# MSc Hydrogeology: Thesis

## University of Birmingham

Rebecca Esther Carmel Simister

**URBAN WATER MANAGEMENT: USING THE CITY WATER BALANCE MODEL TO MODEL URBAN WATER SYSTEMS IN ACCRA, GHANA**

SWITCH

UNIVERSITY OF BIRMINGHAM

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Student:

Supervisor:

**ABSTRACT:**

The use of a scoping model to quantify the movement of water within urban water and waste water systems to the underlying aquifer has been applied to Accra, Ghana. Currently, only 55% of Accra has access to mains water, with water shortages and intermittent water connection to households becoming more common (AVRL 2010). In 2007 Accra became part of the SWITCH project as a demonstration city, which means that it promotes and undertakes on research into sustainable urban water systems. The City Water Balance (CWB) package has been developed by SWITCH to assess the impacts of future water management options in the city on recharge and the urban water cycle. The implementation of different water and waste water management options can be tested in the model to find more appropriate and sustainable water use improvements on a variety of spatial and temporal scales. A model has been successfully developed and calibrated, within the available limits, for the Accra Metropolitan Area that quantifies the inputs, processes and outputs of water within the urban water cycle. In this study, three different population scenarios for Accra in 2030 were tested along with five different water management options for present day city. The population scenarios showed that the imported water might reach up to three times the imported water volume at present, prompting the need for implementing more sustainable water practices in the future. The results from using different water management options show, at the household scale, that the imported water volume for the study area was reduced by 15% by implementing either rain tanks or wastewater recycling options. The effect of implementing swales to prevent flooding reduced the stormwater run-off by up to 30%. Implementing larger scale stormwater tanks and wastewater tanks showed a decrease of imported water by 29%. The mains water supply system and sewer networks in Accra will need to be improved as a result of projected population increase and demand. The use of water management options and sustainable urban drainage schemes have been shown to

reduce the demand of water at the household and at the larger scale and provides a way forward for implementing re-use and recycling of water in the city.

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## LIST OF SYMBOLS

AMA - Accra Metropolitan Area

AVRL – Aqua-Vitens Rand Limited

CWB - City Water Balance (model)

GAMA – Greater Accra Metropolitan Area

GIS - Geographical Information Systems

GSS - Ghana Statistical Survey

GWCL - Ghana Water Company Limited

LA - Learning Alliance

MC - Minicluster

RUAF - Resource centre on Urban Agriculture and Food security

SW - Stormwater

SUDS - Sustainable Urban Drainage Schemes

SWITCH - Sustainable Water Management Improves Tomorrows Cities Health

UNESCO - United Nations Educational Scientific and Cultural Organisation

UB - Unit Block

WRI - Water Research Institute

WW - Wastewater

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# 1. INTRODUCTION

## 1.1 General Background

Being able to fulfil the demand of safe drinking water to cities with growing populations is becoming more difficult as this places pressure on any cities' water resources. Many of these cities are also facing uncertainty in future population growth, which along with climate change may add further pressure to these resources. Accra, the capital city of Ghana, is growing at a rate of 4.4% a year and is already facing challenges in terms of space and demand on many resources. There has been no recent expansion of the water mains system in Accra to supply this increase in population, and many areas are subjected to rationed water and interrupted mains water supplies. At present, only 55% of Accra has a mains connection, with the rest of the population paying higher prices to obtain water from other sources. In terms of wastewater, only a small area of the city is connected to the mains sewer system, which itself has deteriorated over time and does not function at its designed capacity (Adank et al 2010).

The EU formed the SWITCH project in 2007 because of increasing global pressures of change, escalating costs and other risks inherent to conventional urban water management. The idea of urban water management is about being able to supply clean water with uninterrupted access to the whole population, and this has become a challenge to many cities with growing populations. The research that is carried out by different SWITCH cities can be brought together and shared to gain a deeper understanding of the different challenges in order to find sustainable and appropriate solutions (SWITCH (b) 2010).

Previous research involving the use of water balance models has been carried out on Accra- work on an MSc study from the UNESCO IHE Institute of Water Education producing a

water balance model using the programme Aquacycle for the Kpeshie area. This model successfully quantified the water balance and contaminant flow in the area, and calculated the benefits of using household rainwater tanks and wastewater treatment. The research also highlighted the problems of producing water balance models of areas with limited data sets.

## 1.2 Problem description

To be able to plan for future water demand scenarios, a variety of tools and resources will be needed to estimate population increases, population density, water availability etc and to determine what planned changes and improvements in the infrastructure need to take place in the future to meet these demands.

The City Water Balance (CWB) model was developed by the University of Birmingham as part of the SWITCH project. The CWB model can look at different predicted future scenarios and quantitatively measure water movement within the urban water system. It shows the results of implementing different Sustainable Urban Drainage Systems (SUDS) and water management options at a variety of scales. The advantage of using this model will mean different aspects of the water system can be assessed quantitatively and, as a result, provide better facilities and access to clean and safe water. By collecting information on the water resources in Accra, a model can be developed to allow these future scenarios to be modelled and different water management options implemented and trialled to demonstrate the changes in water demand and where water can be saved.

### 1.3 Aims and objectives

The aim of this study is to produce an accurate water balance model for the city of Accra using the CWB package.

The objectives of this study are:

- To collect data to produce a reliable and accurate dataset that can be used in CWB.
- To produce a calibrated model of the water cycle in the Accra Metropolitan Area.
- To use predicted population and climate change information to model different scenarios of Accra as a city in 2030 in order to quantify the changes in water demand and in the water cycle that may occur.
- To apply a set of water management options and SUDS on different spatial scales to calculate the changes in the inputs, processes and outputs of the urban water cycle such as the imported water and aquifer.
- To assess the reliability and applicability of the CWB model in Accra and recommend changes that should be made for this model to be improved for future use.

### 1.4 Structure of report

The report will be structured as follows:

Chapter 2, *Literature Review*, will focus on the development of the concepts of sustainable urban water management and the an introduction to water balance models.

Chapter 3, *Description of the study area*, will look at Accra in terms of its geography, geology and hydrogeology, and define the area that will be modelled in City Water Balance.

Chapter 4, *Methodology*, will discuss the data collected for the input files needed and provide more information about the CWB model.

Chapter 5, *Strategies and Scenarios*, will look at the different model scenarios and water management options that will be implemented.

Chapter 6, *Results*, will show the results of the baseline model and the scenarios outlined in Chapter 5.

Chapter 7, *Discussion*, will discuss the results in terms of their accuracy, reliability and sensitivity. It will also discuss the assumptions that were made in running the model and the problems that were faced.

Chapter 8, *Conclusion*, will state the conclusions that have been made from the results of the model, and provide recommendations for future work using the CWB model.

## 2. LITERATURE REVIEW

### 2.1 EU funded SWITCH Project

The SWITCH (Sustainable Water Management Improves Tomorrow's Cities' Health) project is an 'action research project that is implemented and co-funded by the European Union. It consists of 33 partners from 15 countries, which includes Accra as a demonstration city. SWITCH aims to bring about a paradigm shift in urban water management, from more traditional approaches to a more sustainable and coherent approach and towards sustainable urban water management (SWITCH (b) 2010).

The SWITCH project was formed because of global pressures for change, escalating costs and other risks inherent to conventional urban water management. These were causing cities to face ever increasing difficulties in efficiently managing scarcer and less reliable water resources. The satisfaction of water needs and waste water disposal without creating environmental, social or economic damage remains an increasingly difficult challenge. SWITCH brings together a number of companies, organizations and research institutes to form a Learning Alliance, where members can share research and adopt more sustainable water solutions across different areas (SWITCH (b) 2010).

SWITCH has six research themes that include:

- Urban Water Paradigm shift
- Stormwater management
- Efficient Water use and supply
- Waste water management
- Urban water planning

- Governance and institutions.

A Learning Alliance was set up in Accra in 2007, and has produced a set of aims regarding water management for Accra as a city in 2030, together with plans of how this will be achieved. The idea of the Learning Alliance was to liaise with other members of SWITCH and the Learning Alliance, and to find innovative and scientific solutions which avoided replications of research. The Accra City Stakeholders defined an integrated urban water management vision with the following aims:

- 100% access to uninterrupted water supply
- High water quality at Ghana Standard board criteria
- Non revenue losses in the GWCL system at 20-25%
- Improved productive use of water for livelihoods
- 80% of the population practising better sanitation behaviour using improved facilities
- Integrated solid waste management in a sustainable way
- A cleaner city with good drainage systems (Adank et al 2010).

These aims can be achieved by developing different plans under different scenarios including population, economic growth, climate change, power supply etc. The CWB model can enhance these strategic plans by demonstrating how the water demand would change in different scenarios and quantify water demand in each case.

## 2.2 Introduction to the urban water cycle

To be able to understand more about managing water resources in a sustainable way, the water cycle needs to be defined to look the aspects involved. Total water cycle integration is defined as ‘the collective consideration of the water supply, storm water, waste water and ground water components of urban water service provision’ (Mitchell2006).The term *water balance* denotes an ‘application of the principle of mass conservation used to account for the movement of water in the land phase of the hydrological cycle’ (Mitchell et al. 2003), or as ‘the change in storage equalling the sum of inputs minus the sum of outputs’ (Mitchell et al (b) 2003). The basic calculation is shown as:

$$\Delta S = (P + I) - (E_a + R_s + R_w)$$

Where $\Delta S$ is the change in catchment storage, P is the precipitation, I is the imported water, $E_a$ is the actual evapotranspiration, $R_s$ is the stormwater runoff and $R_w$ is the wastewater discharge. The units can vary for a water balance providing they are consistent throughout, such as millimetres (Mitchell et al (b) 2003).

The need to be able to quantify water resources and movement of water within an area of land is the starting point to being able to identify where water is wasted and where it can be re-used and recycled. In this study, the urban water cycle is represented by a more complex series of inputs, processes and outputs demonstrated by the flow diagram in Figure 2.1. Being able to model these processes allows us to assess a cities’ water resources in more detail by looking at supply and use of water for a geographic area for a specific period of time (Mitchell et al (b) 2003).

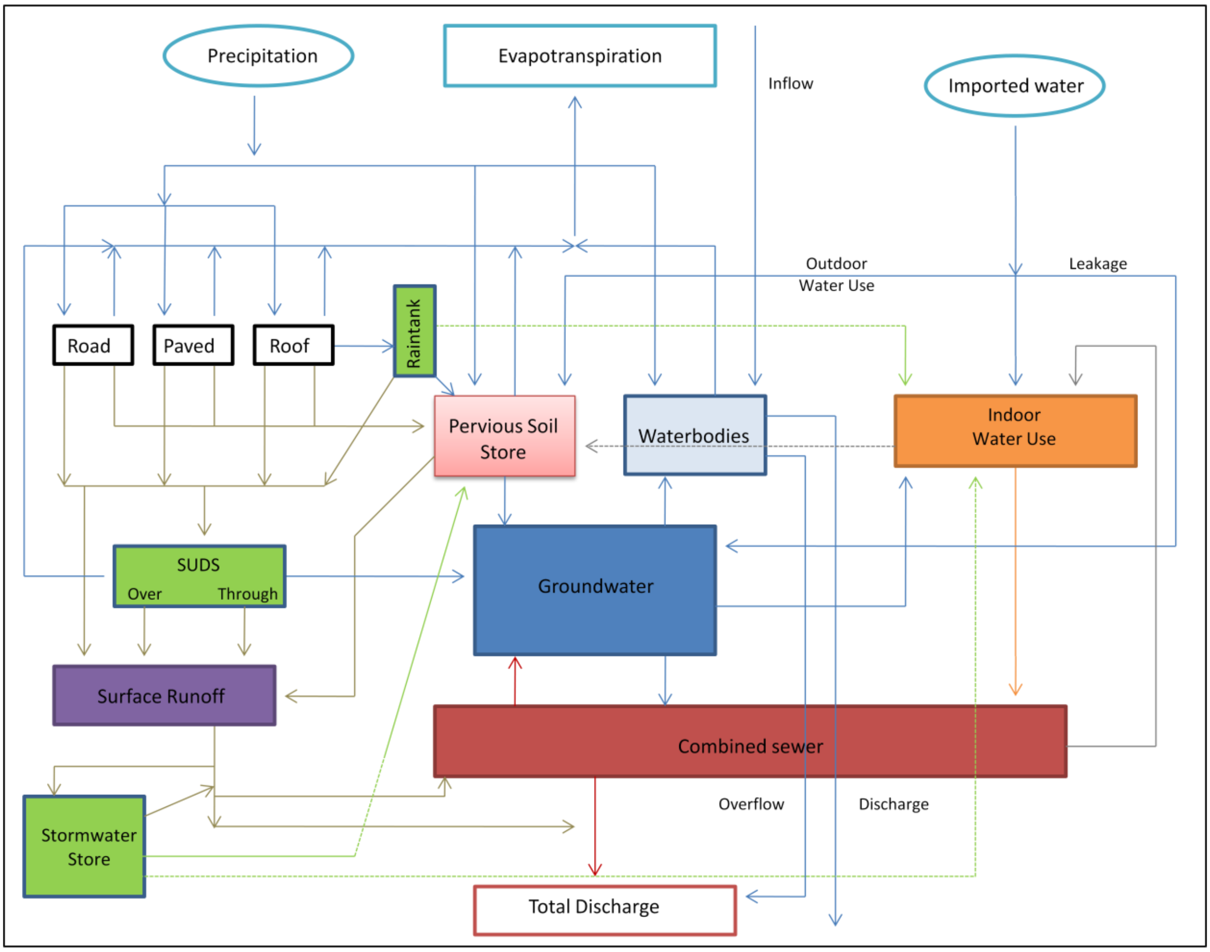



**Figure 2.1 Thecomponents of the Urban Water cycle (Last 2010).**

## 2.3 Urbanisation in cities

In any city, as the development and industrialisation process continues and accelerates, the increase in urbanisation is applying more pressure to the older, traditional water systems in place. Whilst the inputs into the water cycle may not change, such as the precipitation and imported water levels, changes in the city landscape like increased run-off from growing impervious areas apply pressure to the stormwater systems unable to discharge the water fast enough. Increased run-off has the greatest impact during the rainy seasons, which occur twice a year in Accra and lead to the stormwater drainage systems clogging up and localised

flooding occurring. Used water, not suitable for drinking, will often enter the drainage system during flooding and increasing the risk of contaminating drinking water sources.

### 2.4 Integrated Urban Water Management and challenges in developing countries

In the late 19th century, traditional approaches to supplying water in urban areas faced radical changes in a bid to improve health and sanitation following increases in disease outbreaks such as cholera. As cities develop the increase in population and subsequent demand in water started applying more pressure on water supplies. Cities around the world needed to improve on ageing infrastructure to fulfil the demand and as a result the demand for a more sustainable water system arose. Integrated Urban Water Management (IUWM) is the latest approach to water services and assesses all parts of the physical system. It looks at water supply, drainage and sanitation as components of this integrated system. The objective is to reduce water used in different processes and encourage treatment and reuse. By moving away from the traditional supply and demand paradigm, we can consider water in a wider context, by looking at improving quality, sustainability, cost, and access and water management by local stakeholders. Planning needs to take place on several time frames to be able to look at these different future scenarios that could take place (Mitchell 2006).

Accra, like many other cities, is facing a series of issues and challenges due to urbanization and population growth. These include:

1. Rapid growth, especially on the fringes of the city
2. Development of slum areas
3. Poor access to water supply and sanitation problems

4. High water losses in the distribution network and low cost recovery for water supply network

5. Polluted water resources

6. Poor storm water management, with localised flooding occurring.

These problems were highlighted at the beginning of SWITCH in Accra, and the aims of the project are based on finding solutions to these problems (SWITCH 2007).

The ideas of using more sustainable systems are becoming more popular and more recognized as ‘it can be argued that sustainability improves when a system or process operates more equitably, more efficiently or in a way that reduces its environmental impact’ (Lekkas et al. 2008). Globally there are a variety of sustainable water systems that have been introduced in recent years, including:

- Rainwater harvesting
- Green and brown roofs
- Wastewater treatment and re-use
- Wetland drainage systems

### 2.5 Socio-economic water factors and water use in Accra

The difference in water consumption in Accra is mainly based on socio-economic factors. A study by Lamptey (2010) has shown that water consumption rates (in litres per capita per day) are much lower in the high density, low-income areas of Accra in comparison to the low density, high income areas (Figure 2.2). Water consumption is dependent on how water is

provided to a particular area, the price paid for the water in this location and the distance that has to be travelled to obtain the water (Adank et al 2010).

| **Income Group** | **Per Capita consumption (l/c/d)** | **Average Resident population** | **Household size** | **Average monthly consumption/ $m^3$** |
|---|---|---|---|---|
| **High Income** | 120 | 8 | 1 | 28.8 |
| **Middle Income** | 90 | 12 | 2 | 32.4 |
| **Low Income** | 60 | 15 | >3 | 27 |

**Figure 2.2 Water usage based on income group (Lamptey 2010).**

The further away a household is located from a mains connection, the more expensive water will become, as mains water is much cheaper than other sources. If a household is not connected because of the distance to the mains, then water has to be obtained from elsewhere like a local standpipe, filling point or other vendor who will charge much higher water rates. Over half of the population have household connections for drinking water (51.2%) and other uses (55.9%) (Adank et al 2010). Many of these households with connections are likely to be in the more affluent areas of Ghana.

The cost for water per 1$m^3$ is 0.66-0.91 Ghana cedis (£0.31-0.42) for a domestic metered connection. This is in comparison to sachet water which can cost up to double this at 67-100 Ghana cedis (£31.6 to £47) for the same volume of water (Adank et al 2010). These prices will affect water consumption, as water that costs more and has travelled further is more likely to be used efficiently over a longer period of time. The companies responsible for water management in Accra are discussed in Chapter 3.4.

### 2.6 Modelling the urban water cycle

Models have been created previously to attempt to quantify the urban water cycles where improved water management is needed in cities such as Athens, Greece (Lekkas et al 2008). Earlier Water cycle models such as UVQ and Aquacycle focus on modelling the integrated urban water cycle in a quantitative way, looking at all the parts of the physical water cycle and relating the movement between each part. The goal 'was to move towards developing water systems with an increased range of opportunities to develop sustainable systems' (Mitchell et al. 2003). These models were designed as scoping tools to allow people to create 'what if?' scenarios and assess the resulting impacts on urban water systems.

CWB is a more advanced model than earlier models like Aquacycle because of the wide range of sustainability options it has implemented within the code, and the more detailed approach to modelling the aquifer beneath the surface. As part of the scoping model, water re-use and water saving technologies can be tried and tested. These technologies could include green roofs, rainwater harvesting, brown roofs, swales etc. The model outputs show the volume of water entering, stored and leaving the system i.e. from source to sink, and what processes are affecting this water movement. It is demonstrated in terms of water balance graphs and flow diagrams demonstrating more specific water flow (Last 2010).

CWB can also model water movement in a spatial and temporal context. Water consumption is calculated per unit area and water management systems modelled on different scales, from an individual property scale to a much larger area. Water consumption may also vary in time e.g. in cities heavily affected by seasonal populations change such as tourist cities. Water consumption will vary spatially depending on the type of area, such as a residential or industrial area.

The advantages of using the CWB model to quantify water use over other models is that it provides an integrated approach to modelling that looks at water consumption, waste water, energy savings and sustainable water management options all in one model. It is also designed in a way that is easy to use and understand, and its applicability is well suited to many different areas, as the level of detail and input can be decided by the user.

## 3. DESCRIPTION OF THE STUDY AREA

### 3.1 Introduction to Accra

Accra is the capital city of Ghana, located on the South coast of West Africa on the Gulf of Guinea (Figure 3.1), just north of the equator in the Western region of Africa.

