20-70 m band, dominated by sandstone and limestone formation.

Table 4-4: Statistical parameters of the depth of drilling, yield and static water level of boreholes in Dar es Salaam (1997-2001 boreholes records)

Statistical variable	Depth (m.b.g.l*)	Yield (m^3/h)	Static Water Level (SWL) (m.b.g.l*)
Minimum	8.0	0	0
Maximum	125	120.0	53.5
Mean	42.0	6.8	11.2
Median	40.0	4.0	10.0
Standard deviation	16.0	8.0	7.5

**m.b.g.l – metres below ground level*

It has been noticed that all areas with high yield aquifers are located within the basins of Msimbazi River (and tributaries) and Kizinga River. Therefore riverbank infiltration into aquifers is assumed to be most reasonable recharge source. Earlier, this was also suspected by Msindai (1988). The amount of water stored in the aquifers was not calculated, however, Service Plan (1997) estimated the groundwater storage in Mzinga and Kizinga catchments (covering Mbagala area) to be 110 x 10^6 m^3/year and 33.3 x 10^6 m^3/year respectively. The annual average amount of water that is abstracted from these aquifer systems is estimated to be only 5% of the storage capacity (Service Plan, 1997).

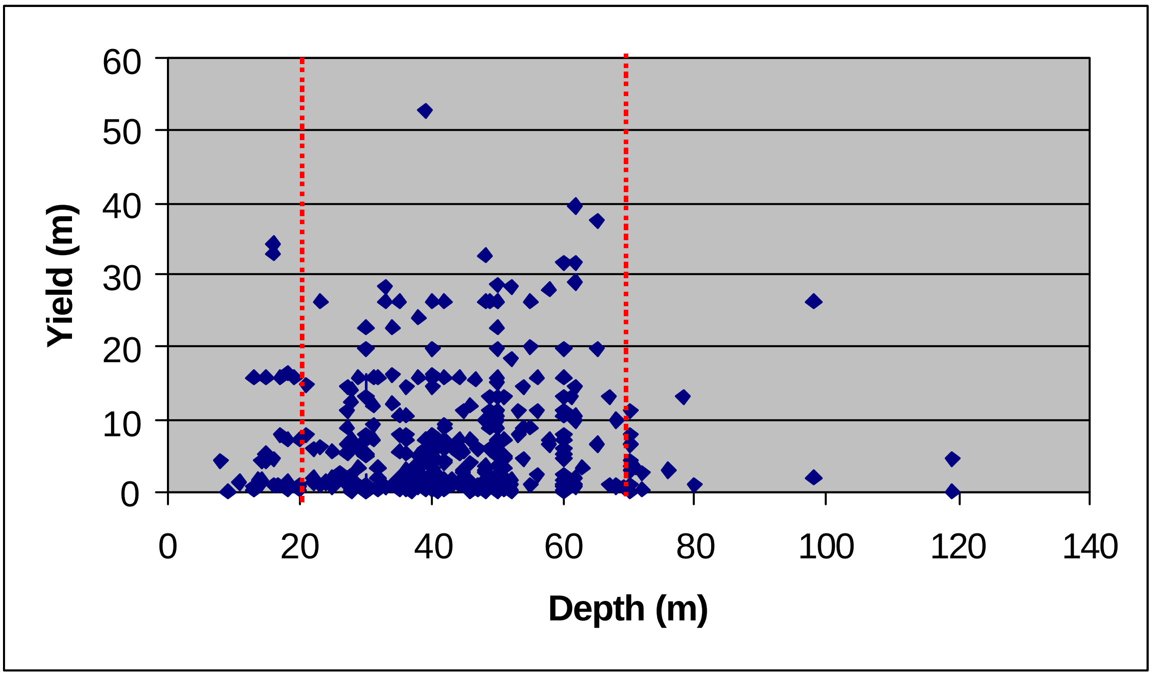

Figure 4-4: Depth-yield plot of aquifers in Dar es Salaam [*Source of raw data: DDCA (2001)*]

The aquifer data was further classified into yield categories as indicated in Figure 4-5. The graph shows that 3.2% of the boreholes were found dry, and about 55% have yield of up to 5 m^3/h, while about 35% have moderate yield of 5-20 m^3/h. Boreholes, which showed high yield of above 20 m^3/h, were only 7.5%. Examples of boreholes with high yield are given in Table 4-5.

Furthermore, spatial variation of drilling depth of boreholes and aquifer yield were investigated by mapping the depth and yield data respectively. Using GIS software (ArcView 3.1), maps shown in Figure 4-6 and Figure 4-7 were developed. The detail of geo-processing is explained in Chapter 5. The borehole depth map further supports the fact the boreholes in the city are mainly drilled at 20-70 m deep. The aquifer yield map shows that Mbagala area has the highest yield aquifer. Areas with moderate aquifers include Segerea, Tabata, Magomeni, Kigogo, Upanga and Mwananyamala. However, all these areas are under human habitation or other urban activities.

Table 4-5: Boreholes drilled in Dar es Salaam City with high yield (DDCA, 2001)

S/N	Borehole Number	Location	Depth (m)	Static water Level (m.b.g.l)*	Yield (m^3/h)
1.	12/97	Police College K rd.	38	4.75	24
2.	20/97	Nzasa II Mbagala	48	3.78	32.7
3.	29/97	Magomeni Garden	48	1.98	26.4
4.	30/97	Dar Tech. College	50	6.43	26.4
5.	37/97	Kinondoni P/School	30	5.7	22.6
6.	39/97	Kigogo Mwisho	33	0.0	26.4
7.	42/97	Temeke Hospital	34	5.8	22.6
8.	108/97	M/nyamala NHC	39	6.77	52.8
9.	110/97	Tandika M/Yanga	58	2.7	28.0
10.	131/97	Nzasa III Mbagala	42	11.22	26.4
11.	132/97	Tandika Mabatini	52	9.92	28.3
12.	138/97	Mbagala Kiburugwa	65	11.09	37.7
13.	86/99	Mwembe Yanga	50	4.10	60.92
14.	88/99	Kidongo Chekundu	30	7.36	61.88
15.	111/99	M/nyamala NHC II	40	7.12	120.0
16.	142/99	Shaurimoyo	42	8.33	39.6
17.	231/99	Mbagala Kiburugwa	60	12.01	21.44
18.	275/99	Yombo Miembeni	60	2.82	24.0
19.	294/99	Kiburugwa S/mchanga	50	8.03	24.0
20.	268/99	Nzasa V Mbagala	54	6.10	28.99
21.	331/99	Kiwalani Minazi Mirefu	48	9.95	39.6
22.	379/99	Tandale (Mr. Mbegu)	41	4.72	21.17
32	379/99	Tandale (Mbegu)	41	4.72	21.17
33.	17/97	Tanzania breweries	-	-	22.6

* m.b.g.l - metres below ground level

The annual average amount of groundwater recharged has been estimated to be 20% of the rainfall (Freeze and Cherry, 1979; Rahman, 2001). The annual average rainfall for Dar es Salaam is 1200 mm and therefore recharge rate is 3.2 x 10^5 m^3/year. Using this estimate it was found that the present groundwater withdrawal in the city (about 1.8 x 10^5 m^3/year – Table 4-2) is about 50% of the recharge rate. However, by the year 2015, when the groundwater water withdrawal may increase to 3.7 x 10^5 m^3/year, the recharge will be less by about 3%. Such circumstances can lead to lowering of groundwater table, which can trigger other problems like land subsidence and effect to terrestrial ecosystems. Though Dar es Salaam may have huge groundwater storage in the aquifers, sustainable utilization of the resource need to be established.

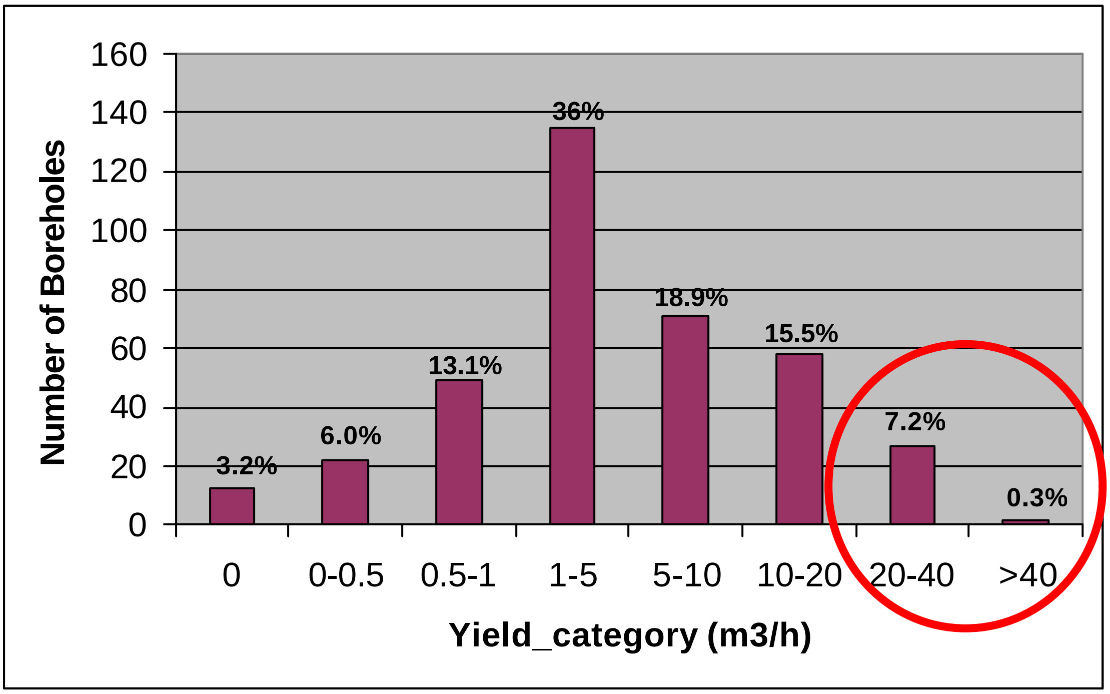

Figure 4-5: Aquifer yields category statistics [*Source of raw data; DDCA (2001)*]

The spatial variation of static water level in Dar es Salaam City was also observed as shown in Figure 4-8. The map shows that in many parts of Dar es Salaam City, the water table is within 0-10 m, mainly dominated by sandy unconfined aquifer (especially areas close to the coastline). The depth tends to decrease towards river valleys. This again points to predominance of riverbank recharge to aquifers. The mean of the depth of static water levels (SWL) as recorded during borehole drilling indicate a mean depth of 11.2 m (Table 4-4 and Figure 4-9). From Figure 4-9, it was deduced that over 80% of the records show that the SWL is less than 20 m below the ground level. This region is dominated by the unconfined aquifer where pollution risks are high.

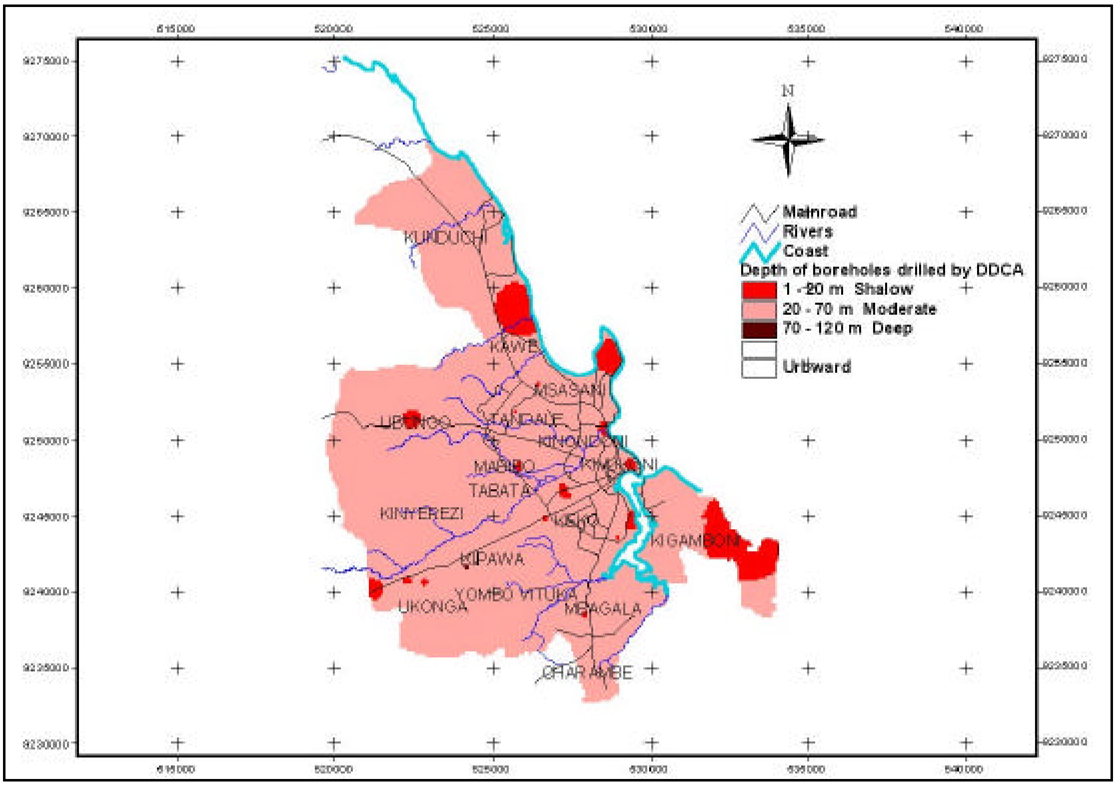

Figure 4-6: Spatial variation of depth of boreholes drilled by DDCA in Dar es Salaam City

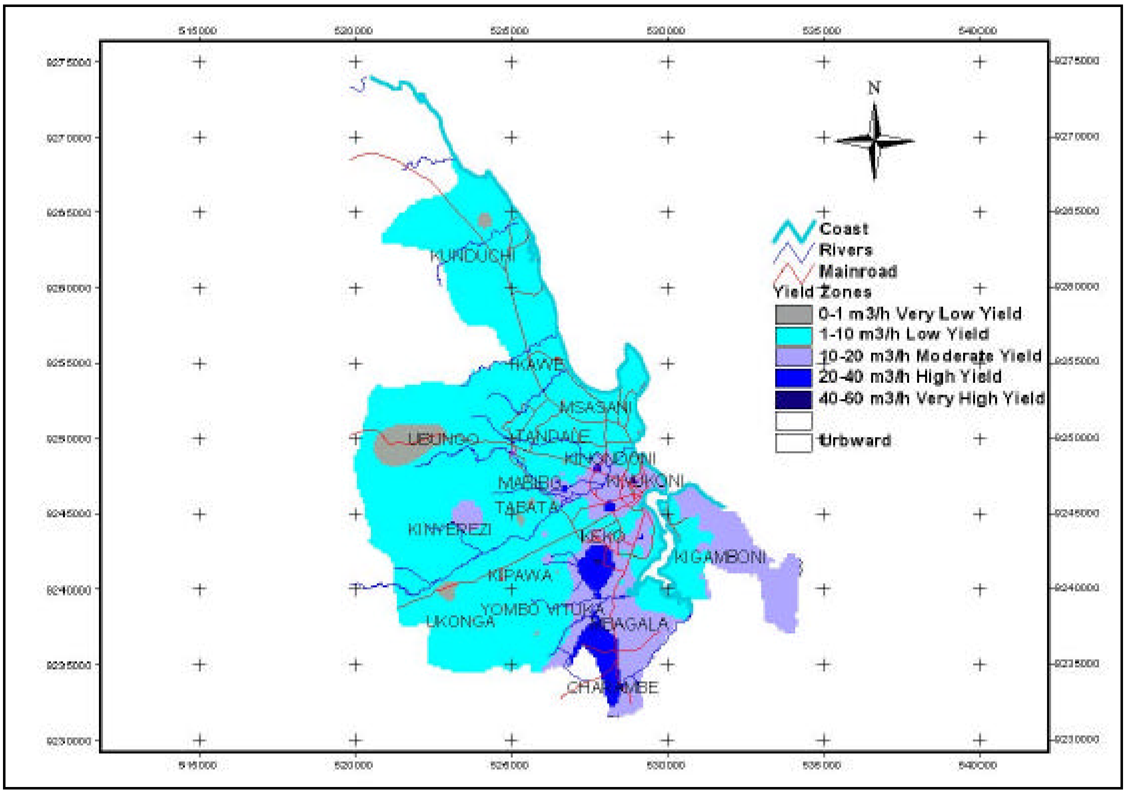

Figure 4-7: Aquifer yield map for Dar es Salaam City (2001)

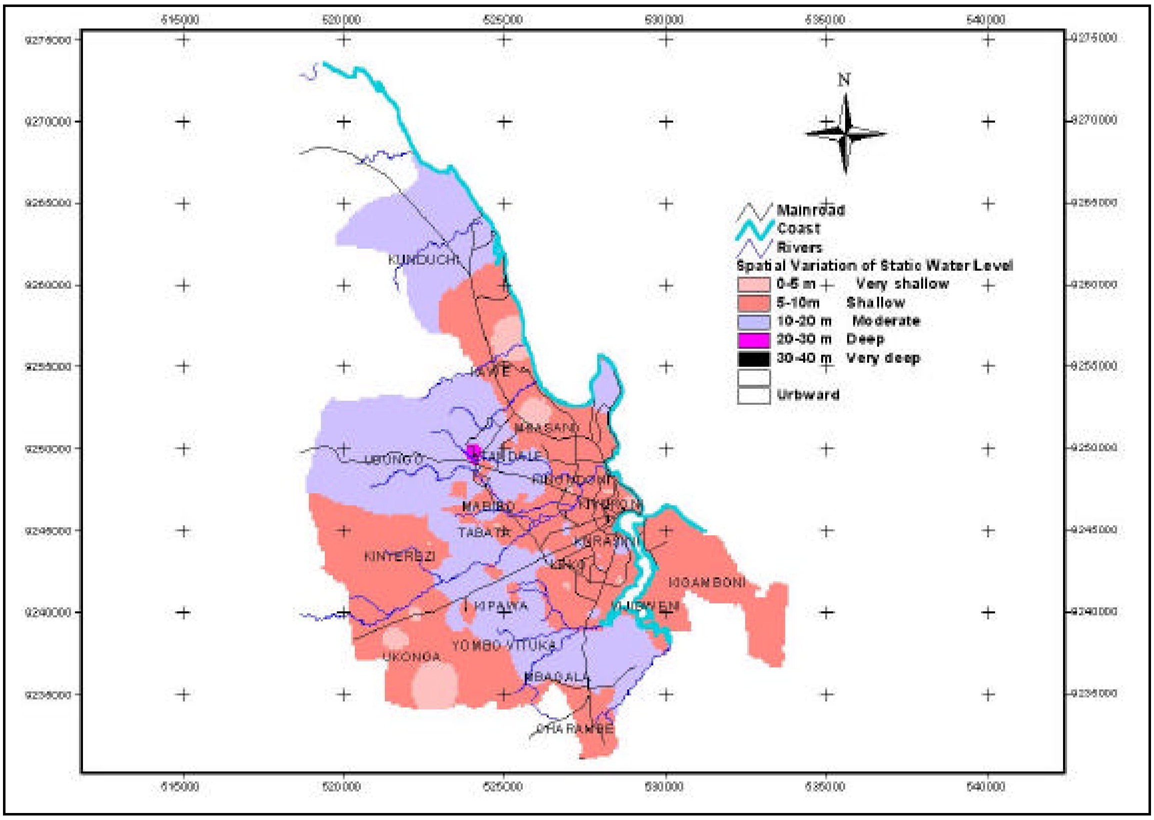

Figure 4-8: Spatial variation of static water level in Dar es Salaam city

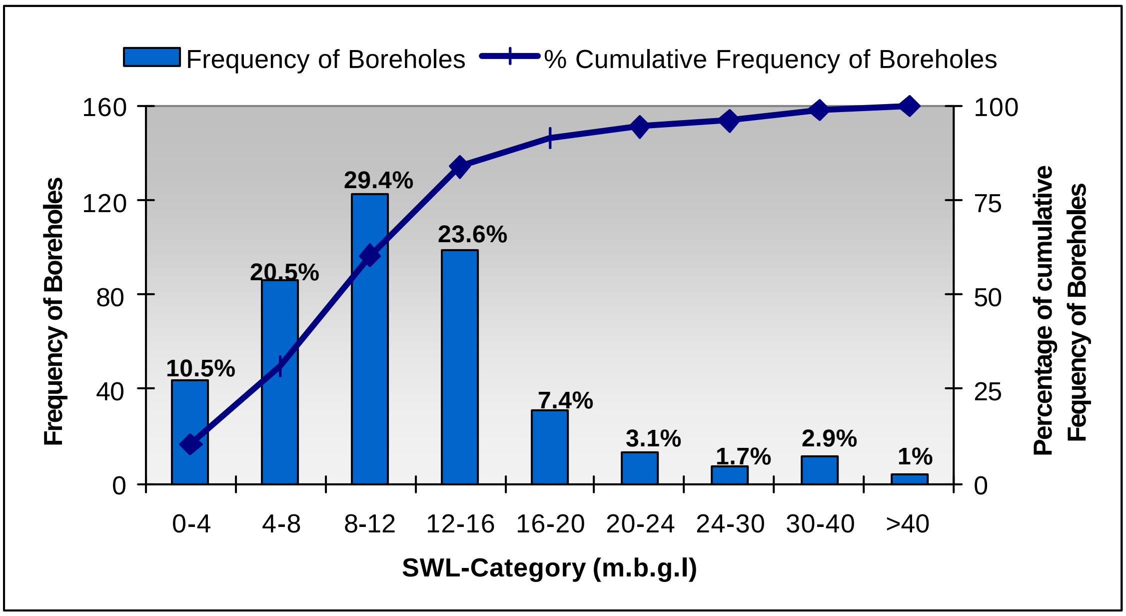

Figure 4-9: Static Water Level (SWL) statistics [*Source of raw data: DDCA,*

4.4 Groundwater Quality

4.4.1 Overview

Water accounts for 60-95% of the weight of living cells (Abernathy, 1994). Organisms need water intakes to replenish that portion lost in various metabolic and excretory processes in cells. However, water may contain substances, whether natural or anthropogenic, that can affect the quality and existence of life (Harrison, 1990). Here, distinction is made between pure and safe water. On one hand, pure water is defined as water that is free from extraneous substances (contaminants), whether harmless or not (Tebbutt, 1992), and from a practical standpoint, it is impossible to produce. On the other hand, safe water is one, which is not likely to cause undesirable or adverse effects, although it may contain various contaminants (Tebbutt, 1992). In this context, "polluted water" is referred to the water that its quality (physical, biological or chemical) can adversely affects human beings or simply the water that is no longer suitable for desired uses (Harrison, 1990). Contaminated drinking water is the cause of about 60% health implications in developing countries (Tebbutt, 1992). It is therefore uncommon to find epidemics (normally accompanied with loss of lives) in places with inadequate provision of safe drinking water. Water-borne diseases like typhoid and cholera are among the common epidemics found in low-income countries with inadequate water provisions.

Similarly, the chemical pollution of water sources, which accompany industrial development and intensive agriculture, can introduce new diseases that low-income countries are not yet sufficiently equipped to fight against. This may result into human suffering and loss of lives. The history of chemical pollution dates back to the 1960s when Carson reported effect of DDT on bird population in USA, which lead later on to the banning of the pesticide in many countries ((LaGrega, 1994). Soon afterwards the contamination of cooking oil with polychlorinated biphenyls (PCBs) in Japan and Taiwan in late 1960s and mid-1970s that exposed thousands of Asians to high concentrations of the chemical resulting in miscarriages and birth defects was reported (LaGrega, 1994). Today, many countries (especially developed countries) have legal provisions with regard to proper management of hazardous wastes so as not to contaminate the environment, including water sources. In many low-income countries, monitoring for toxic micro-pollutants in drinking water is not the norm due to economic and technological limitations. Thus groundwater, which is an alternative source of water supplies for many urban poor (especially in developing countries), must be protected in order to reduce health consequences. As discussed in Chapter 2, water provisions in urban areas in Tanzania is still not adequate and treatment is not guaranteed, therefore, the potential of epidemic outbreaks and other diseases is high.

4.4.2 Previous Studies

Groundwater pollution in Dar es Salaam has not been systematically monitored, though over the years several people have done some independent investigations on the subject. It can be concluded from the reported results that water abstracted from the unconfined aquifer in Dar es Salaam is considered to be faecally polluted such that it poses a serious public health risk (Kiula, 1989; Mgana and Rwegasira, 1993; Chaggu *et al.*, 1994; Selemani, 1994; Muyamandi, 1995; Kokusai, Kogyo Co. Ltd., 1997; Rwegasira, *et al., 1999*; Shemdoe, 2000; Vindi, 2000; Kijazi, 2001). Chaggu *et al* (1994) reported that over 60% of the health complaints in high-density areas in the city might be related to groundwater contamination. Considering that 42% of the water demand for the city residents is met by groundwater (Chapter 2 gives more details), and that many people can easily abstract it from the unconfined aquifer, the observation reported by Chaggu *et al* (1994) might be reasonable.

The Water Laboratory Maji –Ubungo is the government-designated laboratory for water analysis. The water samples collected from boreholes drilled by DDCA are analysed by this laboratory. At least one sample is analysed before a borehole is commissioned for public use. The routine parameters analysed include conductivity, pH, alkalinity, turbidity, colour, hardness, Ca^{2+}, Mg^{2+}, permanganate value, nitrate and faecal coliform. The results of the analysis are stored in respective borehole flat file. However, these data (especially those for nitrate and faecal coliform) are not easily accessed. Information management with regard to groundwater data in the city is explained in more details in Chapter 5. Some of the results accessed to, generally show good quality except for chloride, nitrate and faecal coliform in several locations, where they are above the national set standards (refer to Table 4-6).

4.4.3 Experimental Investigations on Groundwater Quality

The investigation on the current status of groundwater quality in Dar es Salaam was conducted between 1999-2001 by collecting water samples from boreholes drilled by DDCA. The results were geo-processed to obtain groundwater quality maps. At first (December 1999-February 2000), water samples from 36 randomly selected boreholes were analysed for bacteriological and chemical quality at the Environmental Laboratory, University College of Lands & Architectural Studies (UCLAS). During this investigation period, each borehole was sampled at least three times. The results of this initial investigation helped to understand the extent of pollution as well as spatial variation of quality (see Table 4-6 and Figure 4-10). These results are comparable with that reported by Rwegasira *et al* (1999) (see Figure 4-11). The authors collected water samples from 51 deep boreholes in the city and analysed them at the Environmental Laboratory, UCLAS. The results show that all the samples complied with national standards in sulphate and nitrate having ranges of 4.2-96.0 mg/l and 0.7-41.4 mg/l respectively. Compliance in turbidity was 99.8%, while only 47.1% and 39.2% of samples were within the national limits in terms of chloride and faecal coliform.

Table 4-6: Results for physical and chemical tests of groundwater samples collected from randomly selected boreholes in Dar es Salaam City (December 1999-February 2000)

S/N	Location of Borehole	SO_4 mg/l	NO_3 mg/l	Cl mg/l	Turbidity NTU	FC Colonies /100 ml
1	Yombo Makangarawe	60.5	1.6	774	2	0
2	Yombo Dovya	16.5	2.2	875	1	3
3	Tabata TDF-1	71.1	1.1	3106	2	6
4	Yombo Vituka P/S	31.4	0.9	1364	2	1
5	Vituka 1	46.2	11.2	1180	2	7
6	Vituka 2	22.0	73.5	870	1	0
7	Temeke Hospital	50.1	1.6	795	2	2
8	Temeke Stereo	61.0	1.7	782	2	1
9	Tabata Msikitini	54.3	0.9	1183	2	6
10	Tandika Mabatini	83.9	1.5	2713	1	8
11	Tabata TDF 2	22.3	0.8	3023	1	0
12	Segerea	60.2	1.6	1772	0	0
13	Tabata Chang’ombe	39.1	0.7	2085	3	0
14	Buguruni Sokoni	71.2	1.1	850	2	2
15	Buguruni Gengeni	45.8	2.6	860	12	6
16	Buguruni Kisiwani	16.5	0.7	3284	2	0
17	Buguruni Kwamnyam.	110.0	1.1	960	0	0
18	Amana hospital	22.2	1.5	916	1	1
19	Bungoni	-	2.0	765	2	1
20	Malapa Hostel	-	1.1	1165	1	0
21	Mtoni P/S	68.6	1.6	1098	3	0
22	Saba Saba Ground	20.8	1.4	645	1	0
23	Kigogo P/S	70.0	4.1	619	1	1
24	KigogoMwisho	26.8	18.3	1120	5	3
25	Magomeni Garden	60.1	14.6	653	1	0
26	Magomeni Mikumi	54.9	15.6	913	1	9
27	Ilala Boma	30.7	1.8	1625	3	0
28	Msimbazi Mseto P/S	32.1	1.7	920	1	0
29	Shariff Shamba	37.6	2.5	830	0	0
30	Tabata Kimanga	50.0	1.0	4200	0	2
31	Kimanga Darajani	37.6	2.0	1000	0	3
32	Uhuru Mchanganyiko	58.2	3.5	1890	12	0
33	Amana Hospital	123.0	2.0	1262	0	3
34	Gerezani (Kariakoo)	30.7	1.0	765	1	1
35	Dar Technical	30.7	1.0	2236	3	3
36	Changómbe TTC	32.0	3.3	870	3	0
	Average value	*48.1*	*2.9*	*1388*	*2*	*2*
	WHO Standard	200	50	200	25	0
	Tanzania Temporary Standard	600	100	800	30	0

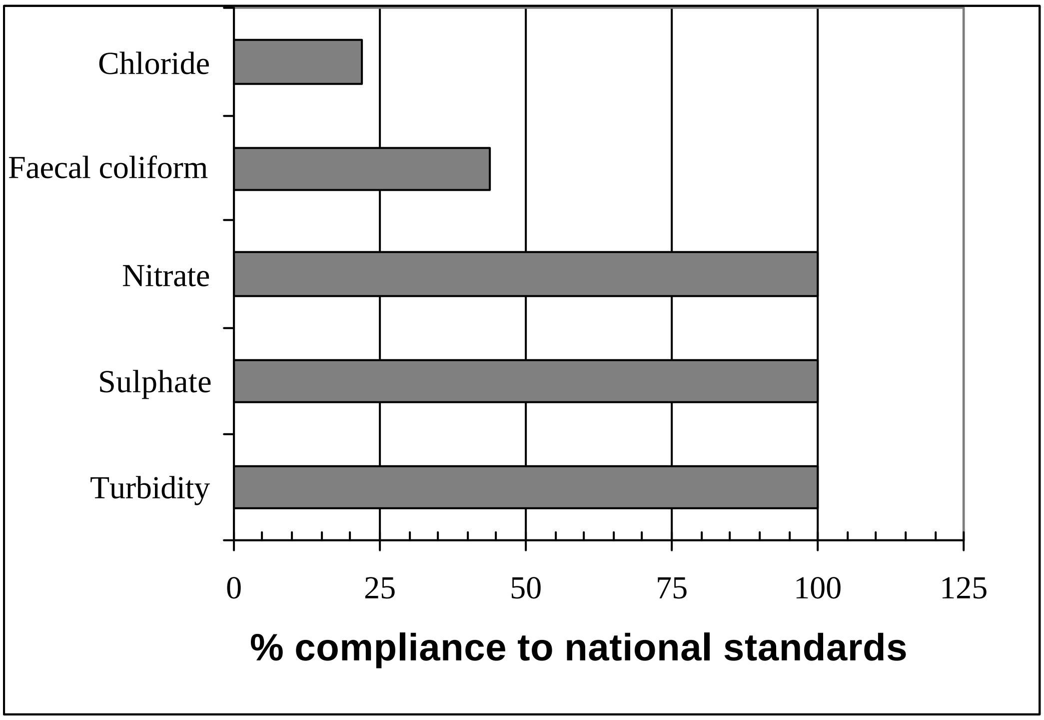

Figure 4-10: Groundwater quality in Dar es Salaam: Percent compliance to the Tanzania Temporary Standard for Drinking Water

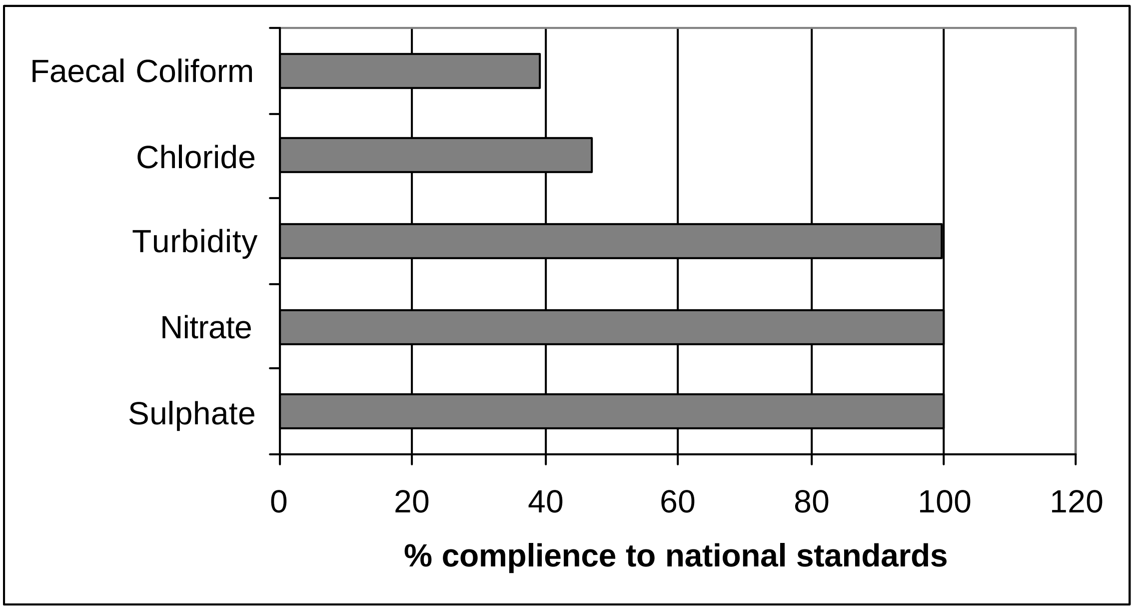

Figure 4-11: Groundwater characterization in Dar es Salaam City: Percent compliance to the Tanzania Temporary Standards (Rwegasira *et al.*, 1999)

Another parallel investigation was carried out in February 2000 to determine the amount of oil diffused in groundwater. Samples from selected boreholes (mainly those located within the city centre) were screen for oil content. Samples were analysed at the Chemistry department, University of Dar es Salaam by gravimetric method. The results of the analysis shown in Table 4-7 indicate that appreciable amounts of oil have reached the water table.

Table 4-7: Oil concentrations in groundwater in Dar es Salaam city
(Samples collected and analysed in February, 2000)

Borehole Location	Oil concentration* mg/l as petroleum ether extract
DAWASA Gerezani	0.018
Indian Ocean (near outfall)	0.032
Uhuru Primary School	0.014
National stadium	0.127
Sabasaba Grounds	0.023
Vingunguti Primary School	0.018
Masjid Al-Jamia - Ilala	0.018

* Tanzanian Standard is 1.0 mg/l

Table 4-8: Micro-organic pollutants in groundwater samples collected from Dar es Salaam City (1999)

Sample No.	Location	Concentration of organic micropollutants (µg/l or ppb)				
		Phthalates	Total alkanes	PAH	Phenol**	Esters
1.	Konyagi	115.3	15.6	3.6*		
2.	Dar. Tech. College	30.7	6.5	0	3.1	3.1***
3.	TOL	686.3	57.0	0	22.4	0
4.	Gerezani	69.3	0	0	3.8	0
5.	Chang'ombe TTC	233.5	6.9	0	3.1	0
6.	Kurasini	51.1	6.1	0	3.2	0

* Only acenaphthene was identified ** 2,4-dimethyl phenol *** Phosphoric acid tributyl ester

Although the results indicate that, the oil content is below the Tanzania standards, the figures can have a different meaning when analysed on the concentration of the specific organic compounds and their amounts. Compound like polycyclic aromatic hydrocarbons (PAH), which are associated with mineral oils, are likely to be constituents of the water wells in Dar es Salaam because of haphazard disposal of waste oils and industrial effluents (as discussed in Chapter 2). It is, therefore, not surprising to find compounds like polycyclic aromatic hydrocarbons (PAH), as constituents of water wells in Dar es Salaam. An earlier screening of organic micro-pollutants in borehole waters in the city was done in March 1999. The analysis of the samples was done at RIC, Kortrijk, Belgium) using a GC/MS. The results indicated the presence of hydrocarbons including PAHs (acenaphthene) (Table 4-8). Further analyses to characterize Dar es Salaam groundwater for micro-organic pollutants are explained in Chapter 7.

The groundwater quality variations were also investigated between March 2001 and July 2001, which is before and after the heavy rain period. The measurements covered the following parameters: pH, conductivity, TDS, nitrate, nitrate-nitrogen, total organic carbon (TOC), chemical oxygen demand (COD) and salinity (see Table 4-9). A total of 24 boreholes located within and around the central Dar es Salaam area were sampled at least once per month. Specific areas covered in the assessment were City Centre, Ilala, Buguruni, Upanga, Kurasini and Keko. At least three representative boreholes were selected from every area for quality analysis. The analysis was done at the Chemical and Process Engineering Department at the University of Dar es Salaam, using laboratory equipment purchased for the research. The conductivity, TDS and salinity were measured in-situ using Hach meter. The nitrate, nitrate-nitrogen, TOC and Cod were determined using Dr. Lange's (Germany) analysis kit. These analyses are all in accordance with the Standard Methods for Analysis of Water and Wastewater. Table 4-8 shows the average values of parameter concentrations during the whole period of measurements.

The results show that there was compliance with TTS in terms of conductivity and TDS. However, the NO_3 and NO_3-N concentrations showed marked variations both spatially and temporal. Areas of Ilala and Buguruni showed elevated levels of up to 151.3-mg/l nitrate (Ilala or Karume Stadium). The Keko and City Centre areas also showed relatively high nitrate concentrations for example, National Stadium borehole had 108 mg/l and Mnazi Mmoja 74.3 mg/l. The variations over a period of four months before and after the heavy rain season were demonstrated through five boreholes (Msimbazi centre, Uhuru Primary School, Ilala Hospital, Kurasini Primary School and Ilala DAWASA) data as shown in Figures 4-12. The nitrate variation graph in Figure 4-12 shows a concentration decrease in May and again rapid increase in July. The fast response to the rains may indicate that much of the water is obtained from the unconfined aquifer. The elevated nitrate values in urban set-up are an indicative of anthropogenic pollution, mainly from domestic sewage disposal (Barrett *et al*., 1999) and urban agriculture. The dynamics to which the aquifers are contaminated to such an extent are not yet known, since there is no clear understanding of the aquifer systems in the city. However, there were very small corresponding variations in TDS as indicated in Figure 4-13.