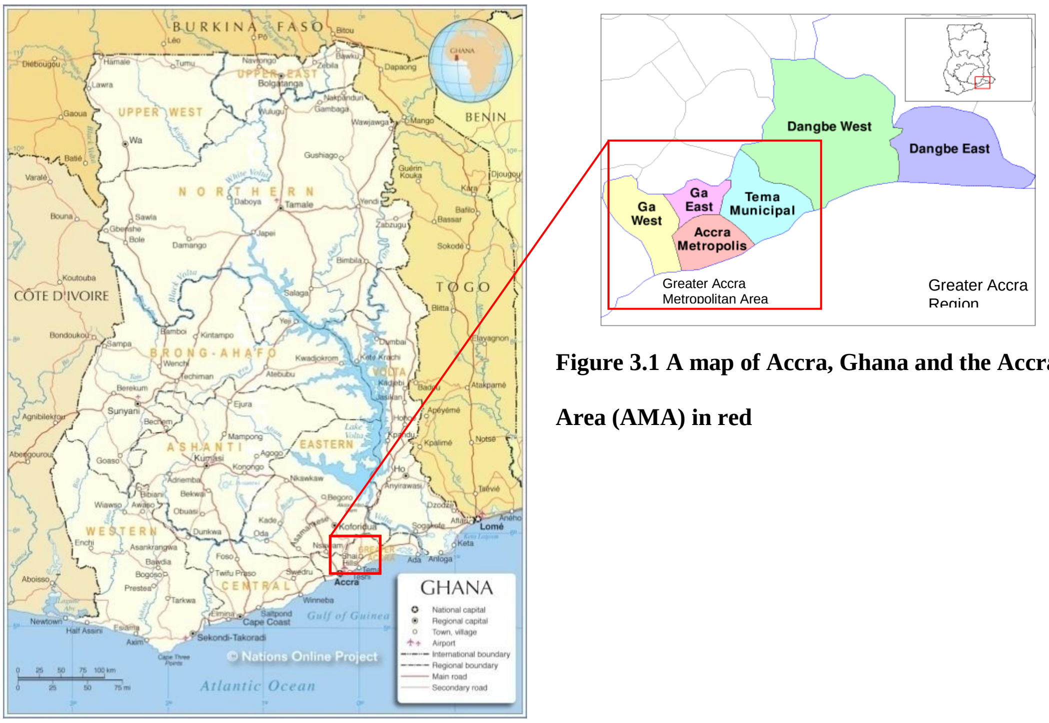



**Figure 3.1 A map of Accra, Ghana and the Accra Metropolitan Area (AMA) in red**

Ghana is in sub-Saharan Africa, surrounded by Cote D'Ivoire to the West, Burkino Faso to the North and Togo to the East. Accra has an area of 185 km$^2$. The Accra Metropolitan area (AMA) consists of 11 sub areas: Ablekuma Central, Ablekuma North, Ablekuma South, Ashiedu Keteke, Ayawaso Central, Ayawaso East, Ayawaso West-Wuogon, La, Okaikoi North, Okaikoi South, and Osu Klottey (Adank et al. 2010).

The city of Accra has grown considerably in the last two decades. The population of Accra Metropolis from the last census in 2000 is 1,658,937 (GSS 2000) and the last measured rate of population growth was 4.4%, and implying that the population has almost doubled over

the past 16 years (GSS 2005). These population increases are from a combination of increased fertility rates and the migration of people from the North in search of work.

Accra also has a large variation in socio-economic classes, as shown in Figure 3.2. There is a variety between high density/low income areas such as James Town, and also low density/high income areas such as Airport Residential and Cantonments. The classification of Accra by socio-economic class is important later as it is the main factor in determining water consumption in different areas.

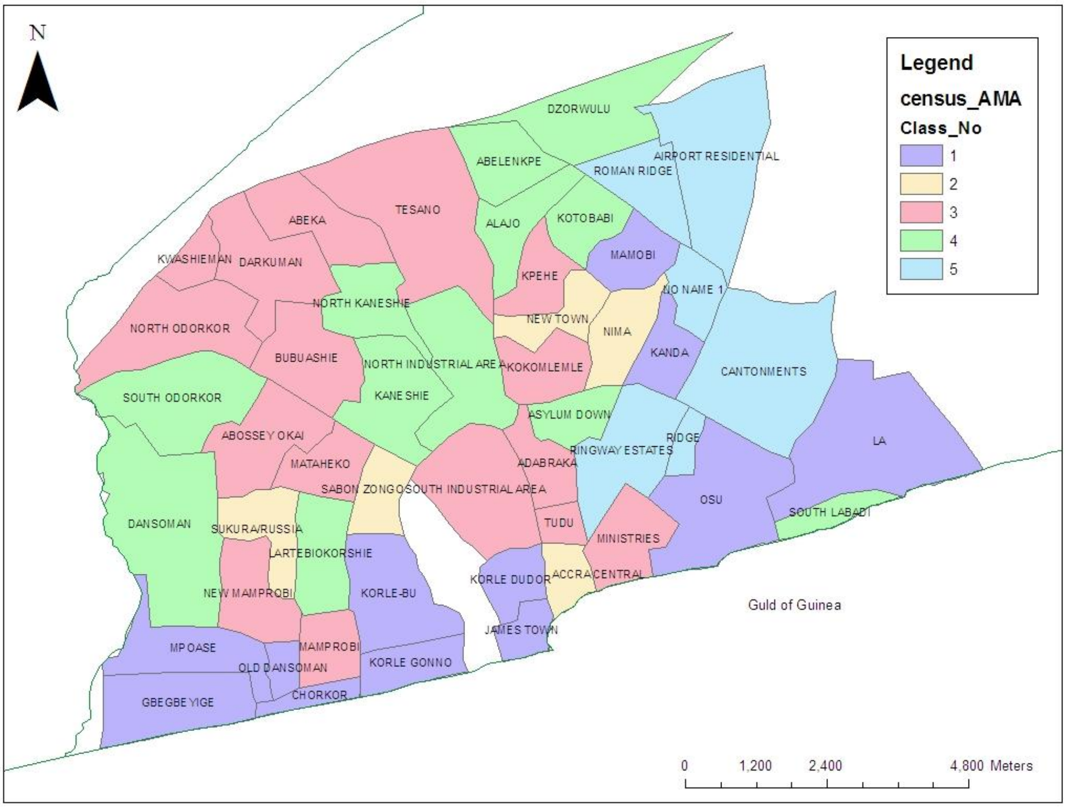



**Figure 3.2 Areas of Accra based on socio-economic class, from 1 to 5 (lowest to highest).**

### 3.2 Geography

The main river that flows through Ghana is the Volta, which is one of the largest rivers in Africa. The Volta Lake was created by the construction of the Akosombo Dam in 1964 that

provides electricity and stores water for supply to areas in Accra (Adank et al 2010) (Figure 3.3).

There are two main rivers that flow through Accra, the Odaw and the Onyasia, and two lagoons including the Korle and Kpeshie. There are three main river catchments that are within the AMA area which includes the Densu catchment, the Korle catchment and the Kpeshie catchment (Figure 3.4).

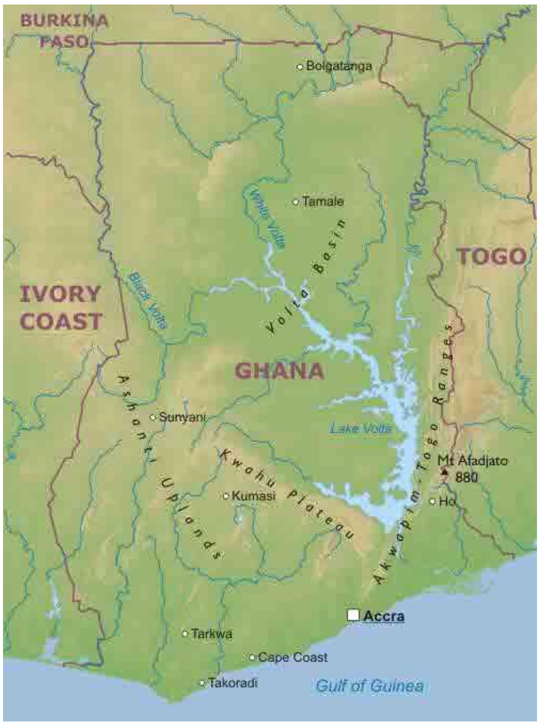



**Figure 3.3 Lake Volta, Ghana.**

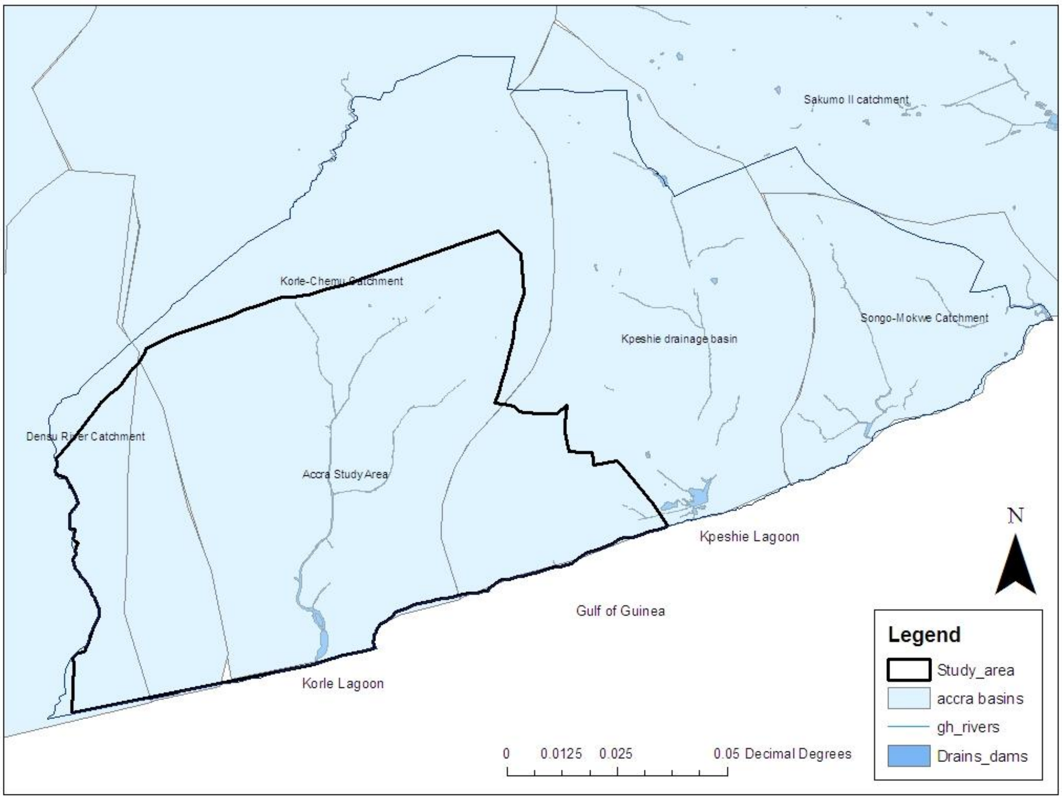



**Figure 3.4 A map to show the rivers and catchments in the Accra area**

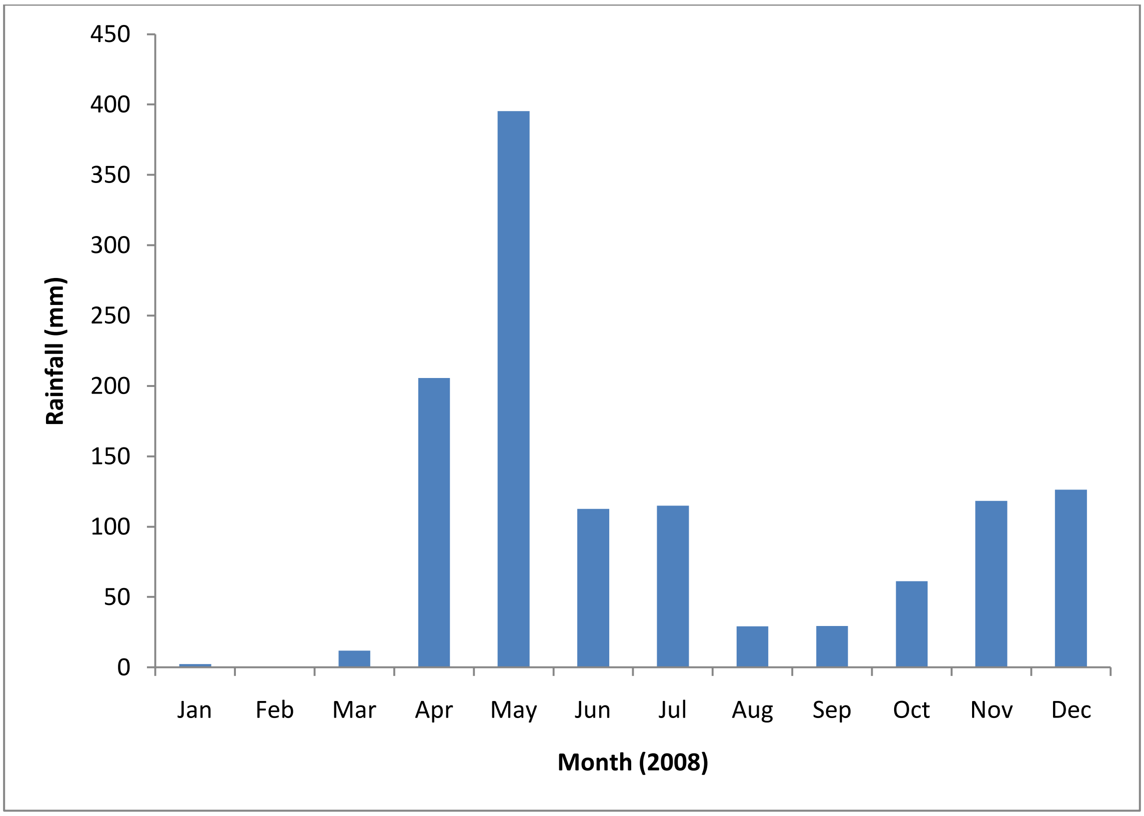



**Figure 3.5 Monthly rainfall in Accra in 2008 (SWITCH 2010).**

The rainfall is variable throughout the year and there are two dominant rainy seasons: June and October (Figure 3.5). In June, rainfall levels have been recorded in previous reach a peak of 400 mm and this rainfall often occurs in heavy and short duration (SWITCH 2010).The temperature variation in Accra is minimal, with temperature variation between 20-35 degrees throughout the year (Urban Groundwater Database 2010).

### 3.3 Geology and hydrogeology

The geology of Accra consists of the Accrian coastal province formation and the Dahomeyan series (Figure 3.6). The Accrian coastal province block is small in

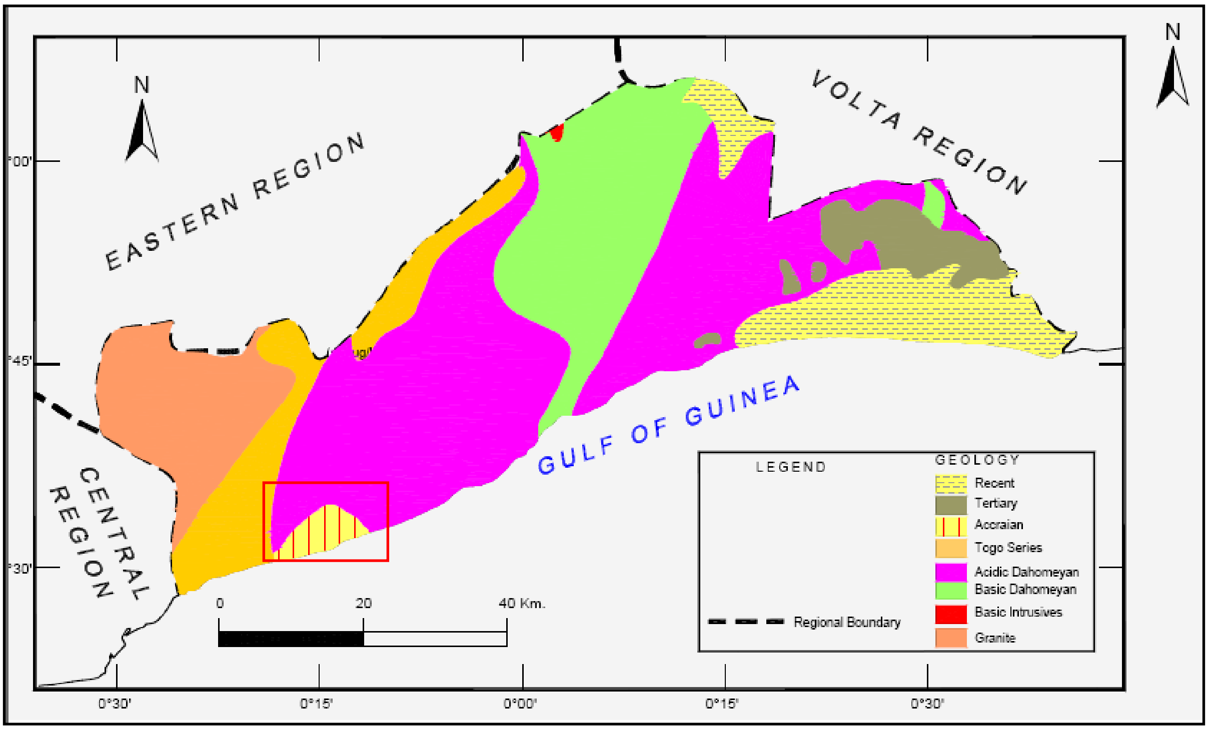



**Figure 3.6 The geology of the Greater Accra Region (UNESCO 2007).**

size and consists of ‘a narrow discontinuous Devonian and Jurassic sedimentary rocks including sandstone, grit and shale that have been faulted and intruded’. The average borehole yields in this region vary from 3.9-15.6 $m^3$/hr. The Dahomeyan series consists of

basement crystalline rocks such as gneiss and migmatites that are massive and have few fractures making them relatively impervious. The average borehole yields are between 1-3 $m^3$/hr (Kortatsi 1994).

Transmissivities for both units are low, with the Accrian series having an average transmissivity at 4 $m^2$/d and for the Dahomeyan series an average of 18 $m^2$/d, indicating groundwater potential is much higher in the basement crystalline rock (UNESCO 2007).The groundwater beneath Accra is saline and is of poor quality as a result of saline intrusions and halite dissolution, due to the proximity of Accra to the sea (Kortatsi 1994). More boreholes are drilled in the North of the area because the likelihood of obtaining fresh water increases as the distance from the coast increases. The majority of recharge occurs in the hills to the North of the Greater Accra Metropolitan Area (GAMA), which forms the main source of any freshwater lenses.

### 3.4 Overview of Urban Water Management in Accra

### 3.5 Water Supply

Accra at present has a mains water supply infrastructure that was designed to supply the whole population of the city. The Ghana Water Company Ltd (GWCL) owns the system and it is currently operated by Aqua-Vitens Rand Limited (AVRL). As mentioned earlier, only 55% of the population has access to a mains supply, which means the rest of the population must access their water through other sources such as tanker's water and public and private standpipes.

There are two reservoirs outside of Accra where the water is sourced: the Weija Dam on the Densu river, and the Kpong system (Akosombo Dam) on Lake Volta. The Densu is located

20km away from Accra and supplies 169,987 $m^3$/day. The Akosombo Dam primarily generates hydro-electricity but also provides water to Accra 193,430 $m^3$/day. AVRL estimates that only 41% of this water is sold to consumers, so there are a high proportion of commercial and physical losses. These losses are also due to other factors such as illegal connections and badly maintained pipelines (Adank et al. 2010). According to Nyarko et al (2008), only 17% have an uninterrupted water supply so the majority of the population need to have strategies in place for when water is not available from the mains. There are often household rainwater storage tanks for storing water that will be filled from the mains or from private vendors.

### 3.5.1 Wastewater treatment and sanitation

There are a range of different sanitation services in the city of Accra that provide waste services to the population. These are:

1. **Municipal managed sewer system**: The centre of Accra is served by an underground sewer system. The grey and black water waste flows from buildings to the sewers and then into a wet well at the Central Accra Pumping station. It then discharges into the Up-Flow Anaerobic Sludge Blanket (UASB) treatment plant in James Town (Adank et al 2010). It is designed to treat 16,080 $m^3$/day but many parts of the plant have broken down and only 5000 $m^3$/d is being treated, with the rest being discharged to sea. The fresh faecal sludge plant currently processes 560 $m^3$/d of black waste that goes to landfill (ASIP pers. comm. 2010)..The public authorities also responsible for servicing public latrines and toilets.