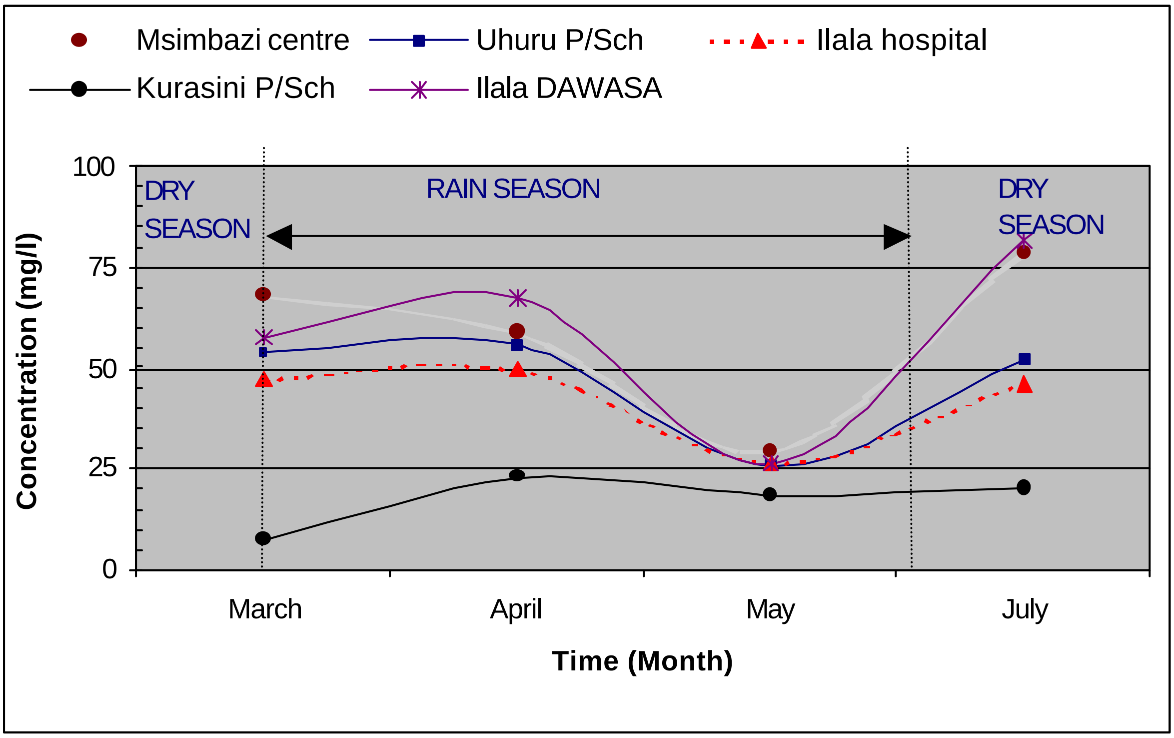

Figure 4-12: Nitrate concentration variation in city centre and adjoining urban areas, Dar es Salaam, March-July 2001

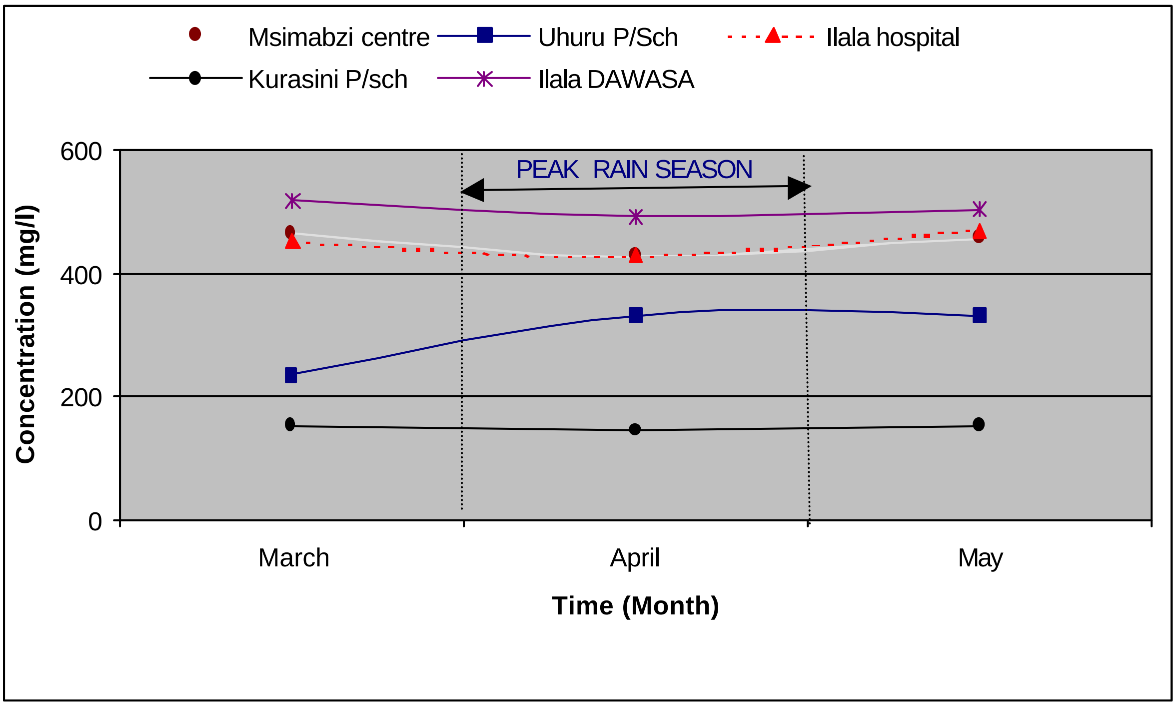

Figure 13: Total dissolved solid concentration variation in city centre and adjoining areas in Dar es Salaam, March-May, 2001

Examination of nitrate concentration data for the period from March to December showed interesting results as shown in Figure 4-14. The data were collected at three different periods: March –July 2001 (for ares of City Centre, Kariakoo, Ilala, Buguruni, Keko, Kurasini, and Upanga), October 2001 (for areas of Ubungo, Manzese, Magomeni, Mabibo, Mburahati, Mwananyamala and Kinondoni) and December 2001 (samples picked to cover the entire Dar es Salaam urban area). The results indicate that over 15% of the samples had nitrate values exceeding 100 mg/l, the Tanzanian limit. About 30%, exceeded the WHO recommendation on nitrate levels in drinking water of 50 mg/l. Also, 30% of the samples had nitrate concentration range of 20-50 mg/l, a level that is below the health guidelines, but to some extent indicate aquifer deterioration. On average only 40% of the samples had nitrate concentration below 20 mg/l, while 60% had above. The results are good indication that the aquifer has started to erode (Freeze and Cherry, 1979 reported a nitrate concentration of 10 mg/l in uncontaminated aquifers).

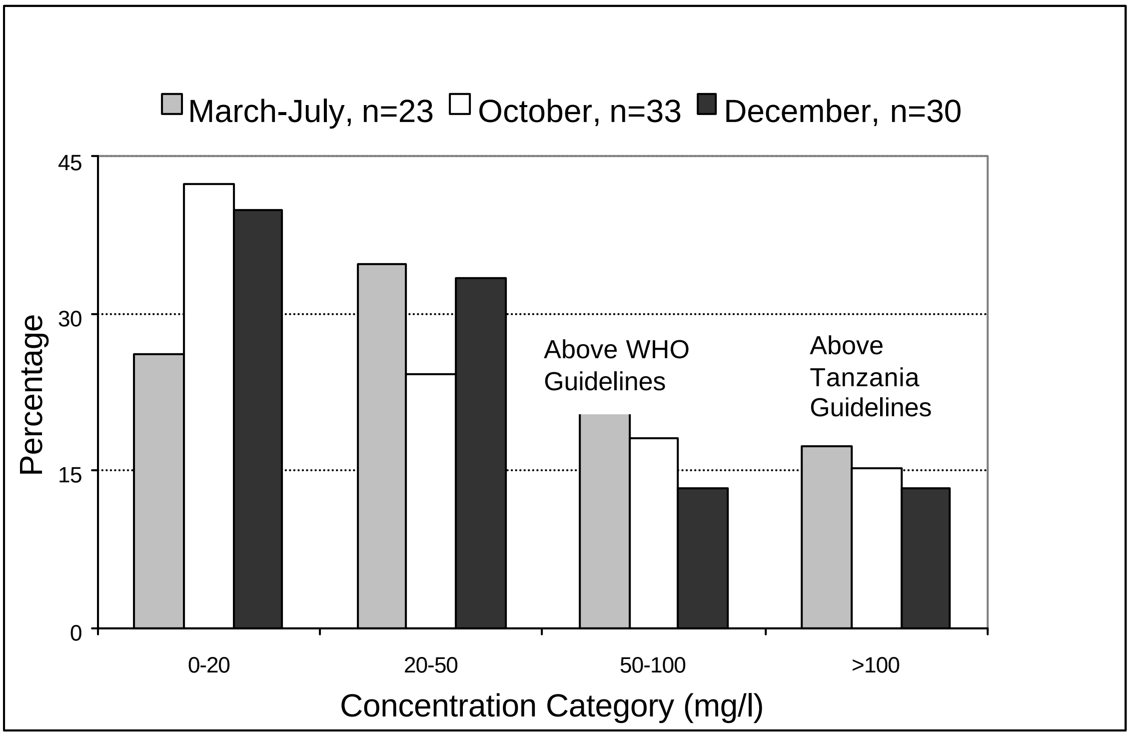

Figure 4-14: Nitrate concentration variation in selected boreholes in Dar es Salaam City, March – December 2001.

Although there are no conclusive results on other pollution indicators like TOC and COD investigated, the available data indicate poor situation. The organic carbon in fresh waters arises from living materials and also as a constituent of many waste materials, peat and effluents. Consequently, TOC can be a useful indication of the degree of pollution in water. In groundwater, TOC is less than 2 mg/l while in surface waters the TOC is generally less than 10 mg/l, unless the water receives municipal or industrial wastes (Freeze and Cherry, 1979; Abertany, 1994). The TOC in municipal wastewater range from 10 – 100 mg/l depending on the level of wastewater treatment. The average TOC measurements varied from 1.6 mg/l (Private borehole in Ilala, on the bank of Msimbazi valley near TBL) to 26.1 mg/l (Ilala DAWASA borehole). The COD generally were below 10 mg/l, and many were found to be below 5 mg/l, which was the detection limit for the instrument used (see Appendix I). Relatively elevated values for TOC and COD were found in samples from Ilala and Buguruni boreholes. The presence of elevated levels of TOC and COD in groundwater, more than the normal or recommended values of 2 mg/l and 6 mg/l respectively. Because there exists substantial evidence, that pollution plume will reach the boreholes; it flicks an alarm for further groundwater quality deterioration in Dar es Salaam. This makes the health safety of drinking water abstracted from boreholes in Dar es Salaam questionable. More organic compounds characterization of the groundwater in the city is explain in Chapter 7.

4.5 Groundwater Quality Mapping

For rapid assessment of the spatial variations of the quality of groundwater, specific parameter maps were developed. The maps were developed as surface maps depicting spatial quality variations. The parameters mapped were electrical conductivity and TDS as shown in Figures 4-15 and Figure 4-16 respectively.

As depicted in Figure 4-15, over 70% of the city of Dar es Salaam, the groundwater is having electrical conductivity values of 1000-2000 ìS/cm, virtually indicating good water for domestic supplies. The southern part of the city, encompassing Mbagala, Yombo Vituka, Charambe and Vijibweni wards are within the low electrical conductivity zone of less than 1000 ìS/cm. Such low conductivity in water indicates low ionic activity, which may indicate less dissolved materials that would render the water unsuitable for domestic use. However, isolated areas of Manzese, Mwananyamala wards are under the high zone, with electrical conductivity values 2000-3000, which indicate increased ionic activity. In such waters, the concentrations of major ions (like Na^+, Mg^{2+}, Ca^{2+}, Cl^-, HCO_3^- and SO_4^{2-}) and minor ions (like NO_3^-, Fe^{2+}, K^+, F^-, and CO_3^{2-}) may be high, sometimes rendering the water unfit for uses like domestic supplies.

The total dissolved solids (TDS) map shows that over 60% of the city, groundwater has a TDS level of 500-1000 mg/l, a value indicating good fresh water. Again the southern parts of Mbagala, Yombo Vituka, Charambe and Vijibweni wards has TDS values of less than 500 mg/l, indicating very good freshwater that may be containing less pollution. But the northern coastline in Kawe ward and parts of Manzese and Mwananyamala wards are within the high TDS zones with TDS values 1000-2000 mg/l which indicate the water may have salty taste.

Table 4-9: Results of water quality analysis of samples collected from selected boreholes in Dar es Salaam, March-July 2001

BH/NO	Location	pH	Conductivity µS/cm	TDS mg/l	NO_3 mg/l	NO_3-N mg/l	TOC mg/l	COD mg/l	Salinity %o
	City Centre								
	Mnazi Mmoja	7.1	1009	477	74.3	16.9	-	11.4	0.5
	Gerezani	7.1	1253	607	58.3	14.1	-	-	0.6
	Dar es Salaam Technical College	7.0	194	92	7.9	2.8	9.3	5	0.1
	Ilala								
	Msimbazi Centre	6.9	963	461	29.4	7.2	3.4	2.2	0.5
	Uhuru Primary School	7.1	630	299	46.7	10.9	12.5	5.0	0.3
	TBL (Near main gate)	6.6	977	468	136	24.2	16.3	-	0.5
	Ilala –Msimbazi valley, near TBL	7.1	1289	630	26.2	6.2	1.6	-	0.6
	Ilala stadium	6.2	1084	525	151.3		7.1	5.0	0.5
	Ilala Boma	7.0	889	441	23.8	5.6	-	5.5	0.4
	Ilala DAWASA	6.6	1057	504	50.5	11.5	26.1	-	0.5
	Ilala Hospital	6.7	945	449	42.4	9.8	3.4	5.0	0.5
	Ilala Garden	-	691	330	24.7	5.8	2.3	12.9	0.3
	Msimbazi Primary School	-	888	425	28.4	6.6	-	-	0.4
	Buguruni								
	Buguruni Primary School	6.1	1228	613	120.9	27.4	12.3	8.4	0.6
	Buguruni Hostel	6.9	1892	931	100	22.1	-	20.7	1.0
	Upanga								
	Fire brigade	7.4	194	92	7.9	2.8	9.3	5	0.1
	Muhimbili hospital – football pitch	5.9	2111	1065	6.6	1.6	6.6	-	1.1
	Muhimbili hospital- maternity	-	912	441	40.4	9.2	-	-	0.5
	Kurasini								
	Kurasini Primary School	6.7	320	151	17.3	4.0	4.1	-	0.2
	Kurasini – near D.C. residence	-	817	397	11.4	2.6	-	-	
	Rainbow falls Ltd	-	570	283	38.6	8.8	3.0	8.2	0.3
	Keko								
	National stadium	6.0	667	318	108	24.3	5.4	6.9	0.3
	Chang'ombe T.T.C	-	669	310	93.7	21.3	8.2	-	0.3
	Police Kilwa Rd –near Chang'ombe								

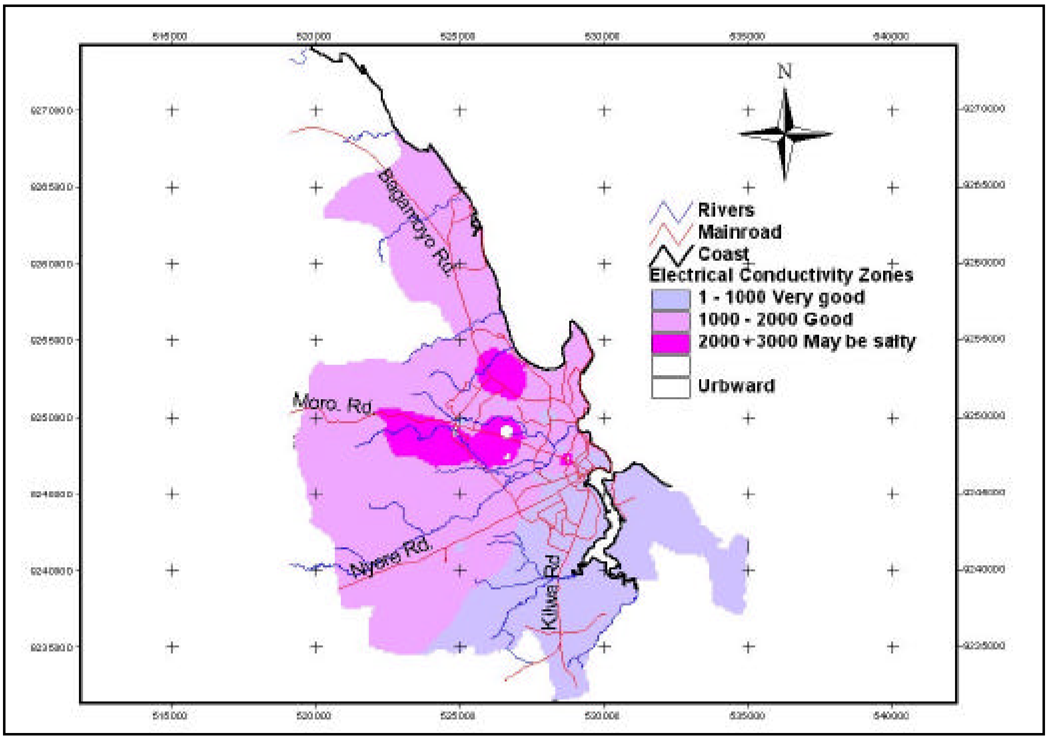

Figure 4-15: Spatial variation of electrical conductivity of groundwater in Dar es Salaam City (2001)

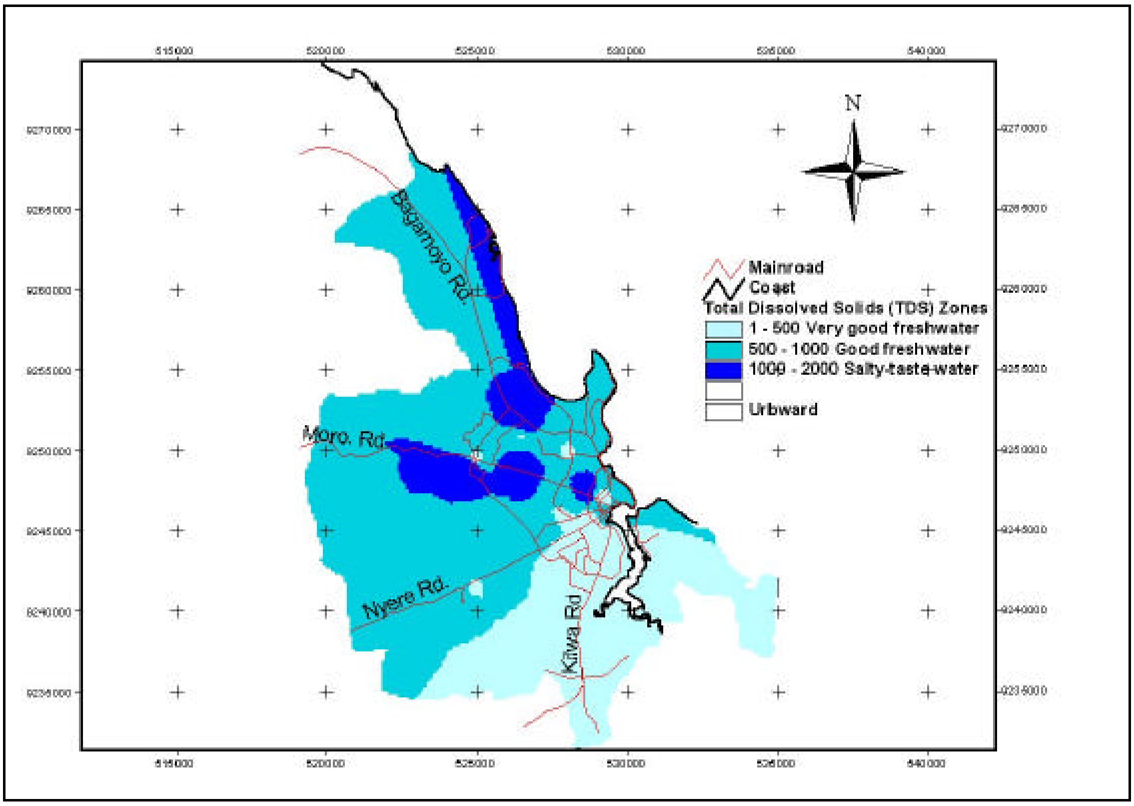

Figure 4-16: Spatial variation of total dissolved solids (TDS) concentrations in groundwater in Dar es Salaam City (2001)

4.6 Conclusion

From the preceding discussion, it may be concluded that:

- Dar es Salaam City receives inadequate water supply to meet only about 48% of the daily demand. About 50% of the demand is obtained from the groundwater sources through public and private boreholes, shallow wells and open hand dug wells, all drilled within the urban zone.
- Over 95% of the boreholes are drilled between 20-70 m deep, and it is the present active zone of groundwater abstraction. However, groundwater exploitation is by multiple layers including both unconfined and confined aquifer bands.
- About 35% and 7.5% of the boreholes have yield of 5-20 m^3/h and over 20 m^3/h respectively. A few patches of the city (e.g. Mbagala) have relatively high yield.
- The average static water level is 11.2 m.b.g.l, a depth within the unconfined aquifer.
- Riverbanks seem to be predominant areas of groundwater recharge. This implies that, the quality of surface water in the rivers has influence on that of groundwater in the city.
- An indicative picture of the hydrogeology of Dar es Salaam City has been developed, however it needs further studies
- The boreholes might be poorly constructed, therefore, allowing surface water inflows or tapping the water at pollution zones.
- The safety of the groundwater in Dar es Salaam is questionable. Exceedence in bacterial, chloride, nitrate and total organic carbon compounds threshold values have been observed. It is concluded that treatment of water abstracted from boreholes is needed before being supplied to consumers.

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Chapter 5

INFORMATION MANAGEMENT FOR GROUNDWATER: APPLICATION OF GIS

Abstract

Lack and poor management of data are among the major problems facing groundwater development in Dar es Salaam City. The groundwater data, which are very expensive to obtain, have been scarce, fragmented, and difficult to access. Microsoft Access and ArcView (version 3.1) GIS software have been used to create databases for non-spatial and spatial groundwater data respectively. The raw data were collected from the Dar es Salaam Drilling and Dam Construction Agency (DDCA) records of boreholes drilled in the city, and more information was obtained by direct measurements. The borehole number has been identified as a primary key, which has been used as a unique entity in the databases. More than 500 boreholes have been entered in the non-spatial database. By applying GIS technology, a borehole map has been produced. The geo-processing with GIS software has also enabled production of groundwater maps depicting spatial variations of water quality and hydrogeological characteristics of the aquifers in Dar es Salaam. The information base laid down by this research promotes avenues for efficient information sharing as well as establishing a structured footing for drawing up groundwater management and protection strategies. The map overlays can be useful in the Environmental Impact Assessment (EIA) of development projects that can potentially affect groundwater resources in Dar es Salaam. The databases can easily be expanded to include many more entities and attributes or overlays, therefore, they form a groundwork for developing a master database of groundwater resources not only for the City but also for Tanzania as a whole.

5.1 Introduction

Groundwater data, in both temporal and spatial characteristics, formed the basis of assessment work of this research. Thus data collection and creating spatial databases were a critical and time-consuming part of the study. This chapter is devoted to data management, especially the application of GIS technology.

Geographical Information System (GIS) is a computer- based tool for organizing, storing, manipulating, retrieving, and displaying spatially related information

(Corwin *et al*, 1997; Loague *et al*., 1998; Burrough and McDonnell, 1998). It is an interdisciplinary and multidisciplinary functional working tool used to provide management information or to develop a better understanding of environmental relationship. GIS technology is characterised by its ability to integrate layers of spatially referenced information, having a great diversity of applications (Maguire, 1991). GIS has increasingly been used for water and environmental problems such as water quality prediction (Golojuch, 1994), water management (Tremblay, 1994 and Barbera *et al*, 1994) and impacts to and vulnerability of groundwater resources (Civita and De Maio, 1997; Navulur and Engel, 1997; Yang *at al*, 1999; Ducci, 1999). Other fields that have been in extensive use of GIS technology include agriculture, rangeland management, forests, environmental management and land use planning to mention just few.

Burrough and McDonnell (1998) referred to Geographic Information Systems as a special software that supports operations like data input, data storage and database management, data output and presentation, interaction with the user and spatial data analysis (see Figure 5-1). Data input covers all aspects of capturing spatial data from existing maps, field observations, and sensors (including aerial photography and satellite) and converting them to standard digital form. The data input subsystem is needed to build a geographical database. Data storage and database management refers to the way in which data on location, spatial linkage, and attribute of geographical elements are interrelated. Data output refers to the way the data are displayed and how the results of analyses are reported to the user. Data may be presented as maps, tables and figures (graphs and charts) in a variety of ways. Spatial data analysis is what differentiates a GIS from a general Data Base Management Systems (DBMS). DBMS are computer programs for organising and managing the spatial and non-spatial database. This makes data quickly available to multitudes of users while at the same time maintaining its integrity by protecting the data against deletion and corruption, and facilitating systematic addition, removal, and updating of data as necessary. GIS specifically uses Relational Database Management System (RDBMS) that stores data in tabular form.

A GIS can be used to characterise the full information content of spatially variable environmental data, thus providing resource managers with a good avenue in decision-making process. In its infancy GIS was primarily used to create inventories of natural resources, but nowadays GIS has become a standard tool for environmental analysis and impact assessment (Loague *et al*, 1998). Recent advances of computing technology have made it possible to couple GIS and environmental models. When GIS and environmental models are coupled, they provide an efficient means for handling the complex spatial and temporal heterogeneities of the earth’s surface and subsurface (Corwin, *et al*., 1998). However, enhanced spatial data servers resting on extended RDBMS are needed as a means by which vast volumes of data necessary as input into that model can be efficiently supplied to the end user. Enhanced GIS technology softwares such as ArcView GIS and ILWIS enable users to customise a user friendly GIS to their specific applications. Embedded spatial data analysis and GIS technology enables an environmental model and a GIS to function as another program in itself.

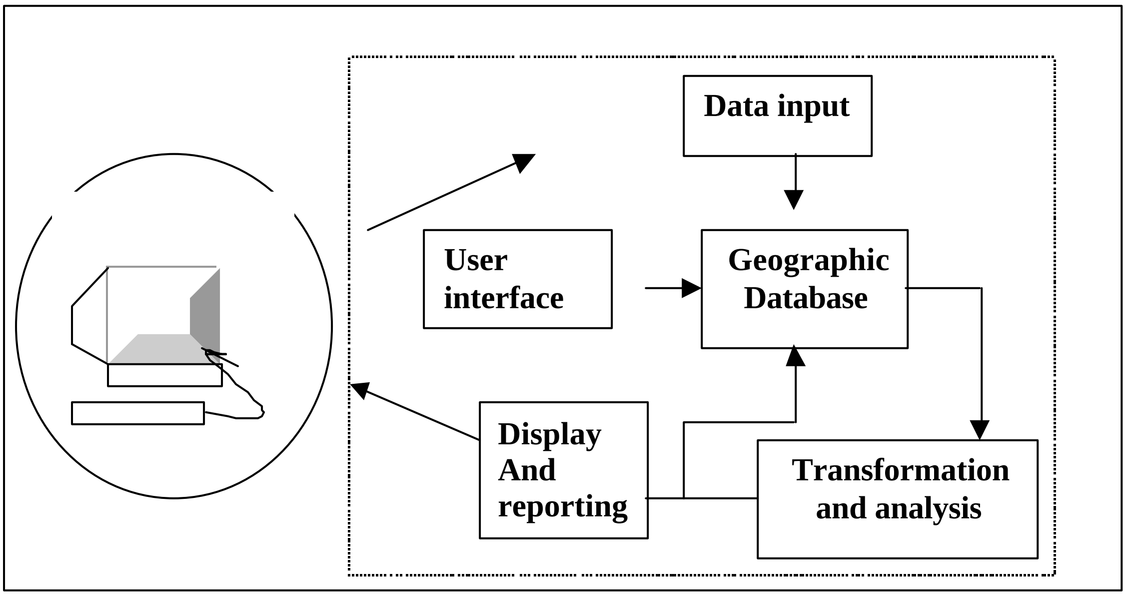

Figure 5-1: The main components of a GIS (cited in Ngereja, 2000)

In Tanzania, GIS is still new but growing in application. The Ministry of Lands and Human Settlements (specifically, the Mapping Division) has adopted the technology for physical mapping purposes. Other institutions using GIS technology are the Institute of Resource Assessment (IRA), University of Dar es Salaam, Geo-Centre at the University College of Lands & Architectural Studies (UCLAS) and Info Bridge (private company), Ministry of Natural Resources and Tourism, Dar es Salaam City Council, the National Environment Management Council (NEMC) and the Ministry of Water (Maji-Ubungo). The Geo Centre at UCLAS has commanded a lead in training both students and professionals in the GIS technology, including application in environmental impact assessment. A project named EISCAP; a collaborative effort between UCLAS and ITC, Enschede, The Netherlands (from mid-nineties) provided the basic infrastructure and software. This research, also received assistance in GIS from the EIASCAP project. Increased use of GIS in Tanzania can improve the existing situation of data scarcity, fragmentation and inaccessibility. With the pace of development and environmental awareness in Tanzania, there is increasingly demand for quick availability of environmental information that may help in decision-making.

5.2 Existing Data Management

Probably the basic issue that frustrates efforts toward proper groundwater resource protection in the city of Dar es Salaam (and Tanzania in general) is poor data management. The existing data on groundwater is scarce, fragmented and many times incomplete (Kongola *et al*., 1999). In many occasions the same data has been collected by a number of users/researches using huge amounts of money unaware that the data was already available. Information on groundwater in Dar es Salaam is mainly obtained from borehole drilling records. The DDCA at Maji-Ubungo keep much of the information on groundwater. This agency was previously a government department within the ministry of water until 1999. Other private drilling companies do keep the data of boreholes they drill. The Water Laboratory, Maji-Ubungo and Soil Testing Laboratory, both government entities within the Ministry of Water, keep records of water quality and soil results of samples analysed respectively. The Dar es Salaam Water and Sewerage Authority (DAWASA) keeps record on sporadic monitoring activities of boreholes connected to the main water reticulation system. There is no central location or institution that collects the hydrogeological data, though the Division of Water Resources in the Ministry of Water have the mandate to do so. Much of the data are kept in paper files and in some cases, these data get lost, and at many times become difficult to access it by searching through old paper files. In addition, the data record format and means of obtaining them are different as each organisation has its own way of keeping such information. For the case of DDCA, each borehole has a paper file, in which the drilling report is kept. Table 5-1 and Table 5-2 show examples of groundwater record formats by DDCA and Water Laboratory, Ubungo. The boreholes data include depth of drilling, static and dynamic water levels, draw down, yield and quality of the water. These are quite valuable data with regard to groundwater development and management in the city, which should not be kept in. in flat files only. The Section of Information Management within the Ministry of Water (located at Maji-Ubungo yard, Dar es Salaam) has started to computerize the boreholes records within their jurisdiction. How and to what extent is still not publicly known. The fact that it is very expensive to acquire groundwater data, the use of modern technology in managing the little data available becomes crucially important. The use of GIS technology in managing groundwater in Dar es Salaam will increase data sharing; while at the same time provide fast data processing capabilities. However, much of the borehole data presented in this book were made available by the DDCA. This study has developed GIS databases that allow groundwater to be recorded, updated, managed and displayed.

5.3 Data for GIS Application

5.3.1 Objectives

The main objectives of applying GIS technology were:

- To develop a database of boreholes in Dar es Salaam featuring their spatial distribution, hydrogeological data and water quality characteristics; and use the database for future groundwater pollution monitoring purposes.
- To improve the conditions and opportunities for information sharing in the area of groundwater development and management in Tanzania.

Table 5-1: Example of borehole drilling records stored by DDCA (1997)

S/N	B/H No.	LOCATION	DISTRICT	RIG.#	DEPTH (m)	SWL (m)	DWL (m)	D/D (m)	YIELD (m3/h)	COND. (uS/cm)	COMM DATE	COMPL. DATE
1	8/97	Ukonga Booster	Ilala	44	76	4.8	-	-	3	1200	120197	250197
2	9/97	Segerea I	Ilala	52	54	4.6	13.8	9.1	14.4	840	220197	70297
3	12/97	Police College K/Rd	Temeke	44	38	4.7	7.8	3.1	24	540	280197	50297
4	13/97	MMC	Ilala	42	31	9.3	11.7	2.3	12	1900	120297	170297
5	14/97	Lugalo Barracks	Kinondoni	47	40	21	25.5	4.5	5	2200	140297	180297
6	15/97	Mikocheni A	Kinondoni	5	14	9	-	-	1.2	-	220297	270297
7	16/97	Tabata - Kisukulu	Ilala	28	35.5	7.4	-	-	2.1	3900	130297	190297
8	19/97	Fire Brigade	Ilala	42	44	7.9	-	-	15.9	8000	190297	220297
9	20/97	Nzasa- Mbagala II	Temeke	44	48	3.7	8.9	5.2	32.7	250	140297	200297
10	21/97	Ubungo- Maji	Kinondoni	28	70	30.2	63.5	33.7	4.2	-	210297	20397
11	22/97	Chang'ombe TTC	Temeke	44	40	9.7	15.7	6	19.8	650	220297	260297
12	24/97	Mikocheni B	Kinondoni	26	13						250297	20397
13	25/97	Buguruni Hostel	Ilala	47	28	7.4	15.8	8.4	2.3	1500	200297	230297
14	27/97	National Stadium	Temeke	31	40	6.1	-	-	5.6	800	200297	250297
15	28/97	Ilala Boma	Ilala	47	30	9.2	12.6	3.4	15.2	940	240297	270297
16	29/97	Magomeni Garden	Kinondoni	44	48	1.9	6.2	4.2	26.4	1000	270297	20397
17	30/97	Dar Tech College	Ilala	42	50	6.4	7.2	0.8	26.4	1350	240297	280297
18	31/97	Uhuru P/S	Ilala	46	42	9.1	14.6	5.5	15.8	820	250297	30397
19	32/97	M'nyamala Hospital	Kinondoni	31	42	8.5	-	-	8.8	1100	260297	10397
20	33/97	Police Barracks	Temeke	46	50	10.9	15.8	4.9	19.8	540	190297	240297
21	35/97	Kiwalani CCM	Ilala	52	28	8.9	9.8	0.9	14.1	750	30397	170397
22	36/97	Air Port	Ilala	47	60	5.9	-	-	1.3	1490	20397	70397
23	37/97	Kinondoni P/S	Kinondoni	31	30	5.7	7.5	1.5	22.6	1690	30397	90397

Table 5-2: Example of water quality analysis records from Water Laboratory, Maji-Ubungo (1997)

B/H	DATE	LOCATION	DEPTH (m)	COLOUR (mg/l)	Ph	CONDUCTIVITY (mS/cm)	CHLORIDE (mg/l)	PV (mg/l)	REMARKS
63/97	290397	Tabata P/S	37	-	6.9	2500	600	5.4	Good
98/97	290397	Keko Gerezani	52	6	8.4	5900	994	13.6	Saline
?	280397	Tacona, Ilala	-	-	7.3	990	74.6	2	Good
?	150397	M'mala Kisiwani	30	4	8.6	1550	121	3.2	Good
56/97	150397	Amana Hosp	50	2	7.8	1000	142	3	Good
53/97	150397	Maji-Temeke	27	2.5	6.6	720	96	2	Good
?	230397	Sasaba Ground	32	5	7.9	800	56.8	1.8	Good
67/97	220397	M'mala P/S	36	2	8.6	1670	167	3.4	Good
64/97	230397	RTD-Nyerere Rd	22	10	8.4	420	43.3	2.4	Good
66/97	220397	Kigogo P/S	28	-	8.5	1900	121	4.2	Good
59/97	240397	Kipawa P/S	51	6	7.7	750	128	4	Good
68/97	240397	K'nyama AliMaua	50	2	8.6	4500	667	5.4	Saline
16/97	180397	Tabata Afri.Islamic	35.5	55	7.5	220	29.1	2	Questionable
37/97	90397	Kinondoni P/S	30	2	8.1	1690	76.7	2.8	Good
57/97	170397	K'nyama Ali Maua	36	13	8.5	1060	68.9	2.6	Good
35/97	150397	Kiwalani CCM	28	7	7.1	1620	351	4.6	Good
39/97	90397	Kigogo Mwisho	33	5	7	1210	234	3.2	Good
36/97	70397	DIA	60	17	8.3	1490	55.4	6	Good
26/97	40397	T.Brew./TANESCO	46	-	7.8	1320	153	4	Good
?	30397	Yombo-Dovya	-	-	2.1	500	19.9	3.6	Good
31/97	30397	Uhuru Girls P/S	42	-	8.3	950	78.1	1.6	Good
?	50397	L. Tumbo Mabibo	-	-	6.8	4800	263	3.8	Saline
?	50397	K. Mskitini Mabibo	-	-	6.4	690	49.7	2.6	Good

5.3.2 Data collection

The first stage in the development of GIS database consisted of the identification, evaluation and collection of various data sets. Data collection covered all aspects of capturing spatial and attribute data from existing maps, previous studies and field observations using various sensors and converting the data into digital form for input into a spatial database. Largely this study was carried out using information collected from previous work and field observations by staff of the DDCA. The attribute data consisted of basic hydrogeological information, physical water quality and chemical water quality. Other information was collected by actual measurements (collecting samples from the field and determining parameters in the laboratory at the Chemical and Process Engineering Laboratory at the University of Dar es Salaam – this has been explained in Chapter 4).

The DDCA boreholes data was found to be lacking geographical positions information (coordinates of spatial entities), which is a key input for GIS analysis and mapping. The geographical references of boreholes were determined using a hand held Global Positioning System (GPS) receiver (Garmin II plus Personal Navigator version 3.0). GPS is a new technology that uses geo-stationary satellite to define the position at any point on the globe (Goodchild, 1991). The GPS instrument was used to determine the spatial location of the boreholes in the UTM grid system (giving Eastings and Northings values). The GPS precision is 5-15 metre as per manufacturer's specification. The actual accuracy was determined by making observations of known reference points (benchmarks) at UCLAS and compared the results with the actual coordinates. The results are given in Table 5-3, where an accuracy of 20-60 m was obtained. This accuracy was considered adequate for the research in view of the fact that there was no existing map showing the boreholes locations and that other alternatives would be very expensive, beyond financial capability of this research. The actual field observations were done by locating each borehole for the purpose of inspecting it physically and fixing its position. The records (hydrogeological data) of the boreholes located were then searched in the DDCA’s archives (paper files) at Maji Ubungo office. Spatial locations of more than 200 boreholes were captured, some of which are shown in Table 5-4.

Table 5-3: Accuracy of the GPS handset receiver

Point	Known coordinates at UCLAS		Observed coordinates		Difference	
	Northings (N)	Eastings (E)	Northings (N)	Eastings (E)	N	E
GPS5	9252112.333	523684.169	9252140	523648	28	36
GPS6	9252152.564	523504.997	9252180	523554	38	50
CA8	9252517.220	523760.600	9252567	523815	50	55

Table 5-4: Example of geographical locations pick with GPS handset for boreholes in Dar es Salaam City

S/N	BH #	NAME	EASTINGS	NORTHINGS
1	21/97	Ubungo Maji Yard	522651	9249670
2	193/2000	Ubungo Mwisho TANESCO	522423	9249388
3	66/2000	Ubungo Darajani	522825	9249034
4	17/2000	Riverside Amoni Enterprise	522813	9248836
5	130/90	Ubungo External (Mr. Kisango)	522843	9248274
6	008/2000	Ubungo Marian Faith	522643	9248466
7	363/98	Ubungo Islamic High School	522560	9248125
8	570/99	Ubungo-Kibangu (Mrs. Pembe)	522758	9248424
9	391/2000	Ubungo Bus Stand	523131	9249563
10	319/2000	Ubungo (Dr. Mbawala)	523178	9249630
11	217/2000	Ubungo NSSF	523461	9249357
12	253/2000	Manzese (Japanese)	525614	9248616
13	281/2001	Manzese Tandale (Mr.Chocks)	526344	9249141
14	379/99	Manzese - Tandale (Mr.Mbegu)	526352	9249234
15	011/99	Manzese - Tandale Dispensary	526177	9249028
16	557/99	Manzese - Tandale (Mrs. Tilya)	526485	9249013
17	103/98	Manzese - Tandale Msikitini	527061	9249091
18	198/2001	Magomeni (R.Yusuph)	527630	9248507
19	181/99	Magomeni Kigera Mahiwi	527283	9248735
20	009/98	Mburahati Dispensary	526738	9248062
21	227/2001	Mburahati (Ms. Mashu)	526785	9247059
22	162/2001	Mburahati Kisiwani	526476	9246856
23	78/2001	Mburahati KKKT	526218	9247330
24	259/2000	Mburahati (Maria Alex)	526039	9247536
25	357/98	Mburahati (Gaspa)	525863	9247548
26	258/99	Mburahati (Mashoto)	526152	9247617
27	258/2000	Mburahati (Ofisi ya Kata)	526194	9248035
28	257/2000	Mburahati (M. Nassoro)	526250	9248035
29	82/2000	Manzese Maryland Bar	526318	9248500
30	68/2001	Ubungo Fishnet	524045	9248904
31	461/2000	Mabibo N.H.C -P/Sch.	525063	9247053
32	258/98	Mabibo (Mashoto)	525766	9247791
33	272/99	Manzese (Mr. Gonza)	525980	9248308
34	61/2001	Manzese (Mama Temba)	525653	9249155
35	130/2001	Manzese (Friends Corner)	526618	9248766
36	142/2001	Manzese (Mr.Fidelis)	525444	9249505

5.4 Database Design and Creation

5.4.1 Overview

Database design was an essential step in creating a database suitable for storing all the boreholes information. This step involved determination of entities and their attributes and establishing the relationships between entities. It also encompassed data processing in which the entities and attributes were organised in a manner suitable for the groundwater pollution database.

A database is a collection of information about things and their relationships to each other stored in a structured manner (Aronoff, 1989). For the purposes of managing and analysing the boreholes data a relational database was designed using the entity relationship (ER) modelling. The ER model facilitates the precise characterisation and documentation of all-important relationships and attributes of an object, event or concept for the purposes of storing them in a database. The Microsoft Access (MSA) software, which is essentially a RDMS, has been used. The MSA stores and retrieves data, presents information, and automates repetitive tasks. The MSA has the advantage of having many in-built functions that help in developing a variety of tasks such as creating queries, forms reports and links between programmes. It has also a data validation rules to prevent inaccurate data regardless of how data is entered (Prague and Irwin, 1997). The MSA was sufficient to enable to fulfil the aim of the research to create a simple and expandable database to help in proper keeping of the little but valuable groundwater records available at the moment.

5.4.2 Identification of entities and attributes for non-spatial database creation

Computers keep information in terms of files. When files are logically connected, they form a database. A database was designed based on the attribute data and spatial data collected. The database contains information of all groundwater information collected (encompassing boreholes, groundwater pollution sources like fuel filling stations and garages). Professional judgement was used in identifying the entities and attributes which are relevant to groundwater management in City of Dar es Salaam.

An entity is an object, event or concept that contains attributes that are important to store in a database. Entities for the pollution database were determined from existing information i.e. from paper records of the boreholes made available by DDCA. The following are entities identified from the analysis of existing information boreholes number, rig number, testing results, casing type and locations, screens, lithology and water quality. Computer files (boreholes log file, drilling file, testing file, casing, screen, stratum and water quality) were created.

Each entity in the database has a number of characteristics. These characteristics are known as attributes. Each attribute will have a given domain and range of possible values which constitutes its value-set. An attribute that exclusively identifies a record was taken as a primary key. This was used to uniquely to describe and locate a record in the database. The Entity Relationship Diagram (E-R-D) was used to identify relationships between the identified entities. A relationship is an association established between common attributes in two tables, and can be one-to-one or one-to-many or many-to-many. One-to-one is an association between two tables in which the primary key value of each record in the primary table corresponds to the value in the matching field(s) of one and only one record in the related table. One-to-many is a relationship between two tables in which i) the primary key value of each record in the primary table corresponds to the value in the matching field(s) of many records in the related table or ii) the primary key value of each record in the related table corresponds to the value in the matching field(s) of one and only one record in the primary table. The many-to-many relationship is an association in which the entities involved have multiple links, that is, for each entity there are many occurrences of the other. Figure 5-2 depicts the identified entity relationships, which reveals that borehole number is a primary key for the database. The corresponding attributes are also presented in Table 5-5.

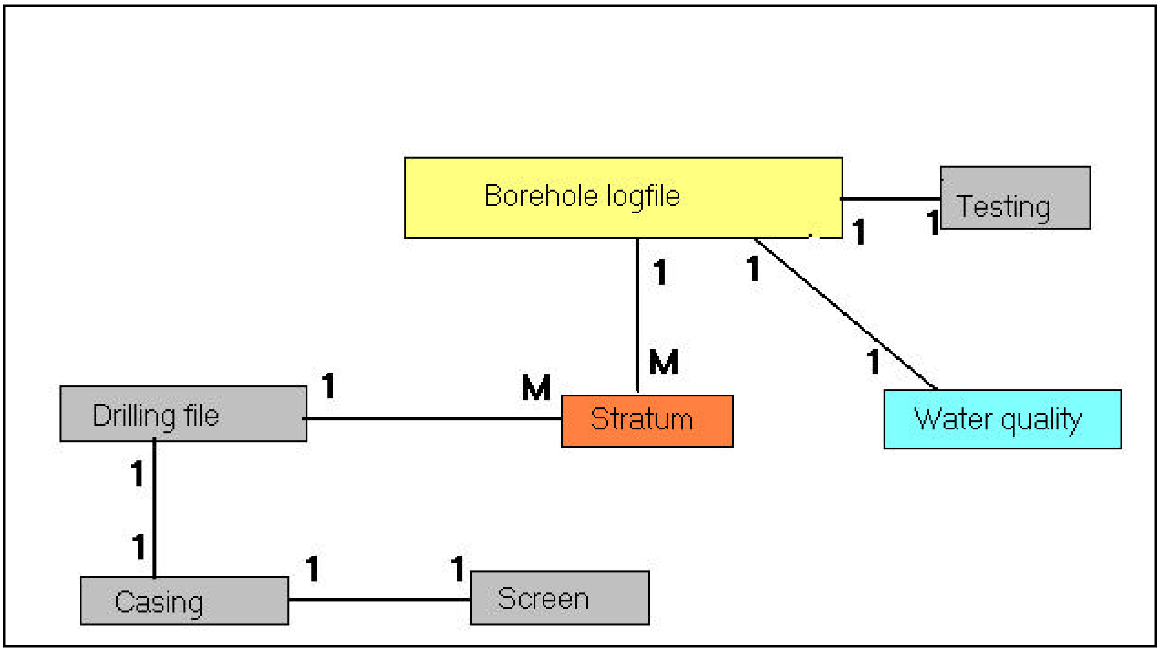

Figure 5-2: Entity Relationship diagram for borehole data in Dar es Salaam

The resulting database framework given in Table 5-5 keeps track of information pertaining to the same borehole by using the borehole number as an index. The Borehole number is therefore a common key used to couple the non-spatial attributes (e.g. hydrogeological and water quality data) and the geographical location (GPS coordinates). The possibility to use the borehole number, as a relational database key is very feasible and strong since it is a unique number supposed to be issued by the Water Resources Department of the Ministry for Water. Although the private drillers (due to inadequate regulation) are violating this, the number can still effectively identify a borehole in the whole database. In addition, the borehole database created can easily be expanded to include records of future groundwater exploitation and quality monitoring (Figures 5-3). It is user friendly, and specific information on boreholes can be retrieved through queries embedded in the database.

Table 5-5: Entities and respective attributes for borehole database creation

Entity	Attribute
Borehole log file	***Borehole ID number****, Northings and Eastings
Drilling file	***Borehole ID number****, locality, District, Rig No, Borehole Depth, Start Height, End _Height, Date commence, Date of completion
Testing file	***Borehole ID number****, SWL, DWL, DD, Quantitative Yield_m^3/h, Qualitative Status
Casing file	***Borehole ID number****, Casing type, Casing diameter, Casing length, Bottom Protection
Screen file	***Borehole ID number****, Screen type, Screen diameter, Screen length
Water quality	***Borehole ID number****, Sampling Date, Total alkalinity, Carbonate hardness, Non-carbonate hardness, Total hardness, Calcium content, Magnesium content, Chloride content, Permanganate Value, COD mg/l, BOD_5 mg/l, PAHs, TOC, NO_3 content mg/l, NO_3 -N content mg/l, TDS mg/l, Turbidity_NTU, Colour_mgPt/l, pH, EC.uS/cm, Remarks
Stratum	***Borehole ID number****, ***Stratum ID****, Stratum Depth, Rock/Soil type, Texture, Colour, Description

*Notes: * Primary key, SWL-Static Water Level, DD – Draw Down. This table corresponds with entries found in Table 5-2 and Table 5-3.*

5.4.3 Development of spatial database

Once a successful link has been established between the entities and attributes in non-spatial database components the data can be integrated into a GIS for spatial visualisation purposes. The ArcView GIS software (version 3.1) was used for spatial analysis (ESRI, 1996). The spatial data (digital Dar es Salaam map layers – urban ward, main roads, coastline, rail, rivers and landforms) and the non-spatial database (explained above) were linked by the spatial location (geographical coordinates) of boreholes in the GIS (Figure 5-4). The digital map layers for Dar es Salaam City used in this research were obtained from the Geo-Centre at UCLAS (digitised from maps produced by the Ministry of Lands and Human Settlements, 1992). The non-spatial tabular data were first changed to dBase IV format before associating them with spatial data in the GIS. Following this association of spatial maps and non-spatial data (hydrogeological characteristics and water quality), a flexible and expandable groundwater spatial database for Dar es Salaam City was created (Figure 5-5).

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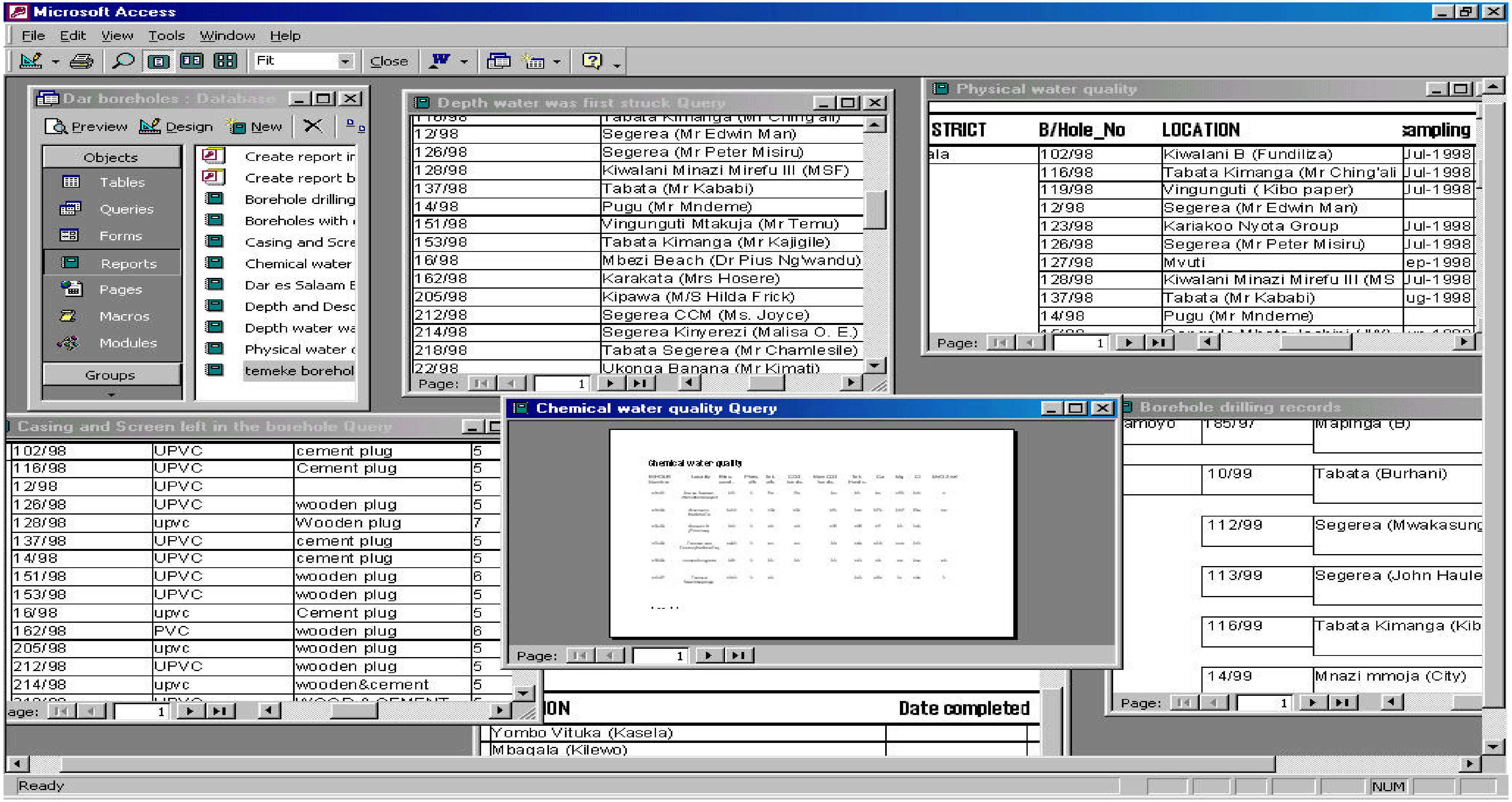


12/98	Segerea (Mr Edwin Man)
126/98	Segerea (Mr Peter Misiru)
128/98	Kiwalani Minazi Mirefu III (MSF)
137/98	Tabata (Mr Kababi)
14/98	Pugu (Mr Mndeme)
151/98	Vingunguti Mtakuja (Mr Temu)
153/98	Tabata Kimanga (Mr Kajigile)
16/98	Mbezi Beach (Dr Pius Ng'wandu)
162/98	Karakata (Mrs Hosere)
205/98	Kipawa (M/S Hilda Frick)
212/98	Segerea CCM (Ms. Joyce)
214/98	Segerea Kinyerezi (Malisa O. E.)
218/98	Tabata Segerea (Mr Chamlesile)
22/98	Ukonga Banana (Mr Kimati)

STRICT	B/Hole_No	LOCATION	ampling
ala	102/98	Kiwalani B (Fundiliza)	Jul-1998
	116/98	Tabata Kimanga (Mr Ching'ali	Jul-1998
	119/98	Vingunguti (Kibo paper)	Jul-1998
	12/98	Segerea (Mr Edwin Man)	
	123/98	Kariakoo Nyota Group	Jul-1998
	126/98	Segerea (Mr Peter Misiru)	Jul-1998
	127/98	Mvuti	ep-1998
	128/98	Kiwalani Minazi Mirefu III (MS	Jul-1998
	137/98	Tabata (Mr Kababi)	ug-1998
	14/98	Pugu (Mr Mndeme)	

102/98	UPVC	cement plug	5
116/98	UPVC	Cement plug	5
12/98	UPVC		5
126/98	UPVC	wooden plug	5
128/98	upvc	Wooden plug	7
137/98	UPVC	cement plug	5
14/98	UPVC	cement plug	5
151/98	UPVC	wooden plug	6
153/98	UPVC	wooden plug	5
16/98	upvc	Cement plug	5
162/98	PVC	wooden plug	6
205/98	upvc	wooden plug	5
212/98	UPVC	wooden plug	5
214/98	upvc	wooden&cement	5

10/99	Tabata (Burhani)
112/99	Segerea (Mwakasung
113/99	Segerea (John Haule
116/99	Tabata Kimanga (Kib
14/99	Mnazi mmoja (City)

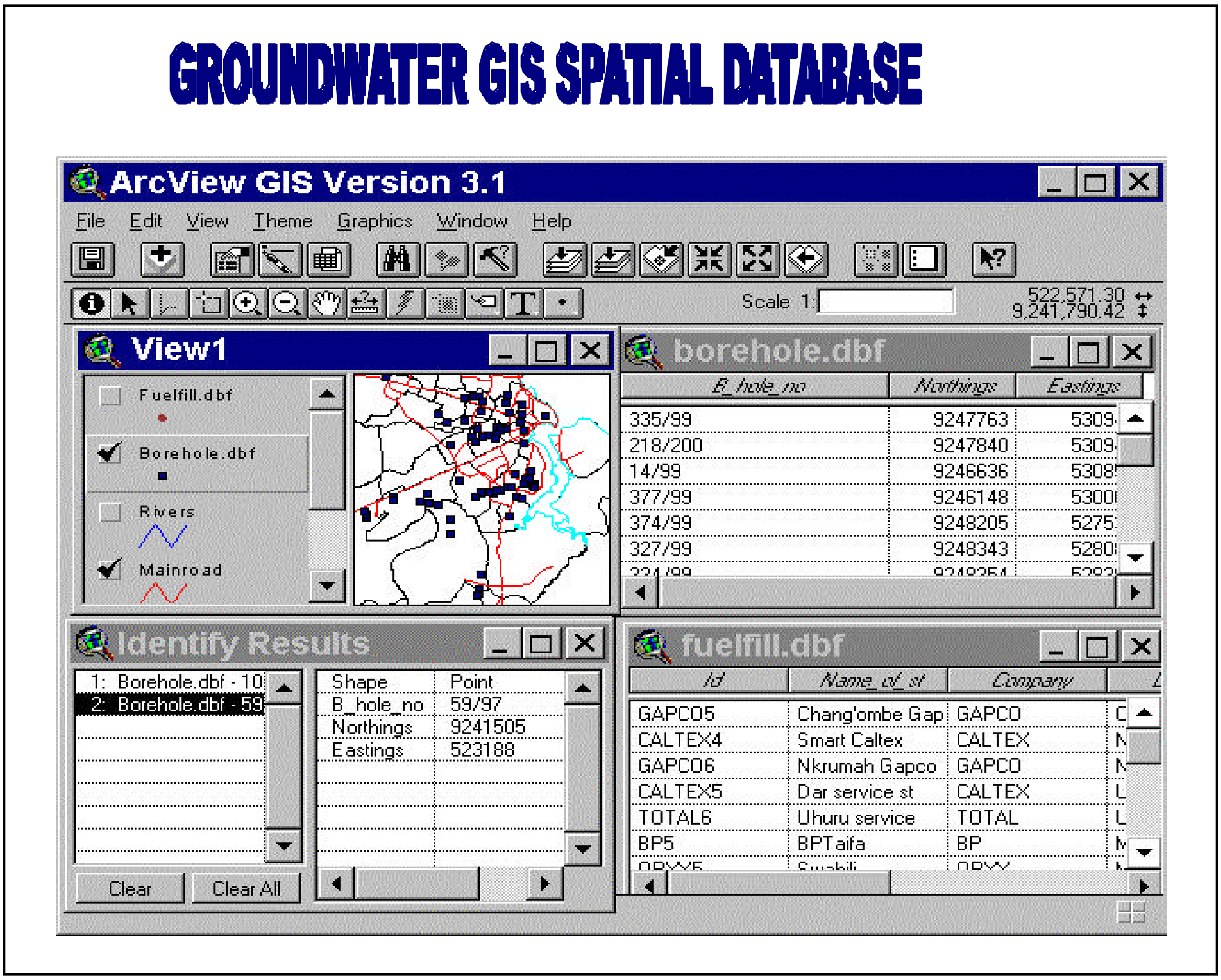
ION	Date completed
Yombo Vituka (Kasela)	
Mbagala (Kilewo)	

Figure 5-3: Non- spatial database establishment – Microsoft Access template

Borehole ID	Northings (X)	Eastings (Y)
106/97	9247386	528435
109/97	9246157	528285
110/97	9241993	528449

BoreholeID	Location	District	Rig No	Depth	SWL	DWL
106/97	Mzimuni Primary School	Kinondoni	41	46	9.7	15.5
109/97	Msimbazi Mseto Primary School	Ilala	41	35	10.24	23.85
110/97	Tandika Mwembeyanga	Temeke	44	58	2.7	9.17

Figure 5-4: Linking spatial locations and attribute data of boreholes



borehole.dbf

B_hole_no	Northings	Eastings
335/99	9247763	5309
218/200	9247840	5309
14/99	9246636	5308
377/99	9246148	5300
374/99	9248205	5275
327/99	9248343	5280

Identify Results

1: Borehole.dbf - 10
2: Borehole.dbf - 59

Shape	Point
B_hole_no	59/97
Northings	9241505
Eastings	523188

fuelfill.dbf

Id	Name_of_st	Company
GAPCO5	Chang'ombe Gap	GAPCO
CALTEX4	Smart Caltex	CALTEX
GAPCO6	Nkrumah Gapco	GAPCO
CALTEX5	Dar service st	CALTEX
TOTAL6	Uhuru service	TOTAL
BP5	BPTaifa	BP

Figure 5-5: Linking spatial and non-spatial data in a GIS

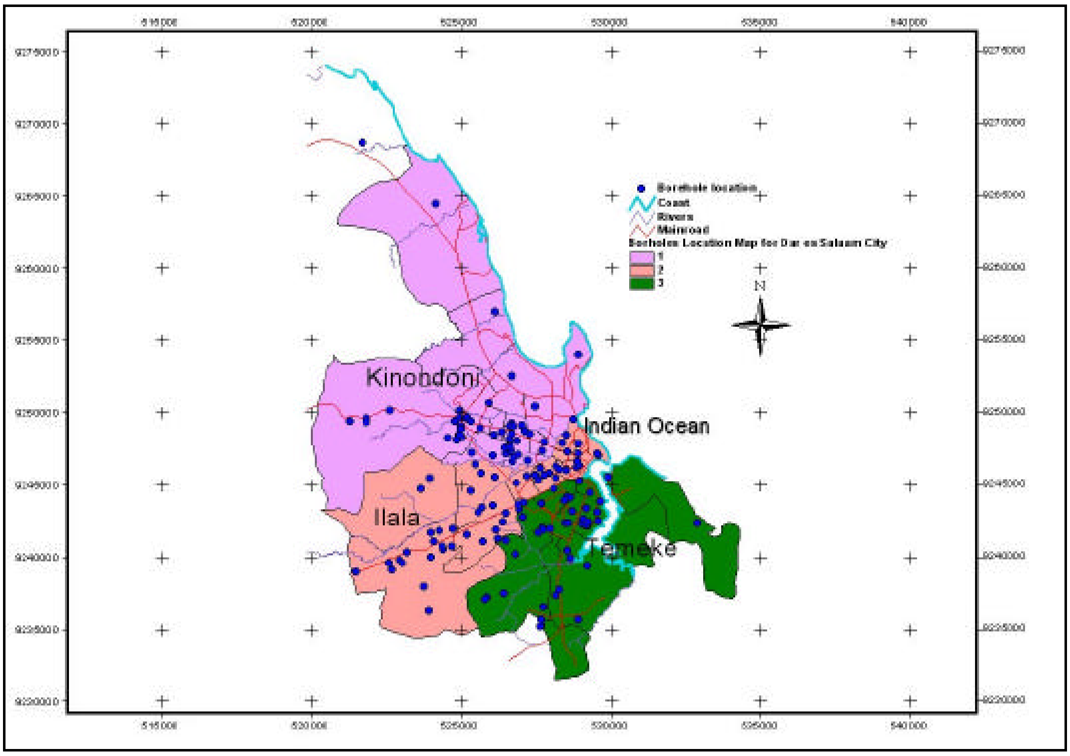


Figure 5-6: Boreholes location map for Dar es Salaam City (2001)

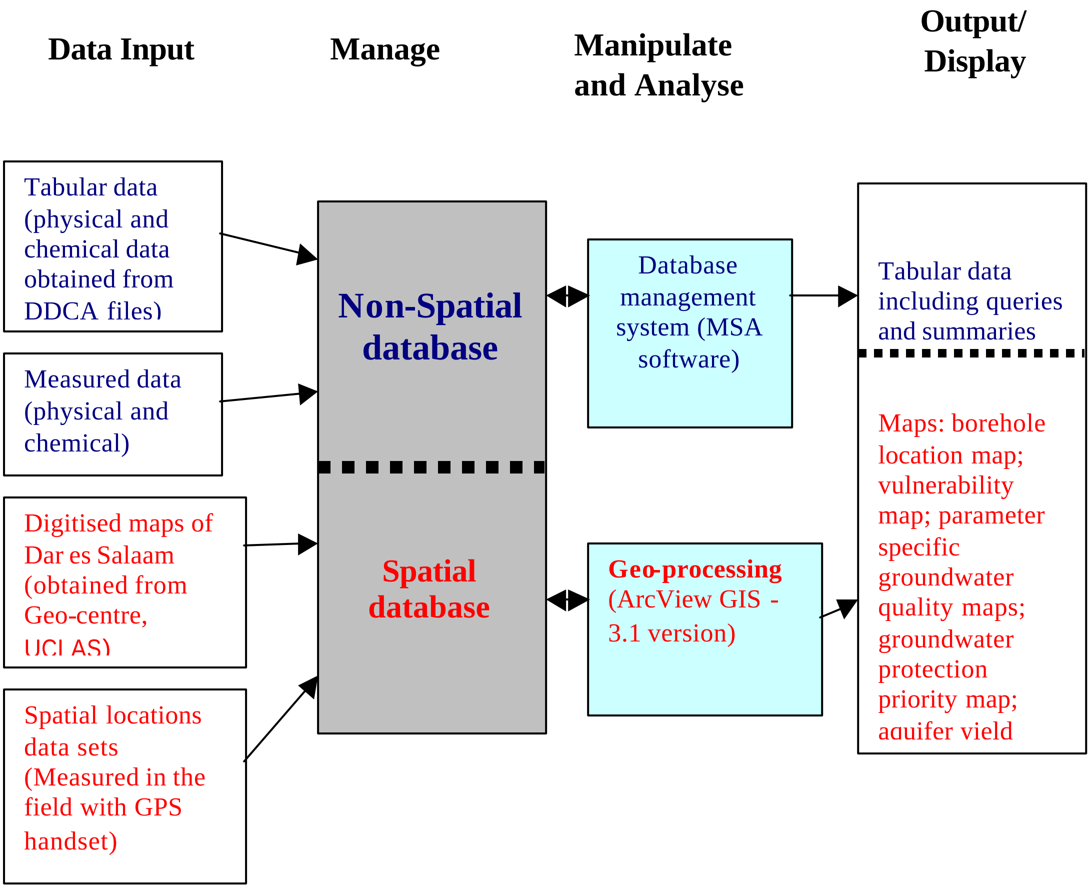


Figure 5-7: Overall database development scheme for Dar es Salaam City

5.4.4 GIS analysis

Establishment of the spatial database within the GIS provides a solid basis for manipulation of the various groundwater maps, whilst extensive field sampling provides an abundance of groundwater chemical data, which is stored in the non-spatial database. The spatial database created enabled mapping of different aspects of groundwater in the city of Dar es Salaam to be conducted.

Maps of part or the whole of Dar es Salaam featuring, for example spatial borehole distribution (Figure 5-6), nitrate concentration, chloride variation, aquifer yield, depth to groundwater etc (presented in Chapter 4) were developed. The GIS maps increased data visualization, which is needed to assist decision-makers pertaining to groundwater management and protection in the city of Dar es Salaam. For example, the boreholes location map enables to visualize the spatial distribution of boreholes within the different land-uses in the city. A user-friendly interface associated with GIS software was used to enable easy identification or retrieval of data on a specific borehole within the city. This is achieved by simply clicking on a selected well in borehole location map window. The number, location, hydrogeological and chemical characteristics are displayed (Figure 5-5). With the ArcView GIS software, it was easier, more flexible and more convenient to overlay, separate and modify the spatial maps. Figure 5-7 represents the overall database development scheme for Dar es Salaam City as adopted from USA National research Council (1993).

5.4.5 Coupling GIS with Environmental models and maps uses

The use of GIS in environmental modelling has proliferated over since the 1980s (USA-National Research Council, 1993; Napolitano, 1995; Corwin *et al,* 1997). Coupling of the created GIS database and DRASTIC model used to estimate groundwater vulnerability for the City of Dar es Salaam were established (details explained in Chapter 6) (Mato *et al,* 2001). The coupling can be categorised as a loose one, where data output from the DRASTIC model were subsequently transferred to the GIS, to produce vulnerability maps. Coupling of the DRASTIC model with GIS has enabled easy visualization of the intrinsic vulnerability of groundwater to pollution and susceptibility to petroleum hydrocarbon pollution (as detailed in Chapter 7) in Dar es Salaam City. The map overlays developed from the GIS data base can easily be understood by non-technical and technical groundwater stakeholders in the city (such as Councillors, Municipal planners, Land Managers, Engineers etc) and can be used as a guide in land use planning processes. The maps can also be useful in the Environmental Impact Assessment (EIA) of developments that can potentially affect groundwater resources in Dar es Salaam.

5.5 Conclusion

Information management on groundwater resources in Dar es Salaam has been improved by applying GIS technology. Historically data management had been fragmented and incomplete and difficult to access and retrieve; despite the huge sums of money used to obtain them. The information base laid down by this research has promoted avenues for efficient information sharing as well as establishing a structured footing for drawing up groundwater management plans. Both GIS spatial and non-spatial databases have increased groundwater data storage, retrieval and visualization capabilities. The map overlays developed provide good guidance for developing groundwater protection policies. They can also be easily understood by non-technical and technical groundwater stakeholders in the city (such as Councillors, Municipal planners, Land Managers, Engineers etc) and can be used as a guide in land use planning processes. The maps can also be useful in the Environmental Impact Assessment (EIA) of development projects that can potentially affect groundwater resources in Dar es Salaam. The databases developed for Dar es Salaam can easily be expanded to included many more entities and attributes or overlays, therefore, they form a basis for developing a master database of groundwater resources not only for the City but for Tanzania as a whole.

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Chapter 6

GROUNDWATER VULNERABILITY ASSESSMENT: APPLICATION OF THE DRASTIC MODEL

Abstract

Groundwater vulnerability assessment is increasingly applied in many parts of the world. It plays an important role in decision-making pertaining to management and protection of the groundwater resource. The groundwater vulnerability assessment for the city of Dar es Salaam using the DRASTIC model coupled to GIS was carried out. The groundwater vulnerability map was developed. The map shows that about 50% of the city falls under the high vulnerability zone. Industrial and high-density residential areas are all located in the “red zones”, that is, high and very high vulnerability classes. About 30 samples were taken from boreholes located in different vulnerability classes to verify the results of the DRASTIC model simulations. The nitrate concentrations in different vulnerability classes showed good correlation to the DRASTIC model predictions. Considering that over 90% of the Dar es Salaam inhabitants are using on-site sanitation facilities, nitrate levels in groundwater can be used as an indicator of aquifer quality status in the city, upon which pollution potential can be based. The groundwater vulnerability map developed for the City of Dar es Salaam marks a milestone in efforts to combat pollution of drinking water sources. The map can be used as a general guidance to groundwater pollution control strategies.

6.1 Introduction

6.1.1 Objectives

This chapter deals with Empirical Assessment Methodology (EAM), particularly vulnerability concept, which has been used to assess the potential of groundwater pollution in Dar es Salaam City. EAM is a groundwater modelling technique employed in cases of scarce data, and aims to identify "hot spots" with greater susceptibility to pollution. The DRASTIC model has been employed in this research to estimates the groundwater vulnerability to pollution for Dar es Salaam City.

The purposes of the groundwater vulnerability assessment made for Dar es Salaam City were:

- to acquire improved information that would help develop groundwater protection strategies;
- to document the information that may help to educate the decision makers and community in Dar es Salaam City on the contamination potential of groundwater; and
- to delineate areas that will be targeted for differential land management in order to protect the quality groundwater resources

6.1.2 Overview of Groundwater modelling: Basic equations

Since the realisation of pollution of groundwater by persistent and potentially hazardous chemicals about three decades ago, mathematical models have been formulated to help evaluate groundwater resources (Gorelick, 1983). The models integrate process descriptions with pollutant properties and environmental characteristics to yield quantitative estimates of subsurface transport and fate of these substances in the soil mass. Model simulations provide additional information to assist in decisions for better management of the groundwater resource. Modelling has now become an important tool in the management of groundwater resources and is used to predict the effect of current and future conditions on groundwater and contaminant movement as well as assessing aquifer vulnerability (Canter, 1996; Getchell, 1996; Bear *et al.,* 1996). Studies have shown that well calibrated models can provide a good estimate on the extent of groundwater contamination (Wang, 1997).

A groundwater model may be defined as a simplified version of a real world groundwater system that approximately simulates the relative excitation-response relations of the real world systems (Bear and Verruijt, 1987; Bear *et al.,* 1996; Getchell, 1996). Mathematical models can be classified as numerical, analytical or empirical. Numerical models are the most sophisticated models, and can be used to simulate the effects of either changing or steady state aquifer conditions (Getchell, 1996). Models are built from a series of mathematical equations that simulate a groundwater situation in a real world aquifer system. Mathematical equations describing groundwater flow in aquifers are based on the continuity equation (Eq. 6-1) and Darcy's law (Eq. 6-2). According to Darcy's law, the average flow velocity is a function of the hydraulic head gradient and the effective porosity (Freeze and Cherry, 1979; Mercer and Faust, 1980a). The flow rate, Q is given by;

$$Q = nVA \qquad (6\text{-}1),$$

where Q is the flow rate in m^3/s, V is the velocity of flow in m/s, n is the effective porosity of the porous medium and A is the cross sectional area. The Darcy’s law is given by;

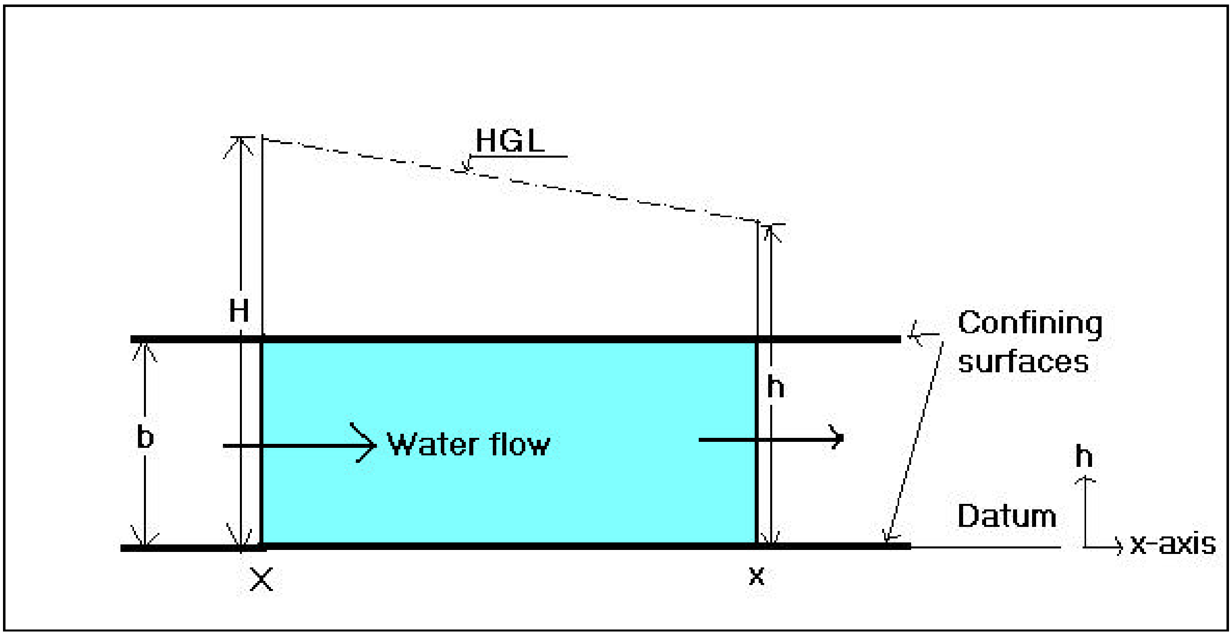
$$V = -\frac{K}{n}\frac{dh}{dx} \qquad (6\text{-}2),$$

where K is the hydraulic conductivity (assumed constant in the entire soil mass), m/s, h is the hydraulic head, m; n is effective porosity; x is the distance of flow (in this case in x-direction) and $\partial h / \partial x$ is the hydraulic gradient in the same direction.

Combining Eq. 6-1 and Eq. 6-2, the Darcy Law can be expressed as;

$$Q = -K\frac{dh}{dx}A \qquad (6\text{-}3)$$

Figure 6-1 helps to explain the equations stated above.



Note: b= aquifer thickness, HGL= Hydraulic Grade Line; H and h are pressure heads at X and x respectively

Figure 6-1: Illustration of groundwater flow regime in a confined aquifer

However, the above equations are more generalised and over simplified. Taking into account that the hydraulic conductivity in a soil mass at a point may vary in all directions, the unsteady or transient, 3-D groundwater flow equation through a saturated anisotropic unconfined heterogeneous porous medium is represented as given in equation (Eq.6-4).

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) + R = S_s\frac{\partial h}{\partial t} \qquad (6\text{-}4),$$

where, K_{xx}, K_{yy}, K_{zz}, are principal components of hydraulic conductivity tensor in x, y, and z-directions, respectively. R represents sources/sinks in the system, and S_s is the specific storage. This equation is sometimes called the diffusion equation.

For many problems, the velocity distribution, and hence the hydraulic head distribution, does not change with time (i.e. the problem is steady state) (Mercer and Faust, 1980b). Many regional groundwater flow systems can be represented as steady-state boundary value. Thus for steady state flow, $\partial h / \partial t = 0$, hence Eq. 6-4 becomes,

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+R=0 \qquad \text{(6-5).}$$

For homogeneous medium, and assuming a closed system where both sources and sinks are zero equation Eq. 6-5 reduces to:

$$K_{xx}\frac{\partial^2 h}{\partial x^2}+K_{yy}\frac{\partial^2 h}{\partial y^2}+K_{zz}\frac{\partial^2 h}{\partial z^2}=0 \qquad \text{(6-6).}$$

And for an isotropic medium, $K_{xx} = K_{yy} = K_{zz}$ = K, equation (6-6) becomes

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}+\frac{\partial^2 h}{\partial z^2}=0 \text{ or } \nabla^2 h=0 \qquad \text{(6-7),}$$

where there are sources of recharge (e.g. precipitation) or sinks of removal (extraction from wells), the 3-D steady state equation becomes;

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}+\frac{\partial^2 h}{\partial z^2}=-\frac{R(x,y,z)}{T} \qquad \text{(6-8),}$$

where *R(x,y,z)* is the volume of water added per unit time per unit aquifer area, and *T* is the transmissivity of the aquifer (i.e. hydraulic conductivity times the saturated thickness, *Kb*). Transmissivity is defined as the rate at which water can pass through the thickness of a saturated aquifer of unit width under a unit hydraulic gradient (Clark, 1988).

6.1.3 Data acquisition

The input data to simulate groundwater flow or contaminant transport can be obtained from three sources, namely: existing databases, measurement methods and estimation methods. In most cases data acquisition, especially through field investigations, is expensive, and both labour and time intensive (Corwin *et al.*, 1997). For example, the approximate cost of a single groundwater sample analysed for all common variables in USA was US $ 1700 in 1992 (Fetter, 1993). In developing countries the cost may be lower than this due to availability of cheap labour, however, it will still be expensive. Many countries are struggling in building databases, the situation being worse in developing countries (especially low-income countries like Tanzania - see to Chapter 5), where the existing economies cannot sufficiently support data acquisition.

The direct measurement of variables and parameters is considered the most reliable means of obtaining accurate information for modelling purposes. Some measurements require expensive equipment and/or well-trained professionals. Advances in science have provided several methods of obtaining model variables and parameters, although some of these may not be cost-effective. Among these include geophysical resistivity methods (such as electromagnetic induction, high-resolution radiometry, magnetic resonance imaging, thermal infrared etc), inorganic and organic analytical methods (which includes instruments like capillary chromatography, GC; high performance liquid chromatography, HPLC; capillary GC/mass spectroscopy, GC/MS etc) (Corwin *et al*., 1997; Soniassy *et al*, 1994). However, a quick and easy means of obtaining these measurements is crucial to the cost-effective modelling of pollutants, especially the non-point source pollutants. In recent years the GIS (discussed in Chapter 5) has been incorporated in groundwater modelling to provide for increased detail of evaluation, minimization of user subjectivity in parameter selection, reduction in costs for analysis due to significant time savings, and increased capability for data processing and retrieval (Corwin *et al*., 1997; Getchell, 1996; Ross and Tara, 1993; Dangremond, 1989; Lee, 1990; Darbar et al, 1995). Nevertheless, the amount of progress made in developing methods for measurements model variables and parameters still much work is needed in the area of instrumentation. Corwin (1996) suggests that instrumentation needed to measure all the parameters and variables needed in the contaminant transport models are still inadequate. This is now true to the case of developing countries only.

The lack or insufficient input data to the model presents a practical problem: how to choose an appropriate groundwater model (Wang, 1997) or how to generate the missing data input. In recent years, scientists have developed means of generating missing information in the model by using available data (Corwin *et al*., 1997). The problem of missing adequate data to feed in the models has led to the evolution of empirical methods that are used in assessing groundwater resources. However, much of the modelling work has been done in developed nations. In developing countries there are two levels of constraints; first, insufficient well-trained professionals who can assist in selecting appropriate models, and two, limited resources makes it difficult to acquire basic data required in many groundwater models. Therefore, absence or inadequacy of data presents a major limiting factor in groundwater models application in developing countries like Tanzania. In such circumstances, empirical models (e.g. DRASTIC) become useful tools for assessing groundwater resources.

6.1.4 Model selection and application

Today there are enormous number of groundwater models (simple and complex) used to simulate subsurface flow and contaminant transport; all varying in simplifying assumptions, governing equations, and both data input and output. Numerical models, such as USG MODFLOW, USGS MOC and PATHFLOW are among the common software in the market today (Getchell, 1996). However, the big question is how to quickly choose an appropriate model to solve a specific groundwater management problem. In order to improve model selection process, Wang (1997) proposed a model selection system by categorizing groundwater models in four principal classes (see Table 6-1).

Wang (1997) suggested that if both hydraulic conductivity and aquifer thickness are not spatially varying within a given subsurface formation, the area is considered to have a simple aquifer condition; otherwise the aquifer condition is complex. Contaminants are divided into conservative and non-conservative. Advection and dispersion processes only affect the former group, whereas adsorption and geochemical reactions also affect the latter.

Models Class I are represented by Eq. 9, and simulate the movement of a conservative substance in aquifers with constant hydraulic conductivity and thickness (simple aquifer condition) and x-axis orientated along the flow direction.

$$\frac{\partial C}{\partial t} = -V_x \frac{\partial C}{\partial x} + D_L \frac{\partial^2 C}{\partial x^2} + D_T \frac{\partial^2 C}{\partial y^2} \qquad (6\text{-}9),$$

where t is time, C is contaminant mass concentration, D_L is longitudinal (x) dispersion coefficient, and D_T is transverse (y) dispersion coefficient. In this case the groundwater flow velocities V_x and V_y are assumed constant and also the models assumed that there are no adsorption and reaction processes.

Models in class II simulate non-conservative contaminant transport in the simple aquifer condition and represented by Eq. 6-10 and Eq.6-11.

$$R_d \frac{\partial C}{\partial t} = -V_x \frac{\partial C}{\partial x} + D_L \frac{\partial^2 C}{\partial x^2} + D_T \frac{\partial^2 C}{\partial y^2} - k_f R_d C \qquad (6\text{-}10),$$

where k_f is the reaction constant, and R_d is the retardation factor defined as a function of the aquifer bulk density, $\tilde{n}_b$, soil-water distribution coefficient, K_d, and effective aquifer porosity, n:

$$R_d = 1 + \frac{\rho_b}{n} K_d \qquad (6\text{-}11)$$

Table 6-1: A general classification of groundwater models (Wang, 1997)

	Model classes			
	I	II	III	IV
Criteria				
Geological condition	Simple	Simple	Complex	Complex
Contaminant characteristics	Conservative	Non-Conservative	Conservative	Non-Conservative
Parameters				
Effective porosity, n	Required	Required	Required	Required
Bulk density, $\tilde{n}_b$	Not apply	Optional	Not apply	Optional
Dispersion coefficient, D	Optional	Optional	Optional	Optional
Hydraulic conductivity, K	Constant	Constant	Variable	Variable
Aquifer thickness, b	Constant	Constant	Variable	Variable
Hydraulic head, h	Constant	Constant	Variable	Variable
Distribution coefficient, K_d	Not apply	Constant	Not apply	Constant
Reaction constant, k_f	Not apply	Constant	Not apply	Constant

Models in class III simulate conservative contaminant transport in the complex aquifer condition, for which there are spatially variations in hydraulic conductivity and/or thickness values. These are represented by Eq. 12 (Wang, 1997).

$$\frac{\partial C}{\partial t} = -\left(V_x\frac{\partial C}{\partial x} + V_y\frac{\partial C}{\partial x}\right) + \frac{1}{b}\left[\frac{\partial}{\partial x}\left(bD_{xx}\frac{\partial C}{\partial x} + bD_{xy}\frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial y}\left(bD_{yx}\frac{\partial C}{\partial x} + bD_{yy}\frac{\partial C}{\partial y}\right)\right] \tag{6-12}$$

Where, V_x and V_y are average groundwater velocities in x and y directions respectively. D_{xx}, D_{xy}, D_{yx}, and D_{yy} are coefficients of hydrodynamic dispersion and b is the aquifer thickness.