2. **Private sector septic emptiers**: Around 70% of houses who are not covered by the sewer system may have septic tanks that are emptied by public and private septic

emptiers (Obuobie et al 2006). These septic tanks are disposed of at the same landfill for black waste in James Town (Adank et al 2010).

3. **Institutional sanitation services:** Many hotels and institutions have their own sewerage system. There are 22 in the Greater Accra area but only 6 were functioning in 2001. These wastewater treatment plants include waste stabilization ponds, trickling filters and activated sludge systems (Obuobie et al 2006). The volume of wastewater being treated through these systems is unknown.

### 3.6 Area chosen for study

The area chosen for developing the model is the Accra Metropolitan Area, which consists of 51 different areas of Accra, shown in Figure 3.7. The area is bordered by the Accra-Tema motorway to the North, the Gulf of Guinea to the South, the AMA border to the West and the Liberation Road to the East. The area was chosen as it was big enough to model groundwater recharge on a large scale, and because many of the data sets were given with data at this level. To measure a smaller area would have increased the level of inaccuracy as on the district/area level many data set boundaries did not coincide.

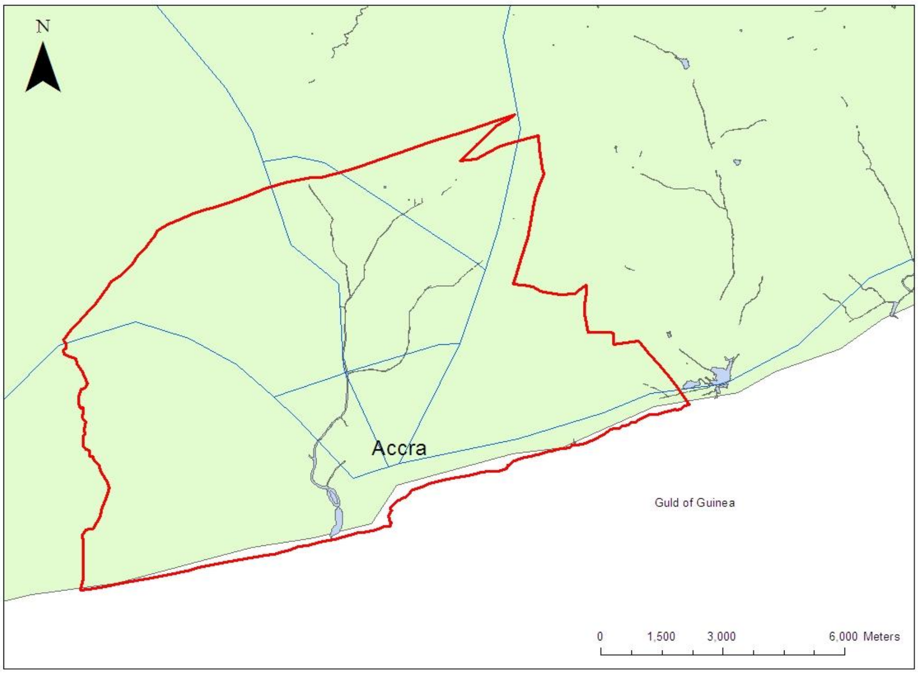



**Figure 3.7 A map to show the area of Accra modelled within CWB (outlined in red).**

# 4. METHODOLOGY

## 4.1 Introduction to data collation

### 4.1.1 Desk Study

A literature review and desk study was carried out first (see Chapters 2 and 3) to gain a deeper understanding about urban water management in cities and the water problems that Accra faces at present and in the future. Contact was made with the SWITCH team in Accra to initiate meetings with companies and contacts in Accra who are part of the Learning Alliance.

### 4.1.2 Data collation in Accra

Two field visits for data collation were carried out, two weeks in June 2010 and later one week in July 2010. Twelve meetings were held successfully with the aim to assessing what data was available and where data sets could be obtained within the first visit. The second, shorter visit was designed to collect data that was missed on the first visit or not available until later on.

From both field visits, it became clear that in comparison to other more developed countries, companies did not keep a wealth of information kept on many of the areas that were needed for the model. This is because data is rarely kept unless there is a scientific or economic motive for storing the data. This meant that only some data was available and the rest of the data had to be estimated from literature values. This limitation is discussed in Chapter 7.

### 4.2 City Water Balance Model software

The City Water Balance model was developed as part of the SWITCH project research at the University of Birmingham. The City Water Balance model 'uses simplifications of a city's water system to describe the distribution of water fluxes and water borne contaminants in space and time' (Last 2010).  It has one main user interface that is used to run different simulations. There are sets of input files that are used in the model which require information from the modelled area to be entered. These input files include climate and soil data, building water uses etc. The input files for the simulation of Accra are shown in Appendix 1.

The model is based on classifying water consumption at different spatial scales- unit block, minicluster and subcatchment scale. These are demonstrated in Figure 4.1.

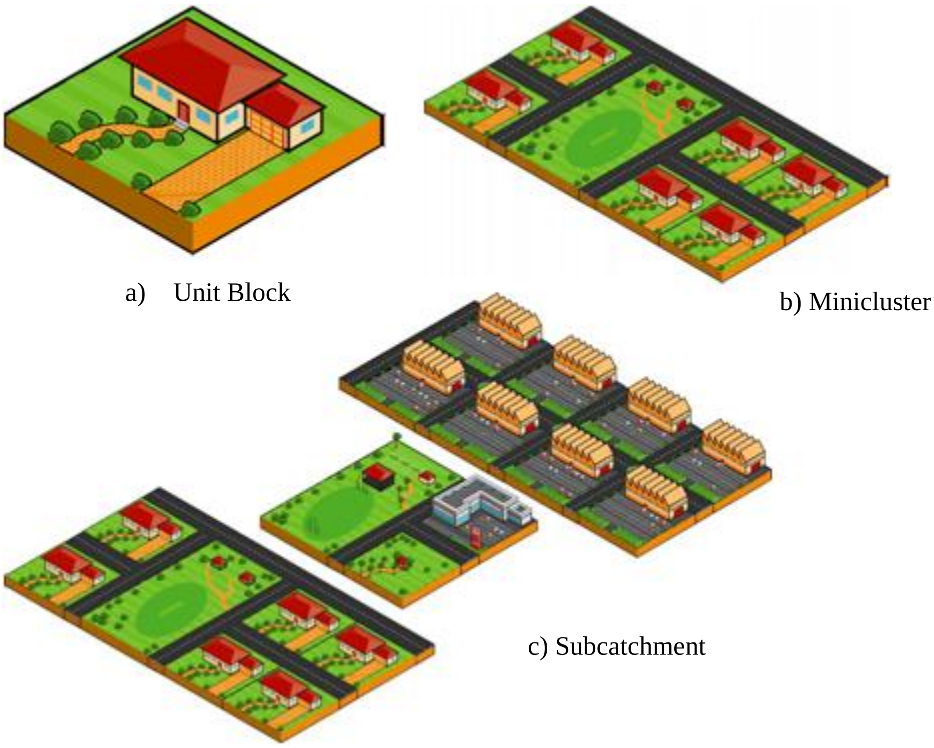



**Figure 4.1 Illustration of Unit Block, Minicluster and Subcatchment scales (UVQ 2005).**

### 4.2.1 Unit Block Scale

The unit block scale is the smallest spatial scale at which water use is classified. A Unit block may consist of impervious and pervious areas, and a water demand suitable for that land use, for example a residential house with a garden, driveway and domestic water use (Last 2010).

### 4.2.2 Minicluster Scale

A minicluster consists of a number of identical unit blocks that are all connected, for example a residential area. At the minicluster scale, additional features such as water movement within roads, public open space and wooded areas are defined.

### 4.2.3 Subcatchment scale

The largest scale that water is characterised on is the Subcatchment scale. This looks at the movement of storm water and waste-water on a large scale within a number of miniclusters. It looks at flow between subcatchments and in CWB is defined as ‘an area of cityscape containing a network of foul or combined sewers that drain to a point at its downstream boundary’ (Last 2010). The subcatchments are numbered in order of flow, so water will flow from a lower numbered to higher numbered subcatchment, as demonstrated in Figure 4.2. The arrows demonstrate the direction of both stormwater and waste-water movement. As the miniclusters must be numbered, they are numbered first in the earlier subcatchments.

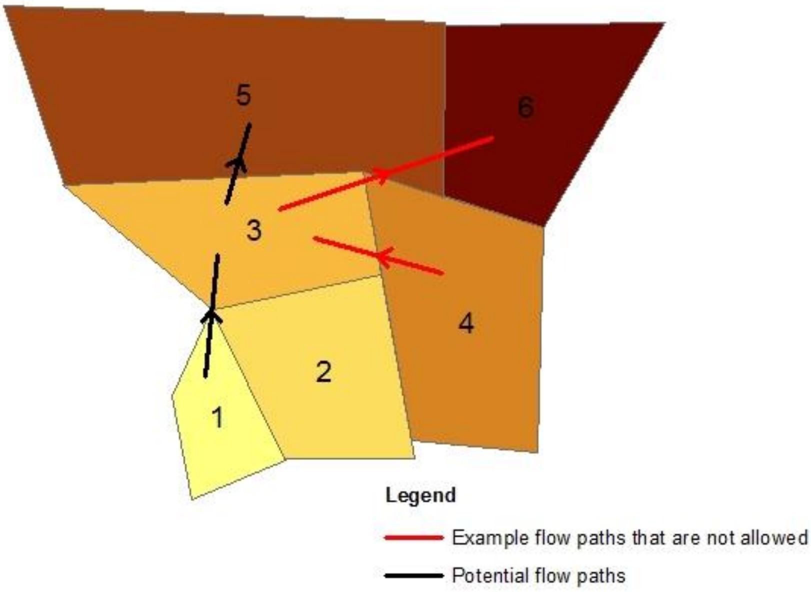



**Figure 4.2 Diagram of subcatchment numbering.**

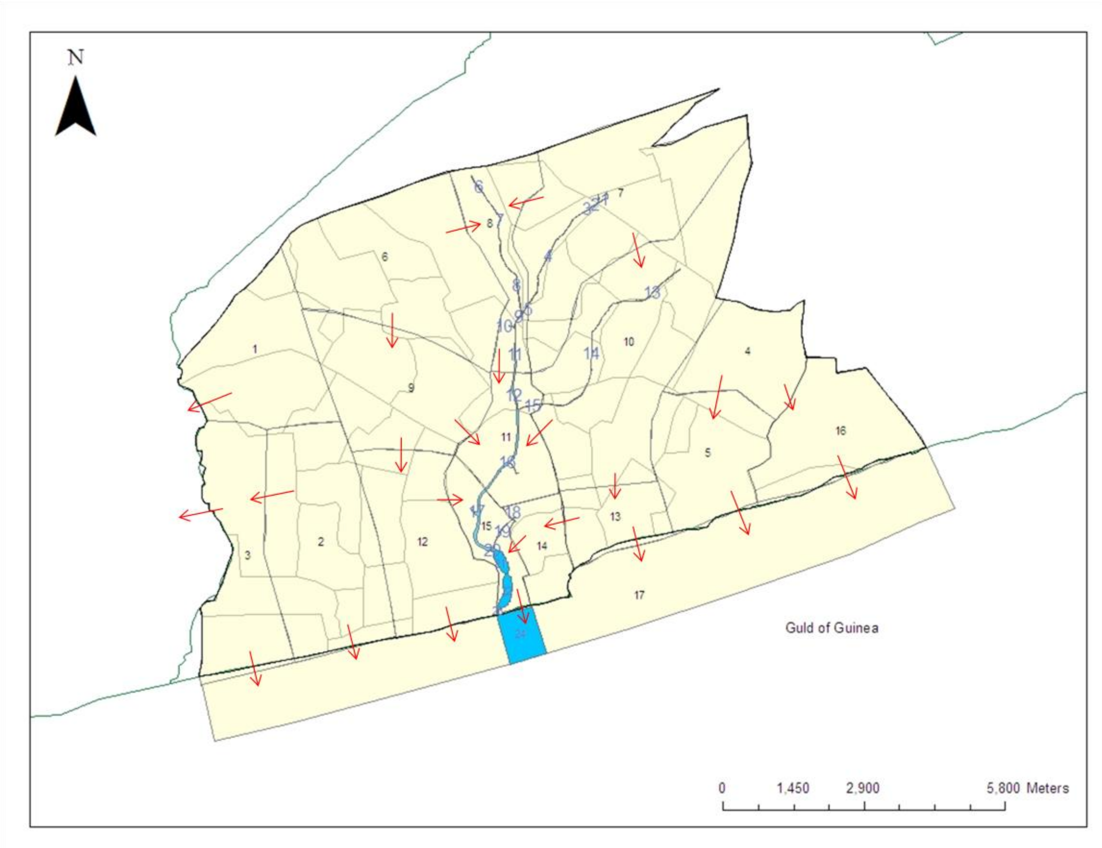



**Figure 4.3 Flow diagram and numbering of subcatchments in Accra.**

The data that was collated in Accra and through other sources was adjusted and changed into the correct format for use in the model. It should also be noted that for this project the model will only look at water balance aspects and will not be using any of the energy or contaminant options available.

## 4.3 ArcMap and Shapedump

### 4.3.1. ArcMap

The ArcGIS(Geographical Information Systems) package allows polygons to be constructed in different shape files (.shp extension) of areas that can be used to represent different land uses. The shape files are created using ArcMap and imported into the file where the polygons are drawn by hand.

The programme was used for a) storing and representing information gained in a spatial format and b) to allow shape files to be constructed in order to gain vertices and centroid information for different polygon sets. The X and Y centroid data was needed for the river, lake and minicluster default files.

A number of shape files, including the base map, were available from the Accra Starter Kit. These files included data on geographical areas, topography, water mains, hydrology, geology, population and sanitation conditions. The map was spatially referenced to the Ghana Metre Grid, which is a projected co-ordinate system. It is assumed that the distances measured are not affected by any distortion at a large scale.

### 4.3.2 Shapedump

The Shapedump programme is a programme that allows components of the shape files constructed in ArcGIS to extract vertices data to subsequently calculate polygon areas. The programme uses X and Y centroid data from a particular shape file and convert this data to a number of vertices, the spatial location of these vertices and the corresponding area of each group of vertices. They are exported as a text (.txt) file and it is used as an input file in the CWB programme.

## 4.4 Unit Block types

The unit block types chosen were based on the water consumption of the six AVRL areas that are part of the AMA area: Accra Central, Accra West, Accra North, Accra East, Damsoman and North West. The unit block types could not be chosen in the 'typical' CWB style, which identifies individual unit blocks as houses, hospitals, restaurants etc. This was because when modelling Accra at a larger scale, it proved difficult to identify a building to a particular usage, as most buildings and uses appeared to be of the same size and roof material. This is demonstrated in Figure 4.4.


**Figure 4.4 A map of Dzorwulu, Accra (Google Maps 2010).**

For some areas such as Accra Central, it was easy to identify a whole area for a particular use e.g. commercial, but further out in residential areas, many of these different building uses are mixed and were difficult to identify. In the field, without mapping individual houses, it is not possible to identify the spatial location of these building types within an area using these maps. This would have resulted in inaccurate recharge into the groundwater system. It was therefore decided that the only way the water consumption could be accurately identified in a spatial context was to 'lump' the different uses together and average them out over a whole area. The unit block types are listed in Figure 4.5.

| Unit Block Number | Land Use | Unit Block Number | Land Use |
|---|---|---|---|
| 1 | Accra Central | 6 | North West |
| 2 | Accra West | 7 | Roads |
| 3 | Accra North | 8 | Public Open Space Impervious |
| 4 | Accra East | 9 | Public Open Space Pervious |
| 5 | Damsoman | | |

**Figure 4.5 Unit block types used for model.**

These unit block types therefore had an average roof, paved and road area and the water consumption would also be an average of the different property types. This water consumption was classified using the 'occupancy per unit area' option, which proved a more effective way of classifying non-residential water consumption (Last 2010).

For each area, the average roof, paved and pervious area for domestic, commercial, industrial and institutional properties were measured using the 'Measure Area' function on Google Earth on properties with a known building use (Figure 4.6).

| | Roof area ($m^2$) | Paved area ($m^2$) | Pervious area ($m^2$) | Total area ($m^2$) |
|---|---|---|---|---|
| **Domestic** | 605 | 415 | 462 | 1483 |
| **Industrial** | 7866 | 3815 | 0 | 11681 |
| **Commercial** | 5203 | 1009 | 1021 | 7273 |
| **Institutional** | 5714 | 2035 | 3182.7 | 10931 |

**Figure 4.6 The average areas for different property types in Accra.**

This was also used to measure the road proportion in a Unit Block. For the domestic properties, ten properties were measured in each area, and three for the other types. An average area was then calculated and used. For the first six unit block types, the assumption was made that none of the pervious areas were irrigated, kept constant throughout the model

as very little land is irrigated in Accra. The proportion of water split between uses 1-4 were split in accordance with the domestic use proportions stated in the London Economics report (1999) carried out in Accra. The calculations are shown in Figure 4.7.

| | **Use 1 (Toilet)** | **Use 2 (Kitchen)** | **Use 3 (Bathroom)** | **Use 4 (Laundry)** | **TOTAL** |
|---|---|---|---|---|---|
| **Consumption (l/d)** | 31.42 | 57.42 | 31.82 | 30.80 | 151.46 |
| **Proportion** | 0.20 | 0.38 | 0.20 | 0.22 | 1 |

**Figure 4.7 Water consumption for typical domestic household of four people (London Economics 1999).**

### 4.5 Input files and definitions

There are a number of input files that need to be assembled before inputting into the model, each of which can be seen in Appendix 1.The key assumptions and data sets however are discussed below.

#### 4.5.1 Climate data

Climate data was available on the Accra Starter kit, which had data for rainfall and potential evaporation rates. The input for precipitation used was for one year. The data was input from March 2007 to March 2008 as calibrating the model before the rainy season started would be easier than during a rainy season (Figure 4.8). Accra is more prone to heavy, short duration rainstorms and this is an important consideration because this is more likely to cause flash flooding in the city. The potential evaporation rates were assumed to be the same each day over a given month.

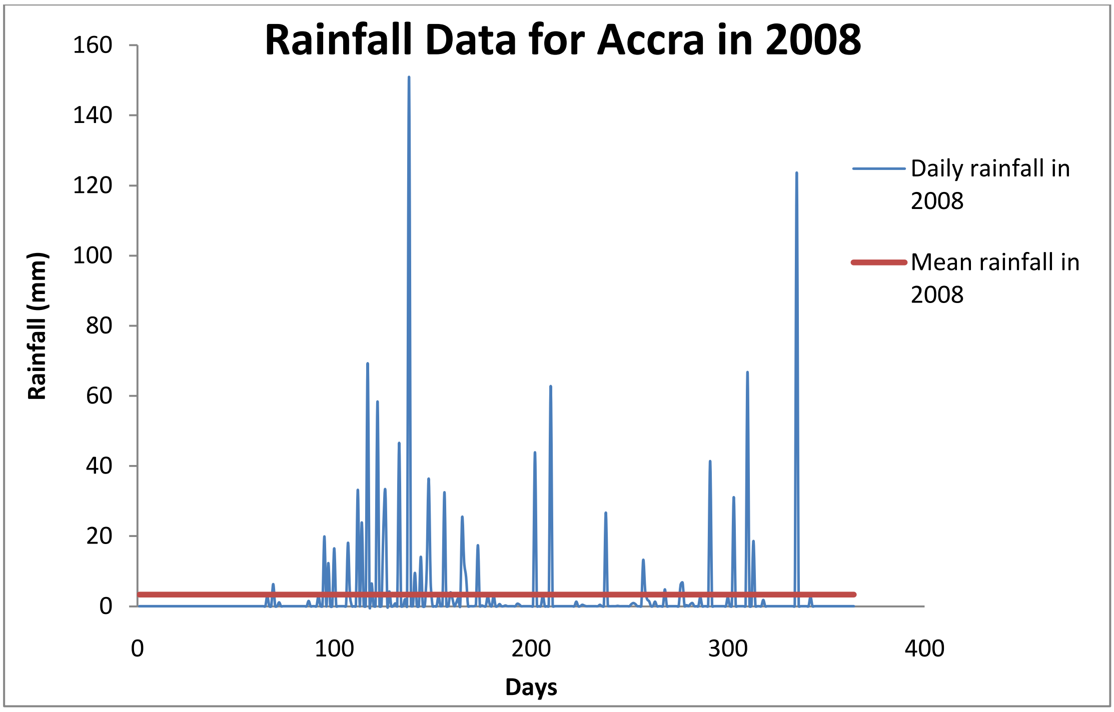



**Figure 4.8 Rainfall data for Accra in 2008 (Accra Starter Kit 2010).**

### 4.5.2. Soil data

Soil descriptions were obtained for the three main soil types in Accra- the Nyigbenya, Oyibi and Alajo types. However, there was not enough data available on each of the soil types to be able to make calculations suitable for the input files required and so the sand default file was used. The pervious store model used was the Partial Layer model, instead of the Two Layer system. The pervious area within this model 'is split into two, with two depths and two areas, and no flow between'. This is more suited for semi-arid and arid areas that feature high evaporation rates and high intensity rainfall, and means that no surface run-off or recharge occurs until the soil is fully wetted. In dry periods, the only water loss is through evaporation (Last 2010).