Eq. 6-13 represents models in class IV, which simulate the transport of a non-conservative contaminant in a complex aquifer condition where there are spatial variations in both hydraulic conductivity and thickness.

$$R_d\frac{\partial C}{\partial t} = -\left(V_x\frac{\partial C}{\partial x} + V_y\frac{\partial C}{\partial x}\right) + \frac{1}{b}\left[\frac{\partial}{\partial x}\left(bD_{xx}\frac{\partial C}{\partial x} + bD_{xy}\frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial y}\left(bD_{yx}\frac{\partial C}{\partial x} + bD_{yy}\frac{\partial C}{\partial y}\right)\right] - k_f R_d C \tag{6-13}$$

The model selection system developed by Wang (1997) provides an avenue to evaluate groundwater protection programme objectives and compare the site-specific data with the model requirements during selection process. It must be remembered that still science knows very little about the subsurface interaction and only a few groundwater flow and contaminant transport problems can yet be modelled with confidence (Wang, 1997).

The mathematical equations discussed under this section are fundamental, and their solutions are available in wide literature (e.g. Freeze and Cherry, 1979). However, from these equations we note that no matter what model is selected, data input are required which may not be available. This problem is partly solved through the use of empirical methods explained below.

6.2 Empirical AssessmentMethodologies (EAM)

6.2.1 Background

Frequent lack or inadequate and quality data required by groundwater models made scientists in 1970s look for alternative means of assessing groundwater resources (Canter and Knox, 1985, Fairchild, 1987). The high costs involved in data acquisition made it logical to restrict monitoring to only few "hot spots" with greater susceptibility to pollution (Canter, 1985). Alternative approach was to use a less complex model to evaluate the potential of pollutants to reach aquifers taking into account the results of the estimation (Aller *et al*, 1985; Boom and Fried, 1987). This evolved the empirical assessment methodologies (EAM) and the concept of “groundwater vulnerability”.

The EAM in the context of groundwater quality management refers to approaches, which lead to the development of empirical indices or classifications of the groundwater pollution potential of human's activities (Canter, 1985). This potential can be based on pollutant characteristics, groundwater system vulnerability, and/or a combination of both issues. Interpretation of the resultant index or classification normally is based on professional judgement. These methodologies have been used in site selection and evaluation for sanitary or chemical landfills and with evaluation of liquid waste pits, ponds, and lagoons (surface impoundment) (Canter, 1996; Foster, 1987; Meinard, 1995; Engel *et al.*, 1996; Kelly and Lunn, 1999). These methodologies typically focus on a numerical index, with larger numbers generally used to denote greater groundwater pollution potential or vulnerability. Methodologies typically contain several factors for evaluation, with the number and type, and importance weighting varying from methodology to methodology. Final integration of information may involve summation of factor scores or their multiplication followed by summation. Thus EAM represent approaches, which can be used, based on minimal data input, to provide a structured procedure for pollution source evaluation, site selection, and monitoring planning.

6.2.2 The Concept of Groundwater Vulnerability to Pollution

The character of the landscape may vary considerably over an area and the possibility to cope with and respond to a contamination event varies with the spatial distribution of the geological formation overlying the groundwater system. The properties of geological formations are heterogeneous which result in their being not equally sensitive to disturbances through human activities or changes in the environment. It is therefore possible to differentiate between areas with regard to the geological materials potential to protect the groundwater; some areas are better protected from contamination than others. To describe the natural potential for protection of groundwater from contamination to an imposed load the term “groundwater vulnerability” is used.

This basic concept has taken on a range of definitions on the technical literature. Bachmat and Collins (1987) define "groundwater vulnerability" as the sensitivity of its quality to anthropogenic activities, which may prove detrimental to the present and/or intended usage-value of the resource. Foster (1987) defines "groundwater vulnerability" as "the intrinsic characteristics that will determine the sensitivity of various parts of an aquifer to being adversely affected by an imposed contaminant load". Friesel (1987) defines vulnerability of groundwater as protectiveness or its openness to recharge, that is the permeability of the covering strata for water. The USA National Research Council (1993) defined groundwater vulnerability as “the tendency or likelihood for contaminants to reach a specified position in the groundwater system after introduction at some location above the upper most aquifer”. All the definitions aim at assessing the natural protection capability of the geological formation that maintains the quality of the groundwater from being adversely affected by anthropogenic activities. However, the definitions of groundwater vulnerability given above are blemished by the fundamental principle that: “All groundwater is vulnerable”. The results of groundwater vulnerability assessment is normally expressed or displayed in a map, known as “vulnerability map”.

The groundwater vulnerability refers to contamination resulting from non point sources or areally distributed point sources of pollution and does not address individual point sources of pollution nor any situation where a pollutant is purposely placed into the groundwater system. The vulnerability is not an absolute property, but a relative indication of where contamination is likely to occur. Furthermore, it is an amorphous concept, not a measurable property. It is a probability (i.e. “the tendency or likelihood”) of contamination occurring in the future and thus must be inferred from surrogate information that is measurable. In this sense, a groundwater vulnerability assessment is a predictive statement much like a weather forecast, but for processes that take place underground and over much longer time scales.

Assessment for groundwater vulnerability has now become a common tool in groundwater management and protection, as is the case of monitoring, modelling and mapping (Canter, 1985; Cramer and Vrba, 1987; USA National Research Council, 1993; Palmer *et al*, 1995; Pebesma and Kwaadsteniet, 1997; Kelly and Lunn, 1999; Ibe *et al.*, 2001). The vulnerability assessment and vulnerability maps represent an important preliminary tool in decision-making pertaining to the management of groundwater quality. They provide a useful framework within which to designate priorities for the implementation of pollution protection and control measures, though field investigations and monitoring are not ruled out (Blau, 1981; Gowler, 1983; Foster, 1985; Aller *et al.*, 1985, Anderson and Gosk, 1987). The vulnerability maps also serve to inform and educate the public, because non-professional people can readily understand their concept. They also create public awareness about potential pollution problems of groundwater, a situation needed for effective implementation of future protection programmes.

6.2.3 Groundwater vulnerability assessment: methods and approaches

There have been several approaches suggested or implemented in literature. In general, two types of vulnerability assessment can be defined. The first, specific vulnerability is used when vulnerability is referenced to a specific contaminant, contaminant class, or human activity (e.g. nutrients, pathogens, micro-organics, heavy metals, etc or unsewered sanitation, agricultural land-use practice, industrial effluent disposal, etc.) (Carter *et al*, 1987). The second type, intrinsic vulnerability, refers to vulnerability that does not consider the attributes and behaviour of particular contaminants. In practice, a clear distinction between intrinsic and specific vulnerability cannot always be made.

The potential for contamination to leach to groundwater depends on many factors, including the composition of soils and geologic material in the unsaturated zone, the depth to the water table, the recharge rate, and environmental factors influencing the potential for biodegradation. The composition of the unsaturated zone can greatly influence transformation and reactions. For example, high organic matter or clay content increases sorption and thus lessens the potential for contamination. The depth to the water table can be an important factor because short flow path decrease the opportunity for sorption and biodegradation, thus increasing the potential for many contaminants to reach the groundwater. Conversely, longer flow paths from land surface to the water table can lessen the potential for contamination for chemicals that sorbs or degrade along the flow path. Recharge rates affect the extent and rate of transport of contaminants through the saturated zone. Finally, environmental factors, such as temperature and water content, can significantly influence the degradation of contaminants by microbial transformation.

Basing on the understanding of the factors that affect the transport of contaminants introduced at or near the land surface, an array of methods for predicting groundwater vulnerability has been developed. These methods falls into three major classes, which are:

- Overlay and index methods
- Process based methods
- Statistical methods

In more details this means:

- Overlay and index methods – are based on combining maps of various physiographic attributes (e.g. geology, soils, depth to water table etc) of an area by assigning a numerical index or score to each attribute. In the simplest form of the method, all attributes are assigned equal weights, with no judgement being made on their relative importance. Thus, areas where simple convergence of the specified attributes occur (e.g. sandy soil and less depth to groundwater-shallow aquifer) are deemed vulnerable. To be more quantitative, different range of scores and weights are assigned to the attributes in developing vulnerability classes. The vulnerability classes are then displayed in a map as surface profiles (normally using GIS tool).
- Process-based methods – employ process based simulation models and require analytical or numerical solutions to mathematical equations that represent coupled process governing contaminant transport. They range from indices based on simple transport models to analytical solutions for one-dimensional transport of contaminants through unsaturated zone to coupled, unsaturated, multiple phase, 2D or 3D models (some are explained in section 6.1).
- Statistical methods- incorporate data on known areal contaminant distributions and provide characterizations of contamination potential for the specific geographical area from which the data were drawn.

Examples of the various methods developed to evaluate groundwater contamination are shown in Table 6-2.

Table 6-2: Selected methods for evaluating groundwater vulnerability to contamination

Class	Method Acronym	Application environment	Intrinsic/Specific	Reference
Overlay and Index Methods	DRASTIC	Groundwater	Intrinsic	Aller *et al*., 1985; 1987
	SEEPAGE	Groundwater	Intrinsic	Moore, 1988
	Groundwater Vulnerability	Groundwater	Intrinsic	Meinard, 1995
Process based Methods	BAM	Soil	Specific	Jury *et al*., 1983
	MOUSE	Groundwater	Specific	Steenhuis *et al*, 1987
	GLEAMS	Soil	Specific	Leonard *et al*., 1987
	CLASS	Soil	Specific	Kelly and Lunn, 1999
Statistical Methods	Discriminant analysis	Groundwater	Specific	Teso *et al*., 1988
	Regression analysis	Groundwater	Specific	Chen and Druliner, 1988

Each of above methods requires that adequate data be available on factors that affect groundwater vulnerability, such as soil properties, hydraulic properties, precipitation patterns, depth to ground water, land use and land cover and other characteristics of the area to be assessed (such as topography). The overlay and index method is the mostly used method in vulnerability assessments because the databases are usually available and it can be easily implemented. However, the overall utility of a vulnerability assessment is highly dependent on the scale at which it is conducted, the scale at which the data are available, the scale used to display results, and the spatial resolution of mapping.

Furthermore, inherent in any such combination of elements in vulnerability assessment, are scientific uncertainties associated with errors in data, errors in method, and potential misapplication of an approach to a given area. Thus in predicting groundwater vulnerability occurrence of errors are recognised as in any other natural and complex systems. This recognition is entailed in second common principle of vulnerability assessment that states, “Uncertainty is inherent in all vulnerability assessments”. Uncertainty is inherent in vulnerability assessments because of limitations in knowledge of contaminants behaviour in the subsurface, as well as significant limitations in the spatial databases used to make assessments. The USA National Research Council (1993) found that different approaches might give vulnerability ratings that do not agree with each other or with observations of groundwater pollutants. The model evaluation problem for large areas, or even a field, is especially difficult because the results (i.e. vulnerability ratings) are not subject to experimental verification using normal scientific methods.

However, with increased knowledge of subsurface environment, data availability and advances in measurements and computing (GIS), these hurdles are continuously being overcome. For example, during the 1990s, groundwater vulnerability assessments have been conducted in many countries as part of comprehensive groundwater protection strategies (Breeuwsma and Duijvenbooden, 1987; Swanson, 1990; Richert *et al.*, 1992; Vrba and Zaporozec, 1994; Lindstrom and Scharp, 1995; Engel *et al.*, 1996; Navulur and Engel, 1996; Melloul and Azmon 1997; Maxe and Johansson, 1998). Of to date, the vulnerability concept has shown attractive to decision makers, physical planners, and land and groundwater managers (Maxe and Johansson, 1998). The gap between the needs and expectations of the users and the possibilities to produce vulnerability assessments fulfilling the requirements will remain a subject of progressive research.

The Ground Vulnerability Assessment (GVA) is a dynamic and iterative process, used for three main purposes, namely:

a) Increasing the awareness and knowledge of the public and decision-makers of the potential of contamination of the groundwater resources that may be their most valuable use. Because groundwater resources are generally hidden (invisible), public knowledge of groundwater system, its use, and its susceptibility to contamination is often poor. A vulnerability assessment can increase such awareness by highlighting “hotspots” areas, or human activities that pose danger to the resource. This increased knowledge often produces a greater willingness to take the necessary steps to protect it against contamination;

b) Providing a tool for allocating resources. The availability of vulnerability assessments can give both land users and managers (e.g. Water Boards – for the case of Tanzania) a proper sense of caution and some information on how to avoid excessive risky actions. They also direct resources for mitigation and monitoring purposes; and

c) Guiding the decisions of land users and landuse managers. The vulnerability assessments play a key role in helping to reach rational decisions on issuing permits for activities that can contaminate groundwater. Therefore, the vulnerability assessments can be a key methodology in Environmental Impact Assessments (EIA) of proposed development

Figure 6-2 summarizes the key players in GVA. It can be depicted in Figure 6-2, that to successfully perform a GVA a cooperative efforts of regulatory policy makers, natural resource managers and technical experts are needed: all parties having a common goal of protecting groundwater.

Figure 6-2: Major players in Groundwater Vulnerability Assessment (GVA)

6.3 The DRASTIC Model

The DRASTIC model was developed in USA for the purpose of protecting the groundwater resources (Aller *et al.*, 1985; 1987). DRASTIC is an empirical groundwater model that estimates groundwater contamination vulnerability of aquifer systems based on the hydrogeological settings of that area (Aller, et al., 1985, 1987). A hydrogeological setting is defined as a mappable unit with common hydrogeological characteristics (Engel et al., 1996). DRASTIC employs a numerical ranking system that assigns relative weights to various parameters. The acronym DRASTIC is derived from the seven factors considered in the method, which are **D**epth to groundwater [**D**], net **R**echarge rate [**R**], **A**quifer media [**A**], **S**oil media [**S**], **T**opography [**T**], **I**mpact of the vadoze zone [**I**], and **C**onductivity (hydraulic) of aquifer [**C**]. Each DRASTIC factor is assigned a weight based on its relative significance in affecting pollution potential. The typical ratings range from 1-10 and weights from 1-5 (see Tables 6-3 – 6-10). The DRASTIC Index [**DI**], a measure of pollution potential, is computed by summation of the products of ratings and weights of each factor (see Eq. 6-14). The final results for each hydrogeological setting is a numerical value, called DRASTIC index. The higher the value is, the more susceptible the area in question is to groundwater pollution. The DRASTIC model is designed to evaluate the vulnerability of groundwater in regions greater than 40 hectares (100 acres).

$$DI = D_rD_w + R_rR_w + A_rA_w + S_rS_w + T_rT_w + I_rI_w + C_rC_w \tag{6-14}$$

The subscripts *r* and *w* in Eq. 14 above denote the rating of the factor being considered and the corresponding weight assigned to the factor. The higher the value of DI the greater the relative pollution potential or high aquifer vulnerability. Navulur *et al* (1996) converted the computed DRASTIC indices into qualitative risk categories of low, moderate, high, and very high (see Table 6-11).

Table 6-3: Assigned importance weights for factors in two DRASTIC models (Aller *et al.*, 1987)

Factor	Importance weight	
	Generic model	Pesticide model
Depth to water (D)	5	5
Net recharge (R)	4	4
Aquifer media (A)	3	3
Soil media (S)	2	5
Topography (T)	1	3
Impact of the vadose -zone (I)	5	4
Hydraulic conductivity of the aquifer (C)	3	2

Table 6-4: Evaluation of the depth-to-groundwater factor in the DRASTIC model (Aller *et al.*, 1987)

Depth to groundwater	
Range (feet)	Rating
0-5	10
5-15	9
15-30	7
30-50	5
50-75	3
75-100	2
100+	1

Table 6-5: Evaluation of the net-recharge factor in the DRASTIC model (Aller *et al.*, 1987)

Net annual recharge	
Range (inches)	Rating
0-2	1
2-4	3
4-7	6
7-10	8
10+	9

Table 6-6: Evaluation of aquifer media in the DRASTIC model (Aller *et al.*, 1987)

Aquifer media characteristic	
Type of aquifer media (Range)	Rating
Massive shale	1-3
Metamorphic/Igneous	2-5
Weathered metamorphic/igneous	3-5
Glacial till	4-6
Bedded sandstone, limestone, and shale sequences	5-9
Massive sandstone	4-9
Massive limestone	4-9
Sand and gravel	6-9
Basalt	5-10
Karst limestone	9-10

Table 6-7: Evaluation of the soil-media factor in the DRASTIC model (Aller *et al.*, 1987)

Soil media	
Range	Rating
Thin or absent	10
Gravel	10
Sand	9
Shrinking and/or Aggregated clay	7
Sandy loam	6
Loam	5
Silty loam	4
Clay loam	3
Non-shrinking and non-aggregated clay	1

Table 6-8: Evaluation of topography factor in the DRASTIC model (Aller *et al.*, 1987)

Topography	
Range (percent slope)	Rating
0-2	10
2-6	9
6-12	5
12-18	3
18+	1

Table 6-9: Evaluation of the impact to the vadose-zone in the DRASTIC model (Aller *et al.*, 1987)

Impact to vadose-zone	
Range	Rating
Silt/clay	2-6
Shale	2-5
Limestone	2-7
Sandstone	4-8
Bedded limestone, sandstone, and shale	4-8
Sand and gravel with significant silt and clay	4-8
Metamorphic/igneous	2-8
Sand and gravel	6-9
Basalt	2-10
Karst limestone	9-10

Table 6-10: Evaluation of the hydraulic conductivity factor in the DRASTIC model (Aller *et al.*, 1987)

Hydraulic conductivity	
Range (gpd/ft^2)	Rating
1-100	1
100-300	2
300-700	4
700-1000	6
1000-2000	8
2000+	10

Table 6-11: DRASTIC index ranges for qualitative risk categories (Navulur *et al.*, 1996)

	DRASTIC qualitative category			
	Low	Moderate	High	Very High
DRASTIC Index [**DI**]	1-100	101-140	141-200	>200

Since its formulation in the United States, the DRASTIC model has been extensively applied and validated (Baker, 1990; Rundquist, *et al.*, 1991; Kalinski, *et al.*, 1994). Navulur and Engel (1996) recommended DRASTIC model as a useful tool in policy and decision-making in groundwater management strategies. Engel *et al* (1996) reported that the DRASTIC approaches for predicting groundwater vulnerability performed reasonably well for both nutrients and pesticides. The maps resulting from these indices were used to target groundwater protection efforts. Areas predicted to have moderate, high and very high vulnerabilities were due for more detailed investigations. Scharp (1994) reported that the DRASTIC model has been used in developing a protection plan for Managua city, Nicaragua. The results of the DRASTIC model were further validated against the local hydrogeological knowledge and found to be useful. Scharp recommends continuous update of the rapid assessment whenever new information is obtained. She also recommends a further simplified method, with less parameters to be considered**.**

The Department of Geology, University of Gothenburg adopted the DRASTIC model, for evaluating Sweden's groundwater pollution potential (Swanson, 1990). The model was applied and complemented by five overlay maps, which provided information on drainage basins, water sources; groundwater supplies and groundwater resources. Adoption of DRASTIC method and its companion overlays provided initial step ever in learning to use functional and reliable methods to help protect and manage Sweden's groundwater supply (Swanson, 1990). The methodology would enable city planners to identify hydrogeologically sound locations for landfill sites.

The DRASTIC model can be a useful tool for identifying areas vulnerable to pollution, even though it cannot reflect the characteristics of individual contaminants. The vulnerability map should enable planners and environmentalists to pinpoint areas of high contamination potential as a first step in forming a groundwater protection plan for existing water supplies and for future economic development. The DRASTIC/GIS technique can supply important data for conservation and water resource management.

6.4 Application of the DRASTIC Model to the City of Dar es Salaam

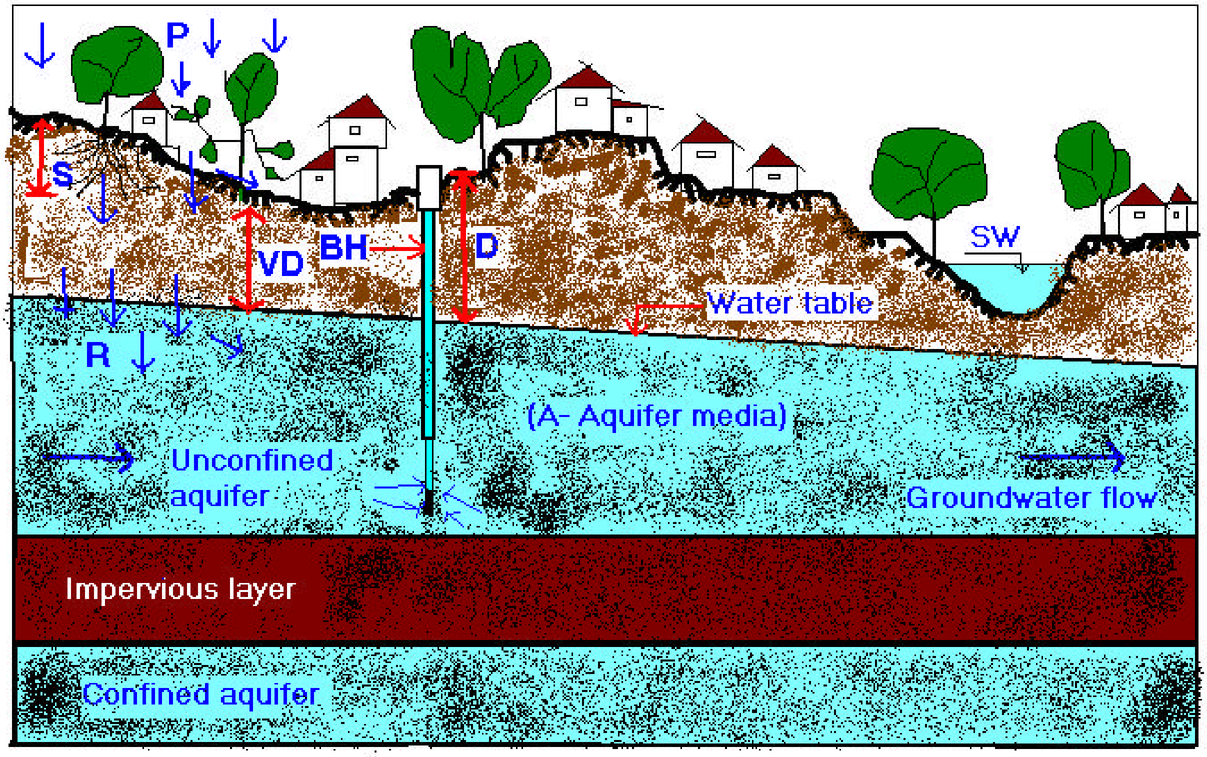
6.4.1 Overview

The DRASTIC model was used to develop the groundwater vulnerability map of Dar es Salaam City. The weights and ratings were adopted as specified in the generic model. The boreholes drilling records availed by DDCA were used in extracting values of the DRASTIC parameters. From these borehole reports, four out of seven DRASTIC parameters were obtained, namely depth to water ***D***, aquifer media ***A***, soil media ***S***, and impact of the vadoze zone media ***I***. The topography ***T*** was estimated from the Dar es Salaam contour map. The hydraulic conductivities ***C*** were obtained by assuming standard values given by the type of aquifer material. However, no data was available for net recharge factor ***R*,** and only an estimate value was used. It was assumed that the net recharge is similar for the entire of study area. The geographical references were obtained from direct measurements with the GPS handset. Each borehole was taken as a node in developing the vulnerability map. Figure 6-3, illustrates the quantities D, A, S, and I.

6.4.2 Ratings for the DRASTIC parameters

Depth to Water

The depth to water is the distance from the ground surface to the water table. This determines the depth of material through which a contaminant must travel before reaching the aquifer. The presence of low permeability layers, which confine aquifers, limits the travel of contaminants into an aquifer. In general, there is a greater chance for attenuation to occur as the depth to water increases because deeper water levels imply longer travel times.



Notes: S- Soil media; VD- Vadoze zone; BH- Borehole; R- Recharge; P- Precipitation; SW- Surface water

Figure 6-3: A sketch to show some DRASTIC model parameters

The depth to groundwater information was obtained by making use of the completion form found in the boreholes drilling reports. In the DDCA’s completion form for borehole drilling, a record on at what depth water was struck is shown. There may be one or more depths at which water was struck; the depth to water is taken as that depth from the surface to the point where water was firstly struck. For example if water was struck at depth 5.5m, 11.0m, 60.7m; then the depth to water is taken as 5.5 m. The same applies when water was struck at a single depth say 20m, then the depth to water is taken to be 20 m. The depth obtained has to be converted in feet as required by the DRASTIC model. The obtained depth to water in feet was then evaluated by using Table 6-4, which shows ranges and ratings for depth to water. The selected rating was then multiplied by the assigned weight for depth to water, which is 5 (Table 6-3) to get DI component for depth to water. Similar procedure was done for each borehole.

Net Recharge

Net recharge represents the amount of water per unit area of land, which penetrates the land and reaches the water table. Recharge water is the principle vehicle for leaching and transporting contaminants vertically to the water table and horizontally within the aquifer. The greater the recharge, the greater the potential for ground water pollution. For Dar es Salaam City, other sources of recharge include leaking underground water supply pipes, effluents from soakaway pits and irrigation water.

The Dar es Salaam City is a relatively small area and experiences same amount of rainfall, with annual rainfall averages between 1000 mm to 1400 mm. Because of this the net recharge was taken to be relatively the same in the entire study area, and estimated to be about 12% of the average annual rainfall (Navlur, 1996). Thus the net recharge was taken as 120 mm – 168 mm. From Table 6-5, the values correspond with a net recharge rating of 6. This rating of 6 was then multiplied by the corresponding weight for net recharge, which is 4 (Table 6-3) to get the DI component for net recharge in the study area, which was 24. This value was applied to the entire Dar es Salaam City.

Aquifer Media

An aquifer is defined as a subsurface unit that will yield useful quantities of water. The aquifer medium influences the amount of effective surface area materials, with which contaminants may come into contact. The larger the grain size and the more fractures or openings within the aquifer, the higher the permeability and the lower the attenuation capacity of pollutants in the aquifer media. From the aquifer set-up, only unconfined aquifer was considered for which the DRASTIC model is valid (Aller *et al.*, 1987). The aquifer media was obtained by taking depths at which water was struck (as it was the case for depth to water determination) and correlating those depths with the lithological description of the borehole or strata description to identify the type of the aquifer media. For instance if water was struck at the depth of say 25 m, and lithological description indicates that strata from say 20m – 30 m is composed of limestone then the aquifer media will be limestone. However, when there exists a situation where water was struck at a succession of depths, say 9m, 18m, 32m and the lithological description indicates that strata from 8m – 10m is say fresh granite; 10m-26m is fresh granite; and 30m – 34m is weathered granite; the shallow depth was selected to be the aquifer media, for this case fresh granite.

After the type of aquifer media was determined, an evaluation of aquifer media rating in the DRASTIC model was done by obtaining the value as per Table 6-6. For example if aquifer media is sand and gravel then the corresponding rating is 4-

9, typical rating is taken to be 8. Then the selected rating is multiplied by the assigned weight for the aquifer media (Table 6-3), which is 3, to obtain the DI component for the aquifer media. The same procedure was repeated for all boreholes examined.

Soil Media

Soil media refers to that uppermost portion of the vadose zone characterized by significant biological activity. In this report, soil is considered as the upper weathered zone of the earth, which averages a depth of one meter or less from ground surface. Soil has a significant impact on the amount of recharge which can infiltrate into the ground and hence on the ability of contaminant to move vertically into the vadose zone. The smaller the grain size, the less the pollution potential. Soil media was obtained from the strata description or lithological description of the borehole records. The material for uppermost portion (about 2.0 m) of the soil profile was taken to be the soil media. The ratings of soil media in the DRASTIC model were determined from Table 6-7. The outcome was then multiplied by the assigned weights for the soil media, which is 2, (Table 6-3) to obtain the DI component for the soil media. The same procedure was repeated for all boreholes examined.

Topography

Topography refers to the slope and its variability of the land surface. Topography helps control the likelihood that a pollutant will run off or pool and remain on the surface in one area long enough to infiltrate. The slope was estimated from the topographical map of Dar es Salaam of scale 1:50000, sheet 186E/6 (prepared by the Ministry of Lands and Human Settlement). The study area was found to be relatively flat with the topography ranging from 0% - 4%. The average topography for each Dar es Salaam ward was then determined, and the slope value obtained was applicable to every borehole within the urban ward. Then Table 6-8 was used to obtain the DRASTIC ratings for topography. The outcome was then multiplied by the assigned weights for the topography, which is 1, (Table 6-3) to obtain the DI component for topography. The same procedure was repeated for all boreholes examined.

Vadoze zone

The vadose zone is defined as the zone above the water table which is unsaturated or discontinuously saturated. This zone determines the attenuation characteristics of the material below typical soil horizon and above the water table. The impact of the vadoze zone media was obtained by using the lithological description or strata description found in the borehole drilling records. The material below 2.0 m (typical soil horizon) down to the water table was considered to be the vadose zone media. Then Table 6-9 was used to obtain the DRASTIC ratings for the vadoze zone. The outcome was then multiplied by the assigned weights for the topography, which is 5, (Table 6-3) to obtain the DI component for the vadoze zone. The same procedure was repeated for all boreholes examined.

Hydraulic Conductivity

Hydraulic conductivity refers to the ability of the aquifer material to transmit water, which in turn, controls the rate at which ground water will flow under a given gradient. The most accurate values for hydraulic conductivity are calculated from aquifer pump tests. Well yields may provide assistance in estimating hydraulic conductivity. Hydraulic conductivities may also be estimated from aquifer material grain size charts. The broad ranges for hydraulic conductivity provided in the DRASTIC model were designed to provide flexibility in selecting appropriate values. This information was estimated from the aquifer type media and hydraulic conductivity chart (Aller *et al*., 1987). Then by using Table 6-10, DRASTIC ratings for the hydraulic conductivity were determined. The results were then multiplied by the assigned weights for the hydraulic conductivity, which is 3, (Table 6-3) to obtain the DI component for the hydraulic conductivity. The same procedure was repeated for all boreholes examined.

The water table was the point of reference for determining groundwater vulnerability. A total of 61 boreholes had complete data sets to enable computation of DI and had geographical references. Many of the boreholes already entered in the database (Chapter 5) could not be used in DI computation either, they had no geographical positions (which was mostly the case) or the aquifer is confined type. Table 6-12 shows example of the DI computations (other calculation results for DI are in the Appendix).

6.4.3 Development of a Groundwater Vulnerability Map for Dar es Salaam City

Table 6-12 was used to generate the Groundwater Vulnerability Map (GVM) for Dar es Salaam City (2001), as shown in Figure 6-4. Borehole positions (as represented by northings and eastings) were used for mapping scenarios. The ArcView GIS software version 3.1 was used to generate the GVM. The spatial GIS database formulated (as explained in Chapter 5) was conjunctively used to produce the map. Estimates for the vulnerability indices spatial distribution were determined by applying appropriate GIS overlay functions. The vulnerability indices were categorized in four major classes-low, moderate, high and very high as shown in Table 6-13. Generally, higher DI value indicates greater susceptibility to groundwater pollution.

Table 6-12: Example of calculated DRASTIC Index for Dar es Salaam City

B/H #	Northings	Eastings	DwDr	RwRr	AwAr	SwSr	TwTr	IwIr	CwCr	DI
DP31/99	9246421	523841	35	24	12	2	9	15	3	100
149/98	9249314	516246	25	24	6	10	9	30	3	107
113/97	9243889	529989	25	24	6	18	9	30	3	115
131/97	9235203	528285	50	24	15	18	9	30	6	152
20/97	9235232	528356	50	24	12	18	9	40	3	156
44/98	9235630	528373	35	24	21	2	9	15	6	112
138/97	9236502	528515	45	24	21	18	9	40	6	163
225/99	9237320	529376	45	24	12	18	9	30	3	141
164/99	9237767	529662	45	24	21	10	9	30	6	145
288/97	9238986	515495	35	24	12	10	5	30	3	119
292/99	9239543	517793	45	24	12	12	5	30	3	131
8/98	9239544	518733	45	24	21	18	5	40	6	159
182/97	9240000	520707	25	24	6	18	5	30	3	111
178/97	9240195	526606	35	24	24	18	9	30	6	146
99/97	9240430	530163	35	24	24	18	9	40	6	156

Table 6-13: Vulnerability classes used to develop GVM for Dar es Salaam City

Vulnerability class	Range of DI
Low	0-120
Moderate	120-140
High	140-200

6.5 Results of the Vulnerability Assessment

The groundwater pollution potential was estimated from the GVM presented in Figure 6-4. The maps mark out areas with varying vulnerabilities (low-moderate-high). Inherent with the DRASTIC model, the demarcated areas are relative indication of susceptibility to pollution from diffuse sources. The vulnerability map delineates areas whose groundwater are highly vulnerable to pollution that include City Centre, Upanga, Magomeni, Manzese, Kurasini, Changómbe, Mbagala, Vijimbweni and Kigamboni areas, which are rated high. Isolated spots in Ukonga and Temeke are also rated high. The map shows that the land triangle formed by Morogoro, Nyerere and Nelson Mandela roads (including areas like Ilala, Kariakoo, Kigogo, Buguruni, Mabibo and Magomeni) is almost all within the high vulnerable zone. The remaining part of Dar es Salaam is under moderate vulnerability class except few isolated areas in Ubungo and Tabata wards that are under low vulnerability class. The areas under high vulnerability classes are generally characterised with soil profiles dominated with sandy/gravel materials (which allow fast pollutant transport), relatively low topography (which provide a better chance for infiltration) and shallow groundwater table.

Under the above classification, it has been noted that the industrial activities in Changómbe and some along the Nyerere Road are within high vulnerable zones, where groundwater can easily be polluted. The areas of Kurasini and Kigamboni, where activities on petroleum products are concentrated, are also in the “red zone”. The unplanned high residential areas of Tandale, Manzese, Buguruni and parts of Mabibo also do fall under the red zone. In addition, areas with the high yield aquifers, covering Mbagala, Ilala, Mwananyamala (Figure 4-6, Chapter 4) also appear in the red zone. The commercial centers of Kariakoo and City Centre do also fall under the high vulnerability zones. The intrinsic hydrogeological characteristics of these areas indicate that they are highly susceptible to pollution. Therefore, indiscriminate waste disposal practices in these areas can easily contaminate groundwater.

6.6 Sensitivity Analysis and Verification of the DRASTIC Model

Sensitivity analysis was performed with the DRASTIC model to check its adaptability to local conditions in Dar es Salaam City. The weights of the factors in the model were changed, while retaining the ratings of the factors. The depth to groundwater, **D**, net recharge, **R** and impact to the vadose zone, **I**, which are assigned highest weight scores in the generic model were changed to minimum value of 1, each at a time. The drastic indices (DIs) were then recalculated to obtain three sets of results, which were used for to generate maps of the different sensitivity analysis. The results are shown in Figure 6-6, Figure 6-7 and Figure 6-8.

The results of the sensitivity analysis indicate that all the three factors severely affect the zones of the vulnerability in Dar es Salaam. Though, the general trend of increasing vulnerability is towards the Indian Ocean, the zones of high vulnerability were highly reduced. Of the three factors tested, the impact to the vadose zone, **I**, depicting the effect of the soil material between the topsoil and the groundwater table, showed to have the most influence to the drastic index. It can therefore, be stated that **I**, is the most important parameter in the drastic model to fit local conditions in Dar es Salaam. This may explain why the vulnerability increases towards the coastline that follow the same trend as sand/gravel formations.

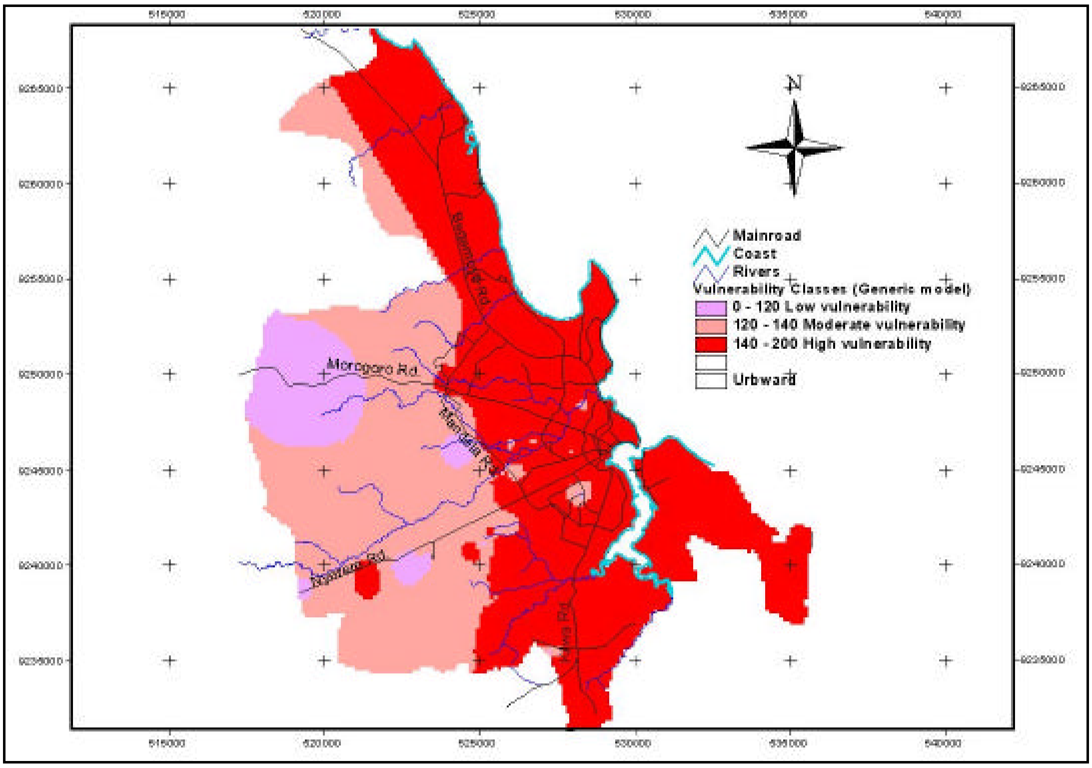


Figure 6-4: Groundwater vulnerability map for Dar es Salaam City (developed using the generic DRASTIC model) (2001**)**

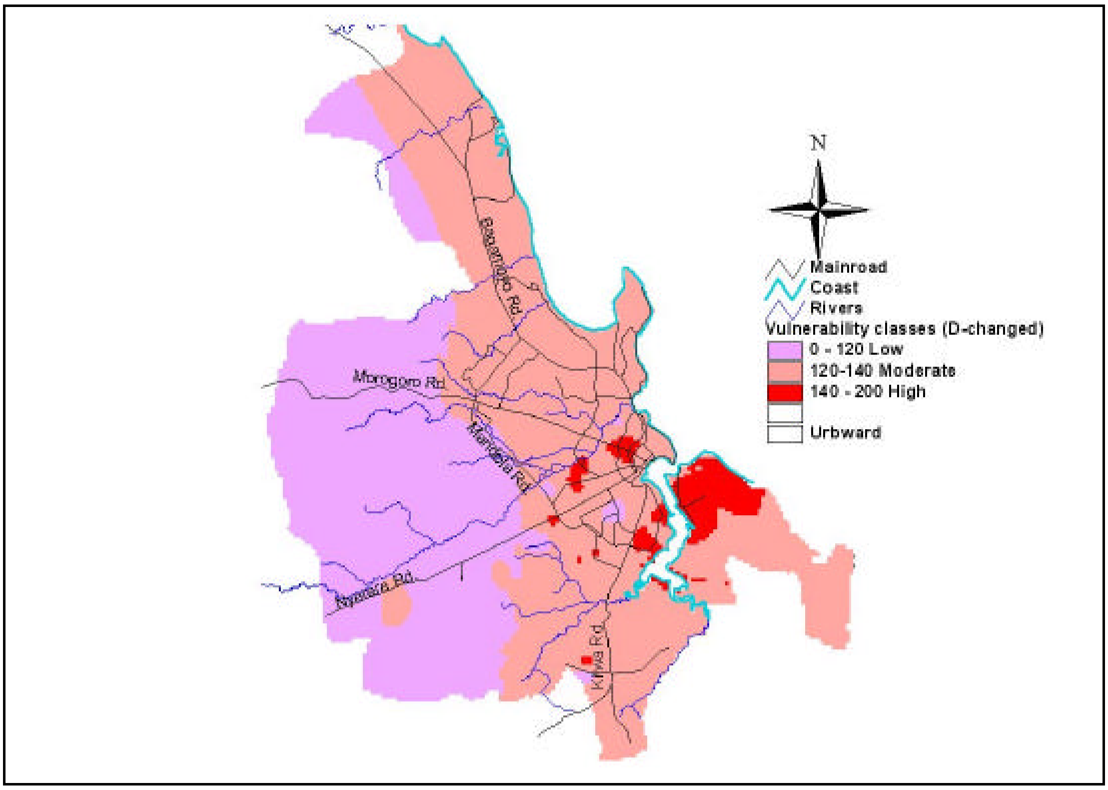


Figure 6-5: Sensitivity analysis of the DRASTIC model- Depth to groundwater factor given a minimum weight value of 1.

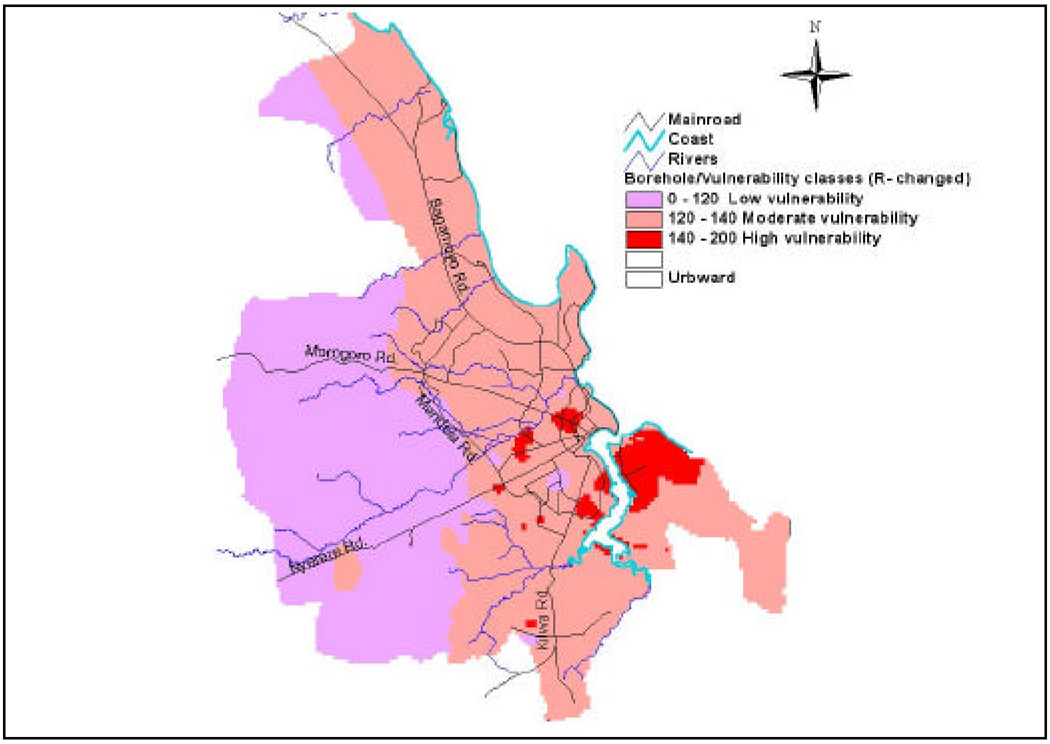


Figure 6-6: Sensitivity analysis of the DRASTIC model- the net recharge factor given a minimum weight value of 1

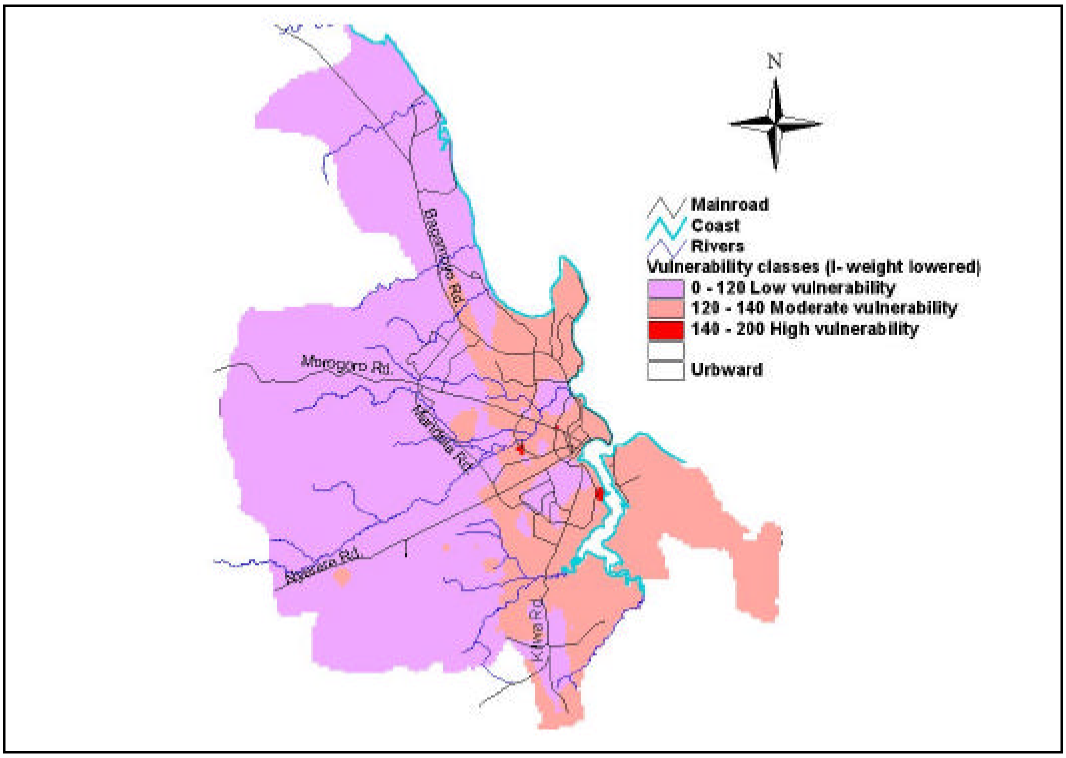


Figure 6-7: Sensitivity analysis of the DRASTIC model- Impact to vadose zone factor given a minimum value of 1

To verify the vulnerability map discussed in Figure 6-5 above, groundwater samples were collected from selected boreholes in the entire Dar es Salaam complex. About 30 boreholes were selected and sampled in early December 2001 (Figure 6-8). The water samples were analysed insitu for TDS, conductivity and salinity (using the Hach Conductivity Meter) and other parameters chloride (Cl^-), nitrate (NO_3) and nitrate-nitrogen (NO_3-N)) were analysed at the Chemical and Process Engineering Laboratory, University of Dar es Salaam. The results of the analysis were then superimposed on the Groundwater Vulnerability Map. Table 6-14 gives the results of the analysis while Figures 6-9, 6-10, and 6-11 present the results of the superimposition exercise. Longitudinal profiles (Figures 6-8, 6-12 and 6-13) were further used to identify trends as one transverses the regions of various vulnerability classes.

As depicted in Table 6-14, generally the groundwater quality water of the samples observed complies with the Tanzania Temporary Standards (TTS) for drinking water, in terms of TDS (1000 mg/l), chloride (800 mg/l), nitrate (100 mg/l) and nitrate –nitrogen. Only few exceedences to TTS were noted, especially with nitrate and chloride concentrations. Out of the 30 samples taken from Dar es Salaam, 5 and 25 were from moderate and high vulnerability zones respectively. All samples from the moderate vulnerability class comply with TTS and comparatively showed low pollutant levels, except for chloride, where one sample had 851 mg/l (Figure 6-15). About 68% of samples taken from the high vulnerable zone showed nitrate concentrations exceeding 20 mg/l, which is viewed as relatively high to indicate early signs of aquifer damage (Freeze and Cherry, 1979; reported that the natural nitrate level in groundwater is around 10 mg/l). About 53% of these (that is 36% of the samples collected in the high zone) showed a nitrate concentration above 50 mg/l (WHO guideline limit in drinking water destined to human beings). About 40% of the samples taken from the moderate vulnerability zone showed nitrate concentrations exceeding 20 mg/l.

There is a general trend, which indicates increasing nitrate concentrations from moderate to high vulnerability zones. The trend was then tested by drawing concentration profiles of pollutants from Kipawa-City Centre (section ABA’ in Figure 6-8; Figure 6-12 and 6-13) and Kipawa—Kurasini (section ABB’ in Figure 6-9; Figure 6-14 and 6-15), covering a total distance of 11.2 km and 8.4 km respectively. There is a general trend of decreasing pollutant concentration from the residential district of Kipawa to City Centre and Kurasini. However, when specific boreholes were observed (through the pollutant profiles) no clear trend that depicts a correlation between pollutant concentration in groundwater and the vulnerability zones (where samples were taken from) could be identified. For instance, relatively low concentrations of all pollutants measured in the City Centre, which is a high vulnerable area, as compared to Kipawa (situated about 11.2 km away). Maybe the high degree of pavements and presence of sewerage system in the City Centre areas could be contributing to low pollutant levels in groundwater.

Interestingly, there is also a general trend for different land uses. High-density residential areas such as Buguruni/Ilala, Tandika, Kigogo and Manzese/Tandale are showing relatively high nitrate and nitrate-N concentrations. The nitrate levels may have arisen from the fact that these areas have no sewerage system, and means of sanitation is totally on-site disposal facilities (pit latrines and septic tanks). Samples from Tandika showed a nitrate level of 130 mg/l, 72.1 mg/l for Ilala Hospital and 97.7 mg/l for Kigogo Primary School.

Although, no specific correlation between vulnerability zones and TDS and chloride levels could be identified, the study has shown that there is good relationship between the groundwater vulnerability classes and nitrate concentration in Dar es Salaam. In this case, nitrate can be used as a good indicator of aquifer deterioration fate in regard to human activities (notably sanitation) in the city of Dar es Salaam. This proposition is supported by the fact that, human excreta is the chief contributor of nitrate in Dar es Salaam groundwater, since about 90% of the population are using on site disposal facilities. Similarly, nitrate can also be used as a “leading pollutant” to guide protection strategies (as explained in Chapter 8).

6.7 Suggestions on the Use of DRASTIC Model in Tanzania

It can be said that the groundwater vulnerability map for Dar es Salaam developed from the DRASTIC model simulations is varied for predicting areas that can easily be impacted by pollution sources. However, more data are needed so as to improve the confidence of the predictions. Mapping of boreholes drilled in Dar es Salaam should continue so as to provide data needed for updating the groundwater vulnerability map. The updating of the vulnerability map should be done in at least every two years (which is considered as enough time to collect new data). The USA National Research Council (1993) suggests that the level of confidence with DRASTIC predictions for any particular location may be quite low; and, it is difficult, if not impossible, to test the validity of these predictions. In literature there are conflicting results on the validity, depending on where the model was used. One should remember that the DI used to develop the groundwater vulnerability map is not a measurable quantity, and hence cannot be validated with direct measurements instead other pollutant parameters (e.g. nitrate) are used.

Table 6-14: Groundwater quality in selected locations in Dar es Salaam (December, 2001)

BH/NO.	Name of borehole	TDS (mg/l)	Conductivity (ì S/cm)	Sal (‰)	Nitrate (mg/l)	Nitrate-N (mg/l)	Chloride (mg/l)
66/2000	Ubungo Darajani	1700	3370	1.8	17.5	4.0	850.8
391/2000	Ubungo Bus Stand	203	428	0.2	20.3	4.4	18.5
011/99	Manzese - Tandale Dispensary	1760	3470	1.8	10.1	1.6	969.9
78/2001	Mburahati KKKT	1630	3240	1.7	1.44	0.5	713.3
461/2000	Mabibo National Housing P/School	998	2020	1.0	5.0	1.2	380.0
40/97	Social.W.F.T. I.	1480	2960	1.5	1.9	0.7	897.6
37/97	Kinondoni P/School	322	686	0.3	37.1	8.4	31.2
67/97	Mwananyamala B P/school	582	1212	0.6	152	34.3	89.3
52/97	Mwenge P/School	1120	2130	1.1	19.9	4.3	592.7
275/97	Kurasini DC S/Quarter	397	844	0.4	49.9	11.8	139.0
94/97	Kijitonyama P/S	433	906	0.4	55.5	12.5	82.2
164/99	St.Anthony Mbagala	264	560	0.3	36.6	8.5	114.9
99/97	Mtoni Primary School	498	1039	0.5	148	33.5	124.8
110/97	Tandika Mwembeyanga	381	792	0.4	130	29.6	89.3
42/97	Temeke Hospital	234	499	0.2	62.2	14.1	53.9
59/97	Kipawa Primary School	482	987	0.5	1.0	0.2	252.4
137/97	Kurasini P/S	142	304	0.1	23.7	5.5	25.5
13/97	MMC I Football ground	1397	694	0.7	19.6	4.4	214.1
19/97	Fire Brigade	1730	3420	1.7	23.3	5.4	699.1
28/97	Ilala Boma	411	859	0.4	9.8	2.1	117.7
30/97	Dar Tech College	108	232	0.1	0.1	0.2	24.1
34/97	Amana Ilala	484	1013	0.5	72.1	16.4	122.0
34/97	Kiwalani CCM	693	1443	0.7	8.7	2.2	337.5
92/97	Buguruni Moto P/School	615	1273	0.6	44.9	10.2	235.4
109/97	Msimbazi Mseto Primary School	428	864	0.4	46.9	10.7	78.0
83/99	DSA Kurasini	351	721	0.3	23.7	5.5	130.5
27/97	Uwanja wa Taifa	328	683	0.3	87.8	19.9	93.6
31/97	Ilala Shule/Uhuru	319	668	0.3	34.0	7.7	79.4
66/97	Kigogo P/S	678	1394	0.7	97.7	22.2	163.1
39/97	Kigogo Mwisho	580	1208	0.6	97.7	22.2	248.9

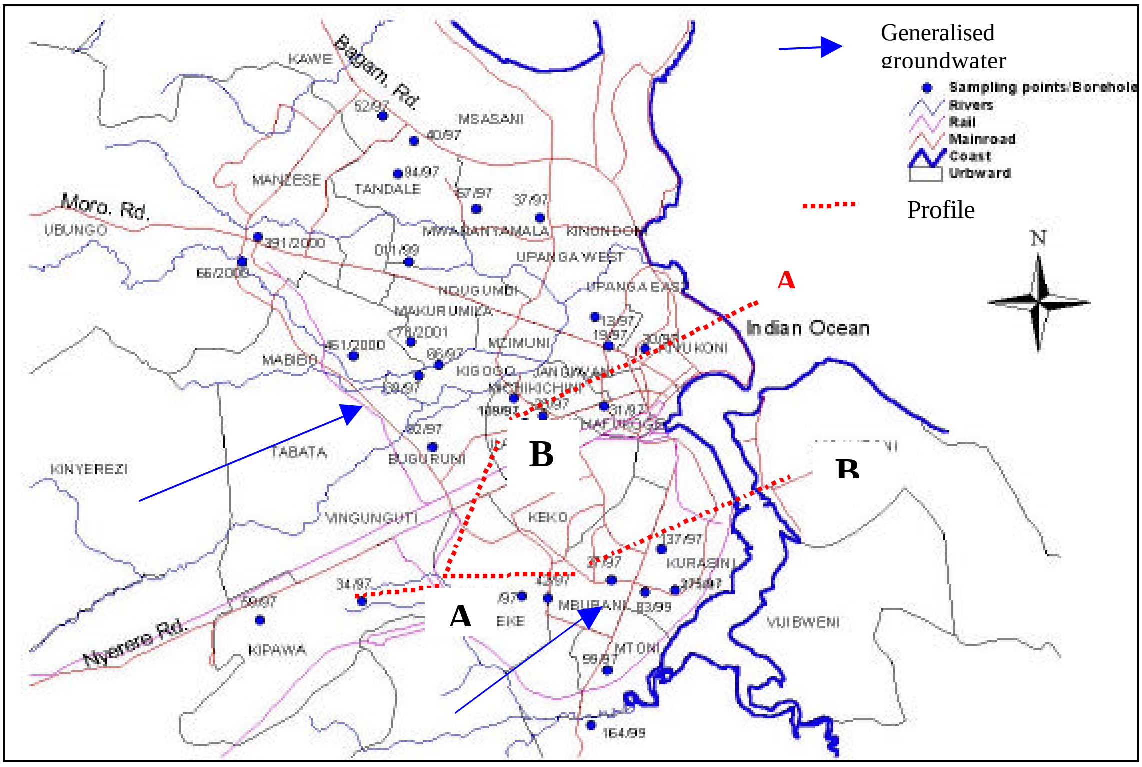


Figure 6-8: Part of the Dar es Salaam map showing sampling locations, December 2001

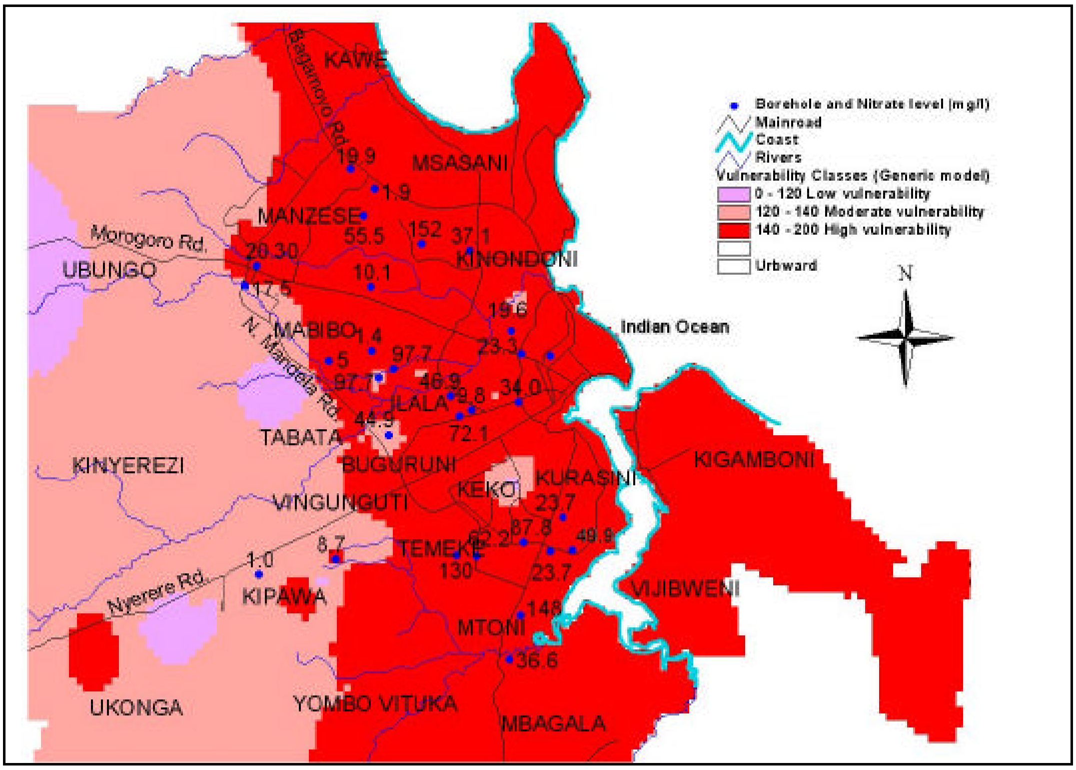


Figure 6-9: Relationship between measured nitrate concentration and groundwater vulnerability map for Dar es Salaam City, December 2001.

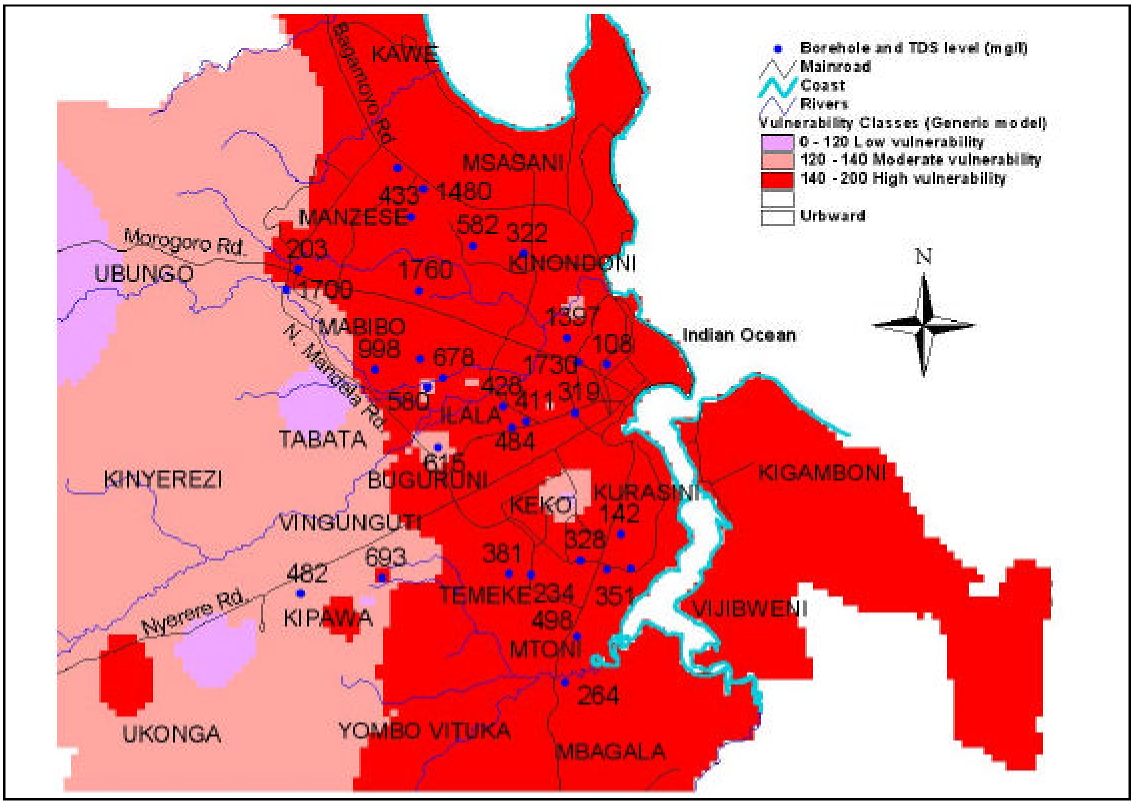


Figure 6-10: Relationship between measured total dissolved solids concentration and groundwater vulnerability map for Dar es Salaam City, December 2001.

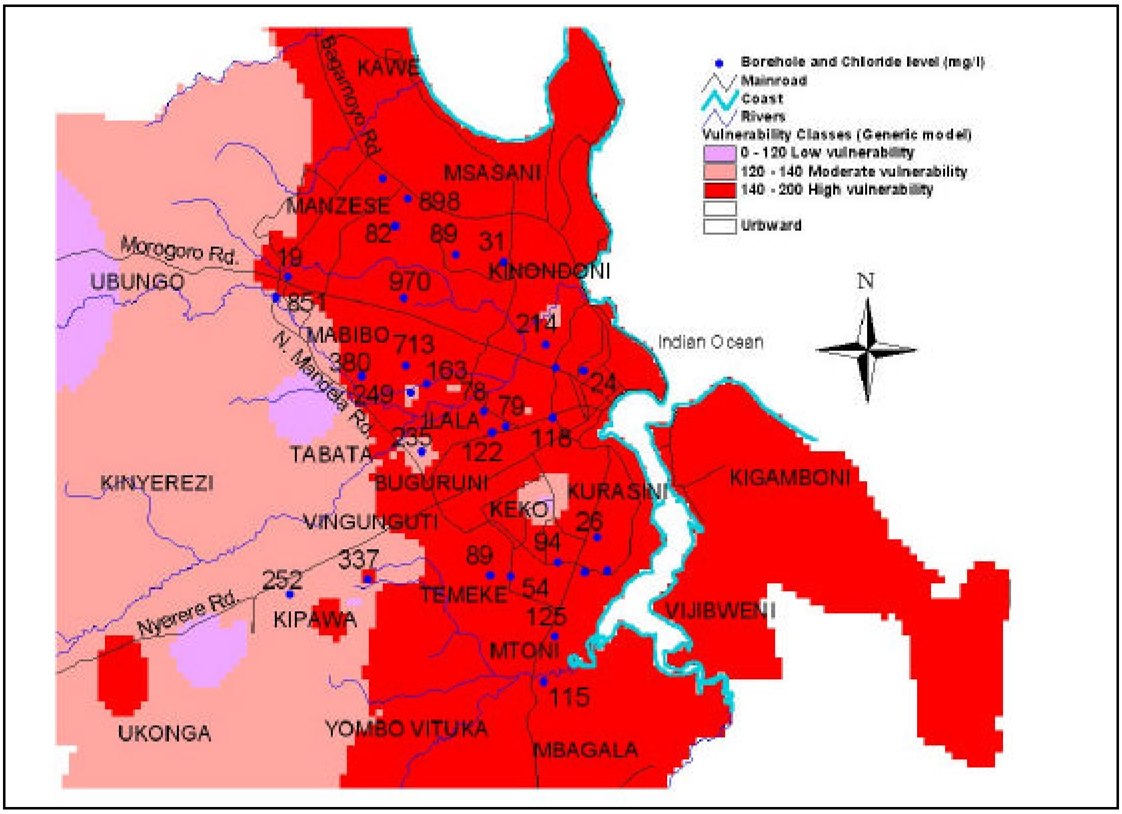
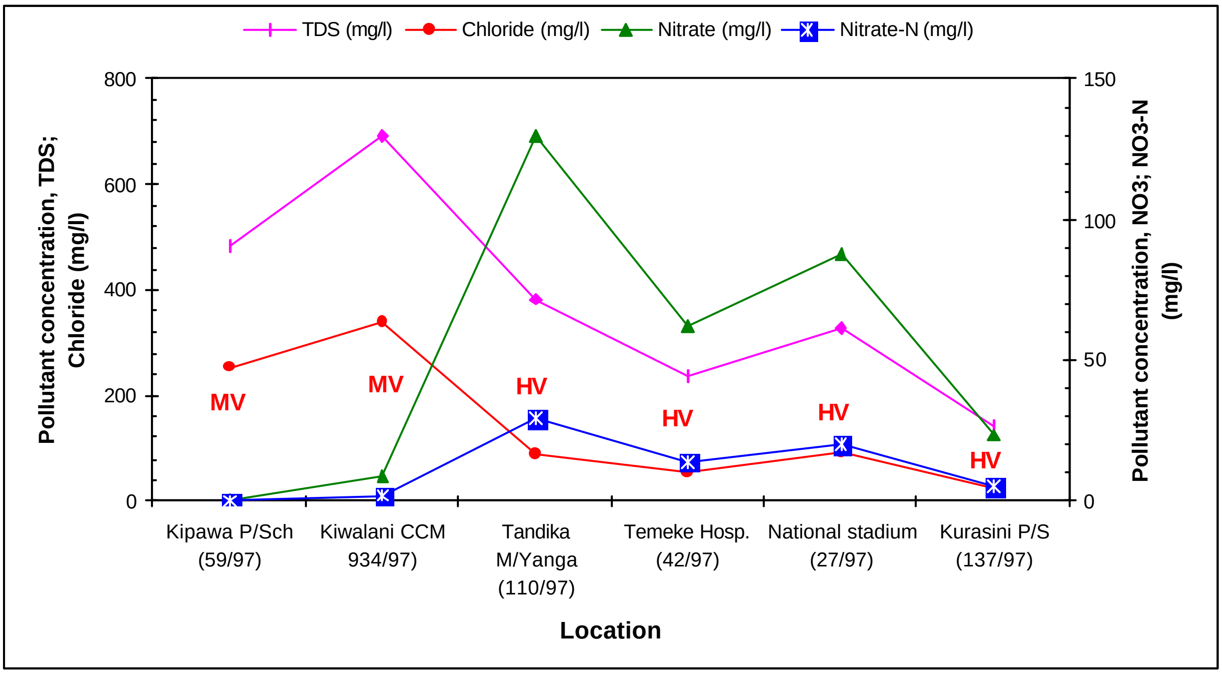


Figure 6-11: Relationship between measured chloride concentrations and groundwater vulnerability map for Dar es Salaam City, December 2001.



Note: MV- Moderate Vulnerability; HV- High Vulnerability

Figure 6-12: Longitudinal profile for selected pollutants, Kipawa to City Centre (2001)

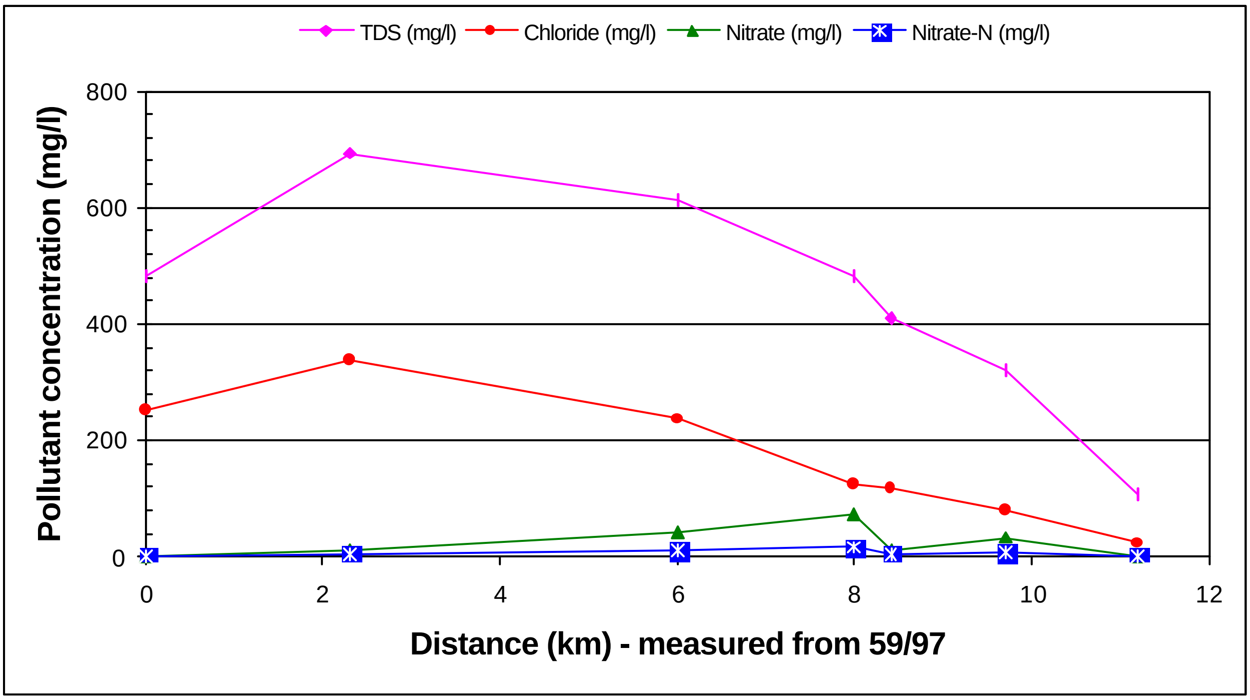
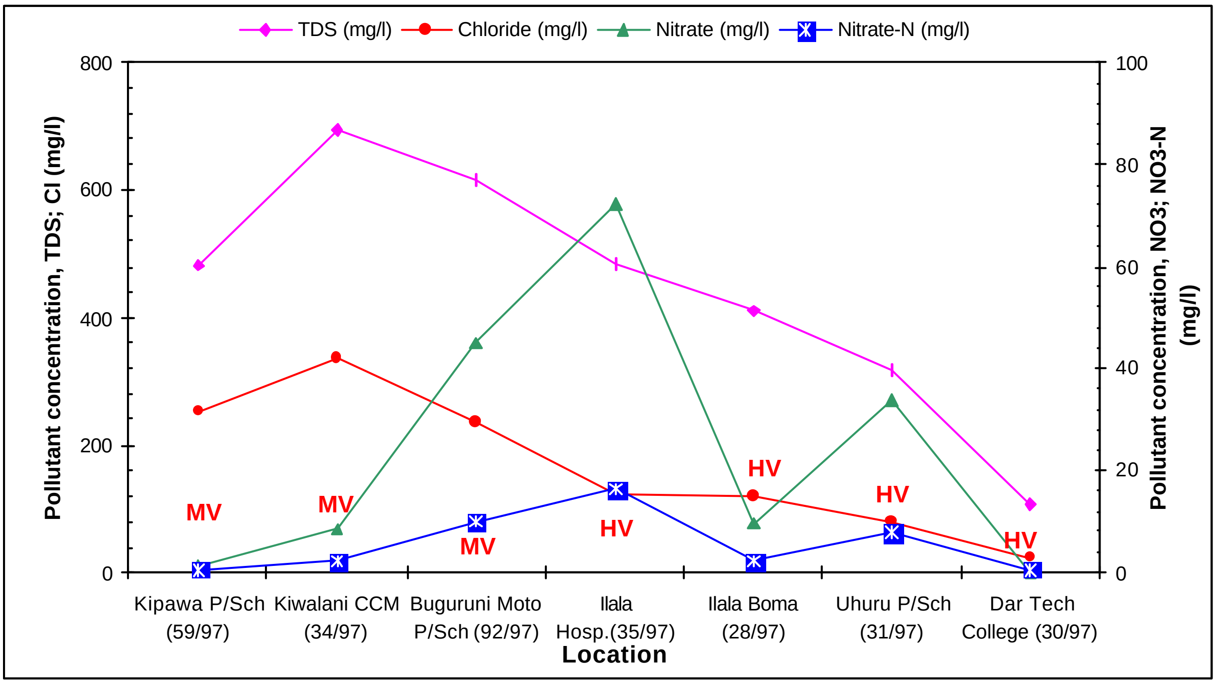


Figure 6-13: Longitudinal profile for selected pollutants, Kipawa to City Centre (2001)



Note: MV- Moderate Vulnerability; HV- High Vulnerability

Figure 6-14: Longitudinal profiles for selected pollutants, Kipawa to Kurasini (2001)

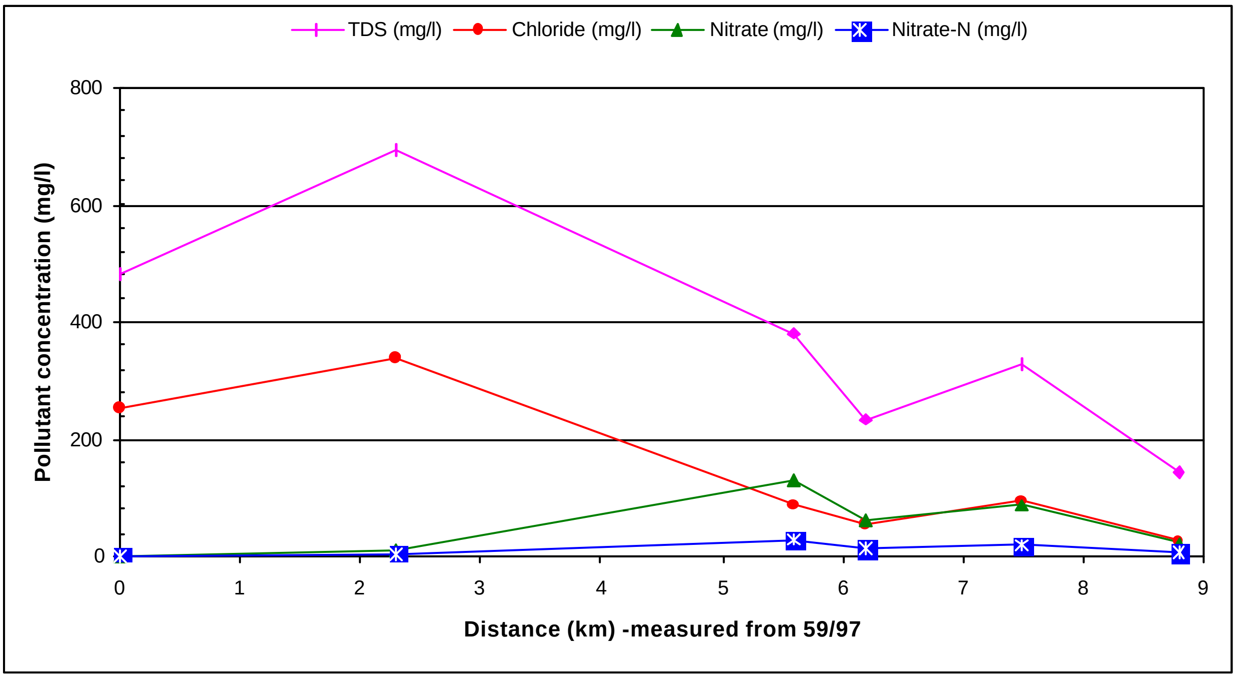


Figure 6-15: Longitudinal profile for selected pollutants, Kipawa to Kurasini (2001)

For the case of Dar es Salaam City, nitrate levels in groundwater have been found to be useful parameter to test the DRASTIC model prediction confidence In its form, the groundwater vulnerability map developed for the City of Dar es Salaam marks a milestone in efforts to combat pollution of drinking water sources. The map can be used as a general guidance to groundwater pollution control strategies (more discussion on these issues is found in Chapter 8). In addition, the groundwater vulnerability ”wall map” is a useful tool to educate the politicians and the general public on the susceptibility of groundwater to polluting activities in Dar es Salaam City; as such groups of people are fundamental parties in successful pollution control programmes.

6.8 Conclusion

Based on the groundwater vulnerability assessment carried out in Dar es Salaam City, the following conclusions are made:

- The groundwater vulnerability map has shown that about 50% of the city fall within the high groundwater vulnerability class, meaning that, the groundwater in the city can be easily polluted, as there is less natural protection against pollution sources. Therefore, indiscriminate waste disposal practices present in Dar es Salaam poses a great danger of polluting the groundwater.
- The coupling of DRASTIC model and GIS increases the visualization and understanding of the results of groundwater vulnerability assessment (mapping).
- The impact to the vadose zone is the most important factor of the DRASTIC model for the case of Dar es Salaam City.
- The DRASTIC model simulations showed a good agreement with nitrate measurements results obtained from samples taken from different vulnerability classes and that nitrate can be used as a good indicator of aquifer degradation in regard to human activities in the city of Dar es Salaam.
- The groundwater vulnerability map developed for the City of Dar es Salaam marks a milestone in efforts to combat pollution of drinking water sources. The map can be used as a general guidance to groundwater pollution control strategies.

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Chapter 7

PETROLEUM HYDROCARBONS DETERMINATION IN GROUNDWATER

Abstract

Petroleum hydrocarbons are among the chemical substances used for energy production and manufacture of various products we use in everyday life in our present times. Some of these have carcinogenic properties and are therefore hazardous to human health. In developed countries the presence of such substances in drinking water are monitored, contrary to Tanzania as well as for other developing countries. Samples from selected boreholes in Dar es Salaam city were analysed for petroleum hydrocarbons. About 10 individual PAHs were identified, and the Mwembeyanga borehole had benzo(a)pyrene (a powerful carcinogen) with a concentration of 1.17 ng/l. The total hydrocarbon content was found highest in the Dar Tech borehole: about 1.0 µg/l. Although the levels of petroleum hydrocarbons are within the standards of countries like The Netherlands, the results showed that these substances have already reached the aquifers in Dar es Salaam City. By superimposing the sources to the vulnerability map, an assessment of the groundwater petroleum hydrocarbon contamination risk was made. It was found that the City Centre areas (including Gerezani mechanics area) are among the locations with high risks of petroleum hydrocarbons contamination. Control of industrial effluents and environmentally sound techniques for construction and operation of fuel filling stations have been cited as key elements for keeping petroleum hydrocarbons within safe limits in aquifers in Dar es Salaam City.

7.1 Introduction

Numerous organic chemicals come to the soil, either intentionally by solid waste, by wastewater or by deposition from the atmosphere. The environmental conditions of the subsurface influence the mobility and persistence of chemical substances and, in the end they determine the micro-organic pollutants composition and concentration in groundwater. A great number of different natural and synthetic organic chemicals are used in chemical industry to make pesticides, plastics, pharmaceuticals, pigments, and other products that we use in everyday life. Many of these compounds are highly toxic such that exposure to very low concentrations can lead to serious health problems for human beings (Houzim *et al.*, 1986;

Blackman, 1993; Masters, 1991; Sacks and Akard, 1994; Cunningham and Saigo, 1997). For example, exposure to pico-gramme levels of dioxins can lead to birth defects, genetic problems and cancer (Kieley, 1997). These compounds also can persist in the environment because they are resistant to degradation and toxic to organisms that ingest them.

Organic chemicals are widely used in industries as degreasers for various processes in the metal, electronic, chemical, paper, textile and leather manufacturing (Kieley, 1997) or in agriculture as pesticides (e.g. sugar beet farming). By the end of 1985 more than 7 million chemical substances have been registered in the Chemical Abstracts System (Friesel, 1987). It is estimated that about 1% of these (i.e. 70,000) are produced and used some where in the world and that some 100,000 chemical substances are of potential danger to the environment (Friesel, 1987). The vast majority of these are organic chemicals (Friesel, 1987). In the USA, for example, it has been estimated that over 4×10^9 m^3 of contaminants (both inorganic and organic chemicals) enter the soil each year to pose a threat to groundwater (Liston, 1989). More than 400 different organic chemicals were identified in U.S.A. groundwater (Coleman *et al*, 1980; Plumb, 1985). The common reported substances found in drinking waters include petroleum hydrocarbons (e.g. alkanes and polycyclic aromatic hydrocarbons, PAHs), polychlorinated biphenyls (PCBs), polychlorinated dibenzodioxins (PCDDs), polychlorinated dibenzofurans (PCDFs) and pesticides (such as insecticides - organochlorine like DDT, organophosphates like malathion and parathion; carbamates like aldicarb; herbicides- phenoxyacetic acids, toluidines, triazines, phenyl urea like fenuron and isoproturon; fungicides- dithiocarbamates like manaeb and zineb, phthalamides like captan and captafol) and metabolites (Coleman et al, 1980; Nazari et al, 1993; Kieley, 1997; Abdrakhmanov, 1998).