### 4.5.3. Rivers and Lakes

The Odaw is the only river in the model area and flows through the centre of the Korle-Chemu catchment before reaching the Korle Lagoon. The depth of the Odaw is estimated at 0.54m for its whole length based on previous measurements. The elevation, width and gradient have been calculated using data from Google maps for each segment of the river. The Mannings coefficient is constant at 0.15. The discharge in the Odaw is unknown and it is likely to vary throughout the year, especially following heavy rain. The hydraulic conductivity estimate is 1 m/d based on previous model estimates. The Korle lagoon has been modelled using the lake option, and the shape of the lagoon has meant three lakes have been entered in sequence. The Korle Lagoon is open to the sea. The other two catchments that are present within the model flow away from the Odaw and eventually flow to the sea (Figure 3.4).

### 4.5.4. Aquifer

The hydrogeology of the Accra area consists of Accrian sediments to the South and Dahomeyan schists to the North (Figure 3.6). There is a lack of hydrogeological data for Accra due to the small number of boreholes that are drilled and monitored because the groundwater is mostly saline. The static groundwater level varies spatially due to the heterogeneity as a result of fracturing, but is on average 5-10m below the surface (WRI 2010). There is also uncertainty in the depth and thickness of both the shallow freshwater aquifer and a deeper saline aquifer. Groundwater below the fractured aquifer i.e. below 120m is being ignored. The properties of both aquifers are listed in Figure 4.9, taken from WRI (2001).

| | **Accrian series** | **Dahomeyan series** |
|---|---|---|
| **Groundwater level (mbgl)** | 24 | 31.6 |
| **Base of layer (mbgl)** | 30 | 30 |
| **Transmissivity ($m^2/d$)** | 4 | 18 |
| **Specific Yield( - )** | 0.26 | 0.32 |
| **Aquifer thickness (m)** | 4.5 | 3.4 |

**Figure 4.9 Hydrogeological properties of both aquifers (adapted from WRI 2007).**

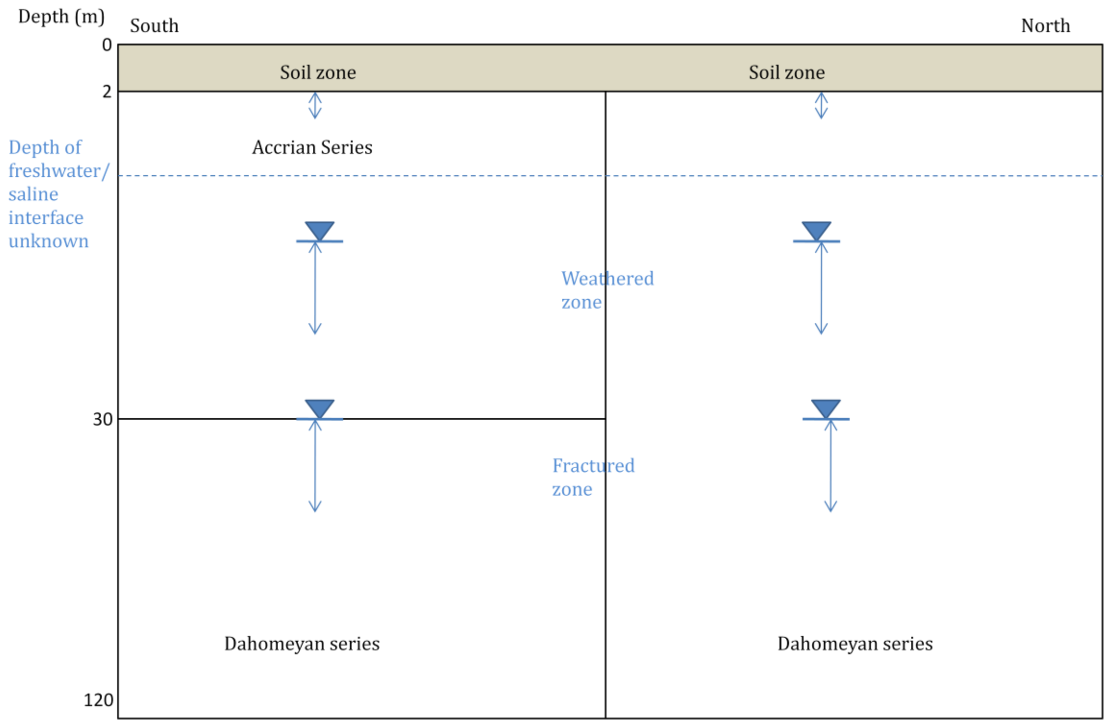



**Figure 4.10 Conceptual diagram of groundwater system in Accra.**

The conceptual model in Figure 4.10 shows that both aquifers, the shallow weathered zone and the deeper fractured zone, contain saline water as a result of saline intrusion (Kortatsi & Jorgensen 2001). The depth of the freshwater/saline interface is also unknown, but estimated to be between the soil zone and the top of the weathered aquifer. There is freshwater entering the soil zone from recharge. The model does not allow the salinity of the water to be considered as CWB models freshwater only. The current version of the model can only

model one aquifer, and so the aquifer properties must remain homogeneous with depth but may vary laterally. The grid resolution of 16 by 16 cells was used in the model, along with the change in hydrogeology is shown in Figure 4.11. The blue area shows the Accrian formation, and the pink area shows the Dahomeyan formation.

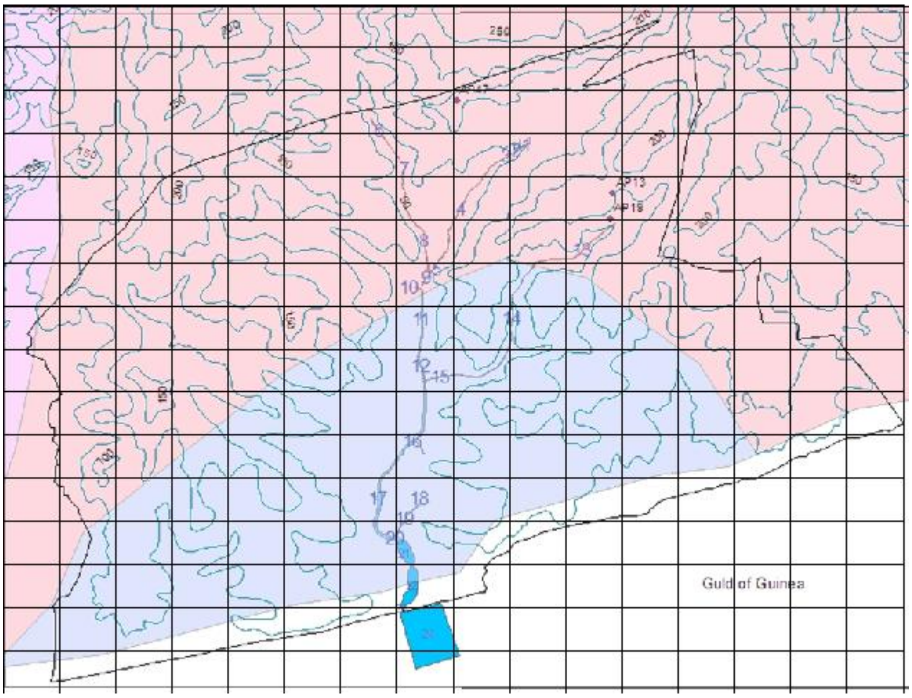



**Figure 4.11 Map of grid resolution used in model.**

### 4.5.6. Water management options

Several water management options were implemented in the initial model run. These options were used with the information that was available, but assumptions to be made when using each one. The different options are shown in Figure 4.12.

| Water Management Option | Description | Data source |
|---|---|---|
| UB rainwater tank | Rainwater tanks used in domestic and commercial buildings for water storage. | Polytank 2010 |
| UB septic tank | Septic tanks used in 70% of domestic housing in areas without municipal sewers. | Polytank 2010 |
| UB porous pavements | All miniclusters with paving assumed to have porous pavements. | Last 2010 |
| MC porous roads | All miniclusters assumed to have porous roads. | Last 2010 |

**Figure 4.12 List of water management options implemented.**

Only a few water management options were activated in the model due to a lack of data. Most domestic households and commercial properties in Accra have a small rainwater tank for either rainwater harvesting or storing water for when there is no mains connection. The water tank sizes available from Polytank (2010) were variable so an average 'small' and average 'large' tank sizes were used. According to the Texas Development Water Board (2005), the first flush can be calculated as 1 to 2 gallons for every 100 square feet of roof area. For a small and large household, with a small or large tank respectively, the first flush volumes were calculated at 194 litres and 908 litres (see 'Model Inputs' in Appendix 1 for calculation).The other SUDS options that were available in the CWB model were deactivated.

### 4.5.7 Other options

The leakage correction factor was constant at 1 because no information was available. The percentage of demand being covered by water mains is 55% (AVRL 2010), but was modelled as 100% to include water use in households without a mains connection.

The ‘Occupancy’ input file was not activated, as there was no evidence for large change in water consumption on a unit block scale for any particular month.

For the minicluster defaults, the surface run-off proportion was 0.6 (Nyaro 2002) and the sewer exfiltration proportion was estimated at 0.59 based on leakage data (Adank et al. 2010). However this latter proportion could be much higher.

The contaminant flow options were not used, as there were no contaminant data available for surface water, groundwater or rainfall levels.

# 5. FUTURE SCENARIOS AND PROPOSED STRATEGIES

## 5.1 Introduction

The first model run will be calibrated with the independent data available to produce a baseline model. This model will represent the current water situation in the Accra Metropolitan Area and will be referred to as the 'Baseline' model throughout. Any other model runs after this will have different or altered model inputs to model either future scenarios, or to model different water management options.

## 5.2 Future scenarios

Three different scenarios have been developed by the SWITCH project to consider the effects that population and economic growth may have on water resources in Accra in 2030. Worst, medium and best-case scenarios have been considered. These have been combined with model results from the IPCC Climate Change report (2003), which discusses the possible changes in precipitation, potential evaporation and potential runoff as a result of climate change. As an example, the worst case scenario considers how the greatest change in population (400%) might affect water resources with no change in precipitation, a 4% change in potential evaporation with no change in runoff. These three scenarios are described in Figure 5.1.

| Scenario | Population change (%) | Precipitation change (%) | Potential Evaporation (%) | Runoff change (%) |
|---|---|---|---|---|
| 1 - Worst | 400 | 0 | 4 | 0 |
| 2 - Medium | 300 | 0 | 0 | -7.5 |
| 3 - Best | 220 | 0 | -5 | -15 |

**Figure 5.1 Predicted changes for the Volta region as a result of climate change (adapted from IPCC 2003).**

The three scenarios may also be run with changes in precipitation because although no changes are predicted, it is beneficial to see the effects of reduced or increased precipitation which may lead to drought or flooding. On a daily time step, Accra is prone to very heavy rain and this would allow examination of the effects of flooding in the urban landscape.

### 5.3 Water management strategies

A number of water management options can be implemented within CWB to demonstrate different ways water can be stored and re-used within cities. A number of realistic water management options in terms of cost, space and maintenance will be implemented. Each water management option, for example, UB Raintanks will be the subject of each different run to demonstrate ways to re-use and retain water on the unit block and subcatchment scale.

The following options will be explored:

| **Water Management Option** | **New changes** |
|---|---|
| UB Rainwater Tank | Use of a larger tank at Unit Block scale to reduce the imported water demand. |
| UB WW recycling | Use of wastewater recycling from Uses 2-4 for Use 1 on unit block scale (UB Septic tank deactivated). |
| UB Swales | Installation of swales at the UB scale modelled in a residential minicluster. Default values from original model used. |
| MC scale SW treatment | Use of stormwater harvesting at the MC scale. Re-use of water from unit block and return for Use 1. |
| MC scale WW treatment | Use of WW recycling at the MC scale. Treatment of wastewater for re-use in Use 1. |

**Figure 5.2 The water management option changes to be tested.**

Although there are several water management options that can be tested using CWB, only the five above can be tested due to the time constraints of this project. Most of the water management options tested are the more traditional water harvesting and water treatment options. These have been chosen because these are the more basic and cost effective improvements are more likely to be sustainable in Accra on a long term, and some of the other options available are more area specific. The model designed aims to look at Accra on a larger scale and not at any specific area. However, one area has been looked at in particular to demonstrate the use of UB swales.

## 6. RESULTS

### 6.1 Introduction

When CWB is run successfully, it produces a number of output files that include:

a) A water flow diagram with quantified flows labelled within the system

b) Several graphs that display a mass balance, showing volume of water inputs and outputs for different areas and at different scales.

For these results, the water flow diagrams and total water balance graphs will be displayed in the appendices. It should be noted throughout the result and discussions that the results given are not accurate to the figures they are presented, as the data sets used will vary to different degrees of accuracy. The results should be considered approximate to the nearest million $m^3$/day and the numbers given are purely the results that the model has produced.

### 6.2 Model calibration

The purpose of model calibration is to adjust the parameters present within the model to produce a set of results that demonstrate the most realistic scenario. The model was calibrated to an independent set of data that was not used to develop the model. The only independent data that was available was the volume of imported water to the AMA before and after leakage. This was taken from the RIDA report with the data based on reports from AVRL 2007. The values from AVRL and from the calibrated model are shown in Figure 6.1.

| Source | Imported water ($m^3$/yr) | Leakage /loss (%) | Leakage volume ($m^3$/yr) | Volume water consumed ($m^3$/yr) | Error (%) |
|---|---|---|---|---|---|
| RIDA Analysis (AVRL) | 71,303,049 | 59 | 42,068,799 | 29,234,250 | 1.01 |
| Before calibration | 88,989,573 | 59 | 52,546,224 | 36,443,348 | |
| After calibration | 72,039,178 | 59 | 42,481,927 | 29,557,251 | |

**Figure 6.1 Calibration values for model (Adank et al 2010).**

The calibration was obtained by changing the leakage proportion in the Minicluster_default.txt file and by decreasing the water consumption in Uses 1-4 in the UB_additional.txt file by 10%. The values of water flow from the output file, given in metres (volume per unit area), were multiplied by the area covered in the model to give a flow for the year. As there was no groundwater level data available, wastewater flows or river/lake flows, the other parameters in the model were estimated and checked against previous examples.

## 6.3 Baseline model results

### 6.3.1 Water Flow in Accra

The results for the initial model run after calibration is shown in Figure 6.2 and Figure 6.3.

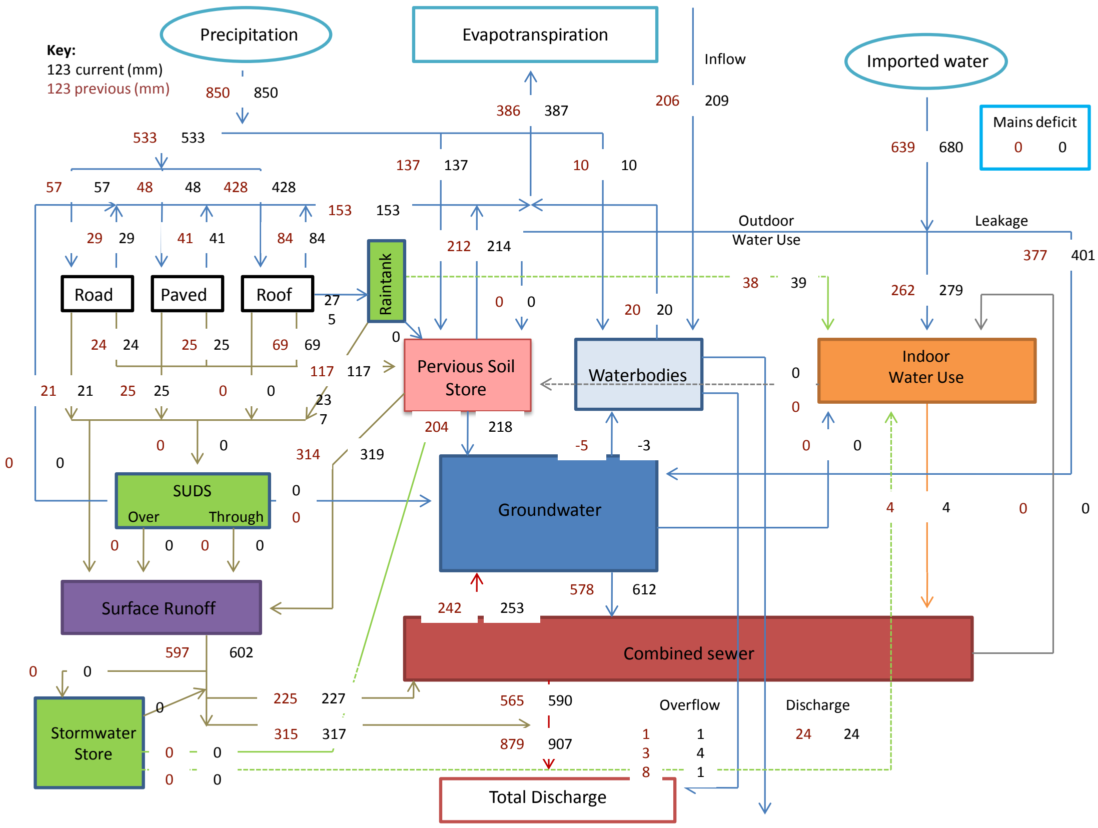



**Figure 6.2 Flow diagram of water in Accra. Previous run results are shown in red.**

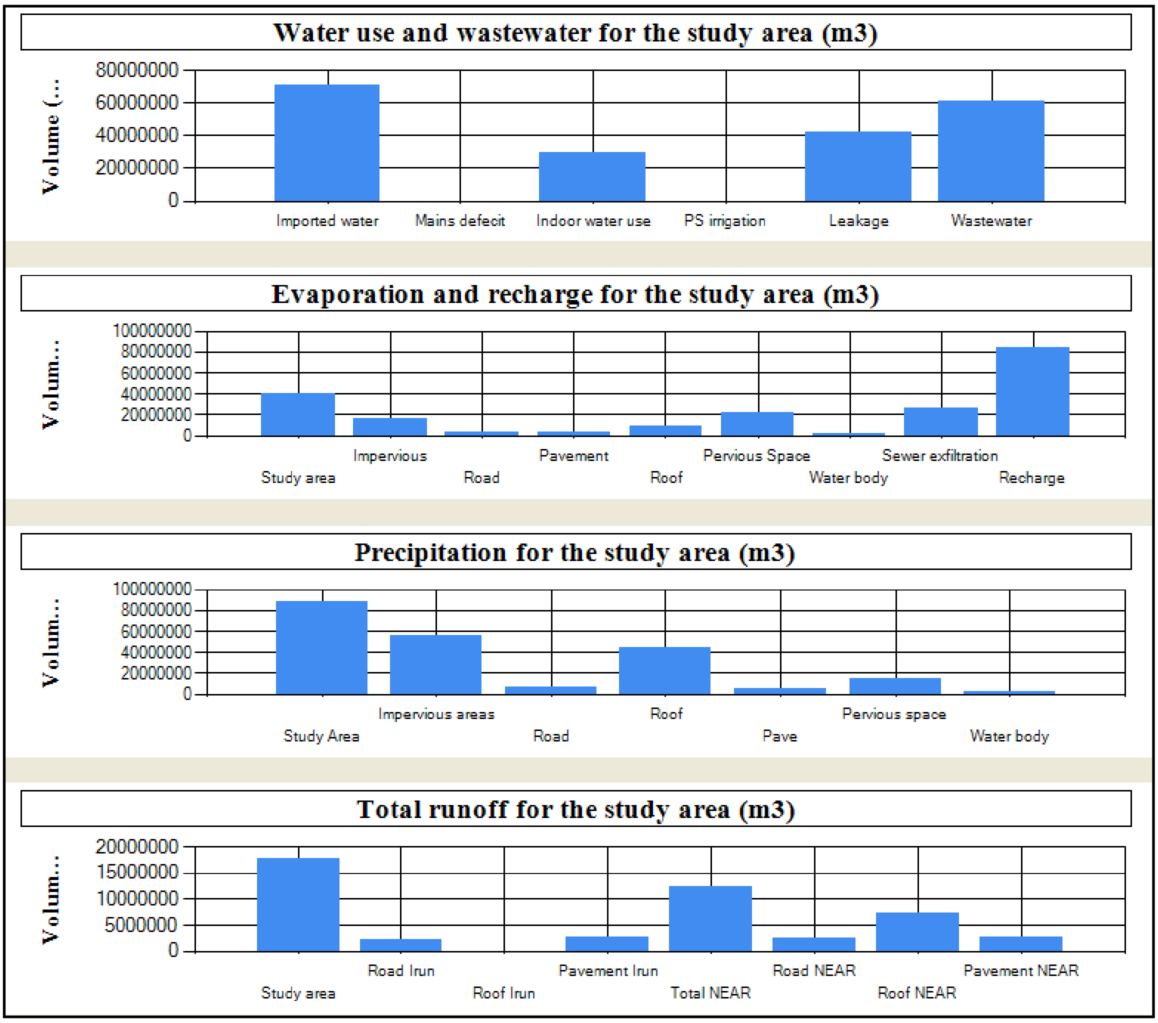



**Figure 6.3 Breakdown of water consumption in Accra.**

Figure 6.2 shows the volume of water per unit area that flows within the model, and Figure 6.3 shows the breakdown of water mass balance for the whole area. The study area receives 88,764,970m$^3$/yr in precipitation, and 71,040,273m$^3$/yr in imported water. 29,126,512m$^3$/yr is consumed at the unit block level, with 41,913,761m$^3$/yr being leaked and entering the groundwater system. The area produces 61,620,416m$^3$/yr in wastewater. There is a high level of runoff at 62,822,847m$^3$/yr.