There are more than 32000 different pesticides compounds being used, containing some 1800 active ingredients (Houzim *et al*, 1986). All differ in the risk they cause to groundwater due to variation in their solubility, persistence, mobility, and toxicity. The potential problem of pesticides is compounded by the fact that their metabolites (breakdown products) may also be toxic or mobile (Hallberg, 1989; Miller, 1985). For example, aldicarb, a highly toxic product used in sugar beet, degrades in compounds which are not only equally or more highly toxic, but are also more persistent and considerably more mobile (OECD, 1986). More than 39 different pesticides have been identified in groundwater in USA and Canada (Kiely, 1997). Soil fumigants and nematicides like aldicarb, which are used on vegetables and other crops, and herbicides like alacolor and atrazine have also been widely detected in groundwater (Kiely, 1997).

On broader terms, the volatile organic chemicals (VOC) are the most common types of industrial chemicals found contaminating groundwater systems. The VOCs are typically liquid chemical substances used in a wide range of commercial and manufacturing processes to clean equipment and other materials and in chemical production of chemicals as solvents. Examples of VOC commonly detected in ground water are halogenated organic substances, benzene, toluene, xylenes, and ethylene benzene (and others mentioned previously in Table 3.3 Chapter 3). Some of these compounds are also natural components of petroleum products like gasoline, diesel and kerosene used widely in transport sector, energy production and home lighting.

According to Kiely (1997), the complex nature of the solvents and other synthetic organic chemicals can cause serious hazards in groundwater from the fact that:

- They are of environmental significance at very low concentrations (parts per billion, ppb or µg/l) quantities;
- They are resistant to degradation and so are persistent; and
- Breakdown products do not always result in harmless or less harmful products.

Moreover, sampling for their determination requires special techniques and analyses are expensive (normally require sophisticated equipment such as Gas Chromatography with Mass Spectrometric detector – GC/MS).

In many developing countries like Tanzania, a large range of synthetic organic chemicals produced in industries are improperly disposed of after use, and this is becoming a threat to the groundwater (Lawrence, 1990). Literature shows that there are increasing documented cases on organic chemical pollution of groundwater (Costodio and Loch, 1987). The early detection and observation of groundwater pollution by organic substances is costly, difficult and time consuming, specially for organisations devoid of expert teams and sophisticated analytical means. In many low income countries drinking water from groundwater sources is not screened for organic chemicals due to the constraints mentioned above. In such circumstances, the impact of industrialization, agriculture and transport sector on groundwater resources is not well known. The same situation exists in Tanzania where presence of micro-organic pollutants is not a norm in routine drinking water analysis (for both water supplies and bottled water). With this background, identification of the presence of petroleum hydrocarbons in groundwater in the city of Dar es Salaam was conducted during the time of this research. Petroleum hydrocarbons were selected for determination due to their extensive use in the transport sector, home lighting and industries and therefore considered as diffuse pollutants. This chapter explains the methods and tools used in the identification, results and mapping of the major petroleum hydrocarbon sources.

7.2 Petroleum Hydrocarbons

Petroleum liquid is a “rock oil”, naturally occurring, oily and flammable liquid (crude) comprised of principally hydrocarbons. It is a major fuel of our society today, and energy source for automobiles, planes, marine vehicles and other machineries. It is also a source for a range of chemical substances such as plastics, lubricating oils and bitumen. The combustion of petroleum fuels is usually incomplete, and unchanged petroleum as well as partly combusted products are discharged to the atmospheric environment, of which their depositions contaminate the soil and water its sources above and beneath. Municipal sewage and urban runoff normally contain low concentrations of petroleum hydrocarbons due to industrial activities and deposits on road surfaces. Therefore, there is a tendency for petroleum contamination to occur to the greatest extent adjacent to urban complexes (Connell, 1997).

The chemical composition of petroleum is complex and can be variable from one deposit to another. Typically hydrocarbons contribute to 50-90% of petroleum; constituting n-alkanes, branched alkanes, cycloalkanes and aromatics (Connel, 1997). The cycloalkanes (naphthenes) comprise the largest group of hydrocarbons by mass in petroleum, most abundant being cyclopentanes and cyclohexanes. Aromatic hydrocarbons comprise compounds like benzene (C_6H_6), tetralin ($C_{10}H_{12}$), polycyclic aromatic hydrocarbons (PAHs) and alkyl-substituted benzenes (e.g. toluene- C_7H_8). Some organic components containing nitrogen (like 2-methylpyridine- C_6H_7N, quinoline- C_9H_7N, and indole-C_8H_7N), sulphur (like ethanethiol- C_2H_6S, thiacyclohexane- $C_5H_{10}S$, dibenzothiophene- $C_{12}H_8S$), and oxygen (like stearic acid- $C_{18}H_{36}O_2$, cyclopentacarboxylic acid- $C_6H_{10}O_2$, phenol- C_6H_6O) also form important constituents of certain petroleum deposits. Some structures of typical polycyclic aromatic hydrocarbons found in petroleum samples are shown in Figure 7-1. Some of the petroleum constituent compounds are carcinogenic and, as a group, the aromatics have a great health and environmental significance (Connel, 1997). However, the toxicological implications to man brought about by these substances is beyond the scope of this study.

The PAHs are the most important compounds in the aromatic group that have high environmental significance. They are ubiquitous in the environment as they stem from many sources, both natural and anthropogenic. They can originate from anthropogenic sources like petroleum spills, domestic sewage, industrial wastes, and washout from industrial pollution. Generally, the PAHs are produced by combustion, which can be natural (e.g., forest fires) or anthropogenic (e.g., combustion in automobiles). Their occurrences have been known for centuries (Milton et al., 1981) and they are widely distributed in aquatic sediments, water, air, plants and animals. However, the PAHs comprise the largest group of chemicals known to induce cancer (with characteristics of uncontrolled cell growth) to organisms (Milton et al., 1981). Some PAHs known to have carcinogenic properties appear in the priority pollutant lists of both European Union and the Environmental Protection Agency of USA (Table 7-1).

Chemically, the PAH family of hydrocarbons consist of molecules containing two or more fused 6-carbon aromatic rings. Naphthalene is considered the simplest of the group with one aromatic ring, while coronene is the most complex with 7 (Connel, 1997) (Figure 7-1). Acenaphthalene and fluoranthene also contain five-member rings in their structures as well. There are also other PAHs based on these structures as a parent structure and that contain attached alkyl and other groups. The most common members of the group of PAHs are naphthalene ($C_{10}H_8$) and benzo(a)pyrene ($C_{20}H_{12}$), the later being the most powerful carcinogen (sometimes the occurrence of PAHs are reported in terms of this substance) (Connel, 1997). Benzo(a)pyrene is also the most persistent PAH in sediment water environment of up to 300 weeks (Connel, 1997). Typical values of some PAHs in the environment are given in Table 7-1. Though there are very high concentrations of PAHs in combustion particulates (Table 7-2), very low levels are normally found in fresh water.

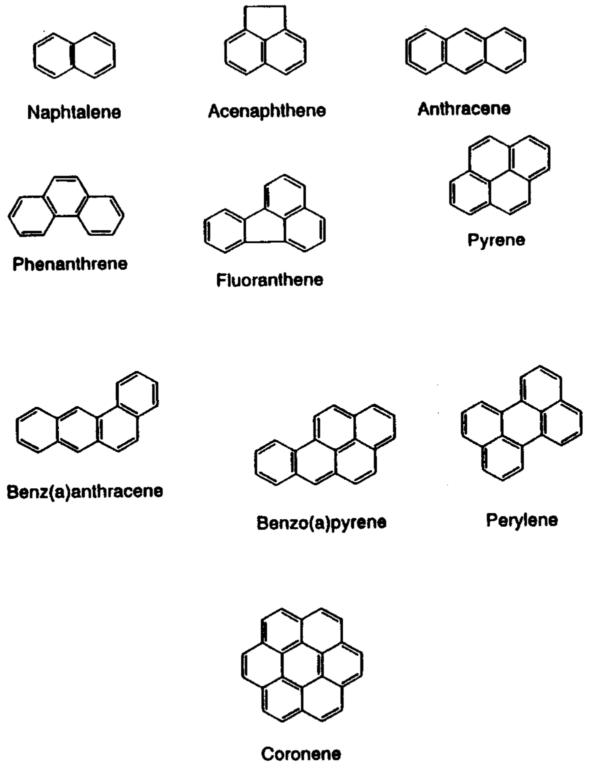


Figure 7-1: Chemical structures of some typical members of the PAH family frequently encountered in the environment

Table 7-1: Polycyclic aromatic hydrocarbons contained in the EU and EPA priority pollutant PAH list

Name	Name
Naphthalene	Benzo(a)anthracene
Acenaphthalene	Chrysene
Acenaphthene	Benzo(b)fluoranthene
Fluorene	Benzo(k)fluoranthene
Phenanthrene	Benzo(a)pyrene
Anthracene	Dibenzo(g,h,i)perylene
Fluoranthene	Indeno(1,2,3-c,d)pyrene
Pyrene	Dibenzo(a,h)anthracene

Table 7-2: Typical examples of some PAHs in the environment (Connel, 1997)

Polycyclic Aromatic Hydrocarbon (PAH)	Combustion Particulate (mg/kg)	Air typical city location (ng/m^3)	Smoked fish (ì g/kg)	Sewage sludge (ì g/kg- dry weight)
Fluoranthene	4-400	1-15	300-3000	2-7
Benzo(a)anthracene	2-160	0.1-20	20-200	1-4
Perylene	0.1-138	1	1-4	0.1-2
Benzo(a)pyrene	0.2-64	1-1000	4-16	0.5-3
Coronene	0.1-40	2	1-10	0.1-2

The PAHs determination is mostly limited to the analysis of 16 compounds in the EU and EPA priority pollutant list, for drinking, surface and wastewaters. Usually a selective and sensitive analytical method for PAH determination is required. The analytical methods commonly used include; capillary gas chromatography-mass spectrometry (GC/MS) and High Performance Liquid Chromatography (HPLC). The concentration of PAH in water ranges from ppt (ng/l) to ppm (mg/l) level.

The pollution of groundwater by petroleum products is recognized as a major threat to water resources in many areas of the industrialized nations. It is now apparent that any facility handling hydrocarbons can be regarded as a potential pollution source and any facility more than a few years old is likely to have become a pollution source (Clark, 1995). The problem has been exacerbated in situations where technical standards of installation or maintenance of installations has been lacking, or where hydrocarbons have been stored or produced in bulk during a long period (Clark, 1995). Wherever mineral oil is produced, stored, transported by vehicle or pipeline or consumed there exists a potential source of oil pollution through direct seepage into the ground. In Tanzania (as for most countries) urban areas are centres where most petroleum hydrocarbons are used, and therefore have high risks of pollution from these substances.

In the city of Dar es Salaam, there is increasingly use of petroleum products in industry, domestic and transport sectors as already elaborated in Chapter 3. In line with the above discussions, there was a need to search for petroleum hydrocarbons in groundwater samples from the city, to see if the aquifers are already contaminated with these substances.

7.3 Experiments to Identify Petroleum Hydrocarbons in Dar es Salaam Groundwater

7.3.1 Sampling

Groundwater samples were taken from about 30 production boreholes in Dar es Salaam City, in July and December 2001. The boreholes sampled form part of the proposed monitoring network discussed in Chapter 8 (where the location map is also found). Samples were taken from taps provided at the delivery end of the pump installations for the boreholes. Where such system was absent, samples were taken from the nearest consumer tap connected to the borehole. Samples were collected from running water, after opening the tap for about 1-2 minutes. Samples were collected in 250-ml brown glass bottles, with rubber stoppers having a Teflon seal lining in the inside.

Samples collected in July 2001 were sent to TES Bretby laboratory, UK for analysis. The samples were analysed for total petroleum hydrocarbons (TPH), benzene, toluene, Ethylbenzene and xylenes using gas chromatographic methods. The results are given in Table 7.3.

Samples collected in December 2001, were first treated with 1-2 ml of chloroform ($CHCl_3$-analytical grade) in order to reduce the microbial activity. The samples were then transported to the Eindhoven University of Technology (TUE), The Netherlands for analysis. Some of the samples were sent to the Research Institute for Chromatography (RIC), Kortrijk, Belgium for further analysis. The results are given in Table 7-4 and Figure 7-2.

7.3.2 Sample preparation and instrumentation

For the samples analysed at the TUE, liquid-liquid extraction was used. The sample (groundwater – 100 mL) was shaken with 3 portions of 30 mL of methylene chloride (dichloromethane). The organic phase collected was then evaporated to 1-2 mL by passing a controlled and gentle flow of air.

A Shimadzu Gas Chromatography-Mass Spectrometer system, GC/MS-QP500 was used for the analysis at the TUE. A Chrompack, 25 m long and 0.25 mm internal diameter, wall-coated open tubular (WCOT) column was used. The column film thickness was 0.40 ìm and the stationary phase was CP-Sil-5 CB (100% dimethylsiloxane). The injector temperature was set to 210 ^{o}C and the oven temperature programmed from 40 ^{o}C to 250 ^{o}C. The carrier gas was helium with a column flow rate of 1.2-ml/min and total flow of 31.2 mL/min. A split injection mode was used, with a ratio of 25. The interface temperature was set to 250 ^{o}C. The mass spectrometer was tuned to scan a mass range of 35 to 400. The injection volume used was 0.5 µL.

7.3.3 Results

The results shown in Table 7-3, essentially suggests the presence of petroleum hydrocarbons in groundwater but in very low confrontations. In all samples analysed in Britain, the petroleum hydrocarbons concentrations were very low.

Table 7-3: Identification of petroleum hydrocarbons in selected borehole groundwater samples in Dar es Salaam City, July 2001 (analysed at TES Bretby, UK)

Site of Sample collection	Date	TPH (mg/l)	Benzene (ì g/l)	Toulene (ì g/l)	Ethyl Benzene (ì g/l)	Xylene (ì g/l)
Amana Hospital	13/7/2001	<0.7	<1.0	<1.0	<1.0	<1.0
Ilala DAWASA	13/7/2001	<0.7	<1.0	<1.0	<1.0	<1.0
Karume Stadium	13/7/2001	<0.5	<1.0	<1.0	<1.0	<1.0
Buguruni Moto P/S	13/7/2001	<0.7	<1.0	<1.0	<1.0	<1.0
Ilala Boma	13/7/2001	<0.7	<1.0	<1.0	<1.0	<1.0
Buguruni S/ Viziwi	13/7/2001	<0.5	<1.0	<1.0	<1.0	<1.0
National Stadium	13/7/2001	<0.5	<1.0	<1.0	<1.0	<1.0
Breweries Bondeni	13/7/2001	<0.5	<1.0	<1.0	<1.0	<1.0
Kurasini P/S	13/7/2001	<0.5	<1.0	<1.0	<1.0	<1.0
Uhuru P/S	13/7/2001	<0.5	<1.0	<1.0	<1.0	<1.0
Msimbazi Centre	13/7/2001	<0.5	<1.0	<1.0	<1.0	<1.0
Ilala Garden	13/7/2001	<0.5	<1.0	<1.0	<1.0	<1.0
Msimbazi Mseto P/S	13/7/2001	<0.5	<1.0	<1.0	<1.0	<1.0
Twiga Paper Keko	13/7/2001	<2.5	<1.0	<1.0	<1.0	<1.0

The results of the analysis in Table 7-4 indicate that all the 5 samples showed the presence of PAHs and other hydrocarbons. The highest concentration of an individual PAH was found in Ilala Boma borehole, where phenanthrene was 15.45 ng/l (or 0.015 µg/l). Benzo(a)pyrene was detected in appreciable amounts in Mwembeyanga borehole, at a concentration of 1.17 ng/l (or 0.001 µg/l), a level below the Dutch standard for drinking water of 10 ng/l (or 0.01 µg/l). Comparatively, Mwembeyanga, Ilala Boma and Dar Tech boreholes, had a total number of individual PAHs identified exceeding 5. Relatively, Mwembeyanga is the most affected of all the samples analysed. However, in all the boreholes, the total amounts of PAHs are within the standard for drinking water for a country like The Netherlands, where the maximum allowed limit is 100 ng/l (or 0.1 µg/l).

The total hydrocarbon content was found highest in the Dar Tech borehole, of 1.01 µg/l (Figure 7-2). With the exception of Kurasini P/School borehole, all the samples had a concentration of total hydrocarbon of about 0.8-1.0 µg/l. The Kurasini P/School sample had only 0.24 µg/l total hydrocarbons. Though the amounts of hydrocarbons are relatively low, the results indicate that appreciable amounts of petroleum hydrocarbons have already reached the aquifers in Dar es Salaam. In the next section the potential risks of groundwater from petroleum hydrocarbons contamination in the city is discussed.

Table 7.4: The PAH concentrations in selected borehole water samples in Dar es Salaam, 2001 (analysed at RIC-Kortrijk, Belgium).

	Borehole				
	Mwembeyanga	Kurasini P/Sch	Ilala Boma	Dar Tech	Uhuru P/Sch
PAH	ppt or ng/l	ppt or ng/l	ppt or ng/l	ppt or ng/l	ppt or ng/l
Naphthalene	8.32	< 1.0	5.28	6.44	6.58
Acenaphthylene	< 1.0	< 1.0	< 1.0	1.13	< 1.0
Acenaphthene	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0
Fluorene	2.86	< 1.0	2.12	3.25	2.50
Phenanthrene	6.59	3.74	15.45	12.19	12.88
Anthracene	1.06	< 1.0	1.33	1.00	< 1.0
Fluoranthene	7.87	1.09	1.79	3.55	2.62
Pyrene	10.01	1.38	2.19	3.16	1.82
Benzo(a)anthracene	1.08	< 1.0	< 1.0	< 1.0	< 1.0
Chrysene	1.63	< 1.0	< 1.0	< 1.0	< 1.0
benzo(b)fluoranthene	1.13	< 1.0	< 1.0	< 1.0	< 1.0
Benzo(k)fluoranthene	1.21	< 1.0	< 1.0	< 1.0	< 1.0
Benzo(a)pyrene	1.17	< 1.0	< 1.0	< 1.0	< 1.0
Indeno(1,2,3-c,d)pyrene	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0
Dibenzo(a,h)anthracene	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0
Benzo(g,h,i)perylene	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0
Hydrocarbons Total (ppb or µg/L)	0.79	0.24	0.92	1.01	0.81

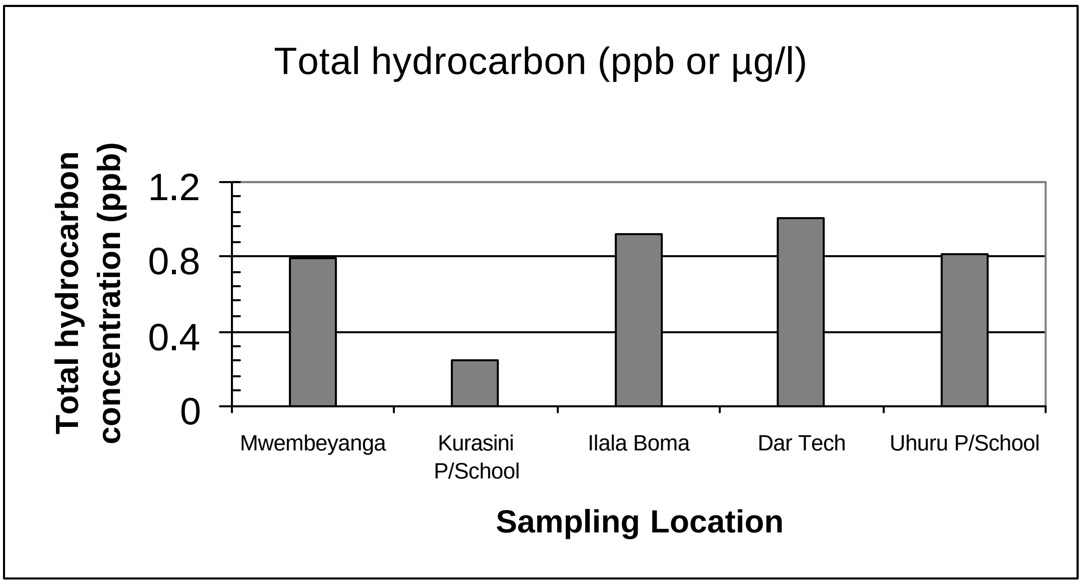


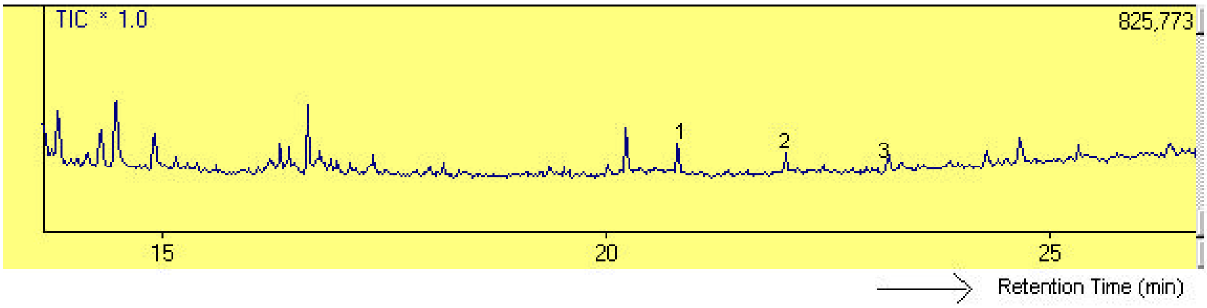
Figure 7-2: Comparison of total hydrocarbon concentrations in selected boreholes in Dar es Salaam, 2001.

Table 7-5: Groundwater samples analysed at TUE

Borehole Location				
Mabibo NHC	Mtoni P/Sch	Kipawa P/Sch	Kijitonyama P/Sch	*Fire brigade
*Buguruni Moto P/Sch	Kwalani CCM	Konondoni P/Sch	Msimbazi Mseto P/Sch	Amana (Ilala) Hosp
Kigogo P/Sch	Mbagala St. Ant.	Mwananyamala P/Sch	*MMC (playground)	*Mwenge P/Sch
D.C. Kurasini	Kigogo Mwisho	Ubungo Darajani	Social Welfare Institute	Temeke Hosp and

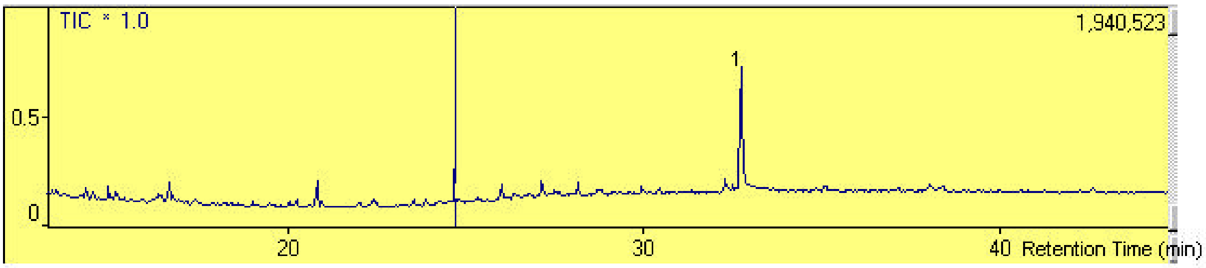
* Samples with petroleum hydrocarbons

The results of analysis at TUE also showed the presence of petroleum hydrocarbons, especially n-alkanes and other organic compounds (e.g. phthalates) in some samples. However, in all samples, the concentrations were very low. Pure substances of n-alkane (ranging from C10 to C20) were used to confirm the presence of these compounds in the test samples by comparing the retention times. The samples analysed at TUE are given in Table 7-5, and an example of chromatogram results is shown in Figures 7-3 to 7-6.



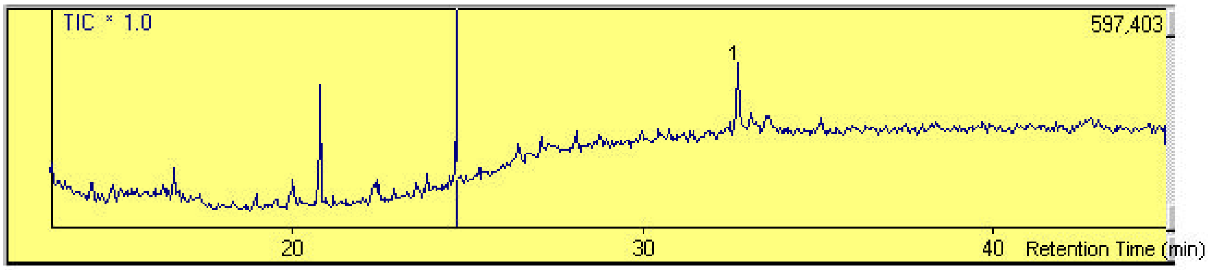
Peaks: 1: hexadecane ($C_{16}H_{34}$); 2: heptadecane ($C_{17}H_{36}$); 3: Octadecane ($C_{18}H_{38}$)

Figure 7-3: Part of the chromatogram for Mwenge P/School borehole sample



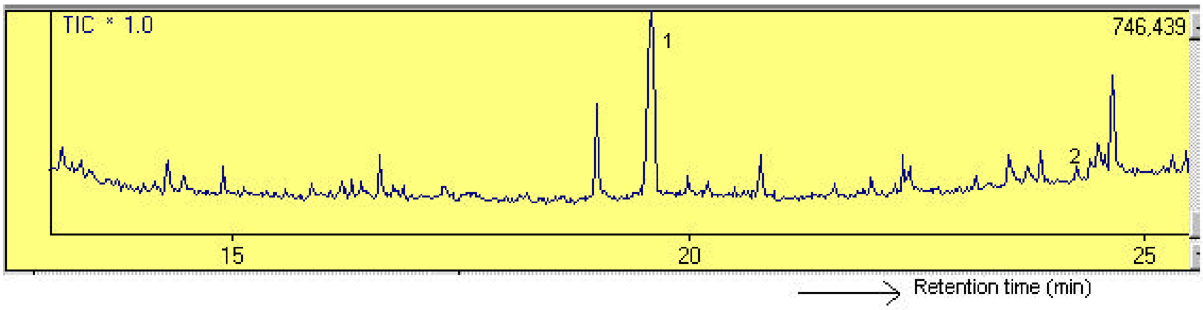
Peak 1: Di-n-octyl phthalate ($C_{24}H_{38}O_4$) – a typical plastic constituent

Figure 7-4: Part of the chromatogram for Fire brigade borehole sample



Peak 1: Di-n-octyl phthalate ($C_{24}H_{38}O_4$) – a typical plastic constituent

Figure 7-5: Part of the chromatogram for Muhimbili Hospital (MMC) playground borehole sample



Peaks: 1: Pentadecane ($C_{15}H_{32}$); 2: Nonadecane ($C_{19}H_{40}$)

Figure 7-6: Part of the chromatogram for Fire brigade borehole sample

The GC-MS was also operated in the Single Ion Mode (SIM) and the samples were scanned for the presence of benzo(a)pyrene. However, benzo(a)pyrene was not detected in all the samples tested. Many other peaks were observed in the samples as indicated in Figures 7-3 to 7-6. These peaks indicate the presence of other organic compounds in the samples, although they were not identified.

7.4 Mapping the Groundwater Contamination Risk from Petroleum Hydrocarbons in Dar es Salaam

During the time of this study an inventory of major petroleum hydrocarbon sources in Dar es Salaam, namely, fuel depots and filling stations and automobile garages was made. In this case, the industrial sources (time did not allow to map them) and atmospheric deposition were excluded, though are also a major source. The geographical positions of the facilities were recorded using a GPS handset (GARMIN'S GPS II$^+$). The co-ordinates of these sources were spatially analysed using ArcView GIS software (version 3.1) and the city's map with petroleum hydrocarbons sources was produced. This map was then superimposed upon the groundwater vulnerability map, so as to visualize the risk of contamination from petroleum hydrocarbons. This process resulted in another map known as “petroleum hydrocarbon contamination risk map” (Figure 7-7 and Figure 7-8). It should be noted that the map is not exhaustive as there are many other fuel filling stations and garages that were not mapped due to limitations in time and a lack of funds.

The petroleum hydrocarbon contamination risk differs from one area to another, depending on many factors such as the type of the hydrocarbon source, quantities being handled, handling procedures and safety installations available and the groundwater vulnerability class in which the facility is located. An interest developed in assessing the ranks of the contamination risks. A simple comparison scheme was developed for this purpose, in which the contamination risks due to different sources could be compared. A 3x3 matrix of vulnerability classes against type of source located in the areas was constructed (Table 7-6). The sources were weighted in the following manner: fuel depots (high, h), fuel filling stations (moderate, m) and garages (low, l). The groundwater vulnerability map developed in chapter 6, has three classes, namely, low (L), moderate (M), and high (H). Table 7-6 shows the results of the matrix manipulations, the contamination risk level (CRL). In this assessment scheme, the attenuation characteristics of the petroleum hydrocarbons were assumed to be the same and the age of the facility was not considered (due to unavailability of data).

Table 7-6: Petroleum hydrocarbon contamination risk level matrix for Dar es Salaam

Pollution source ↑	→ Vulnerability		
	L	M	H
h	**M**	**M**	**H**
m	**L**	**L**	**H**
l	**L**	**L**	**M**

The results show that high risk of groundwater contamination from petroleum hydrocarbons is concentrated in and around the city centre, and mostly in the lower edge of Kurasini where main oil depots are located. Using the evaluation scheme in Table 7.6, it was revealed that all the major sources of petroleum hydrocarbons surveyed are rated high risk, mainly because they are located within the high vulnerable zones. Close observation also indicated that within the same areas are located production boreholes for drinking water (Figure 7-7 and Figure 7-8). Although the analytical data show that the groundwater is safe from petroleum hydrocarbons now, still the risk of contamination remains. Hydrocarbons spilled on the land surface may reach the groundwater table by diffusion or simply transported by recharge water. The velocity of gasoline in sand soil is about 0.5-1.0 m/annum. Assuming this flow velocity, it will take about 20-40 year for gasoline spilled on the land surface to reach the productive aquifers (which are located about 20-70 m deep) in Dar es Salaam. It was noted that some of the fuel filling stations have been in operation for more than 20 years, time enough for the pollution plume to reach the aquifers. It is thus expected that in due time higher concentrations of petroleum hydrocarbons will occur in groundwater in Dar es Salaam based on earlier experiences in Europe and USA. The best way of insuring safe drinking water is by taking up protection measures e.g. safe environmentally operation of filling stations and fuel depots to have proper loading procedures as well as a contingency plan to deal with oil accidents. More broader groundwater protection approaches are discussed in Chapter 8.

7.5 Suggested Measures to Reduce Petroleum Hydrocarbons Contamination

Other measures that can help to protect groundwater in Dar es Salaam City from petroleum hydrocarbons contamination include:

- Good construction of fuel filling stations and depots that will minimize soil contamination. For instance, paving the entire station and/or applying a geomembrane below the paved surface in order to limit oil layers from penetrating to the groundwater. The cost for geomembrane is estimated at US $ 5-10 per m^2;

- Constructing a drainage channel around the station that can hydraulically isolate it from the surrounding ground in case of huge spillage. The channel will also drain away contaminated storm runoff. The cost for the drainage channelled is estimated at US $ 20 per linear metre;

- Provision of properly designed spent oil disposal area at automobile service station and garages. The cost for installing an oil separator is estimated at US $ 600.

- Drill monitoring wells around petrol stations for yearly analysis to monitor groundwater contamination due to petroleum products. The cost for analysis is estimated at US $ 100-200 per sample; and

- Operators at the stations must be educated on the hazards of petroleum products to the environment.

These measures should be mandatory and a responsibility of any oil company that constructs a fuel filling station or depot in Dar es Salaam. However, much effort must also be directed towards the control of industrial effluents, which despite that they may have petroleum hydrocarbons they are also the major source of dangerous chemical pollutants of other nature. Industries must be challenged to install or innovate appropriate waste treatment methods in order to reduce the pollutant loads they are currently emitting to the environment.

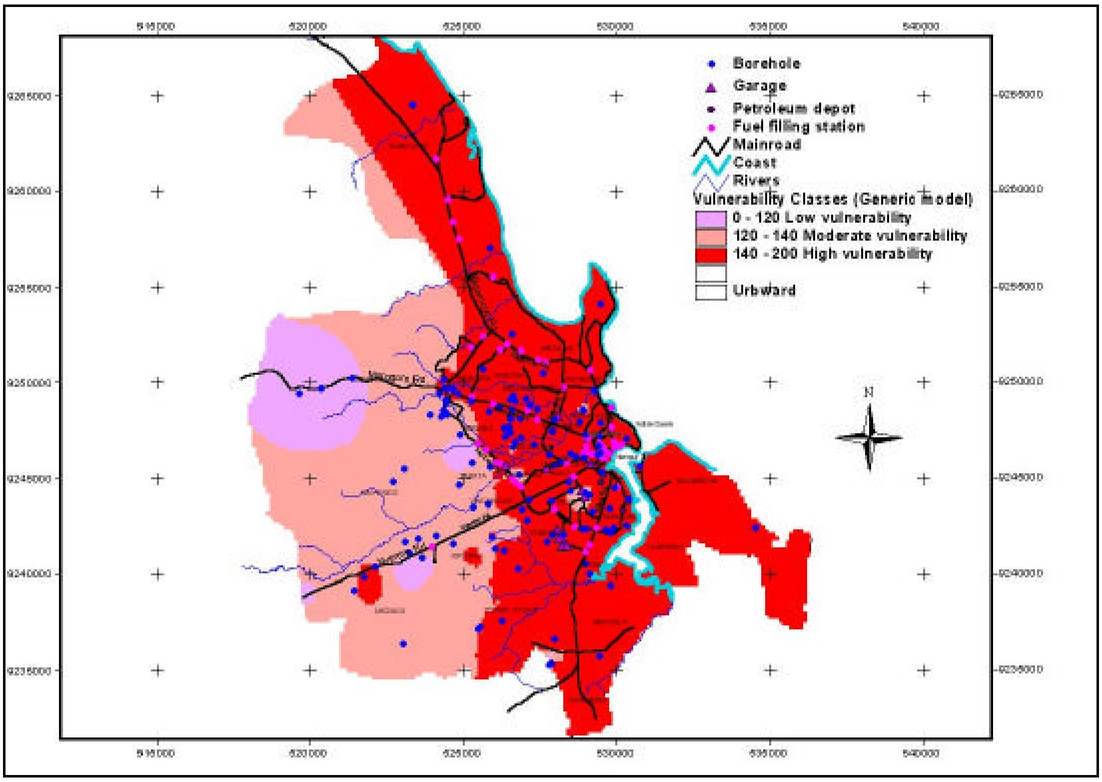


Figure 7-7: Petroleum hydrocarbons contamination risk map for Dar es Salaam city (2001)

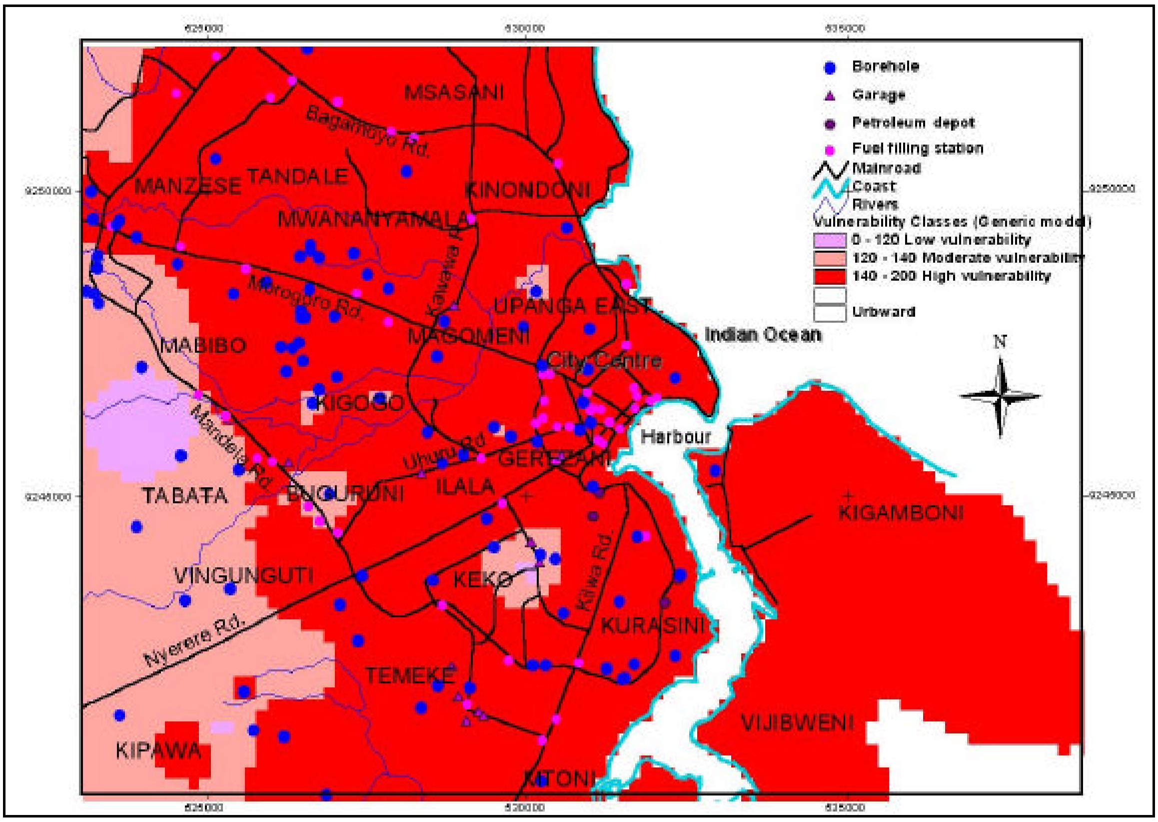


Figure 7-8: Enlarged map to show petroleum hydrocarbon pollution risk to groundwater

7.6 Conclusion

From the preceding discussion, the following can be concluded:

- Petroleum hydrocarbons have been identified in Dar es Salaam groundwater, however, the concentrations are lower than the drinking water standards in Europe and USA.
- The boreholes in the city centre areas are located in high risks zones, for petroleum hydrocarbons contamination.

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Chapter 8

DEVELOPMENT OF GROUNDWATER MANAGEMENT STRATEGY: ASSESSING PROTECTION PRIORITIES

Abstract

Groundwater quality protection has increasingly become a public issue worldwide, and it aims at preserving the quality and the quantity of groundwater in agreement with other interests of land use. In many countries, groundwater protection plan is used as a guide in supervision of water legislation, issuing of permits, planning land use etc. This chapter gives explanations on the groundwater management strategy for Dar es Salaam City, which has been formulated. The strategy is an essential element for achieving sustainable utilization of the groundwater resource in the city. The strategy entails seven key inputs, namely: identification of pollution sources, establishment of databases and information management; development of vulnerability map, assessment of protection needs and priorities, initialisation of monitoring network, improved institutional coordination and public participation. A rapid assessment model, the WYVUL model, for assessing groundwater protection priorities has been formulated and applied. Using the model, a groundwater protection map for Dar es Salaam has been developed. The map delineates areas of Mbagala and Charambe having high protection priorities. In addition, a monitoring network for taking surveillance on groundwater quality has been formulated and initialised.

8.1 Introduction

Sustainable groundwater management encompasses groundwater development, protection and conservation; it normally strikes a balance of the three components. Groundwater quality protection, particularly as related to the control of anthropogenic pollution sources has increasingly become a public issue worldwide (Canter, 1987), although to some countries it is a relatively new area of environmental concern. The need for protecting aquifers arises after detection of increased demands for groundwater resources development and usage, and the recognition of deteriorating quality resulting from pollution sources. The protection protocol is based on the principle that prevention is less expensive than remediation of polluted aquifer, which is a costly, long term and technically demanding task if not impossible. The general objective of protection programmes is to ensure good quality and sustainability of groundwater as a strategic source of drinking water and undeniable supporter of terrestrial ecosystem. In this context, sustainability requires avoidance of any groundwater pollution, which needs precautionary efforts on all kinds of land uses and human activities; and consideration of a balanced water budget for a groundwater system. Groundwater protection carries high stakes and serves as substantiation for society's efforts at sustainable development. However, it is not an easy task to create awareness for the high priority of groundwater protection as an ecological issue because unlike rivers and lakes groundwater cannot be seen or felt; rather it can only be observed through a narrow keyhole of boreholes and geophysical logs, or through the quality of the water drawn from it. Hence in the framework of sustainable development, which many countries (including Tanzania) have adopted within policy goals, groundwater protection becomes a major responsibility of our present society for future generations.

Protection of groundwater resources aims at preserving the quality and the quantity of groundwater in agreement with other interests of land use (Granlund *et al.*, 1994). Groundwater protection plan is used as a guide in supervision of water legislation, issuing of permits, planning land use, etc. Thus, data is needed on hydrogeological conditions, possible sources of pollution and all interests involved. To achieve this goal, monitoring, vulnerability mapping and modelling have become indispensable actions embedded in groundwater protection programmes. This Chapter defines a groundwater management plan, which can be implemented in Dar es Salaam; it also formulates a specific rapid assessment model for assessing groundwater quality protection priorities for the city.

8.2 Groundwater Management in Tanzania

As earlier stated (Chapter 2), development of groundwater in the country is going on almost unregulated; and therefore, there are no broad groundwater management strategies in place to control abstraction rate and pollution of aquifers (Kongola *et al.*, 1999). This is not a good practice in relation to the value of the groundwater resource. The status of groundwater management in Tanzania, which to a greater extent has influence on the groundwater protection strategy for Dar es Salaam City, has the following characteristics.

8.2.1 Development

Both registered and unregistered drillers do drilling. Hand augers are normally used for shallow wells and mechanical equipment used for medium and deep wells. The drilling success rate is more then 75% (Kongola *et al.*, 1999).