There are parts of the model that show no movement of water (Figure 6.2) and these are marked with a 0. This is shown in the SUDS and stormwater parts of the model that were not

in use. The precipitation in the model shown in Figure 6.3 falls mostly on impervious areas, with 111,381,521 m$^3$/yr falling on impervious, roof, road and paved areas, with 15,354,481 m$^3$/yr falling on pervious areas, rivers and lakes.

### 6.3.2 Groundwater level results

The groundwater depths for the area after one year are shown in Figure 6.4. The diagram shows that the depth to groundwater varies, with an average level 2.61 mbgl (metres below ground level). The depth of the water increases as the height of the ground level increases, with the lower lying areas of Accra featuring higher levels of groundwater.

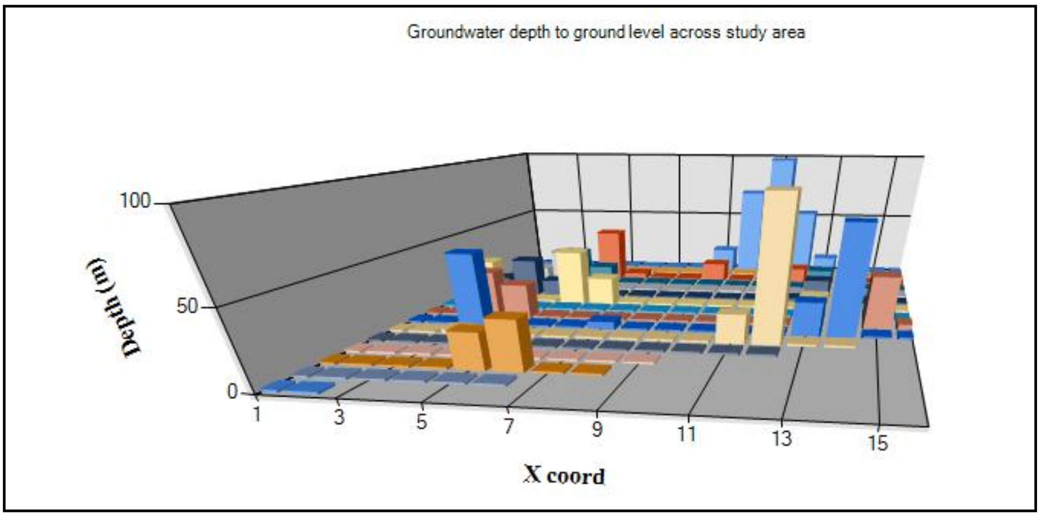



**Figure 6.4 Depth to groundwater level in initial model run.**

Results for individual miniclusters were not carried out within the results because they did not represent the minicluster spatially or accurately at that scale. The model in this study aimed only to look at the large scale changes in water movement in Accra.

### 6.4 Population and climate change scenarios

The population and climate change scenarios described in Chapter 5.1 have been run in the CWB model. The results are shown in Figure 6.5 and Figure 6.6, and water flow diagrams and water balance graphs can be found in Appendix 6.

| | **Baseline 2007** | **Scenario 1 (worst)** | **Scenario 2 (medium)** | **Scenario 3 (best)** |
|---|---|---|---|---|
| **Imported water ($m^3$/yr)** | 71,040,273 | 311,196,824 | 230,706,458 | 166,494,508 |
| **Consumed water ($m^3$/yr)** | 29,126,512 | 127,590,698 | 94,589,647 | 68,262,748 |
| **Total wastewater ($m^3$/yr)** | 61,620,416 | 254,219,020 | 189,409,480 | 135,260,044 |
| **Average groundwater level (mbgl)** | 2.61 | 2.14 | 2.38 | 2.51 |

**Figure 6.5 Results from different predicted future population and climate scenarios.**


**Figure 6.6 Groundwater level changes with predicated population changes.**

The three scenarios which were run showed an increase in imported water demand and wastewater production that was proportional to the population increase. The groundwater

depth decreases as a result of the population increase and water demand. This is shown in Figure 6.6. These results will be discussed in Chapter 7.

## 6.5 Water management options in Accra

### 6.5.1. Unit Block Rainwater and Wastewater tanks

A number of water management options were suggested in Chapter 5.3 that might be suitable for use in the Accra area at the UB scale. These results are displayed in Figure 6.7, and the water flow diagrams and mass balance graphs in Appendix 7.

| | **Imported water ($m^3$/yr)** | **Consumed water ($m^3$/yr)** | **Total WW ($m^3$/yr)** | **Average GW level (m)** | **Total water saved ($m^3$/yr)** |
|---|---|---|---|---|---|
| **Baseline** | 71,040,273 | 29,126,512 | 61,620,416 | 2.61 | - |
| **UB Raintank** | 53,699,670 | 22,016,864 | 53,160,556 | 2.89 | 17,340,603 |
| **UB WW** | 62,124,766 | 25,471,154 | 68,086,958 | 2.93 | 8,915,507 |

**Figure 6.7 Results from the water management options implemented into the baseline model.**

Each water management scenario has been applied for each minicluster in the study area. The results show that using a larger raintank on a household level has reduced the water demand by 17,340,603 $m^3$/yr. In comparison, implementing wastewater tanks on a UB scale only reduces the water demand within the area by 8,915,507 $m^3$/yr. Implementing both the large rain tank and waste water tank separately on a UB scale has also increased the depth to groundwater level in the model.

### 6.5.2. Unit Block Swales option

The results for implementing small infiltration swales in one minicluster, MC 34, which is a residential area, are shown in comparison to the same minicluster without swales installed. The results are shown in Figure 6.8, Figure 6.9 and Appendix 7.

| Minicluster 34 | Stormwater Runoff ($m^3$/yr) | Wastewater from minicluster ($m^3$/yr) | Minicluster evaporation ($m^3$/yr) |
|---|---|---|---|
| **With Small retention swales** | 755,021 | 4,809,945 | 2,341,875 |
| **Without swales** | 1,084,016 | 5,058,907 | 2,229,193 |
| **Change in water volume** | 328,995 | 248,962 | -112,682 |

**Figure 6.8 Results from MC 34 with Swales**

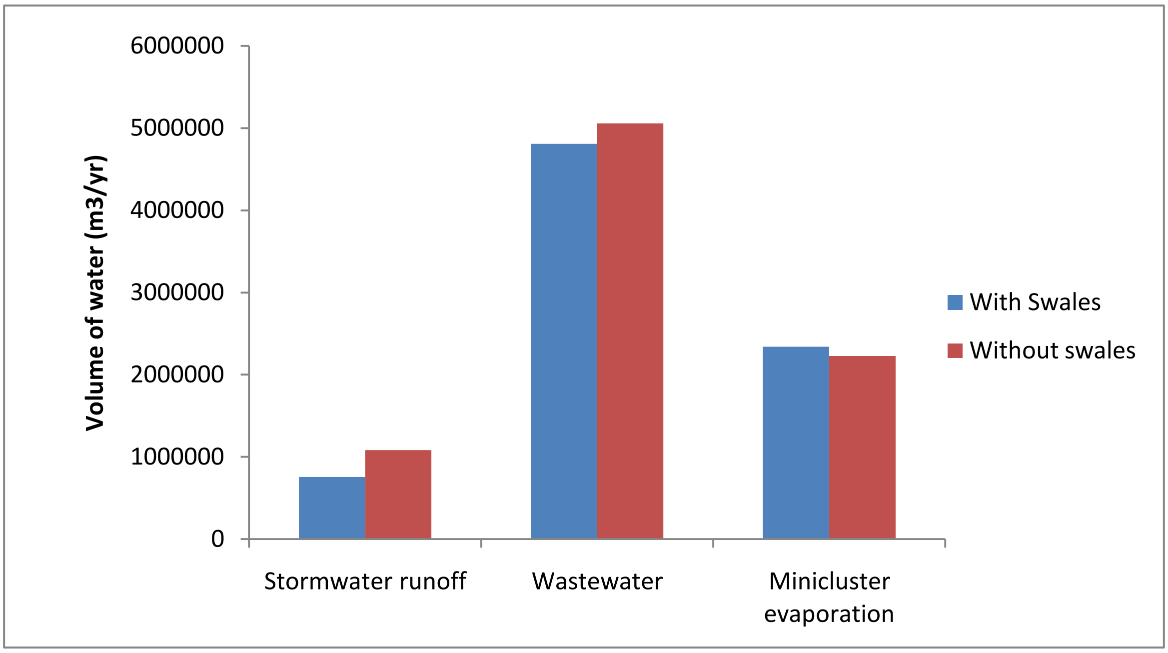



**Figure 6.9 Comparison of water flow in Minicluster 34 with and without swales.**

The results show that at the minicluster level, there is a change in the volume of water flow within the MC. When swales are present, the volume of stormwater run-off over the year is reduced by 328,995 $m^3$/yr. The level of wastewater leaving the cluster decreases by 5.8% to

4,809,945 $m^3$/yr when swales are present. The volume of water evaporated from the MC increase by 9.1% to 2,341,875 $m^3$/yr as a result of swales installed at this scale.

### 6.5.3 Minicluster scale Water Management Options

MC scale SW recycling and WW recycling water management options were implemented to demonstrate the effect of water recycling at the MC scale. The results in Figure 6.10 show the changes in MC 34, a residential area, as a result of using MC Stormwater and Wastewater tanks.

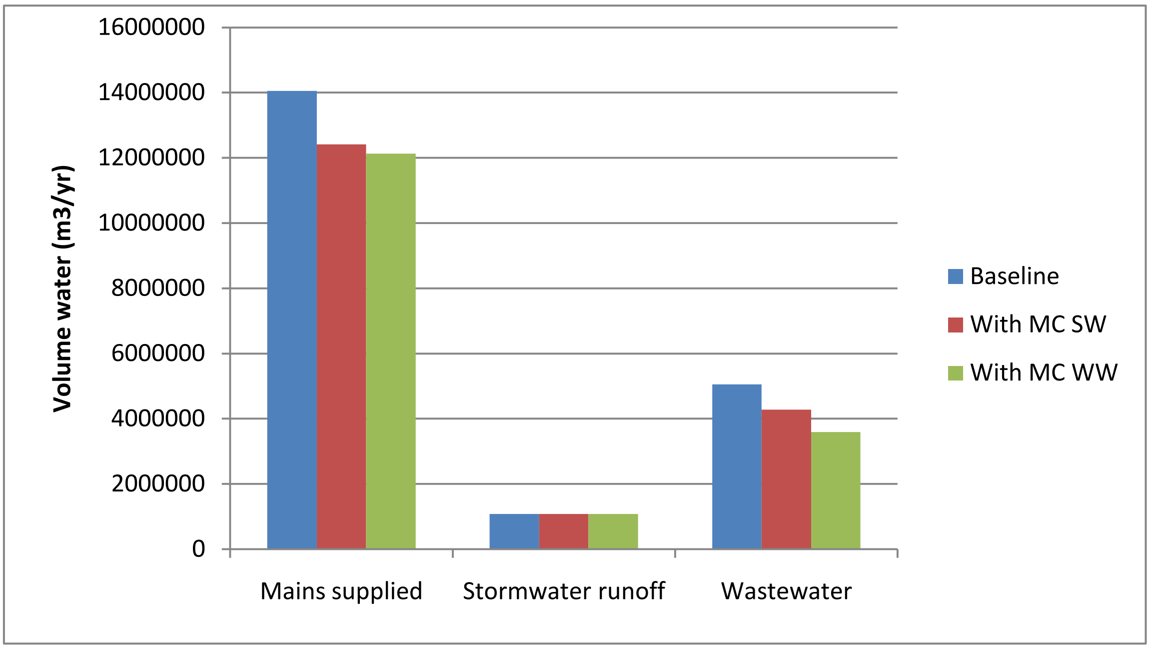



**Figure 6.10 Graph showing the results of MC scale Stormwater and Wastewater tanks in MC 34.**

| | Mains supplied ($m^3$/yr) | Stormwater runoff ($m^3$/yr) | Wastewater ($m^3$/yr) |
|---|---|---|---|
| **Baseline** | 14,053,605 | 1,084,016 | 5,058,907 |
| **With MC SW** | 12,413,427 | 1,084,643 | 4,283,378 |
| **With MC WW** | 12,125,868 | 1,084,643 | 3,588,260 |

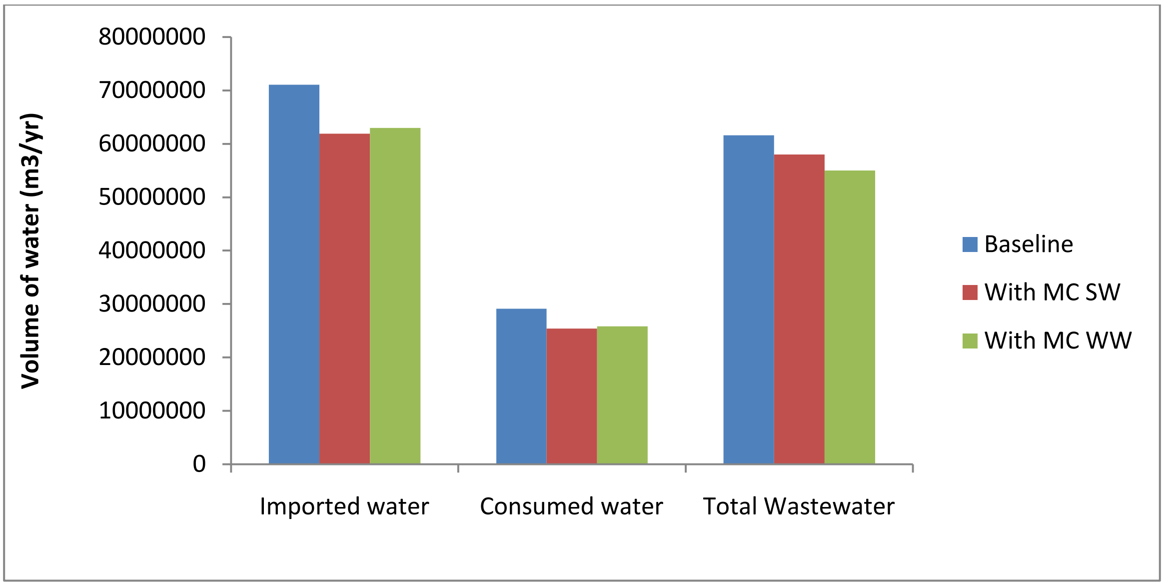
**Figure 6.11 Results of implementing MC scale Stormwater and Wastewater tanks in MC 34.**

Figure 6.11 shows that the mains demand in MC 34 decreased by 11.6 % to 12,413,427 $m^3$/yr as a result of using MC SW recycling, and the demand decreased by 13.1% to12,125,868 $m^3$/yr as a result of using MC WW recycling. The stormwater runoff does not change as a result of the implication of MC scale water management options.

The wastewater produced at the MC level is also reduced as a result of MC SW and WW re-use. There is an 8.9% decrease in wastewater produced as a result of MC SW re-use to 4,283,378 $m^3$/yr. There is a decrease of 29 % in WW production as a result of MC WW recycling, with 3,588,260 $m^3$/yr leaving the MC.

### 6.5.3 Minicluster Stormwater Water and Wastewater in the AMA

The results in Figure 6.12 show a decrease in imported water, consumed water and wastewater as a result of MC SW and WW options being implemented separately.




| | Imported water ($m^3$/yr) | Consumed water ($m^3$/yr) | Total Wastewater ($m^3$/yr) |
|---|---|---|---|
| **Baseline** | 71,040,273 | 29126,512 | 61,623,678 |
| **With MC SW** | 61,912,252 | 25,384,023 | 58,017,197 |
| **With MC WW** | 62,945,125 | 25,807,501 | 55,002,272 |

**Figure 6.12 Results of implementing MC scale Stormwater and Wastewater tanks in AMA.**

When the MC SW option was implemented, there was a reduction of both imported water and consumed water by 12%, with 61,912,252 $m^3$/yr of imported water and 25,384,023 $m^3$/yr of consumed water. The total wastewater produced was reduced by 6% to 58,017,197 $m^3$/yr.

Implementing the MC WW option showed a 13% decrease in the total imported water to 62,945,125 $m^3$/yr and a 13 % in consumed water to 25,807,501 $m^3$/yr. The total wastewater fell by 11 % to 55,002,272 $m^3$/yr.

### 6.5.4. Water Management options with precipitation change

Two UB water management options have been tested in scenarios with an increase of 10% precipitation and a decrease of 10% precipitation. These are displayed in Figures 6.13 and Appendix 8.

| | Imported water ($m^3$/yr) | Consumed water ($m^3$/yr) | Total Wastewater ($m^3$/yr) | Total run-off ($m^3$/yr) |
|---|---|---|---|---|
| **Baseline** | 71,040,273 | 29,126,512 | 61,623,678 | 62,823,723 |
| **10% decrease in rainfall** | 50,819,940 | 20,836,175 | 60,898,488 | 49,588,606 |
| **10% increase in rainfall** | 49,078,220 | 20,122,070 | 65,977,138 | 57,419,850 |

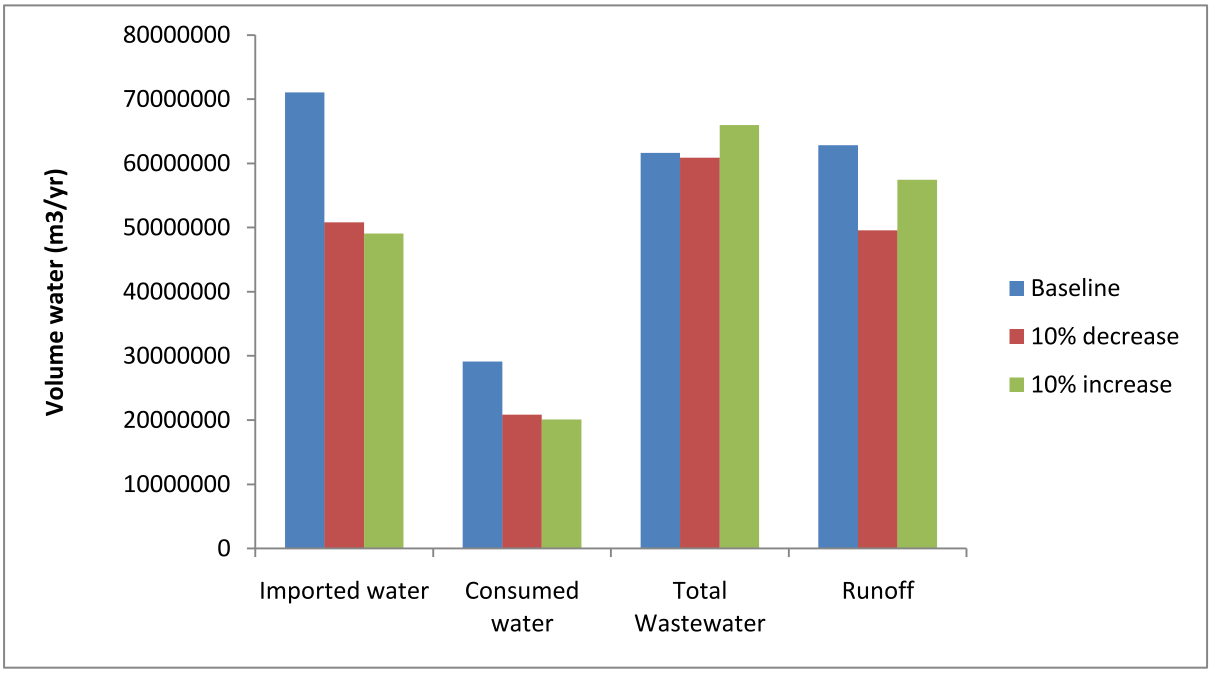



**Figure 6.13 Results from scenarios with 10% increase and decrease in precipitation.**

With a 10% decrease in precipitation, the imported water and consumed water volumes both decreased by 28% to 50,819,940 $m^3$/yr and 20,836,175 $m^3$/yr respectively. The total wastewater discharged decreased by just 1% to 60,898,488 $m^3$/yr and the run-off decreased by 21% to 49,588,606 $m^3$/yr.

With a 10% increase in precipitation, the imported water and consumed water volumes both decreased by 30% to 49,078,220 $m^3$/yr and 20,122,070 $m^3$/yr respectively. The total wastewater discharged increased by 7% to 65,977,138 $m^3$/yr and the run-off decreased by 8% to 57,419,850 $m^3$/yr.

The depth to groundwater also decreases in both scenarios. With a 10% decrease in rainfall, the groundwater level falls to 3.04 m but with an increase in rainfall this decreases to 2.95 m.

### 6.6 Aquifer grid resolution

The baseline model was run with two different aquifer grid resolutions to observe the effects of increasing the grid resolution. The results from running the baseline model with a 8 x 8 grid and a 16 x 16 size grid are displayed in Figure 6.14. The model shows an increase of 20% for the imported water volume, consumed water and total wastewater. There was a decrease of 5% in the total run-off volume.

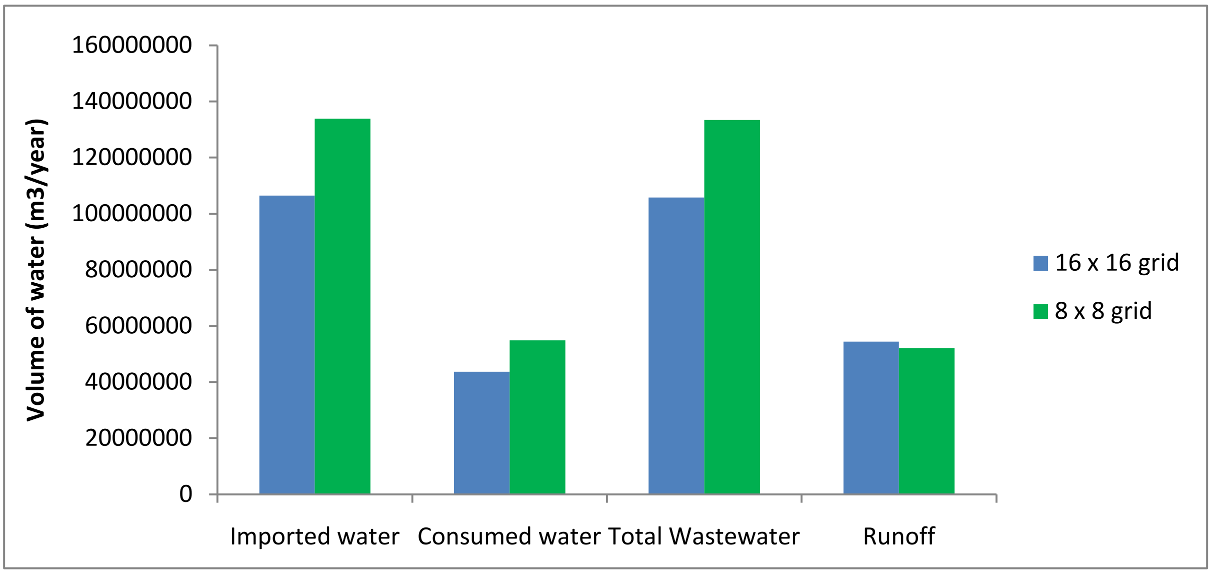



**Figure 6.14 The effects of using different aquifer grid resolutions.**

## 7. DISCUSSION

### 7.1 Model calibration

The baseline model was successfully calibrated for only one area of the water system, which was for the imported water volume both before and after leakage. The calibration was not carried out on the rest of the system because of a lack of data.

During calibration of the imported water volume, the initial volume was higher than the volume consumed at the UB scale. These initial water demand figures for water use at this level were calculated from recent AVRL reports for each of the areas in the model (see AVRL report Appendix 3). There are several reasons why there might be a difference in water demand between the original calculations and the model results:

1. The area covered in the model is smaller than the area of the six AVRL districts covered, which may lead to small inaccuracies in consumption rates per unit area.

2. Only 55% of AMA has mains supply, but in the model this was kept as 100% so houses with a different type of water supply, such as tanker service, could be modelled in terms of water consumption and output. The tanker and standpipe water will originate from the same source of imported water but take different ‘routes’ to a household so it will affect the leakage volume. There are illegal mains connections in Accra that are also unaccounted for.

3. There is a small area of Accra covered by waterbodies that will have no water consumption and may lead to a small error in initial water consumption calculations.

Calibration for the water demand was successful after this change.

## 7.2 Baseline results

### 7.2.1 Water consumption

The baseline model result represents the current water management situation in Accra. Figure 6.3 shows at the household level, there is only a small proportion of water entering the combined sewers from ‘Indoor Use’. This is because many houses are connected to a septic tank which processes the wastewater and only a small area of Accra is connected to the sewer network for grey and black water disposal.

### 7.2.2 Natural systems

The flow between the groundwater and the water bodies is relatively small, suggesting that the Odaw River and the Korle Lagoon are losing water to the groundwater, particularly after heavy rainfall. The discharge of water from the model results from surface runoff, overflow, waterbody discharge and from the combined sewers. The output from the river will be much higher than the input as all of the groundwater in CWB will only flow towards the lakes and rivers, and the sea is represented in this model by the final lake. This means the water leaving the model area is much smaller. The overflow from flooding is much higher than anticipated. This is likely to result from flooding in heavy rain periods as a result of very shallow groundwater levels.

There is more evaporation occurring in the impervious areas as more of Accra has impervious cover when, compared with grass and public open space, as the water will infiltrate through the material at a much slower rate. The evaporation levels will slightly overestimate the real level of evaporation that occurs, as it is the potential evaporation levels that have been used within the model.

The precipitation results are more likely to be significant when contrasting the results between the dry and wet seasons, rather than for the whole year. This is because the groundwater levels are more likely to vary as a result of heavy rainfall.

### 7.2.3 Groundwater

The groundwater levels are much higher at 2.61 mbgl than the initial 5 mbgl value at the start, with the main inputs from the mains supply leakage. There are illegal connections to the mains pipeline in Accra, which may result in a lower return between produced and sold water meaning that leakage is over-estimated in the model. The initial estimate of an average 5mbgl for the groundwater depth is an over-estimate and the depth to groundwater, particularly in low lying flood prone areas will be much smaller. The other main inputs to the groundwater are from recharge through the soil layer, and a similar proportion from the combined sewer. The latter will lose water to the groundwater aquifer when the water levels are relatively low.

Alternatively, the movement from the groundwater to the combined sewer occurs because of high groundwater levels, particularly after rainfall, and from leakage. However, in drier periods the groundwater level falls below the level of the sewers and gives rise for sewer exfiltration into the groundwater.

There is also no grey-water recycling demonstrated within the baseline model as the UB_GreyIrrigate.txt file is not activated within the current CWB version. However, in Accra grey water recycling is carried out manually rather than using a tank and there is not an appropriate way to represent this. The baseline model quantifies where water in the system can be utilised and recycled for households to use. The potential sources are from reducing leakage and intercepting surface and building run-off.

## 7.3 Population and climate change scenarios

The set of future scenarios for predicted population increases and climate change shows different levels of increase in population, and a proportional increase in water demand with each scenario. These results are important for those who need to plan future water demand, such as AVRL and the planning authorities. The results for each scenario are discussed as follows.

### 7.3.1 Worst Case Scenario

Currently, the volume of water imported from the Kpong and Weija systems is 363,513 $m^3$/d and only 148,180 $m^3$/d is being sold. The two systems combined are designed to process a capacity of 424,134 $m^3$/d. The worst-case scenario for a 400% population increase indicates a demand of 852,594 $m^3$/d or 311,196,824 $m^3$/yr. This means that in the worst-case scenario, even after with carrying out improvements on the existing pipeline and water systems, only half of this demand could be satisfied. It is clear that in this scenario, major changes in terms of water recycling and re-use at both a household and a subcatchment level would have to happen.

The effects of a potential evaporation increase in this scenario are not clear. Importing a much higher proportion of water into the system has resulted in an increase of water in the groundwater and sewer system, therefore decreasing the evaporation levels.

The water flow diagram shows that there is a very high level of water flowing in and out of the groundwater system from the large volume of leakage from mains and large surface runoff. The waterbodies in this scenario are gaining water from the groundwater and results in an unrealistically high level of overflow. The high groundwater level results in groundwater entering both the combined sewer system and waterbodies. As a result, the sewer system is transporting much larger water volumes.

### 7.3.2 Medium Case scenario

The medium case scenario shows that with a 300% population change, the water demand of 230,706,458 $m^3$/yr. This is still much higher than the capacity of water that can currently be imported. The scenario predicted displays the same relationships seen in the 'Worst Case' scenario, but with reduced water volumes and the groundwater level reduced. The water volume passing through the system is likely to be much more than the present sewer and groundwater system can cope with, as there is a large overflow and surface run-off occurring. The effect of the decrease in run-off predicted by the IPCC has reduced the input of water into the combined sewer system in comparison with the Worst Case Scenario.

### 7.3.3 Best case scenario

The best-case scenario shows that with a 220% population change the water demand of 166,494,508 $m^3$/yr is at a similar level to the design capacity of the Kpong and Weija systems. This scenario highlights the need for an improved water system in Accra to cope with the smallest predicted population increase. There is a much smaller volume of groundwater entering the waterbodies and in this scenario, the flow is from the combined sewers to the groundwater. This suggests that the groundwater level rarely reaches a relatively shallow level. Overflow, discharge and surface runoff have also decreased as the leakage has decreased. The decrease in potential evaporation has no effect on the results in this run.

All of these scenarios show that in 2030 Accra will need to significantly increase its water production to supply the rapidly increasing population. These scenarios also highlight the importance of reducing the leakage from the mains going into the groundwater system and the consequences on groundwater levels and discharge.

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### 7.3.4 Problems with future population and climate change scenarios

There are several problems and assumptions underlying the future scenarios that were developed. The first assumption made was that the increase in population would occur in the area that was modelled. The population increase was applied at the Unit Block level in Uses 1-4, so it could represent the overall increase in demand for the area. However on a household level this may not be true. Population growth seems most likely to occur in the outskirts of Accra in less populated areas. Also, there are some areas in Accra such as the high-income areas that are less likely to become overpopulated. Despite these issues, this appeared the most reliable way to represent this change, as there are very few areas of undeveloped land and public open space where this increase in population could be represented.

Another assumption that was made was for any particular scenario was that the population change had a certain climate change scenario associated with it. For example, the worst-case scenario in terms of population was paired with the worst-case scenario in terms of climate change. This might not necessarily be the case and a number of different combinations were possible. However, due to time constraints only a small number of scenarios were run so the scenarios represent what might happen given a set of future conditions.

## 7.4 Water management option scenarios

### 7.4.1 Unit Block Rainwater and Wastewater tanks

The UB Raintank and WW tanks were tested separately to show the cumulative effect of implementing these water management options in each UB over the whole area. The large UB rainwater tank saved twice the volume of water compared to the UB Wastewater tank.

However, these large rainwater tanks may not be practical to implement in a crowded residential area in terms of space and cost. The UB Wastewater tank is likely to cost more to implement but still reduces wastewater and imported water. Both are viewed as possible water saving options at the UB level.

### 7.4.2 Unit Block Swales

The UB swales option was tested on an individual minicluster, as it is more expensive and realistically would not be implemented in many areas. However it might be important in areas prone to flooding. This scenario demonstrated that the swales could reduce the run-off in the area by 30%.

### 7.4.3 Minicluster scale Stormwater and Wastewater Options

The MC scale Stormwater and Wastewater management options within MC 34 showed the expected decrease in the imported water and total wastewater but no effect on stormwater. The stormwater run-off values would be expected to change as this is the aim of the MC SW option.

The MC Stormwater and Wastewater management options on the whole area show that the imported water and stormwater runoff is reduced the most using the MC SW option. Wastewater volumes are reduced further by implementing the MC Wastewater option.

## 7.5 Problems with scenarios

There were several problems in developing future scenarios in terms of implementing different water management options. At the UB scale, rain tanks are frequently used for water storage from the mains supply for when houses are not connected, and more frequently in the wet season for rainwater harvesting. CWB does not have the ability to use the UB Rainwater

tank in this way and highlights the importance of people obtaining water in the most simple way and will be a more common practise in developing countries.

Another assumption made when implementing UB scale water management options is that all types of housing can afford to run these options and that they have the space to install them. In reality, it may only be in high income, low density areas that are able to afford these options in the near future. The results may vary due to the mixed type of Unit Blocks used in this model, an average size of house, roof area etc was used. These scenarios have mainly focused on water management options and less on SUDS as less information was available to implement these options. It is also more likely that more basic water recycling methods such as rain water harvesting will be more successful as they are cost effective, effective and easy to implement in a variety of different socio-economic areas.

### 7.6 Precipitation Scenarios

The precipitation scenarios tested with a 10% increase and 10% decrease in rainfall both show a decrease in imported water and consumed water volume. This implies that during an increase in rainfall, more water is likely to be obtained from household rain tanks and less from the imported water source. When there is a decrease in rainfall however, the level of water imported also decreases. The increase in runoff with increased precipitation is expected, as more rainfall will lead to a higher level of run-off, with the opposite for a decrease in precipitation also occurring. The smaller changes seen in wastewater volumes occur because the household level wastewater production should not change much as a result of a change in precipitation.

### 7.7 Aquifer grid resolution

It was observed that using a different grid resolution for the hydrogeological data in the Aquifer.csv file produced a different set of baseline results. . The results show that using a coarse grid size within the model calculates a larger volume of water passing through each section of the model, for the imported, consumed water and total wastewater. The run-off volume has decreased as a result of using a coarse grid resolution.

This 20% increase in water volume was significant and highlighted the importance choice of grid resolution for the model. This difference is likely to occur as a result of the calculations used within the model for groundwater heights at the centre of each cell. Having a coarse grid resolution, or decreasing the number of cells representing the groundwater system, is likely to create a bigger inaccuracy in the groundwater as a result of extrapolating groundwater data over a larger distance between two known measurements. These errors are common because of the way methods used to model groundwater within the code. Although the groundwater data gathered for the model was not accurate because of small and infrequent readings measured for groundwater data, it is still important to highlight this change in results as it had a strong effect on the results produced.

### 7.8 Problems faced when developing the model

There were several problems faced when developing the model

- **Lack of data** – There was a lack of data available in Accra for many parts of the model. This included geochemical data, accurate hydrogeological data, water levels and water flow rates, occupancy data, infiltration rates and soil data. The missing data was filled in using literature values and specifications from the original Birmingham

CWB model. This model has been constructed in the most appropriate way based on the limited data set, and can be continuously improved as new data becomes available. The lack of data available meant that only a small part of the model could be calibrated.

- **Current version of CWB** – The CWB package is consistently undergoing improvement as a result of testing the model in different cities. There are several changes that could be made to the Aquifer.csv file. The original version used is not able to model more than one aquifer. The properties of the aquifer in this model are heterogeneous and are more fractured higher up. The model also cannot take into account the salinity of the groundwater and this may affect groundwater level results.
- **Lack of building use data** - Due to the short time scale of the project and lack of quality spatial maps (as discussed in Chapter 4), it was not possible to identify the use of individual houses and buildings as many of them are of the same size and roof size. If time permitted then a more detailed field study could have been carried out to solve this problem. This was a drawback of the model created, as one of the main features of the model lies in it being able to map different building uses spatially. To ensure that the recharge to the groundwater was not estimated incorrectly in certain areas, an average for each AVRL district was taken. This meant that within the model, calculations carried out on a small scale for unit blocks and miniclusters may not be accurate. At a larger scale e.g. for a subcatchment the results are more accurate.
- **Leakage and Mains Deficit –** The Leakage and Mains deficit parts of the model do not accurately represent the situation in Accra in CWB. The leakage rate from imported water to Indoor Use is 59%, but not all of this is leaked into the groundwater system as there are frequent illegal connections that have not been accounted for. The mains deficit in the CWB model is designed to simulate drought and not just for a

proportion of the city that has no mains connection. Although only 55% of Accra has a mains connection, this was left at 100% within the model because this group of the population will collect water from tankers and standpipes originating from the same imported water source. This means that the correct value of imported water could be simulated but gives an overestimate of leakage.

- **Measuring areas using Google Earth** – The method used to measure paved, pervious and roof areas were all carried out using the 'Area measure' tool on Google Earth. It was noted that when hand-drawing the polygons of the area, the measurements given would often vary between very high and very low values. As a result the measurements cannot be considered to be that accurate.
- **Age of data** – the data sets that were collated were not all taken at the same time. Although the rainfall, climate and water usage data were all from 2007, some data sets such as groundwater level estimates were taken from up to 10 years before that. The groundwater levels will have changed since but these are the best estimates that were available.

These problems and assumptions need to be considered when using the CWB model results for making projections for future scenarios. They highlight the problems faced when taking a model that was designed for a developed city in one that is in a developing city. There are parts of the model that do not apply to cities like Accra and there is a need to develop the existing water management options so they are more applicable.

# 8. CONCLUSIONS AND RECOMMENDATIONS

## 8.1 Conclusion

The CWB model is able to model the water system in Accra well, considering the assumptions and limitations made when producing the model. The model demonstrates the success of water re-use and water recycling in implementing different water management options for present and future scenarios. It can also be used as a scoping model to assist planning authorities in Accra to develop strategies for providing sustainable urban water management in the city. The CWB model of Accra is accurately calibrated in terms of the imported water input in the model, but further calibration could improve the results generated. The lack of quality data is highlighted in this project is the major limitation in producing more reliable results.