8.2.2 Monitoring

Groundwater quality monitoring is a process, which provides data and information for the development, protection and general management of groundwater.

UNESCO/WHO (1978) defines monitoring as standardized measurement and observation of the environment. Meyer (1973) defines monitoring of groundwater quality as a scientifically designed programme of continuing surveillance, including direct sampling and remote quality measurements, inventory of existing and potential causes of change, and analysis and predicting of the nature of the future quality changes. In Tanzania, limited monitoring networks are available either basinwise (e.g. Makutupora and Pangani Basins) or under urban water authorities (e.g. DAWASA, Arusha, Tanga, Mwanza etc). However, the monitoring of groundwater levels fluctuation, quantity of abstraction and quality. The monitoring is fragmented (limited to the basin, urban authority or project in question) and not complete (data may cover only few aspects and information can have many gaps). Inadequate funding is attested to analysis of poor groundwater quality monitoring programme (Kongola *et al*., 1999).

8.2.3 Legislation: Water rights and pollution control

The control of water affairs in Tanzania is under the ministry responsible for water, currently the Ministry of Water and Livestock Development. The regulatory and institutional framework for water resources management (including groundwater) is provided for under Water Utilization (Control and Regulation) Act No.42 of 1974, referred to as Principal Act, and its Amendments Acts of 1981 (that is, Amendment Act No.10 of 1981, Amendment Act No. 17 of 1989 and Amendment Act No.8 of 1997). These are the main legislations pertaining to utilization, protection and conservation of water resources in Tanzania. The legislations define water as all water flowing over the surface of the ground or contained or flowing in or from a spring or stream or natural-lake, swamp or beneath a watercourse. Section No.8 of the Act declares that all water in the country is vested to the United Republic of Tanzania. It also sets conditions on use of water and authorizes the Principal Water Officer with authority, to be responsible for setting policy and allocation of water rights at national level (Section No.10 and 15). The Act (section No.5) empowers the Central Water Board to coordinate and resolve conflicts on water utilization. Section 11 (1) of the act deals with permissible levels for abstraction groundwater. The section permits to sink or enlarge any well or borehole thereon and abstract water there from, not exceeding 22,700 litres in any day. Provided that this section shall not authorize the sinking of any well or borehole within 230m of any other well or borehole or within 90m of any body of surface water or enlargement of any well or borehole which is within those distances from any well or borehole.

The above legislation also put in place norms for pollution control, specifically discharge of effluents. Under Section 15A(1) of the act, no person shall discharge effluent from any commercial, industrial or other trade waste systems into receiving waters without a consent duly granted by the Water Officer. The Act also contains two schedules, which set standards for receiving waters and effluent quality (Tanzania Temporary Standards). Section No.18 (A), the legislation prohibits the discharge of wastewater or effluents at distance of 230 m or less from a well or other water source.

However, enforcement of the above legislation is still low and to some extent the fines stipulated in the legislation are low compared to the environmental damages caused (as some may be irreversible). All in all, full enforcement of the Water Utilisation (Control and Regulation) Act can bring radical changes towards sustainable groundwater utilization. Hence, the legislation is a good footing for supporting groundwater protection programmes in Tanzania.

Other important legislations touching groundwater resources in Tanzania include the Water Policy (1991: currently under review) and the National Environmental Policy (1997). Both policies advocate rational utilization, protection and conservation of water resources.

8.3 Groundwater Management Strategy for Dar es Salaam City

The principal goal of a groundwater management strategy is to conserve the groundwater resource by preventing/reducing quality deterioration and overexploitation. Recognising that the groundwater quality in Dar es Salaam is deteriorating (Chapter 4) and that there are many potential pollution sources (Chapter 2) a management plan was found inevitable. Literature have many general recommendations for achieving a good groundwater management scheme; including pollution sources elimination/minimization, setting monitoring networks, interagency coordination etc (Cramer and Vrba, 1987; Foster, 1985; 1987; Pokrajac, 1999; Soetrisno, 1999; Vujasinovic *et al*., 1999). However, groundwater management plan is a location specific and multidisciplinary task, which needs inputs of different professionals. During this research, some key foundation elements for a comprehensive groundwater management plan for Dar es Salaam have been put in place (some have been explained in previous chapters). The following elements are considered to be key in establishing a sound groundwater management scheme for Dar es Salaam City:

- Identification and mapping of sources of pollution;
- Establishment of database and information management system;
- Development of groundwater vulnerability map;
- Assessing groundwater protection needs and priorities;
- Initiation of a monitoring network;
- Integration of groundwater protection in the urban planning process, legislation and institutional coordination; and
- Promotion of public awareness and participation.

Each of the key elements for groundwater management in Dar es Salaam is explained briefly in the forthcoming sections.

8.4 Identification and Mapping of Sources of Pollution

This subject has been dealt with in details in Chapter 3. For a successful groundwater management programme all major sources of pollution should be determined and mapped. This will help managers to know where the pollutants enter the groundwater systems, which is the key in finding means for controlling them. Mapping will help visualization and hence more understanding of the situation. Since, the sources of pollution are continuously changing, updating the maps becomes a norm. The different source of pollution identified within the framework of this research forms part of the list.

8.5 Establishing a Database and Information Management System

The importance and status of data and information management for Dar es Salaam City has been explained in Chapter 5. It has been shown in Chapter 5 that systematic data handling is urgently required in Dar es Salaam. The strategy is to increase information sharing, as well as avoiding duplication of efforts for data acquisition. Key information like boreholes location, groundwater quality, amounts of abstraction, and the hydrogeology should be maintained in the database. Major drillers like the Dar es Salaam Drilling and Dam Construction Company (DDCA) should consider to publish their borehole characteristics information. As a strategy toward increased information sharing, all key players in the groundwater management system should be given access to the information. National institutions like the National Environment Management Council (NEMC), research institutions etc should have access to such databases. To whatever extent, the information helps to define the status of groundwater resource at anytime, to identify problems and to monitor the impacts of the management strategies. Data collected during the execution of this research forms part of the database on groundwater in Dar es Salaam City; and are kept at the Department of Chemical & Process Engineering, University of Dar es Salaam.

8.6 Development of Groundwater Vulnerability Map

Vulnerability maps are increasingly becoming management tools for groundwater resources. The groundwater vulnerability map for Dar es Salaam has been developed in this research by considering the intrinsic characteristics of the ground formations (Chapter 6). The map is a useful tool for managing groundwater in the city as it delineates areas that can easily be polluted by anthropogenic activities. This information is needed by the groundwater manager for regulating human activities so as to prevent/reduce the chances of polluting groundwater.

The vulnerability map also can be used by land use planners (or physical planners) in allocating land for different urban activities in the city – for instance polluting activities such as chemical industries, which should not be built in high vulnerable areas. A superimposition of pollution sources on the vulnerability map helps to visualise the pollution risks or liability that exist (Chapter 7) and such information is very important to groundwater managers.

In some cases single value maps depicting intrinsic data (e.g. depth to groundwater, aquifer yield, hydraulic conductivity etc) are needed as foundation databases. To effect this a vulnerability assessment of the groundwater resources must be done and continuously updated. Since the vulnerability map for Dar es Salaam City has been developed within the GIS environment, updating is easy. Figure 8-1 shows a generalised vulnerability assessment scheme.

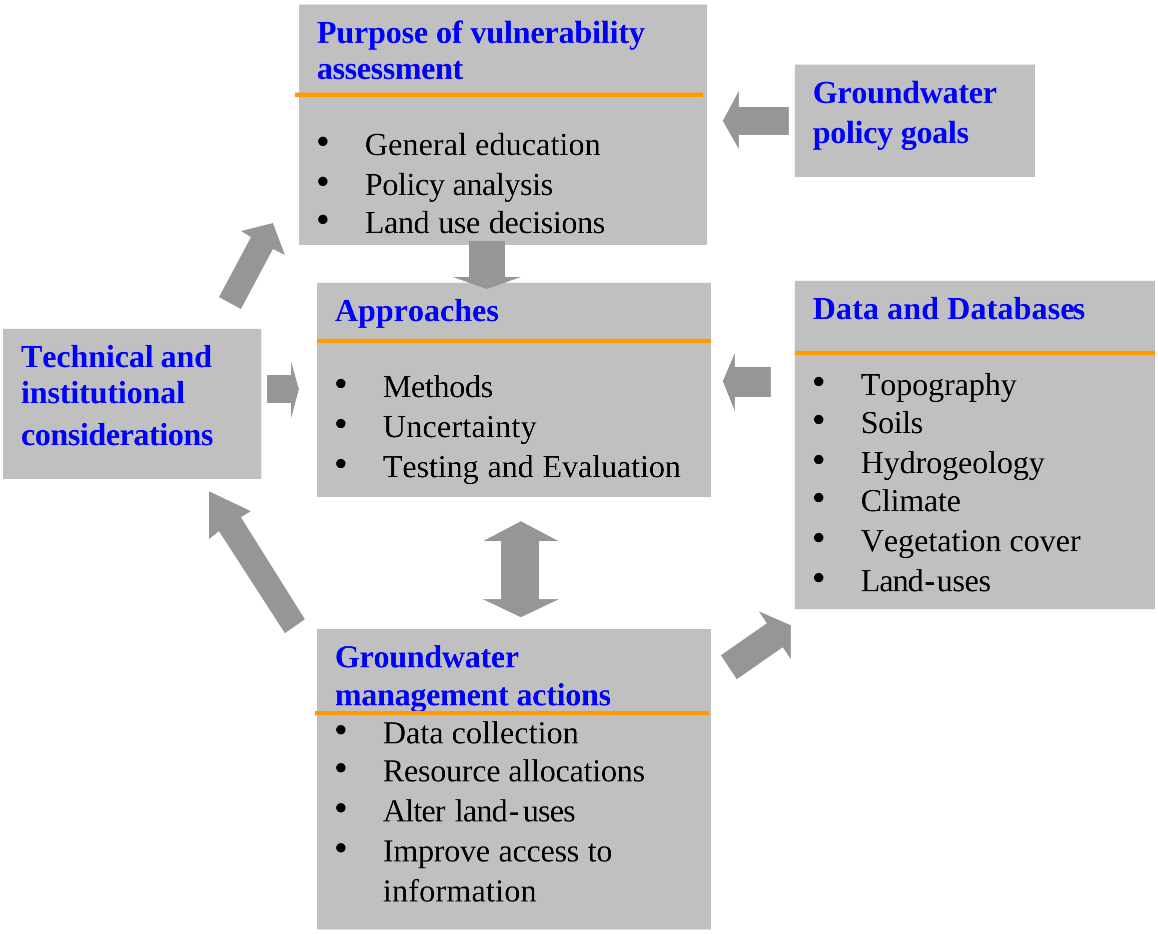

Figure 8-1: Groundwater vulnerability assessment scheme (after, USA National Research Council, 1993)

The figure also shows an interrelationship between vulnerability assessment, groundwater management actions, databases and institutional framework. The driving force being the policy goals that define the main intentions for groundwater management schemes. Thus the policy goals determine the purpose of the vulnerability assessment, while available databases and institutional coordination regimes dictate on the approaches to be adopted.

Worldwide, the aquifer vulnerability map and groundwater pollution risk assessment have provided a useful framework within which to designate priorities for the implementation of pollution protection and control measure (Foster, 1985, Blau, 1981).

8.7 Assessing Groundwater Protection needs and Priorities: The WYVUL Model

8.7.1 Overview

Groundwater protection is generally presented by a set of prevention procedures or measures, which should primarily deter pollution from occurring, particularly in water source zones and on the ground containing considerable groundwater accumulation (Rasula, 2000). The justification for groundwater protection is that the costs needed for remediation is normally unbearable to many countries. Rasula and Rasula (2001) reported that groundwater prevention measures may be are 10-20 times lower than the funds required for cleanup and revitalize polluted aquifers. In urban areas, ways are sought where groundwater protection and other urban activities can co-exist.

For the city of Dar es Salaam, the need for protection arises from the fact that groundwater is continuously being harvested for domestic and industrial uses. An empirical assessment methodology (EAM), a numerical index method, was adopted to establish a decision support model to determine protection priorities for different areas. A dimensionless quantity, protection index (PI) (analogous to DRASTIC index, DI) has been introduced. The protection index is a relative numerical number, which distinguishes the need for protection between areas/zones of Dar es Salaam. The PI expresses the protection value or importance of the groundwater in that particular location and hence it helps decision makers in identifying areas to target both financial and human resources. Similar concept was reported by Johansson *et al* (1999) and was used to establish a framework for groundwater protection in Managua, Nicaragua.

8.7.2 Factors and Weights

The groundwater protection priority model for Dar es Salaam, given an acronym *WYVUL*, is made of five factors, which are:

- Water quality, *W*
- Yield of the aquifers, *Y*
- Vulnerability index of groundwater to pollution, *V*

- Use value of the groundwater, *U*
- Land-use characteristics, *L*

The WYVUL factors were given weights in accordance with the recognized importance in dictating groundwater protection of a certain location within Dar es Salaam area. The weights have a range of 1-5 and are shown in Table 8-1. The weighted were assigned basing on the technical knowledge of the potential of the factors to influence groundwater management plans.

The overall concept behind the WYVUL model is *"to protect clean aquifers with huge amounts of water located in vulnerable areas, where groundwater is of high demand particularly places with very low physical development".* Areas fulfilling this are having high protection index and hence greater protection priority.

Table 8-1: Weights of factors in the WYVUL model

Factor	Weight
Water quality	5
Yield of aquifers	4
Vulnerability of groundwater to pollution	3
Use value of groundwater	2
Land-use characteristics	1

Water Quality

The water quality defines the types and amounts of substances contained (in suspended or dissolved form) in groundwater. The water quality factor is regarded as a determining factor in the use of groundwater. The principle is to protect groundwater that has not yet been polluted. The water quality factor can be derived represented by one pollution parameter or an aggregate of many parameters. For the city of Dar es Salaam, the nitrate concentration was taken as a principal component in assessing the water quality of the groundwater. The reason for choosing nitrate is because of rampant use of on-site sanitation systems in the city, which can lead to nitrate contamination of the groundwater (refer to Chapter 4). The water quality factor was given a weight of 5 in the model (this is the highest weight value) (see Table 8-1). A rating system for water quality was established as shown in Table 8-2. The WHO and Tanzania nitrate standards of 50 mg/l and 100 mg/l respectively, were taken as reference values for establishing the ratings. The highest water quality score is 10 and was awarded to an area where the nitrate concentration in the groundwater was below 20 mg/l, a value considered to represent clean aquifer (Freeze and Cherry, 1979). Ratings of 8 and 6 were applied where the nitrate levels were 21-50 mg/l and 51-100 mg/l respectively. The minimum rating of 1 was applied to an area where nitrate concentration was above 120 mg/l, a value far above the Tanzanian standard, for which the state of the aquifer was considered to be very poor or greatly damaged.

Table 8-2: Rating for water quality factor in the WYVUL model

Nitrate Concentration range (mg/l)	Rating
<20	10
21-50	8
51-100	6
101-120	4
Above 120	1

Yield of aquifers

Aquifer yield is defined as the maximum rate of withdrawal of water that can be sustained by an aquifer without causing an unacceptable decline in the hydraulic head in the aquifer (Freeze and Cherry, 1979). The yield factor in the WYVUL model expresses the available amounts of groundwater that needs protection. It was considered the second important factor in the groundwater protection scenario, with a weight of 4 (Table 8-1). The *WYVUL* model considers being most logical to protect unpolluted aquifers with high yields. The philosophy is that the larger the yield of aquifers the higher the protection priority. Accordingly, ratings for aquifer yield were formulated as shown in Table 8-3. The highest score is 10 and is awarded to aquifers with yield of more than 40 m^3/h, sufficient to develop a public water supply scheme.

Table 8-3: Rating for the yield of aquifer factor in the *WYVUL* model

Yield Range (m^3/h)	Rating
Less than 5	2
5 – 10	4
11 – 20	6
21 – 40	8
Above 40	10

Vulnerability of groundwater to pollution

Groundwater vulnerability has been defined in Chapter 6. This factor takes care of the intrinsic hydrogeological characteristics of the area and its potential to pollution. Here, priority for protection is given to an area which has good groundwater quality, high yield from the aquifers and vulnerable to pollution. The vulnerability of groundwater to pollution factor was considered third important and was given a weight of 3 (Table 8-1). The ratings for this factor were formulated from the groundwater vulnerability map of Dar es Salaam City, explained in Chapter 6. The rating has a range of 1-10, with the highest score of 8-10 when the area to be protected falls within the high vulnerable zone (Table 8-4). The minimum score of 2-4 was given to a low vulnerable zone, for which it was considered that the existing natural protection due to soil profile could sufficiently attenuate the pollution loads before reaching the groundwater.

Table 8-4: Rating for the vulnerability of groundwater to pollution factor in the *WYVUL* model

Vulnerability (DRASTIC Index)	Rating
<120	2-4
121 – 140	5-7
>140	8-10

Use value of groundwater

This factor expresses the value of groundwater to communities in specific location in Dar es Salaam. The general proposition is that areas without piped water supplies depend directly on groundwater as alternative source. For instance areas of Kiwalani, Kipunguni depend largely on groundwater. In such areas where water supply from piped water is very low or not in existence, the groundwater is considered to have a higher use value and therefore higher protection priority. In the WYVUL model, the use value of groundwater is given a weight of 2 (Table 8-1), and ratings range from 1-10 as shown in Table 8-5. Alternatively, it was considered that since groundwater is used to augment public water supplies for the entire Dar es Salaam City, it has a constant use value. Both alternatives were considered in computing the protection indices.

Table 8-5: Rating for use value of groundwater factor in the *WYVUL* model

Water supply status	Rating
Groundwater (GW) not used as alternative source	1
With piped water supply (service over 4 days per week), GW alternative source	6
With piped water supply (service less than 4 days per week), GW alternative source	8
Without piped supply, GW alternative source	10

Land Use Characteristics

The type of human activities or urban infrastructure on a certain geographical areas is referred to as land use characteristics in the WYVUL model. The landuse characteristics factor takes care of the level of physical development of the areas, which can give difficulties in varying degrees to protection programmes, and it is given a weight of 1 (Table 8-1). The model considers that the less the physical development which is in place, the easier may be to execute protection programmes. A rating with a range of 1-10 has been formulated with urban-rural areas (rural areas within the broader Dar es Salaam City environment e.g. Charambe and parts of Mbagala wards etc) having the highest score of 10 (Table 8-6). The argument is that it is easier to take groundwater protection measures in the urban-rural settings than in a developed (built-up) urban area e.g. unplanned areas of Manzese, Tandale, Keko etc. Therefore, unplanned "squatter" areas were assigned a rating of 1.

Table 8-6: Rating for landuse characteristics factor in the *WYVUL* model

Landuse characteristics	Rating
Rural-urban area	10
Commercial or Institutional	5
Planned residential areas	2
Unplanned residential and Industrial areas	1

8.7.3 WYVUL model

The WYVUL model is defined by the following formulation:

$$PI = W_w W_r + Y_w Y_r + V_w V_r + U_w U_r + L_w L_r \text{ ....Eq. 8-1;}$$

where PI is the protection index and the subscripts, w and r denote assigned weight and rating of each factor. The lower and upper limits for *PI* are 5 and 500 respectively.

The protection index was computed for each borehole location (where all the parameters were known). The borehole location was taken as a node to represent the surrounding area. Two options were considered in computing the protection index, (i) the use value of groundwater factor was considered variable in Dar es Salaam (in this report considered as option I and (ii) the use value of groundwater factor was considered constant – assumed that all areas in the city have piped water, but rationed and groundwater used as alternative source; or groundwater is used as alternative source for public water supply in the entire city (considered as option II). Examples of the computation for protection index **PI** for both options are shown in Table 8-7 (other computations for **PI** are in Appendix). In both scenarios, the protection index was between 50 and 200. About 50% of the PI simulations with generic WYVUL model were above 100. The higher the relative number of protection index the higher the priority the area has for being protected as a potential groundwater source. For further visualization of the protection index concept, mapping of the indices was carried out.

8.8 Mapping Groundwater Protection Priorities

Using the ArcView (version 3.1) software, mapping of the protection indices was conducted. The boreholes location provided the geographical references needed for GIS analysis.

Table 8-7: Example of the protection index computation spread sheet

BH/NO.	Name of borehole	Northings	Eastings	Ww	Wr	Yw	Yr	Vw	Vr	Uw	Ur	Lw	Lr	PI	PI-W min	PI-Vul. Min	PI-Land. Max	PI-Use value fixed	PI-Y mini.
66/2000	Ubungo Darajani	9249034	522825	5	10	4	6	3	8	2	8	1	1	115	75	99	119	111	97
391/2000	Ubungo Bus Stand	9249563	523131	5	8	4	4	3	8	2	8	1	2	98	66	82	106	94	86
78/2001	Mburahati KKKT	9247330	526218	5	10	4	2	3	8	2	6	1	1	95	55	79	99	95	89
461/2000	Mabibo (Mrs. Nyange)	9247053	525063	5	10	4	4	3	8	2	6	1	1	103	63	87	107	103	91
40/97	Social.W.F.T. I.	9251574	526278	5	10	4	2	3	8	2	8	1	2	100	60	84	108	96	94
37/97	Kinondoni P/School	9249960	528801	5	8	4	8	3	8	2	8	1	2	114	82	98	122	110	90
67/97	Mwananyamala B P/school	9250147	527539	5	1	4	2	3	8	2	8	1	2	55	51	39	63	51	49
52/97	Mwenge P/School	9252083	525642	5	10	4	4	3	8	2	8	1	2	108	68	92	116	104	96
275/97	Kurasini DC S/Quarter	9242121	531527	5	8	4	2	3	10	2	6	1	2	92	60	72	100	92	86
94/97	Kijitonyama P/S	9250874	525960	5	6	4	2	3	8	2	6	1	2	76	52	60	84	76	70
164/99	St.Anthony Mbagala	9239285	529844	5	8	4	2	3	8	2	8	1	2	90	58	74	98	86	84
99/97	Mtoni Primary School	9240430	530163	5	1	4	4	3	8	2	8	1	2	63	59	47	71	59	51
110/97	Tandika Mwembeyanga	9241993	528449	5	1	4	8	3	8	2	8	1	2	79	75	63	87	75	55
42/97	Temeke Hospital	9241966	528985	5	6	4	8	3	8	2	8	1	2	104	80	88	112	100	80
59/97	Kipawa Primary School	9241505	523188	5	10	4	2	3	6	2	8	1	1	93	53	81	97	89	87
137/97	Kurasini P/S	9242978	531248	5	8	4	4	3	10	2	8	1	2	104	72	84	112	100	92
13/97	MMC I Football ground	9247855	529911	5	10	4	6	3	8	2	6	1	5	115	75	99	135	115	97
19/97	Fire Brigade	9247255	530190	5	8	4	6	3	8	2	6	1	2	102	70	86	110	102	84
28/97	Ilala Boma	9245787	528872	5	10	4	6	3	8	2	6	1	2	112	72	96	120	112	94
30/97	Dar Tech College	9247183	530916	5	10	4	8	3	8	2	6	1	2	120	80	104	128	120	96
34/97	Amana Ilala	9245636	528519	5	6	4	6	3	8	2	6	1	2	92	68	76	100	92	74
34/97	Kiwalani CCM	9241889	525239	5	10	4	6	3	8	2	10	1	1	119	79	103	123	111	101
92/97	Buguruni Moto P/School	9245143	526661	5	8	4	4	3	8	2	8	1	1	97	65	81	101	93	85
109/97	Msimbazi Mseto Primary School	9246157	528285	5	8	4	4	3	8	2	6	1	2	94	62	78	102	94	82
83/99	DSA Kurasini	9242087	530926	5	8	4	6	3	10	2	8	1	2	112	80	92	120	108	94
27/97	National Stadium	9242334	530244	5	6	4	2	3	8	2	8	1	5	83	59	67	103	79	77
31/97	Ilala Shule/Uhuru	9246004	530097	5	8	4	6	3	8	2	6	1	5	105	73	89	125	105	87

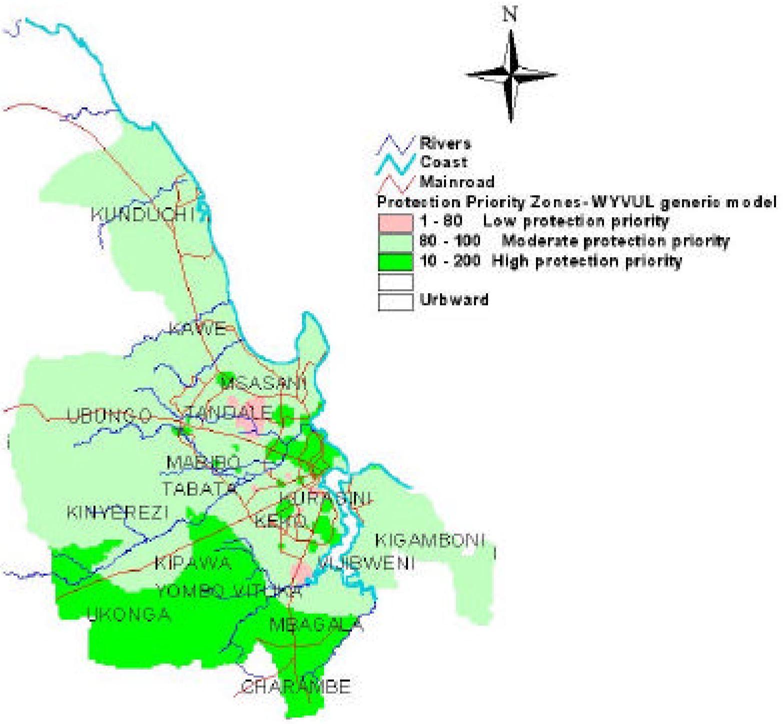

Figure 8-2: Groundwater protection priorities for Dar es Salaam City, 2001 (Option I)

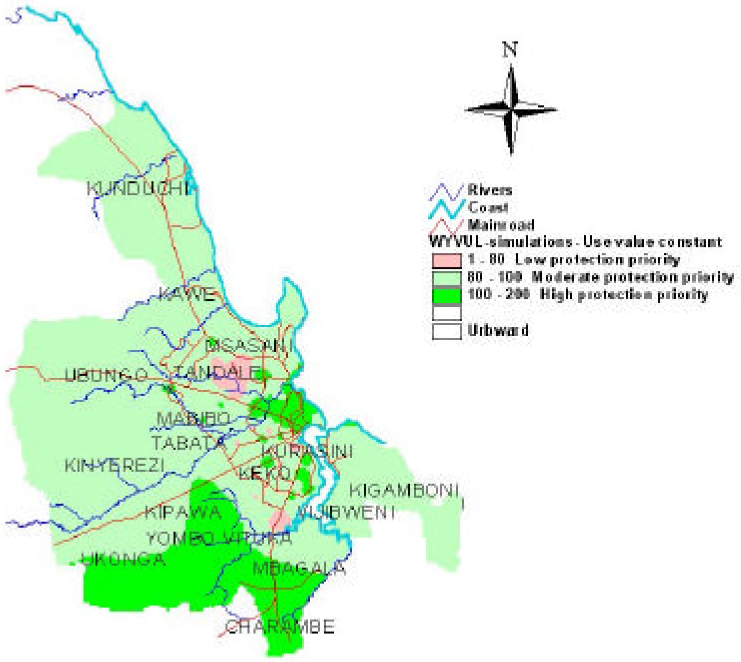

Figure 8-3: Groundwater protection priorities for Dar es Salaam City, 2001 (Option II)

The results of the geo-processing are shown in Figure 8-2 and Figure 8-3 representing the Dar es Salaam City groundwater protection priorities for option I and option II. The protection indices were rated according to Table 8-8 so as to obtain the different zones of protection priorities. The maps shown in Figures 8-2 and 8-3 delineate areas of Dar es Salaam with varying degree of groundwater protection importance. The maps show that major parts of Charambe, Mbagala, Ukonga and Yombo Vituka wards have high protection priorities. The zone of high protection priorities also includes the built-up areas of City Centre and parts of Upanga and Kariakoo. These areas may have the high status because of the presence of a sewerage system, that drains away most of the nitrate sources from reaching the groundwater. The remaining parts of the city fall under moderate priority zone except for few areas, like Magomeni, Manzese, Kinondoni, Mwananyamala and Mtoni, which are delineated as low priority.

Table 8-8: Protection priorities categorization

Protection index Range	Protection Priority Category
1-80	Low
80-100	Moderate
100-200	High

It was interesting to note that the change of the ratings of use value of groundwater factor in the WYVUL model did not bring any significant changes in the protection priorities zones, since the protection priorities maps for option I and II were the same. This may signify that groundwater is basically a useful water source for the entire city of Dar es Salaam, or the factor is not significant in the WYVUL model. Following this, a sensitivity analysis of the WYVUL model was conducted.

8.9 Sensitivity Analysis for the WYVUL Model

Changing the weights of the factors given in Table 8-1 helped to perform the sensitivity analysis for the WYVUL model. The factors were changed one after the other as given in Table 8-9. The factors whose weights were changed during the analysis include water quality, yield, vulnerability and landuse characteristics. The factors ratings were not affected during the sensitivity analysis. Changes in the weights resulted into different sets of protection indices.

These indices were then geo-processed using the ArcView GIS software to produce map overlays for each operation. The map overlays are shown in Figure 8-4, Figure 8-5, Figure 8-6, and Figure 8-7.

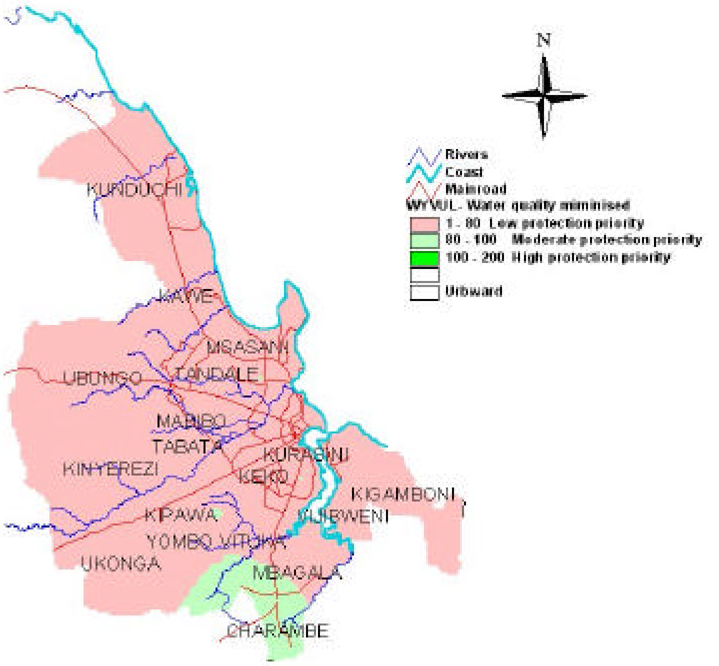

Figure 8-4: Sensitivity analysis for WYVUL model-Water quality factor minimised (Scenario I)

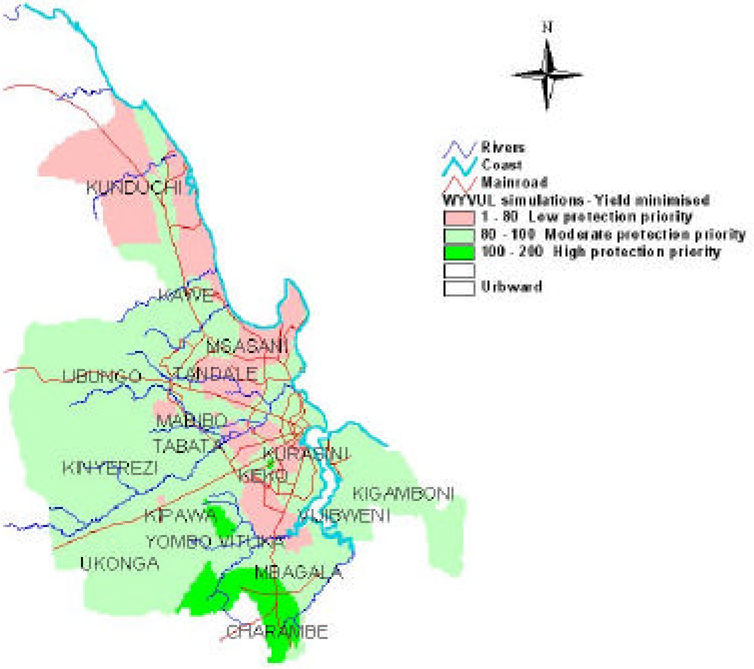

Figure 8-5: Sensitivity analysis for WYVUL model- Yield factor minimised (Scenario II)

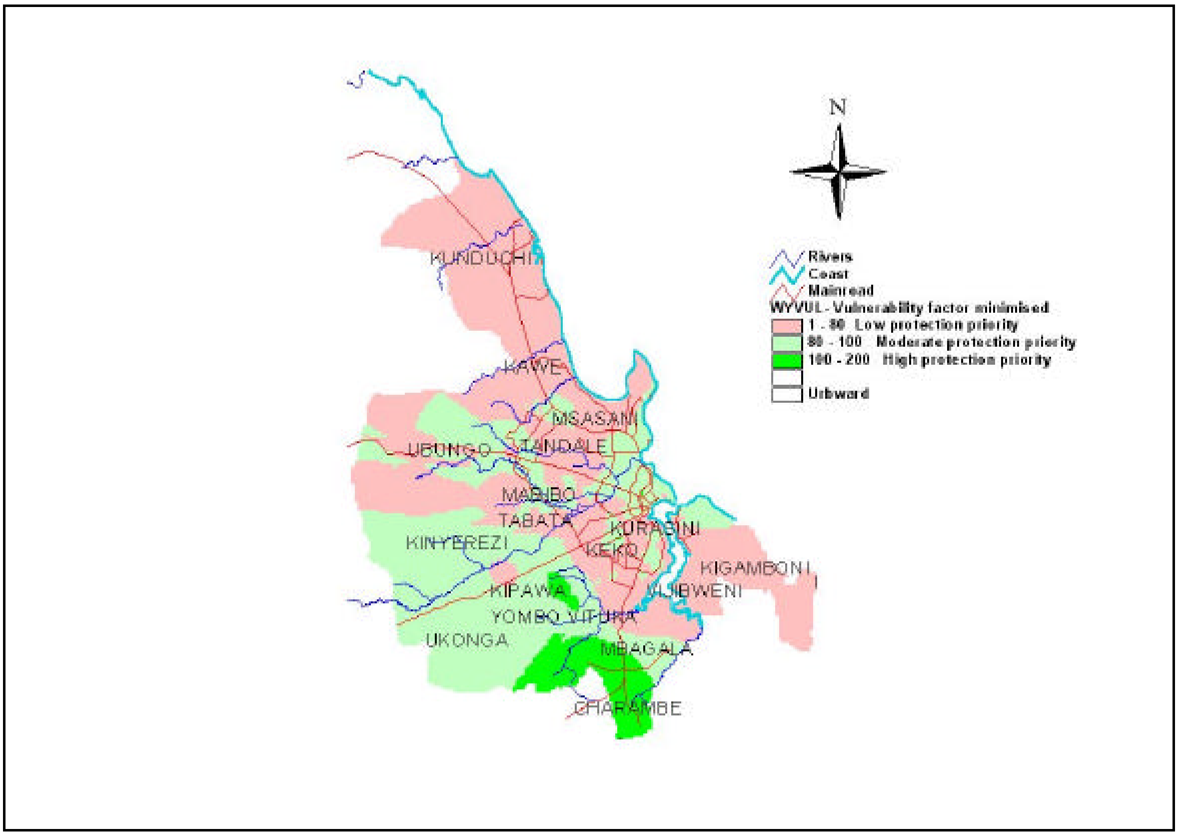

Figure 8-6: Sensitivity analysis for WYVUL model- Vulnerability changed (Scenario III)

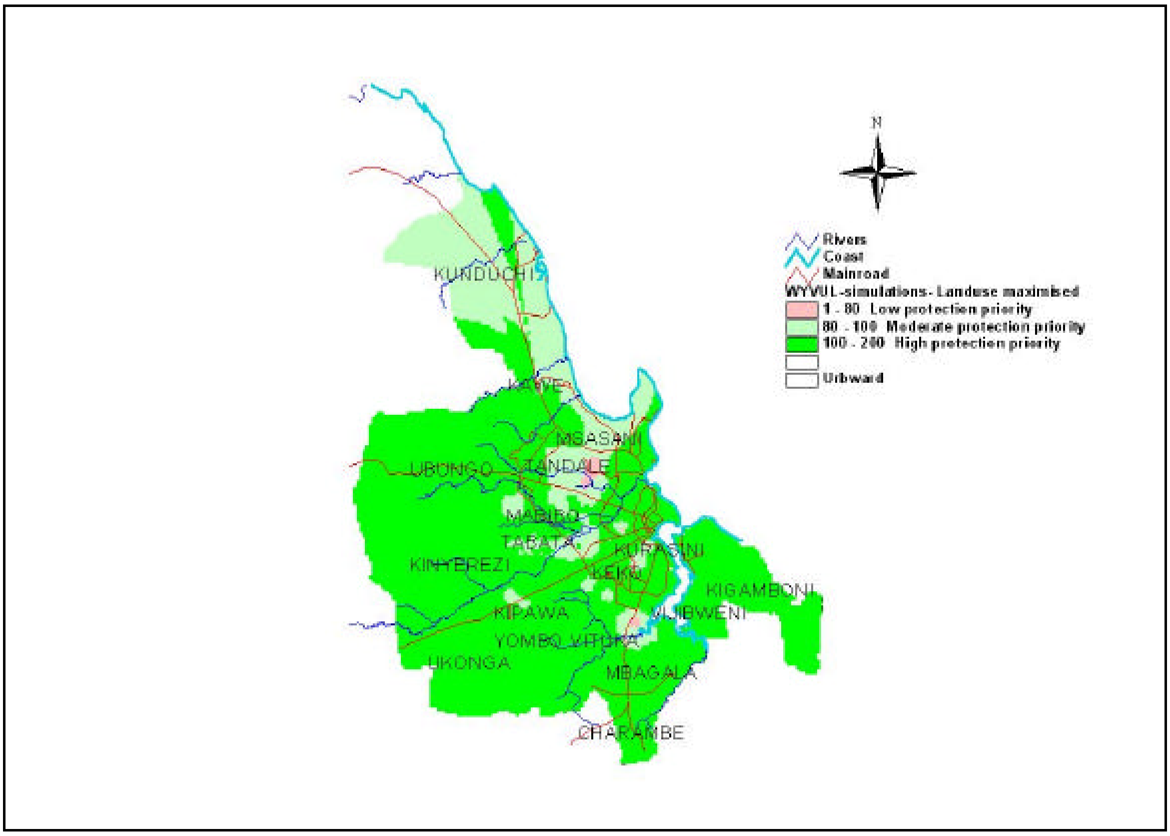

Figure 8-7: Sensitivity analysis for WYVUL model- Landuse factor maximised (Scenario IV)

Table 8-9: Sensitivity analysis of the WYVUL model: Weighting scheme

Factor	Weight				
	Generic model	Scenario I	Scenario II	Scenario III	Scenario IV
Water quality, W	5	**1***	5	5	5
Yield, Y	4	4	**1***	4	4
Vulnerability, V	3	3	3	**1***	3
Use value, U	2	2	2	2	2
Land-use, L	1	1	1	1	**5***

* New weight

The results of the sensitivity analysis indicate that water quality, W; yield, Y; vulnerability, V and landuse characteristics, L are all important factors due to remarkable changes in the protection priority zones. The analysis indicated that water quality and landuse are on two extreme ends, each pulling toward low and high protection priority respectively. These two factors do dictate in determining the protection priority. In more general terms it means that the status of the groundwater quality and the level of physical development of the area may dictate the level of protection strategy to be applied. However, Mbagala and Charambe ward areas were outstandingly rated high protection zones by all the sensitivity analysis scenarios.

8.10 Model validation

Since the protection index is a relative and immeasurable quantity, it cannot be directly measured in the field. Validation of the model to some extent was made through the knowledge of the areas. The areas of Mbagala and parts of Charambe are places with high aquifer yield (the DDCA regard these areas as “well field”), relatively good quality water, low physical development (mostly rural-urban fringe), with sand soils and very low water provision. Such areas having a high priority of protection is in agreement with the WYVUL concept, “to protect clean aquifers with huge amounts of water located in vulnerable areas, where groundwater is of high demand particularly places with very low physical development”. The Recharge areas of Ukonga ward (Service Plan, 1997) are in the high protection priority zone. In these areas physical development is still low, and sand soils prevail. Upanga area and City Centre, which are rated high priority, show considerably high yield, low nitrate concentration (may be because most areas are sewered) and sand soils; however, physical development is relatively high. Again, this situation indicates the high pulling power of the water quality factor in the model. However, such areas (City Centre) can be included in groundwater protection programmes at regional scale. Comparatively, unplanned “squatter” residential districts with rampant use of on-site sanitation facilities and shallow groundwater dominate areas like Manzese and Mtoni designated as low protection priority zones.

The *WYVUL* model results give indication of areas that need protection so as to achieve sustainable groundwater utilization in Dar es Salaam. The results can be used by physical planners (during land allocations) and groundwater resource managers, the Central Water Board, the custodian of water resources according to the Water Utilization (Control and Regulation) Act. The maps can also be used by drillers (like DDCA) to guide their drilling plans and communities to understand the urgency needed to safeguard the water they depend on. However, more data inputs (data sets from the field) in the model will refine the protection priorities demarcation. Noting that the environment is changing over time, the protection priorities maps also need to be updated with time to accommodate the changes that take place. An aggregate of parameters for the water quality, W, factor in model may be a good representation of the actual status of groundwater quality.