The future population scenarios have successfully demonstrated that all of the different projected increases in population in 2030 will mean that the current source of imported water will not be able to cope with the population change of 220 to 400%. The 'worst case' population scenario shows only a third of the population would have mains water access. This would rise to 80% if the best case scenario occurred. This shows that the current water supply system needs to be improved dramatically to avoid a large percentage of the population not having access to safe drinking water.

However, the model is not able to successfully predict the effects of climatic changes on the system in terms of precipitation and evaporation changes, either because their negligible effects or an error within the CWB model. The effects of the increased population show the thickness of the aquifer increasing by 0.41m as a result of an increased leakage volume, which is one of the main inputs into the aquifer.

The different water management options have been implemented successfully to demonstrate how much water can be saved at the minicluster and subcatchment level in Accra. The results show that using large UB Rainwater tanks can reduce the volume of imported water by 24%, and by implementing UB Wastewater tanks for recycling wastewater the volume can be reduced by 12% on the large scale. Using swales at the minicluster level can reduce stormwater run-off by 30%, which can be implemented built up areas heavily affected by flooding. Using MC scale Stormwater and Wastewater options can reduce the imported water and wastewater volume by up to 11% and 13% respectively on the minicluster scale, and by 12% and 13% respectively on the large scale.

The CWB model can be applied to developing cities like Accra once simplifications and assumptions are made to make the model replicate the water systems in place. The main assumptions in this model are that the households in each area are all of the same size and type, and that socio-economic factors can be ignored when modelling Accra at the large scale. The role of the CWB model in creating scenarios is a useful tool in spatially quantifying losses and gains in the water system as a result of planned or expected changes. The future of Urban Water Management has developed from more basic models to more accurate, in depth models such as CWB, to be able to provide a more in-depth analysis.

## 8.2 Recommendations

There are several recommendations that can be made regarding future water management research and the CWB model for use in Accra. The production of the next version of CWB model will allow components of the aquifer to be modelled in further detail. This could allow groundwater levels to be predicted more accurately with further data. It would be recommended that further geological data from drilling logs may provide this information.

A sensitivity analysis on the CWB model that was not included into this project could also be carried out. This would allow a deeper understanding of the parameters that are more likely to affect water movement within the water cycle, and the implications that these changes have.

A number of further scenarios could also be modelled to combine future population scenarios with some of the water management options that have not been used. Combinations of strategies that have not been tested could also be carried out. These scenarios, with the other additional City Water packages that examine cost and energy consumption could also be tested.

As with any model, the future success of this model depends mainly on the quality of data that is used to build it. Its potential can be developed further by implementing field work and data collection in Accra as part of the SWITCH project. More meaningful results at a smaller scale than has been tested in previous models will increase CWB's applicability provided the resources and data are available.

## 9. REFERENCES


Adank, M., Bertha, D., Assan, D., van Roojen, D. 2010.Analysis of Water Resources, Infrastructure, Demand and Access (RIDA) to Urban Water Services in Accra. *SWITCH*.

Ghana Statistical Service. 2000. Ghana Population and Housing Census *(GPHC).*

Ghana Statistical Service. 2005. Analysis of district data and implications for planning: Greater Accra Region.

Intergovernmental Panel on Climate Change (IPCC). 2001. Climate Change 2001: Working Group II: Impacts, Adaptation and Vulnerability. Retrieved 2007, from http://www.grida.no/climate/ipcc_tar/wg2/383.htm#1021

Kortatsi, B.K. 1994. Groundwater Utilisation in Ghana.Future groundwater Resources at Risk (Proeceedings of the Helsinki Conference, June 1994).*IAHS* Publ. No. 222.

Kortatsi, B.K., & Jorgensen, N.O. 2001. The origin of high salinity waters in the Accra Plains Groundwaters. First conference on Saltwater Intrusion and Coastal Aquifers, Morocco.

Lamptey, F. 2010. Determination of Domestic Water Consumption patterns in Accra. *Kwame Nkrumah University of Science and Technology, Ghana*.

Last, E., Mackay, R. 2007. Developing a New Scoping Model for Urban Water Sustainability. *SWITCH and University of Birmingham, UK.*

Last, E. 2010. Model Concepts. *University of Birmingham*, unpublished.

Lekkas, D. F., Manoli, E. Assimacopoulds, D. 2008. Integrated urban water modelling using the Aquacycle model. *GlobalNEST*, **10**, no. 3, 310-319.

London Economics. 1999. Final Report Ghana Urban Water Sector, Willingness and ability to pay, Demand Assessment and Tariff Structure Study, Final Report, London.

Mitchell, V.G., Diaper, C., Gray, S., Rahilly, M. 2003. UVQ: Modelling the Movement of Water and Contaminants through the Total Urban Water Cycle. *28th International Hydrology and Water Resources Symposium, The Institute of Engineers,* Australia.

Mitchell, V.G., McMahon, T.A, Mein, R.G. 2003.Components of the Total Water Balance of an Urban Catchment.*Environmental Management*, **32**, 6, 735-746.

Mitchell, V.G., Diaper, C. 2005. UVQ User Manual Version 1.0.

Mitchell, V.G. 2005. Aquacycle- A daily urban water balance model. *Monash University* www.toolkit.net.au

Nyaro, B.K. 2002. Application of rational model in GIS for flood risk assessment in Accra, Ghana. *Journal of Spatial Hydrology*, **2**, 1.

Nyarko, B.K., Odai, S.N., Owusu, P.A., Quartey, E.K., 2008. Water Supply Coping Strategies in Accra.*33rd WEDC International Conference,* Accra, Ghana.

Obuobie, E., Keraita, B., Danso, G., Amoah, P., Cofie, O.O., Rashid, S.L., Drechsel, P. 2006. Irrigated Urban Vegetable Production n Ghana- Characteristics Benefits and Risks. *Chapter 6- Sanitation and Urban Wastewater Management.*

SWITCH. 2010. Accra Starter Kit.

SWITCH (b) 2010. SWITCH website http://www.switchurbanwater.eu/

SWITCH. 2007. Visions and Goals for Urban Water Management. www.switchaccra.wordpress.com

Texas Water Development Board. 2005. The Texas Manual on Rainwater Harvesting, Third Edition, Austin, Texas. Retrieved 2007, from http://www.twdb.state.tx.us/publications/reports/RainwaterHarvestingManual_3rdedition.pdf

Urban Groundwater Database. 2010. http://www.utsc.utoronto.ca/~gwater/IAHCGUA/UGD/accra.html#hydroge

Water Research Institute. 2007. Assessment of the Greater Accra Water Resources Monitoring (Surface and Groundwater) for Sustainable Managment. Final report, *CSIR-Water Research Insitute.* Accra, Ghana.

## 10. APPENDICES

**Appendix 1**

File ‘Model_Inputs.xls’ included on disc.

**Appendix 2**

Original input files for Accra listed as ‘Accra_Baseline’ folder on disc.

**Appendix 3**

Data collected in Accra from AVRL, ASIP and WRI on disc,

**Appendix 4**

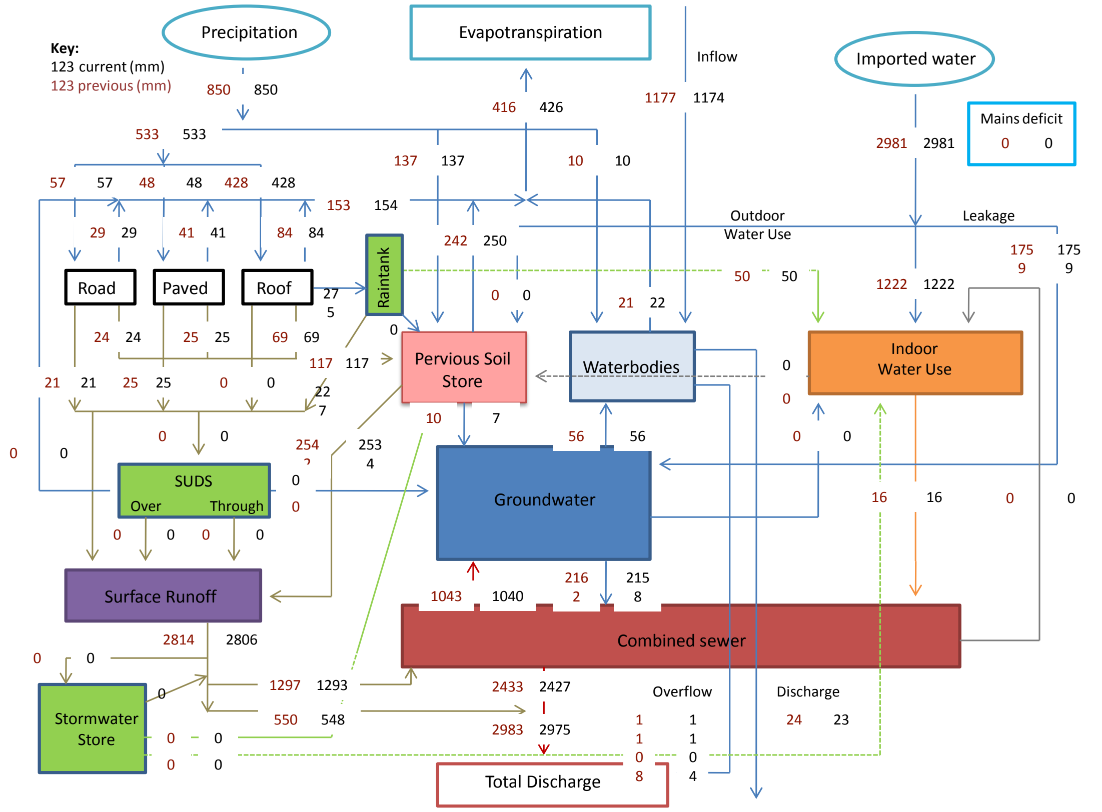
Model files for different population options implemented on disc.

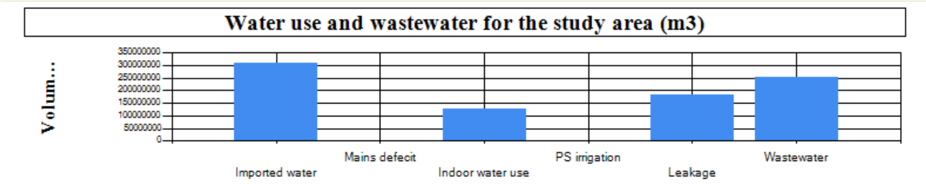
**Appendix 5**

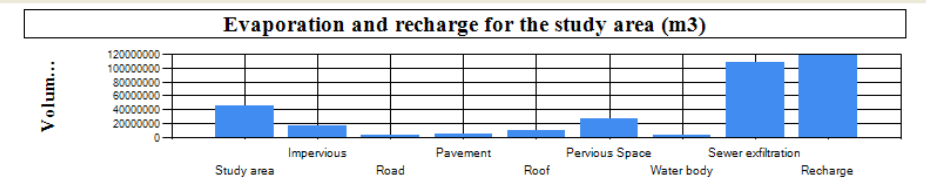
Model files for different water management options implemented on disc.