8.11 Suggested Groundwater Quality Protection Measures for Dar es Salaam

The following protective measures are able to arrest the continued pollution of aquifers in Dar es Salaam, especially to areas earmarked protection (for instance Mbagala well field).

- Elimination of pollution centre – this includes control of waste disposal, especially human excreta and solid waste. Improved excreta disposal system should be used, especially a system which contains the wastes. The existing pit-latrine and septic tank designs should be revisited so as the sewage is not allowed to percolate into the groundwater system. At the same time, no larger solid waste dumpsites should be sited in these areas.

- Limitation of both industrial activities and human habitation in the areas – Industrial activities and human habitation have indicated to be a thorn to groundwater quality in Dar es Salaam. Therefore, efforts should be put to limit development in groundwater protection zones, allowing only activities that can well be monitored or regulated. For instance, a certain level of human habitation can be allowed but efficient means of waste collection mechanism must be put in place. Industrial activities should better not be located in the groundwater protection zones, especially at times when monitoring capabilities and environmental control are still very low.

- Groundwater pollution potential should be an important consideration in various permit processes for major development intended in the protection zones. The same scrutiny should be applied before issuing a water right for abstracting groundwater.

- Control or regulation of drilling activities: This measure does not apply to potential areas for protection but also the entire Dar es Salaam City.

Unprofessional borehole drilling may open the deep aquifers to polluting agents, making it easier for pollutants to migrate to the deep aquifers that are potential drinking water sources. If the drilling is done in a well field, then there is high risk of contaminating large quantities of water that are needed for the future generation. Depending on the pollution parameter, remediation may not sometimes be possible. In such circumstances, therefore, it is proposed that more stringent drilling regulation be exercised in high yield aquifer zones.

- Control on agricultural applications – since the targeted areas for protection are located within the urban-rural fringes where agriculture is part and parcel of the people’s lives, it is essential to have control on the type or quantities of agro-chemical applications. Only biodegradable agro-chemicals should be used in the groundwater protection zones.

- Modification to land management practices, and to design urban installations to reduce or eliminate subsurface polluting loads.

- Designate the Mbagala/Charambe “well fields” as special groundwater protection areas

8.12 Proposed Groundwater Monitoring Programme for Dar es Salaam

The monitoring programme has an objective of establishing a "monitoring network" for gathering information on groundwater quantity and quality in order to determine the extent of pollution and exploitation levels in Dar es Salaam City. There are two types of monitoring, which are (a) Basinwide Ambient Trend Monitoring (BATM) - it encompasses a large geographical area and concentrates on determining long-term fluctuations in the overall groundwater quality (and quantity) of an area, and (b) Source Assessment Monitoring (SAM) - it is concerned with the assessing the existing or potential impacts on groundwater quality from a proposed, active, or abandoned pollutant source - the monitoring is localised and concentrates on the changes and stresses in groundwater quality in the immediate area of the source. The monitoring to be established in Dar es Salaam is the BATM type. The main concerns in planning the BATM are: (i) the number of boreholes to be included in the network; (ii) the spacing and location of boreholes and; (iii) the optimum sampling frequency; (iv) the indicator parameters; and (v) data storage, presentation; and interpretation.

The major reasons for developing a monitoring network for Dar es Salaam city are:
(i) to check whether the groundwater abstracted for drinking in the city satisfies the legislated mandates;
(ii) aquifer testing for groundwater resources planning and environmental impact assessment;

(iii) to document regional background water quality; and
(iv) research and development purposes.

Worldwide there is a growing amount of information on methodologies for designing a groundwater monitoring networks. One of these earlier works lists 15 steps for developing and implementing a monitoring network. These are: -

- Step 1- Select area or basin for monitoring
- Step 2 - Identify pollution sources, causes, and methods of waste disposal
- Step 3 - Identify potential pollutants
- Step 4 - Define groundwater usage
- Step 5 - Define hydrogeological situation
- Step 6 - Study existing groundwater quality
- Step 7 - Evaluate infiltration potential for wastes at the land surface
- Step 8 - Evaluate mobility of pollutants from the land surface to the water table
- Step 9 - Evaluate attenuation of pollutants in the saturated zone
- Step 10 - Set priorities on sources and causes
- Step 11 - Evaluate existing monitoring program
- Step 12 - Establish alternative monitoring approaches
- Step 13 - Select and implement the monitoring program
- Step 14 - Review and interpret monitoring results
- Step 15 - Summarize and transmit monitoring information

The above steps are guidelines that can help to design a good and workable monitoring network. During the execution of this research, Step 1-7 and Step 10-11 have been dealt with as explained in the previous Chapters of this report. The aim is to improve the existing sporadic and fragmented groundwater monitoring into one comprehensive programme to cover the whole of Dar es Salaam city. DAWASA has a monitoring programme, which assesses the water quality from water sources and selected consumption nodes in Dar es Salaam. The programme is exclusively for internal use within the company as well as a means of quality assurance. The data sheet of DAWASA (Table 8-9) contains 30 parameters that are monitored. However, the monitoring programme is not consistent in both parameters and frequency primarily due to inadequate of resources (funds, reagents, laboratory equipment etc). The monitoring programme advocated in this report is aimed at gathering data that will be available for all stakeholders in Dar es Salaam City. To start with, a simple network can be established - one that can easily be expanded in future.

The proposed set-up of the monitoring programme is explained below.

(i) Monitoring wells – to start with 30 boreholes have been proposed (Figure 8-8). The boreholes were selected to cover the entire area of Dar es Salaam City. All are production boreholes, both public and privately operated. The boreholes have been mapped (Figure 8-8) and entered in a GIS database.

(ii) Quality parameters – to include physical, chemical (both inorganic and organic) and biological parameters. The parameters include pH, TDS, Conductivity, Nitrate, Nitrate-nitrogen, chloride, TOC, and faecal coliform. In addition, micro-organic pollutant screening for PAH and pesticide traces should be done, and specific identified compound reported.

(iii) Frequency of water quality monitoring – samples from the monitoring well should be collected and analysed twice every year, preferably May (after the heavy rains) and September (after the dry season).

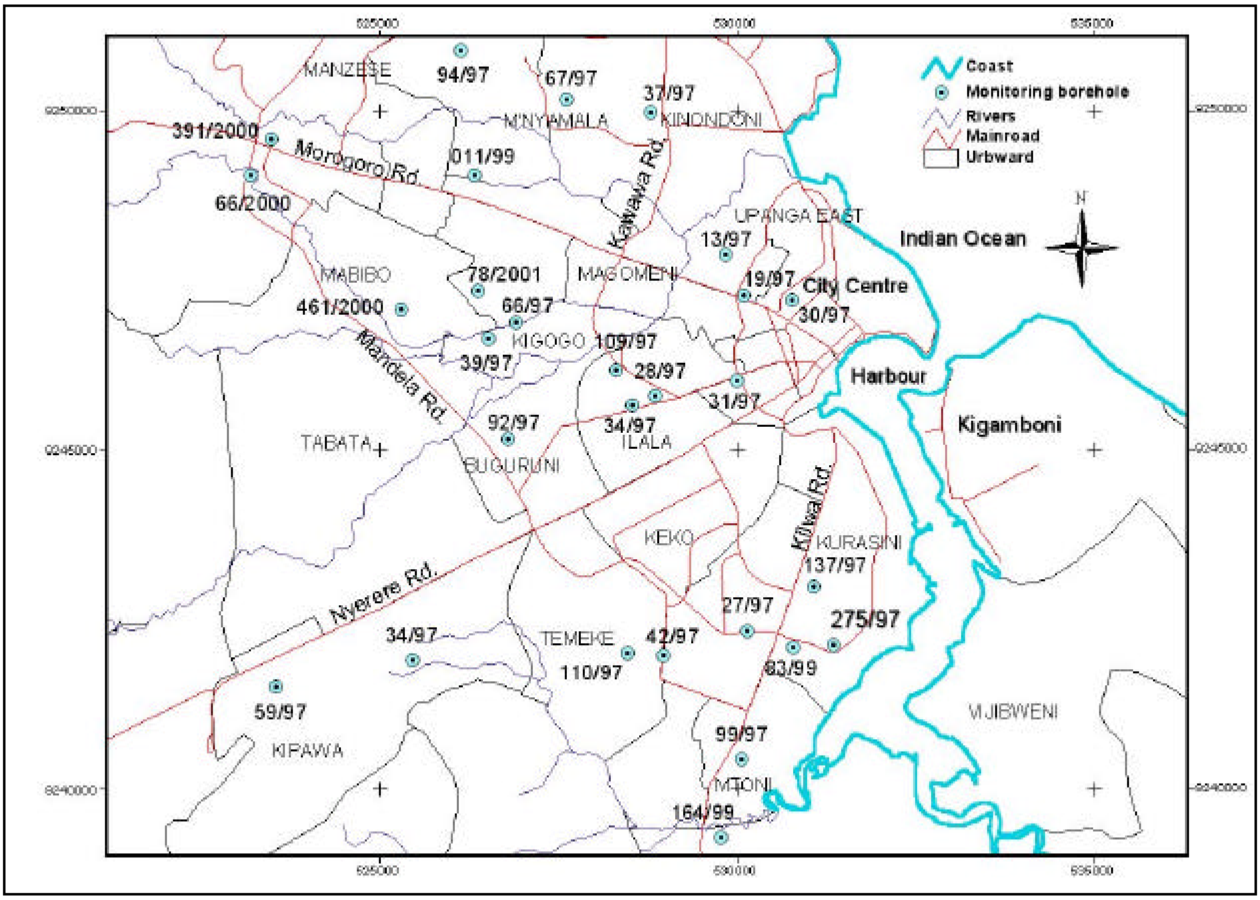

Figure 8-8: Proposed monitoring boreholes location for Dar es Salaam City (2002)

(iv) Exploitation rate – all major abstraction centres to be fitted with flow measuring devices for recording the consumption rates. Boreholes for public water supplies, industrial and institutional uses should have flow measurement devices. The list should include private boreholes, which are used commercially (i.e. for selling water). The aim for this measure is to document exploitation rate and not for billing purposes.

(v) Piezometric level observations – it is important to measure the fall and rise of groundwater level, an activity, which is not done in Dar es Salaam.

To achieve this goal, observation wells should be established in the city. All commercial drillers, who have a stake to groundwater resources, should make one observation well for every 100 wells drilled in the city. The location of the observation wells should be determined by the Water Resources Department, Ministry for Water. The Central Water Board or the Water Resources Department in the Ministry of Water will see to it that all drillers adhere to the requirements.

(vi) Laboratory – there are several laboratories in Dar es Salaam, which can analyse water samples for common parameters. To start with, the Water Laboratory – Maji Ubungo, being a government facility (and within the Ministry of water) can be assigned to conduct the monitoring. The DAWASA internal monitoring programmes can compliment the efforts by supplying groundwater quality results for boreholes not included in the new programme. The University of Dar es Salaam (Chemical Engineering Department) has a GC/MS instrument (purchased under EVEN project), which can be used to analyse for micro-organic pollutants such as PAHs and pesticides.

(vii) Funding – it is recognised that funding can be a big problem in Tanzania. However, safeguarding the health of the Dar es Salaam residents through monitoring the quality of drinking water is something that is fundamentally essential, and therefore, a good reason for spending money and committing resources. Funding sources will be identified as more awareness is conducted to the people, so this may take sometime to realize. In this case, at first, the laboratories will analyse the samples as service and later on, when sufficient funds are available analysis can be done at agreeable fee. It is thought under this point that, a general fund be established within the custodian of the groundwater resources, which will be used for monitoring purposes. May be a percentage of "Water right " fee or drilling permit fee. This needs to be jointly settled out by all stakeholders.

(viii) Information – in principle all stakeholders should easily access the results of the monitoring programme. The results should be configured within the information network on groundwater so proposed in this report. All stakeholders must agree upon a common centre, where groundwater information is to be collected. May be it is high time for establishing a Water Resources Research Centre (WRRC) in Tanzania, where up to date information on water resources can be found. Institutions like the Rwegarulila Water Resources Institute may be converted to such a centre or can be assigned with such responsibilities.

The custodian or implementer of the monitoring programme can be city water authority (in the present case DAWASA), the Water Laboratory-Ubungo, the Hydrogeology section of the Department of Water Resources (Ministry of

Water) and the Central Water Board. These institutions can share responsibilities of the monitoring programme. Other institutions can be called in where specific knowledge or equipment is required.

8.13 Integration of Groundwater Protection in the Urban Planning Process, Legislation and Institution Coordination in Dar es Salaam City

A groundwater prevention measure, which is least expensive, is in the domain of city planning and development control. In many cities, especially in developing world, there is lack of recognition that municipal systems are interrelated and need to be managed integrally (Pokrajac, 1999; Vujasinovic *et al*., 1999). The separate management and planning of municipal systems can cause groundwater problems: for instance, water supply without a proper wastewater collection and disposal system potentially leads to pollution of groundwater (Pokrajac, 1999). Development of urban infrastructure should be coordinated within the urban planning domain so as a synergetic health and environmental benefits can be realized. This can lead to management decisions, which support protection of useful aquifers for the present and future generations. For instance, the urban planning department could delineate a certain land area as groundwater protection zone (e.g. the case of Mbagala/Charambe in Dar es Salaam), and therefore, restrict erection of large industrial plants (with huge waste production), solid waste dumpsites, petroleum depots and other dangerous substances within this neighbourhood. Therefore groundwater protection in Dar es Salaam City should be well integrated and linked with qualitative and quantitative aspects of groundwater and other components of hydrological cycle with landuse planning and practices.

To assist the successful inclusion of groundwater protection measures in the normal Dar es Salaam city planning process, the groundwater vulnerability and protection priorities maps should be used. The maps can give broad guidance on the fragility of groundwater resources and relative ranking of protection importance. They may also assist in orienting planners, water authorities and other decision-markers in Dar es Salaam city, towards sustainable groundwater utilization.

The maps can easily be used in conjunction with other planning maps available in planning department, especially if used in a GIS environment.

Above all institutional coordination is required. Six requirements have been identified as necessary pre-requisites for an effective groundwater quality management programme, which are applicable for an appropriate institutional capacity at any level of government (Cramer and Vrba, 1987):

- The political will;
- A legal/regulatory framework that defines the groundwater programme and establishes its statutory authority;

- An organizational structure to implement the programme and coordinate the activities of the various agencies and levels of government;
- Information requirements to help define the status of the groundwater resource, identify current problems, and to monitor the impacts of the management strategies;
- Financing needs and sources in order to fund the groundwater programme; and
- The personnel and expertise needed to implement all phases of the programme

There is sufficient political will in Tanzania to support water resources development and conservation and are embedded in various policies like the Water Policy (1991) and Environmental Policy (1997). For instance, in section 108 of the National Environmental Policy (1997), on “Institutional Capacity Building”, states that:

> "Particular attention will also need to be paid to the establishment and strengthening of institutions responsible for systematic monitoring of the state of environment to cover for environmental management gaps. Presently, linkage of environmental degradation, loss of economic opportunity and deterioration of human health to causative factors is not made explicit on account of such information gaps. Although monitoring networks exist for meteorological measurements of temperature, rainfall, humidity and solar radiation there are no regular measurements for more specific environmental planning purposes such as water pollution by industries and sewage discharge, or air pollution. Existing monitoring activities in the field of environment are project oriented, with specific short-lived deadlines. This means that they are limited in special coverage, and are not regularly updated from time to time".

There is also adequate legislation and expertise to effect groundwater protection. The major shortfall is lack of organization engine for implementing and coordinating programme activities. Because of the lack of such an effective organization engine, information availability and funds mobilization have been marginally achieved. In this case the ideal of having a Water Resources Research Centre (WRRC) becomes apparent: it can first be established as an active unit within the existing institutions (say be part of the Rwegarulila Water Resources Institute based in Dar es Salaam). To be broader, the centre can be given mandates to research on all aspects of water resources in the country (groundwater inclusive). This idea is being suggested with full understanding that the Government of the United Republic of Tanzania is currently restructuring management within the ministries so as to optimise the available resources and to achieve good governance.

However, more enforcement of the existing legislation must be enhanced. Although there has been a debate that the existing environmental legislation in Tanzania is fragmented and outdated, still more vigour in enforcing the existing ones is required. The dynamics of enforcing them should be worked out so as to realize environmental protection. It is true that some of the legislations need to be revisited, for example the “Tanzania Temporary Standard for Drinking Water”, which was proposed by the Tanzania Water Health Standard Committee in 1974, has remained temporary to-date. Amendments of such legislations are needed to reflect the current environmental profiles and technological advancements. The current stress on carrying out Environmental Impact Assessment (EIA) for development projects in Tanzania may have positive results to the groundwater resources. The vulnerability and groundwater protection priorities maps developed in this research may be a good guidance on potential impacts to the groundwater resources in Dar es Salaam that may accrue from implementation of some of the development projects.

8.14 Promotion of Public Awareness and Participation

The basic purpose of public participation is to promote productive use of inputs and perceptions from the community and public interest groups in order to improve the quality of environmental decision-making and implementation of specific programmes (Canter, 1997). Public participation is defined as:
“ A continuous, two-way communication process, which involves promoting full public understanding of the processes and mechanisms through which environmental problems and needs are investigated and solved by the responsive agency; keeping the public fully informed about the status and progress of studies and findings and implications of plan formulation and evaluation activities; and actively soliciting from all concerned citizens their opinions and perceptions of objectives and needs and their preferences regarding resource use and alternative development or management strategies and any other information and assistance relative to plan formulation, implementation and evaluation” (Canter, 1997).

Unfortunately most people have inadequate understanding of groundwater resources and this has led to inappropriate development of groundwater. Much of the understanding has remained with the professionals, leaving the common man, politicians and other decision makers with less knowledge on groundwater resources. It is true that groundwater is a renewable resource, but the time required for renewal is much greater than the surface water. The recharge of deep aquifers, for example, can be in terms of hundreds or thousands years, more than man’s life expectancy of our age. Such awareness needs to be shared within the entire community, lack of which can lead to non-implementation or failures of any groundwater management programme envisaged. The experience in Turkey shows that, no matter how perfect the efficiency of the technical work, protection of the water resources is primarily related to the consciousness of the local authorities (Ekmekci and Gunay, 1997). Dar es Salaam is non-exceptional; hence groundwater education is needed to all levels of the society. To achieve this objective, public-private partnership is required as well as involving environmental interest groups like the Community Based Organizations (CBOs) in preparing guidelines for integrated groundwater management plans.

It is presumed that educating the people of Dar es Salaam on the protection of groundwater resources won't present resistance because more than 50% of the deep boreholes in the city are currently owned by private people or companies (DDCA working files, 2001). In addition, most shallow and hand-dug wells are also owned by the communities (private). Water from private boreholes is sometimes sold within the neighbourhood. As such, the people of Dar es Salaam have a stake to the groundwater resources, and therefore must be involved in groundwater management plans. It is also essential that the wider community of Dar es Salaam not only become aware that groundwater is an important water supply source, but also it is prone to pollution by different urban activities. The health implications associated with drinking contaminated water must also be shared among the communities. For efficient promotion of public awareness, the water resource managers need to become effective communicators and providers of community based education programmes.

Public participation (sometimes referred to as community involvement) in managing water supply systems has been experienced through a few programmes in Dar es Salaam. To many programmes, the effort has been directed towards managing the infrastructure, leaving out the resource base. For instance, the Tabata Water Supply Project, being managed by the Tabata Development Fund (TDF), a CBO. The project consists of two electrical powered boreholes (with a total yield of 11.7 m^3/h) supplying water to 20 kiosks (Mazwile, 2000). The communities have successfully managed the project since 1997, resulting into improved clean water accessibility to more than 12,000 people (Mazwile, 2000). It is presumed that such efforts if complimented with groundwater education aimed at sustainable use of the resource can be accepted and integrated in the CBOs management plans.

8.15 Conclusion

From the preceding discussions, it can be concluded that:

- A groundwater management strategy for Dar es Salaam City is an essential element for achieving sustainable utilization of the groundwater resource.
- The proposed groundwater management strategy for Dar es Salaam entails seven key inputs, namely: identification of pollution sources, establishment of databases and information management, development of vulnerability map, assessment of protection needs and priorities, initialisation of monitoring network, improved institutional coordination and public participation.
- The assessment scheme, the *WYVUL* model, dveloped and used for assessing groundwater protection priorities in Dar es Salaam gave valid results. The model identified Mbagala, Ukonga, Yombo Vituka and Charambe areas as having high priority for protection at the present time.

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Appendix

Table A-1: Calculated DRASTIC index for Dar es Salaam City

B/HOLE #	Northings	Eastings	DwDr	RwRr	AwAr	SwSr	TwTr	IwIr	CwCr	DI
DPL31/99	9246421	523841	35	24	12	2	9	15	3	88
149/98	9249314	516246	25	24	6	10	9	30	3	95
113/97	9243889	529989	25	24	6	18	9	30	3	103
131/97	9235203	528285	50	24	15	18	9	30	6	137
20/97	9235232	528356	50	24	12	18	9	40	3	144
44/98	9235630	528373	35	24	21	2	9	15	6	97
138/97	9236502	528515	45	24	21	18	9	40	6	148
225/99	9237320	529376	45	24	12	18	9	30	3	129
164/99	9237767	529662	45	24	21	10	9	30	6	130
288/97	9238986	515495	35	24	12	10	5	30	3	111
292/99	9239543	517793	45	24	12	12	5	30	3	123
8/98	9239544	518733	45	24	21	18	5	40	6	148
182/97	9240000	520707	25	24	6	18	5	30	3	103
178/97	9240195	526606	35	24	24	18	9	30	6	131
99/97	9240430	530163	35	24	24	18	9	40	6	141
221/98	9240526	521558	35	24	12	2	9	30	3	103
97/97	9240750	521532	35	24	15	18	9	15	6	107
85/98	9241064	524370	45	24	21	12	9	40	6	142
121/97	9241155	525902	35	24	21	18	9	40	6	138
96/97	9241264	525393	45	24	12	18	9	30	3	129
173/97	9241322	524823	45	24	12	2	10	15	3	98
59/97	9241505	523188	35	24	12	18	9	30	3	119
272/97	9241639	528173	45	24	21	18	9	40	6	148
86/99	9241875	528490	35	24	12	18	9	40	6	129
34/97	9241889	525239	35	24	21	18	9	30	6	128

Appendix A-1 Continues

B/HOLE #	Northings	Eastings	DwDr	RwRr	AwAr	SwSr	TwTr	IwIr	CwCr	DI
42/97	9241966	528985	45	24	21	18	9	40	6	148
110/97	9241993	528449	45	24	21	4	9	40	6	134
275/97	9242121	531527	45	24	15	18	9	40	6	142
143/99	9242178	531450	45	24	21	12	9	40	6	151
27/97	9242334	530244	45	24	12	18	9	40	3	148
143/97	9242343	531685	45	24	21	18	9	40	6	157
94/98	9242411	531565	45	24	21	18	9	40	6	157
49/98	9242441	525736	35	24	12	18	9	30	3	128
168/97	9242484	526374	35	24	12	18	9	30	3	128
137/97	9242649	531268	50	24	21	18	9	40	6	162
102/97	9242738	527124	45	24	21	18	9	30	6	147
82/99	9243090	532247	45	24	15	18	9	30	3	141
33/97	9243189	530530	35	24	21	18	9	40	6	147
5/99	9243615	526778	45	24	21	18	9	40	6	148
311/97	9243823	532451	45	24	21	20	9	40	30	150
157/97	9244450	531733	45	24	6	18	10	40	3	133
92/97	9245143	526661	35	24	15	10	10	30	6	114
159/99	9245295	528131	45	24	21	18	10	40	6	148
142/99	9245489	529346	45	24	12	18	10	40	6	139
34/97	9245636	528519	35	24	21	10	10	40	6	130
184/99	9245652	527920	45	24	21	18	10	40	6	148
56/97	9245654	528530	35	24	15	18	10	40	6	132
28/97	9245787	528872	45	24	15	18	10	30	6	132
26/97	9246089	529662	35	24	21	18	10	40	6	138
109/97	9246157	528285	45	24	21	18	9	40	30	148
11/97	9246240	529374	45	24	21	2	9	30	6	122
39/97	9246628	526378	45	24	21	4	9	30	6	124
66/97	9246705	527498	45	24	21	4	9	30	6	124
398/99	9247047	525048	45	24	21	18	9	30	6	138
19/97	9247255	530190	45	24	30	18	9	50	6	167
106/97	9247386	528435	45	24	15	18	9	40	6	142
13/97	9247855	529911	35	24	21	18	9	40	6	138
29/97	9247969	528555	45	24	21	6	9	40	6	136
38/97	9248459	530085	35	24	21	10	9	30	6	120
21/97	9249653	522745	45	24	12	18	9	30	3	129

Table A-2: Computations for the WYVUL Model

BH/NO.	Name of borehole	Northings	Eastings	Ww	Wr	Yw	Yr	Vw	Vr	Uw	Ur	Lw	Lr	PI	PI-W min	PI- Vul. Min	PI- Land. Max	PI- Use value fixed
66/2000	Ubungo Darajani	9249034	522825	5	10	4	6	3	8	2	8	1	1	115	75	99	119	111
391/2000	Ubungo Bus Stand	9249563	523131	5	8	4	4	3	8	2	8	1	2	98	66	82	106	94
78/2001	Mburahati KKKT	9247330	526218	5	10	4	2	3	8	2	6	1	1	95	55	79	99	95
461/2000	Mabibo (Mrs. Nyange)	9247053	525063	5	10	4	4	3	8	2	6	1	1	103	63	87	107	103
40/97	Social.W.F.T. I.	9251574	526278	5	10	4	2	3	8	2	8	1	2	100	60	84	108	96
37/97	Kinondoni P/School	9249960	528801	5	8	4	8	3	8	2	8	1	2	114	82	98	122	110
67/97	Mwananyamala B P/school	9250147	527539	5	1	4	2	3	8	2	8	1	2	55	51	39	63	51
52/97	Mwenge P/School	9252083	525642	5	10	4	4	3	8	2	8	1	2	108	68	92	116	104
275/97	Kurasini DC S/Quarter	9242121	531527	5	8	4	2	3	10	2	6	1	2	92	60	72	100	92
94/97	Kijitonyama P/S	9250874	525960	5	6	4	2	3	8	2	6	1	2	76	52	60	84	76
164/99	St.Anthony Mbagala	9239285	529844	5	8	4	2	3	8	2	8	1	2	90	58	74	98	86
99/97	Mtoni Primary School	9240430	530163	5	1	4	4	3	8	2	8	1	2	63	59	47	71	59
110/97	Tandika Mwembeyanga	9241993	528449	5	1	4	8	3	8	2	8	1	2	79	75	63	87	75
42/97	Temeke Hospital	9241966	528985	5	6	4	8	3	8	2	8	1	2	104	80	88	112	100
59/97	Kipawa Primary School	9241505	523188	5	10	4	2	3	6	2	8	1	1	93	53	81	97	89
137/97	Kurasini P/S	9242978	531248	5	8	4	4	3	10	2	8	1	2	104	72	84	112	100
13/97	MMC I Footbal ground	9247855	529911	5	10	4	6	3	8	2	6	1	5	115	75	99	135	115
19/97	Fire Bridgade	9247255	530190	5	8	4	6	3	8	2	6	1	2	102	70	86	110	102
28/97	Ilala Boma	9245787	528872	5	10	4	6	3	8	2	6	1	2	112	72	96	120	112
30/97	Dar Tech College	9247183	530916	5	10	4	8	3	8	2	6	1	2	120	80	104	128	120
34/97	Amana Ilala	9245636	528519	5	6	4	6	3	8	2	6	1	2	92	68	76	100	92
34/97	Kiwalani CCM	9241889	525239	5	10	4	6	3	8	2	10	1	1	119	79	103	123	111
92/97	Buguruni Moto P/School	9245143	526661	5	8	4	4	3	8	2	8	1	1	97	65	81	101	93
109/97	Msimbazi Mseto Primary School	9246157	528285	5	8	4	4	3	8	2	6	1	2	94	62	78	102	94
83/99	DSA Kurasini	9242087	530926	5	8	4	6	3	10	2	8	1	2	112	80	92	120	108
27/97	Uwanja wa Taifa	9242334	530244	5	6	4	2	3	8	2	8	1	5	83	59	67	103	79
31/97	Ilala Shule/Uhuru	9246004	530097	5	8	4	6	3	8	2	6	1	5	105	73	89	125	105
66/97	Kigogo P/S	9246862	526787	5	6	4	6	3	8	2	8	1	1	95	71	79	99	91
39/97	Kigogo Mwisho	9246628	526378	5	6	4	8	3	8	2	8	1	1	103	79	87	107	99
008/2000	Ubungo Marian Faith	9248466	522643	5	10	4	4	3	6	2	6	1	1	97	57	85	101	97

Appendix A-2 Continues

BH/NO.	Name of borehole	Northings	Eastings	Ww	Wr	Yw	Yr	Vw	Vr	Uw	Ur	Lw	Lr	PI	PI-W min	PI- Vul. Min	PI- Land. Max	PI- Use value fixed
363/98	Ubungo Islamic High School	9248125	522560	5	8	4	2	3	6	2	6	1	1	79	47	67	83	79
570/99	Ubungo-Kibangu (Mama Pembe)	9248424	522758	5	8	4	4	3	6	2	6	1	1	87	55	75	91	87
319/2000	Ubungo (Dr. Mbawala)	9249630	523178	5	10	4	4	3	6	2	6	1	1	97	57	85	101	97
379/99	Manzese - Tandale (Mzee Mbegu)	9249234	526352	5	1	4	8	3	8	2	8	1	1	78	74	62	82	74
557/99	Manzese - Tandale (Mama Tilya)	9249013	526485	5	8	4	2	3	8	2	8	1	1	89	57	73	93	85
103/98	Manzese - Tandale Msikitini	9249091	527061	5	1	4	4	3	8	2	8	1	1	62	58	46	66	58
181/99	Magomeni Kigera Mahiwi	9248735	527283	5	6	4	2	3	8	2	6	1	2	76	52	60	84	76
259/2000	Mburahati (Maria Alex)	9247536	526039	5	10	4	4	3	8	2	6	1	1	103	63	87	107	103
357/98	Mburahati (Gaspa)	9247548	525863	5	6	4	2	3	8	2	6	1	1	75	51	59	79	75
258/98	Mburahati (Mashoto)	9247617	526152	5	8	4	6	3	8	2	6	1	1	101	69	85	105	101
258/2000	Mburahati (Ofisi ya Kata)	9248035	526194	5	10	4	4	3	8	2	6	1	1	103	63	87	107	103
257/2000	Mburahati (M. Nassoro)	9248035	526250	5	10	4	4	3	8	2	6	1	1	103	63	87	107	103
14/99	Mnazi mmoja	9246189	530794	5	8	4	4	3	8	2	6	1	5	97	65	81	117	97
?	Gerezani	9245266	531006	5	8	4	2	3		2	6	1	5	65	33	65	85	65
?	TBL (Near main gate)	9246240	529374	5	1	4	6	3	8	2	6	1	1	66	62	50	70	66
	Ilala –Msimbazi valley (TBL)	9246089	529662	5	8	4	6	3	8	2	6	1	1	101	69	85	105	101
25/97	Buguruni Hostel	9245520	527227	5	6	4	2	3	8	2	6	1	2	76	52	60	84	76
38/97	Muhimbili hospital- maternity	9248457	530085	5	8	4	4	3	8	2	6	1	5	97	65	81	117	97
	Rainbow falls Ltd	9242274	531224	5	8	4	2	3	10	2	6	1	2	92	60	72	100	92
22/97	Chang’ombe T.T.C	9242334	530029	5	6	4	6	3	10	2	6	1	5	101	77	81	121	101
//12/97	Police College Kilwa Road	9243377	531440	5	6	4	8	3	10	2	6	1	5	109	85	89	129	109
20/97	Nzasa- Mbagala II	9235232	528356	5	10	4	8	3	8	2	10	1	10	136	96	120	176	128
33/97	Police Barracks	9243189	530530	5	6	4	6	3	10	2	6	1	5	101	77	81	121	101
121/97	Yombo Dovya Primary School	9241155	525902	5	10	4	6	3	8	2	8	1	10	124	84	108	164	120
131/97	Nzasa III	9235203	528285	5	10	4	8	3	8	2	10	1	10	136	96	120	176	128
132/97	Tandika Mabatini	9241639	528173	5	6	4	8	3	8	2	6	1	1	99	75	83	103	99
143/97	Kurasini kwa Masista	9242343	531685	5	8	4	6	3	10	2	6	1	2	108	76	88	116	108
311/97	Kurasini-EngenDepot	9243823	532451	5	8	4	2	3	10	2	6	1	2	92	60	72	100	92
188/97	Kurasini(NASACO)	9242111	531488	5	8	4	4	3	10	2	6	1	2	100	68	80	108	100
106/97	Mzimuni Primary School	9247386	528435	5	8	4	6	3	8	2	6	1	2	102	70	86	110	102
144/97	Kawawa Primary Schoolchool	9247143	525936	5	8	4	4	3	8	2	6	1	2	94	62	78	102	94
96/97	Kiwalani II	9241264	525393	5	10	4	6	3	8	2	10	1	1	119	79	103	123	111

Appendix A-2 Continues

BH/NO.	Name of borehole	Northings	Eastings	Ww	Wr	Yw	Yr	Vw	Vr	Uw	Ur	Lw	Lr	PI	PI-W min	PI- Vul. Min	PI- Land. Max	PI- Use value fixed
240/97	Tazara staff	9243321	526839	5	8	4	4	3	8	2	6	1	2	94	62	78	102	94
22/97	Wippers Karakata	9241943	522285	5	6	4	4	3	8	2	10	1	1	91	67	75	95	83
21/97	Ubungo- Maji	9249653	522745	5	8	4	2	3	8	2	6	1	5	89	57	73	109	89
29/97	Magomeni Garden	9247969	528555	5	8	4	8	3	8	2	6	1	2	110	78	94	118	110
97/97	Ukonga A/ Wing	9240750	521532	5	8	4	2	3	8	2	8	1	10	98	66	82	138	94
102/97	Nyerere Road	9242738	527124	5	8	4	2	3	8	2	8	1	1	89	57	73	93	85
138/97	Mbagala Kiburugwa	9236502	528515	5	10	4	8	3	8	2	10	1	10	136	96	120	176	128
157/97	Kurasini C SO	9244450	531733	5	8	4	6	3	10	2	6	1	2	108	76	88	116	108
178/97	Yombo Vituka CCM	9240195	526606	5	10	4	4	3	8	2	10	1	10	120	80	104	160	112
283/97	Kipunguni B	9244266	529385	5	10	4	4	3	8	2	10	1	10	120	80	104	160	112
289/97	Keko Msikitini	9244139	530157	5	6	4	2	3	8	2	6	1	1	75	51	59	79	75
171/97	Mnazi Mmoja Hospital	9246310	530974	5	8	4	6	3	8	2	6	1	5	105	73	89	125	105
98/97	Keko Prison	9244075	530400	5	6	4	4	3	8	2	6	1	1	83	59	67	87	83
DSM1	Bohari maji	9247045	532369	5	8	4	4	3	10	2	6	1	2	100	68	80	108	100

A-3: DAWASA Laboratory Analysis Sheet (2001)

DAR ES SALAAM WATER & SEWERAGE AUTHORITY

WATER QUALITY REPORT SHEET

Water Authority……………………………………………………………………………….
District…………………………………………Date……………………………………..
Sampler/Analyst……………………………………………………………………………….
Sample Number…………………………………………………………………………………

1) Location ……………………………………………………………………………..
2) Source ………………………………………………………………………………..
3) Time ……………………………………………………………………………………..
4) Physical description ………………………………………………………………..
5) Odour/Taste ……………………………………………………………………………
6) Faecal coliform taste ………………………………………………………………..
7) Total coliform count ………………………………………………………………..
8) Turbidity ……………………………………………………………………………….
9) Free chlorine ……………………………………………………………………………
10) Combined chlorine …………………………………………………………………..
11) Conductivity ………………………………………………………………………….
12) Temperature …………………………………………………………………………..
13) pH ………………………………………………………………………………………..
14) Nitrates ……………………………………………………………………………….
15) Nitrates ……………………………………………………………………………….
16) Ammonia ………………………………………………………………………………
17) Aluminium …………………………………………………………………………….
18) Boron …………………………………………………………………………………..
19) Copper …………………………………………………………………………………
20) Fluorides ………………………………………………………………………………
21) Magnesium ……………………………………………………………………………
22) Manganese ……………………………………………………………………………
23) Hardness ………………………………………………………………………………
24) Ozone …………………………………………………………………………………….
25) Sulphates ……………………………………………………………………………..
26) Sulphides ……………………………………………………………………………..
27) Phosphate ……………………………………………………………………………..
28) Zinc ………………………………………………………………………………………
29) Iron ………………………………………………………………………………………
30) Alkalinity ……………………………………………………………………………..

Comments	QC Comments
……………………….	…………………………………..
Sign …………………………….	Sign …………………………….

Curriculum Vitae

The author of this thesis was born on the 12th December 1958, in a village located on Lake Victoria shore called Isanju, Bunda district, Tanzania. He obtained his primary and secondary education in Isanju/Mugara primary schools and Mara secondary school respectively. From 1978 to 1981, he trained at the then Dar es Salaam Technical College (Now Dar es Salaam Institute of Technology) and obtained a Full Technician Certificate in Laboratory Technology. In 1983 to 1986, he studied at the then Ardhi Institute (Now University College of Lands & Architectural Studies, UCLAS) and graduated with an Advanced Diploma in Public Health Engineering. Then in 1992/93, he studied at the Newcastle Upon Tyne University, England, where he graduated with a Master of Science Degree in Environmental Engineering. The author has also obtained specialised training in sewage works engineering and environmental impact assessment each of three months during in Tokyo (Japan) and Aberdeen (Scotland) respectively.

The author is employed as a lecturer by the University College of Lands & Architectural Studies in the Department of Environmental Engineering. His areas of interest are water and waste engineering, environmental impact assessment, waste management and pollution control. Since graduation in 1986, the author has been involved in research and consultancy activities in the field of environmental engineering of which some are mentioned in the forthcoming pages. The author is a member of the International Water Association (IWA) and International Association of Hydrogeologist (IHA).

Mr. Mato, the author, is married to Mary and they have three children, Azaria, Enock and Naomi.

Publications

The author has published several papers in journals and conferences both internationally and locally. He has also offered consultancy services in the field of environmental engineering and management. Some of the publications are listed below.

For this Thesis

[*]Mato, R.R.A.M.; Janssen, F.J.J, Katima, J.H.Y.; Cramers, C.A.M.G. The Challenge of Urbanization and Groundwater Resources Protection in Tanzania Urban Areas. To be published in Habitat International

[*]Mato, R.R.A.M.; Janssen, F.J.J, Katima, J.H.Y.; Cramers, C.A.M.G. Groundwater deterioration in Dar es Salaam City, Tanzania. To be published in Journal of Hydrogeology

[*]Mato, R.R.A.M.; Janssen, F.J.J, Katima, J.H.Y.; Cramers, C.A.M.G. Evaluation of the potential of groundwater pollution sources in the city of Dar es Salaam, Tanzania. To be published in UrbanWater Journal

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Mato, R.R.A.M.; Janssen, F.J.J.G., Katima, J.H.Y.; Cramers, C.A.M.G (1999), Development of a "rapid assessment model" for evaluating groundwater pollution risk in Dar es Salaam city, Tanzania. A paper presented to the 7th International conference on the Israel society for ecology and environmental quality sciences on "Environmental Challenges for the next millennium", Jerusalem, Israel, 13-18th June 1999.

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[*] To be published in indicated journals

Other Publications

1. Mato, R.R.A.M; Mufuruki T.S (1999), Noise Pollution Associated with the Operation of the Dar es Salaam International Airport. International Journal of Transport and Environment, Transport Research Part D, 4(2), pp. 81-89. Pergamon.
2. Mato, R.R.A.M.; M.E. Kaseva (1999), Critical review of Industrial and Medical Solid Wastes Handling Practices in Dar es Salaam City. Resources, Conservation and Recycling, (25), pp. 271-287. Elsevier.
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Statements

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1. Indiscriminate waste disposal on/or underneath the ground where groundwater is used for water supplies is like a man cutting a tree branch on which he is anchored. *(Chapter 3, this Thesis).*

2. Groundwater is an archeological resource that gives one opportunity to taste the ancient past. *(Chapter 1, this Thesis).*

3. Many problems of mankind are a result of a lack of knowledge.

4. Living in urban areas with a rural-mind setting is one of the main causes of environmental problems in Tanzanian towns.

5. Community appreciation of the role of groundwater for daily lives of the members is a fundamental issue towards successful protection programmes. *(Chapter 8, this Thesis).*

6. All groundwater is vulnerable. The question remains how vulnerable is vulnerable. *(Chapter 6, this Thesis).*

7. The world resources to sustain human existence on earth are adequate. However, the distribution among the people is poor and hence the term poverty.

8. A good hope brings peace in the heart of a person and makes life enthusiastic even in distress. Thus the anticipation of the future can change the character of a person better than the historical past.

9. The statements accompanying a PhD thesis in The Netherlands form the most popular part of the work.

10. Sweet end is a reward for the patient one.

R.R.A.M. Mato, 2002