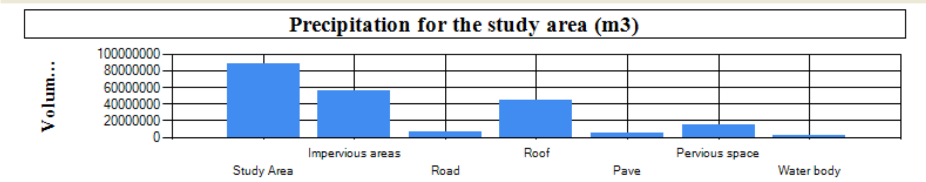
## Appendix 6

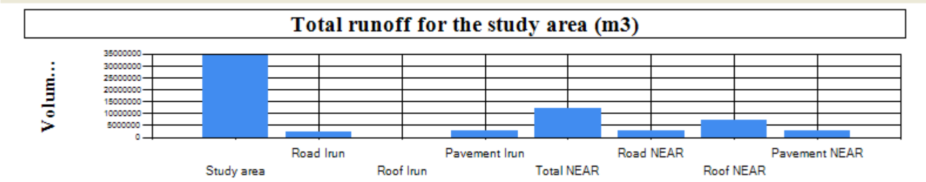
### a) Worst Case Scenario



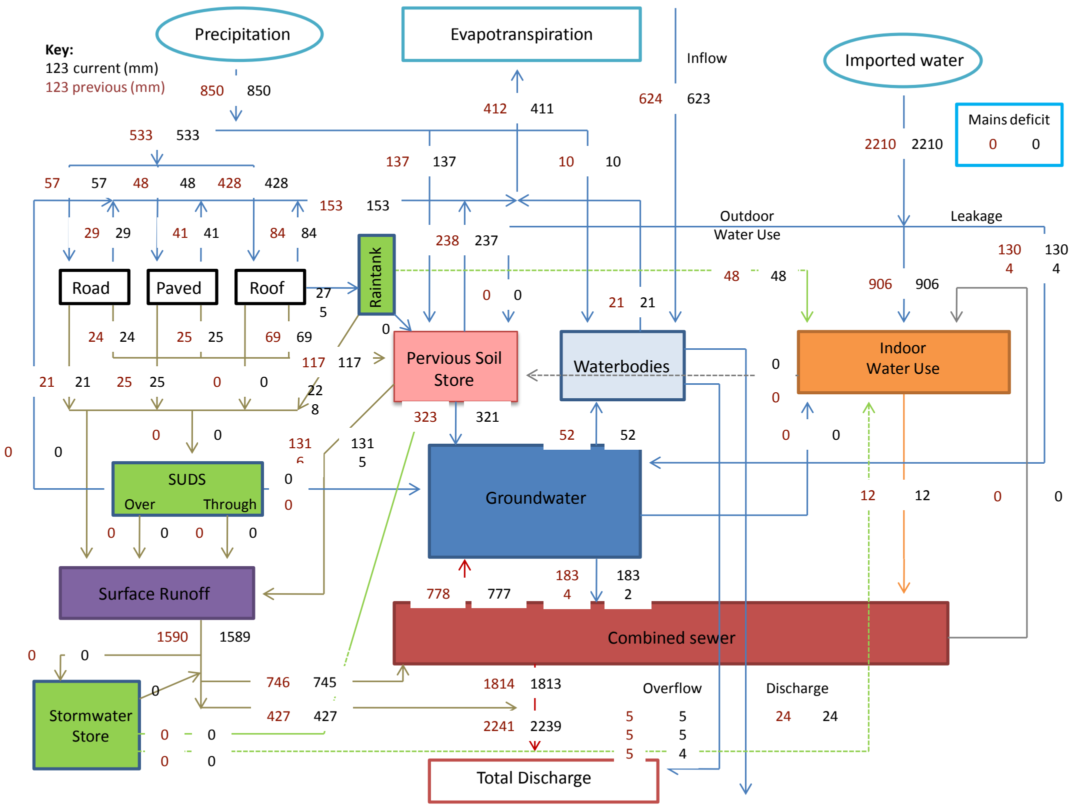



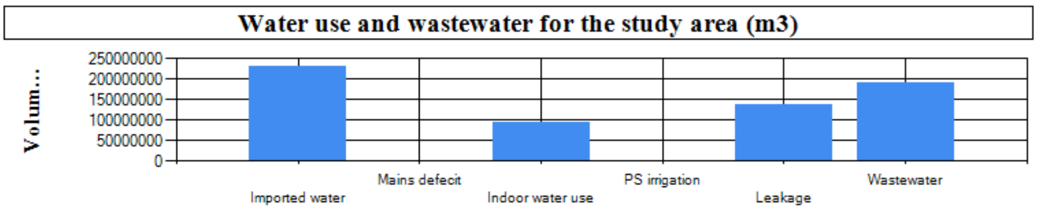



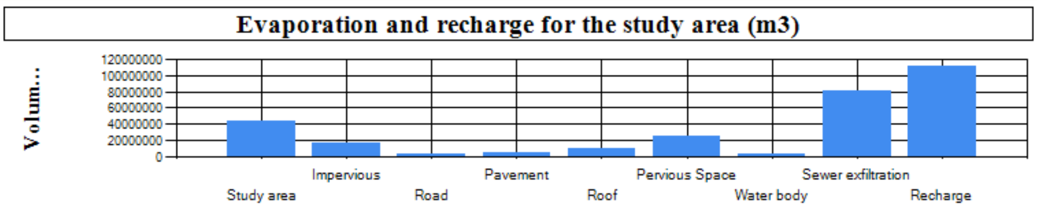



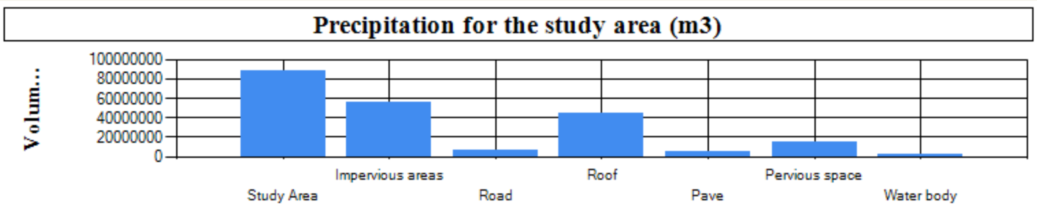



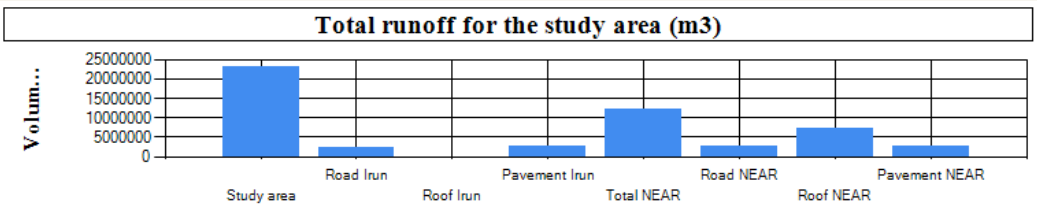
## b) Medium case Scenario



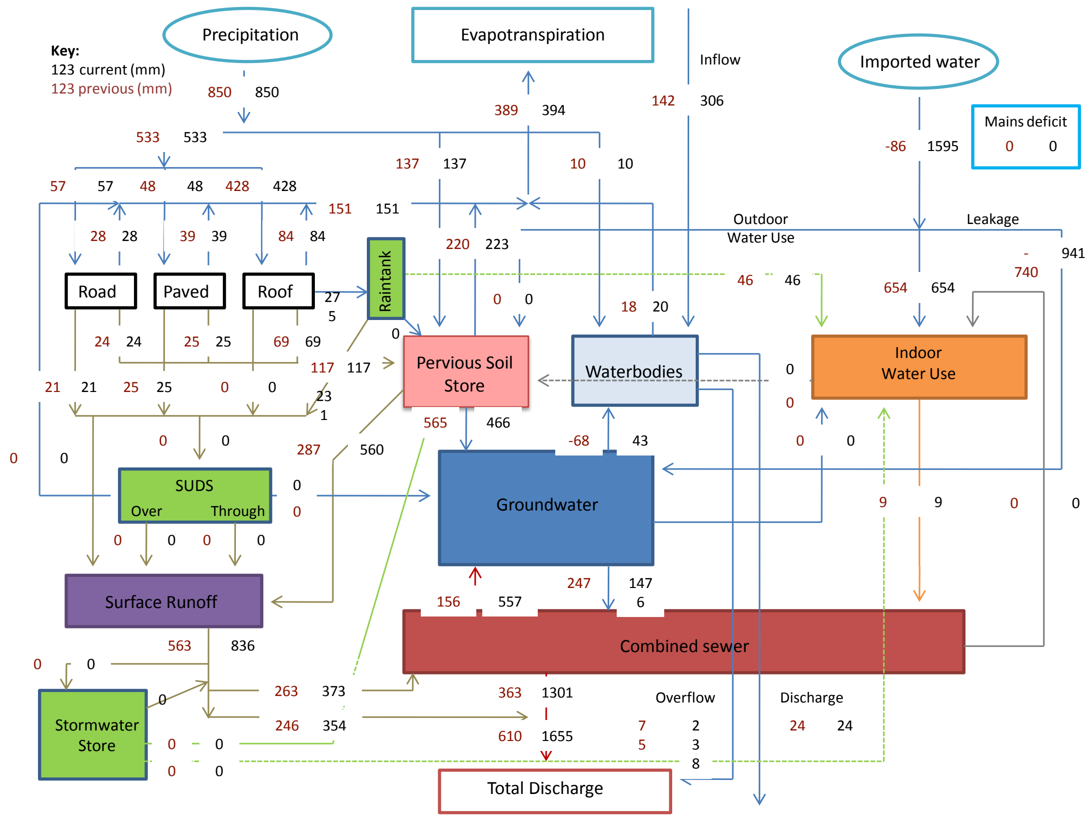



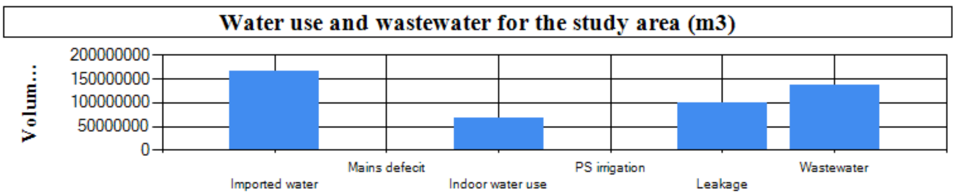



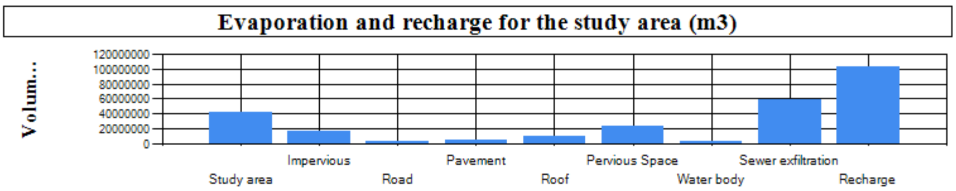



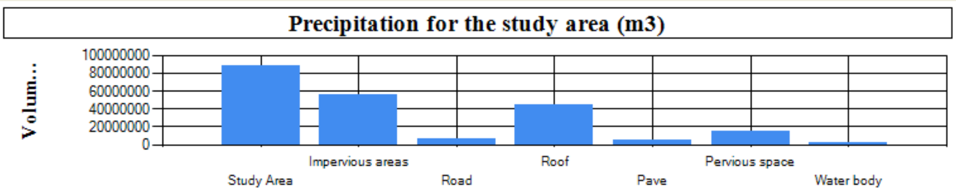



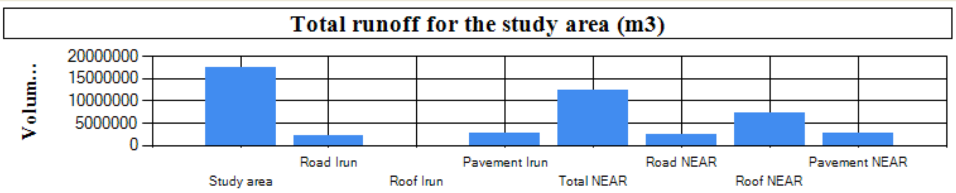
## c) Best Case Scenario



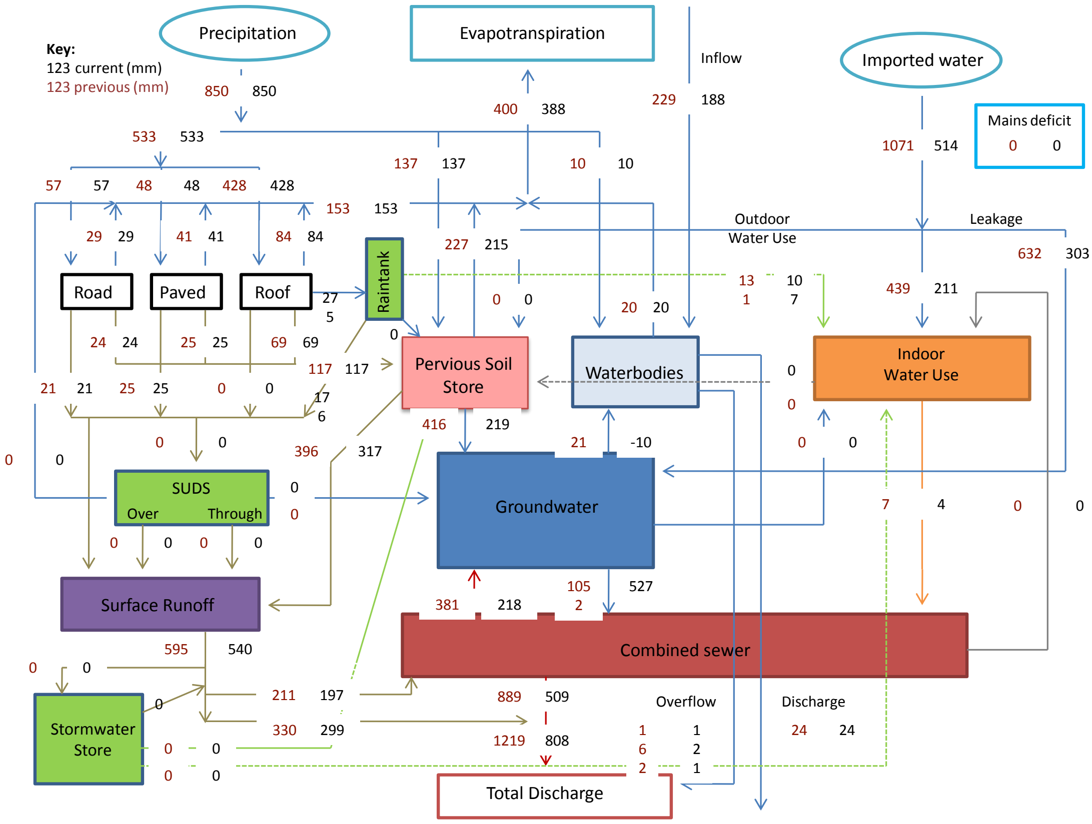



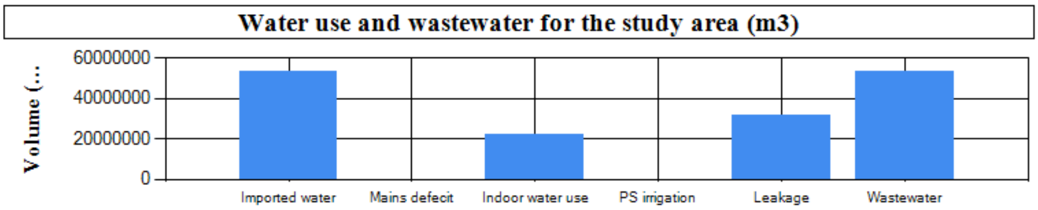



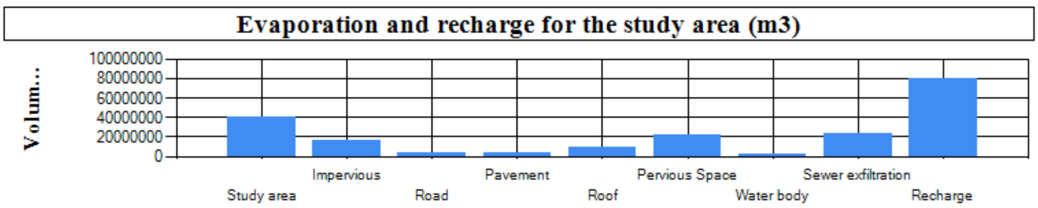



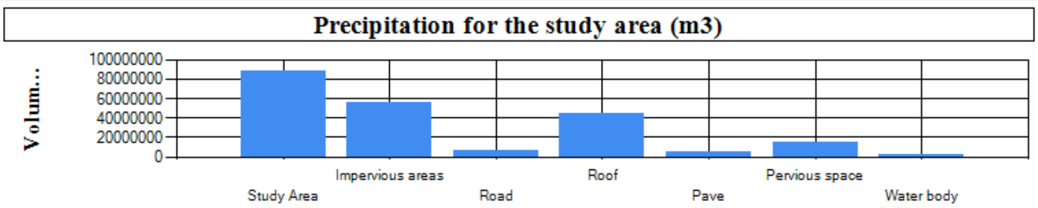
## Appendix 7

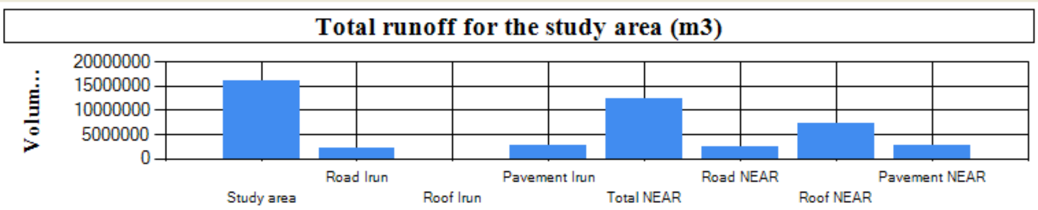
a) UB Rainwater Tank- Water Flow diagram and mass balance



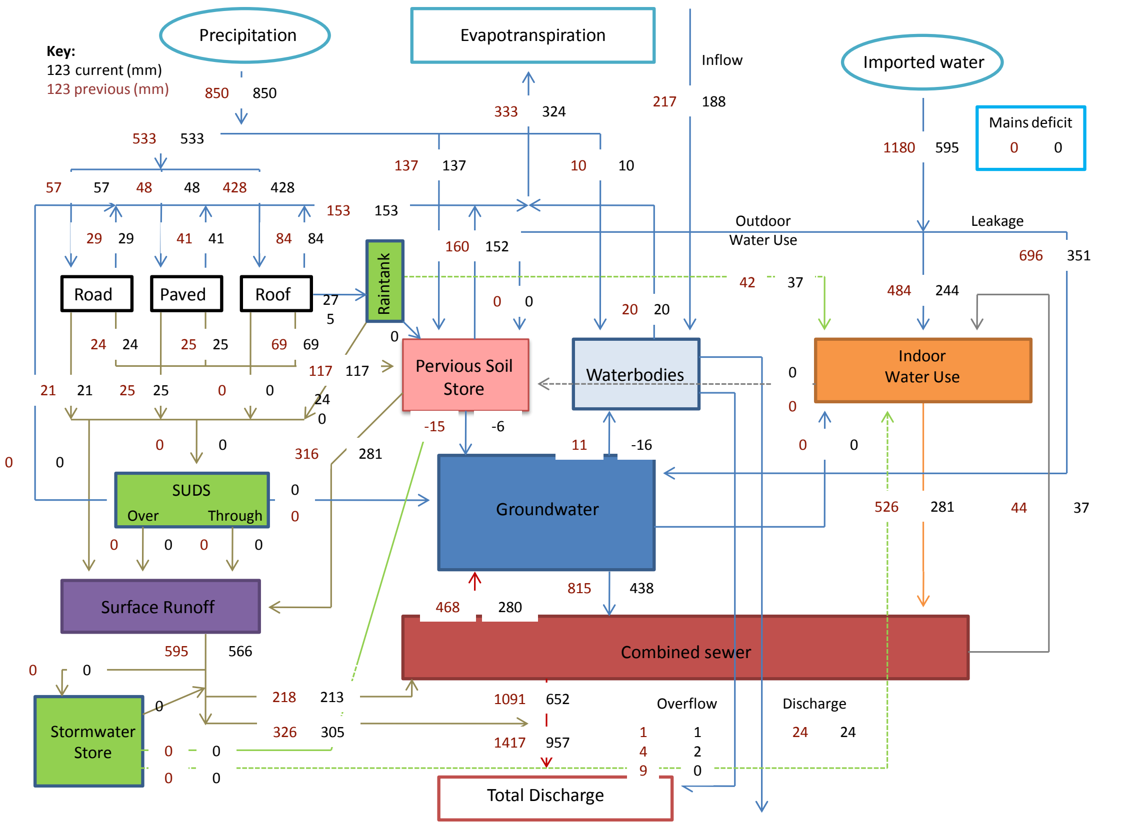



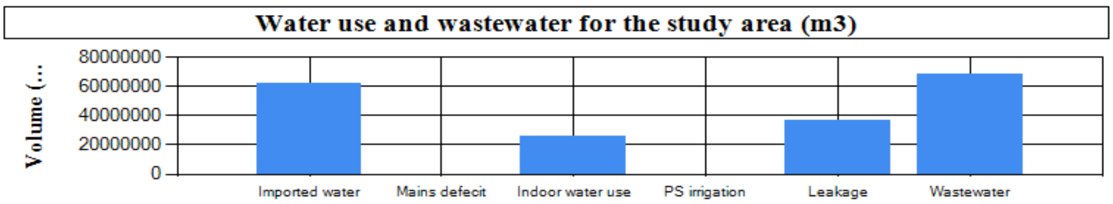



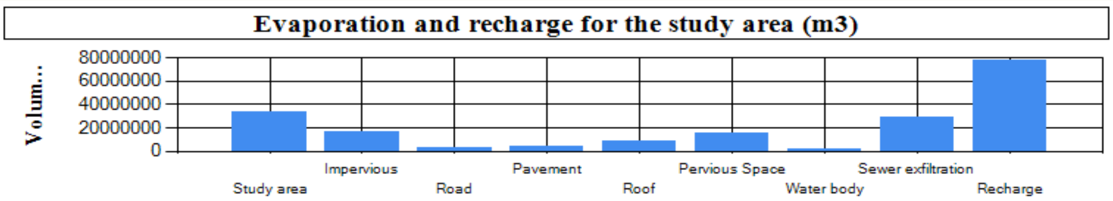



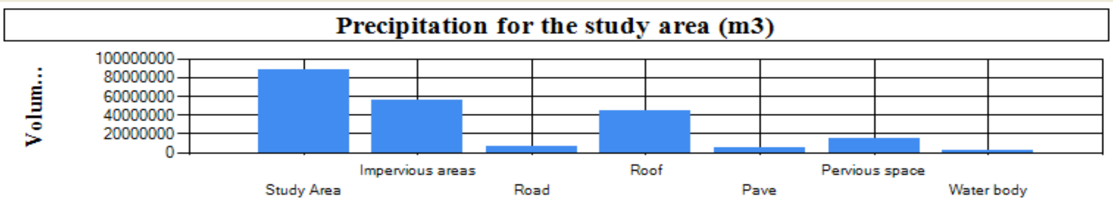



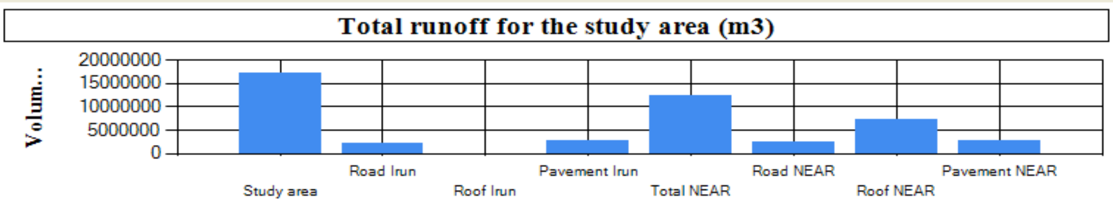
b) UB WW Treatment- Water Flow diagram and Mass balance diagram



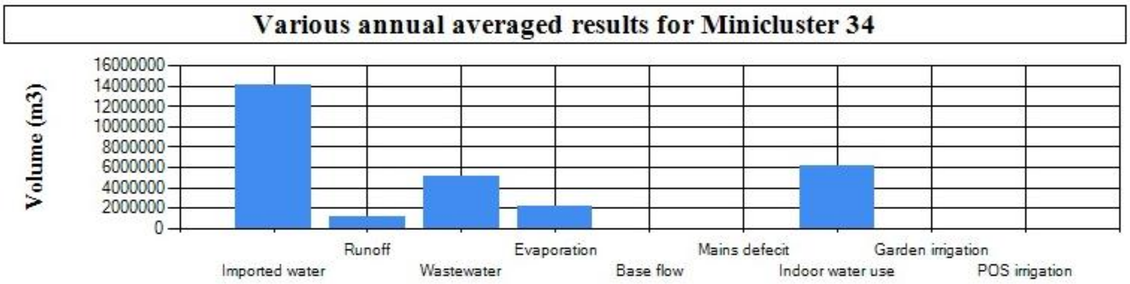



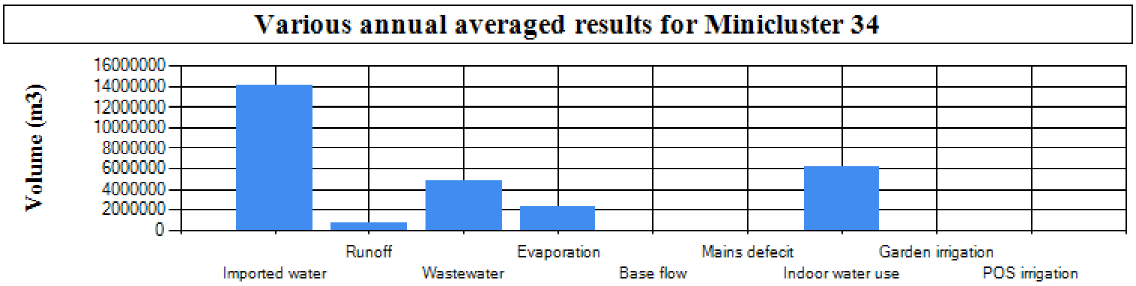



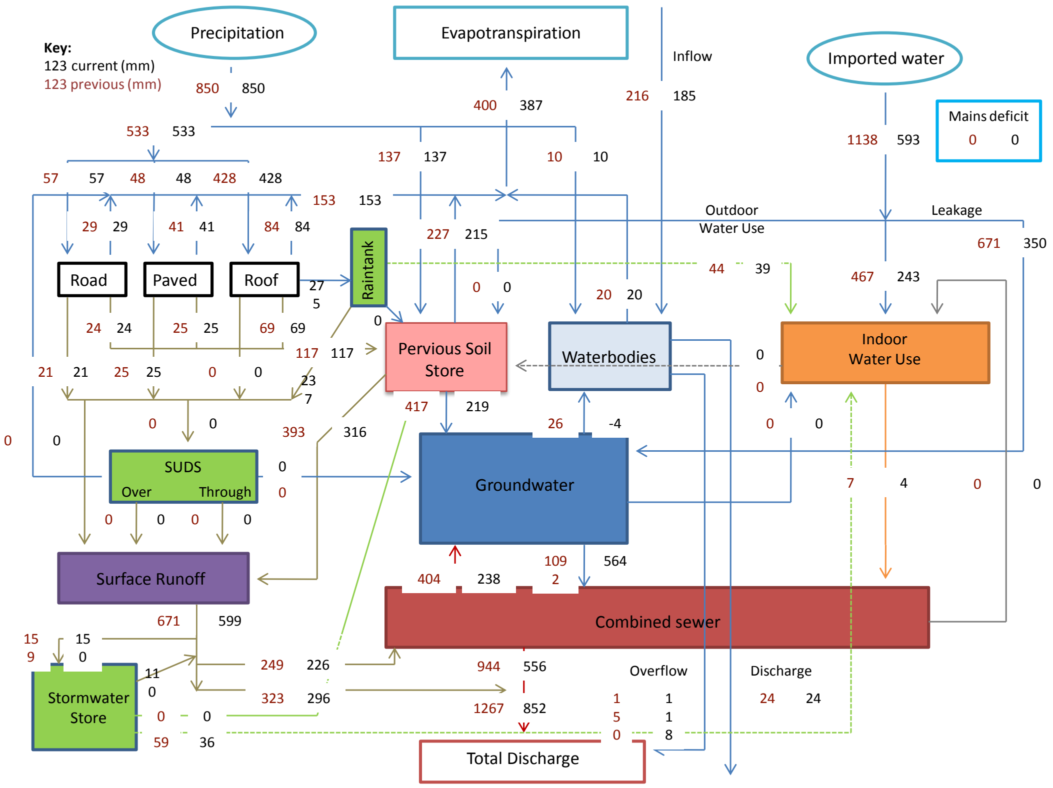



UB Swales- Water balance for Minicluster 34 without and with swales.

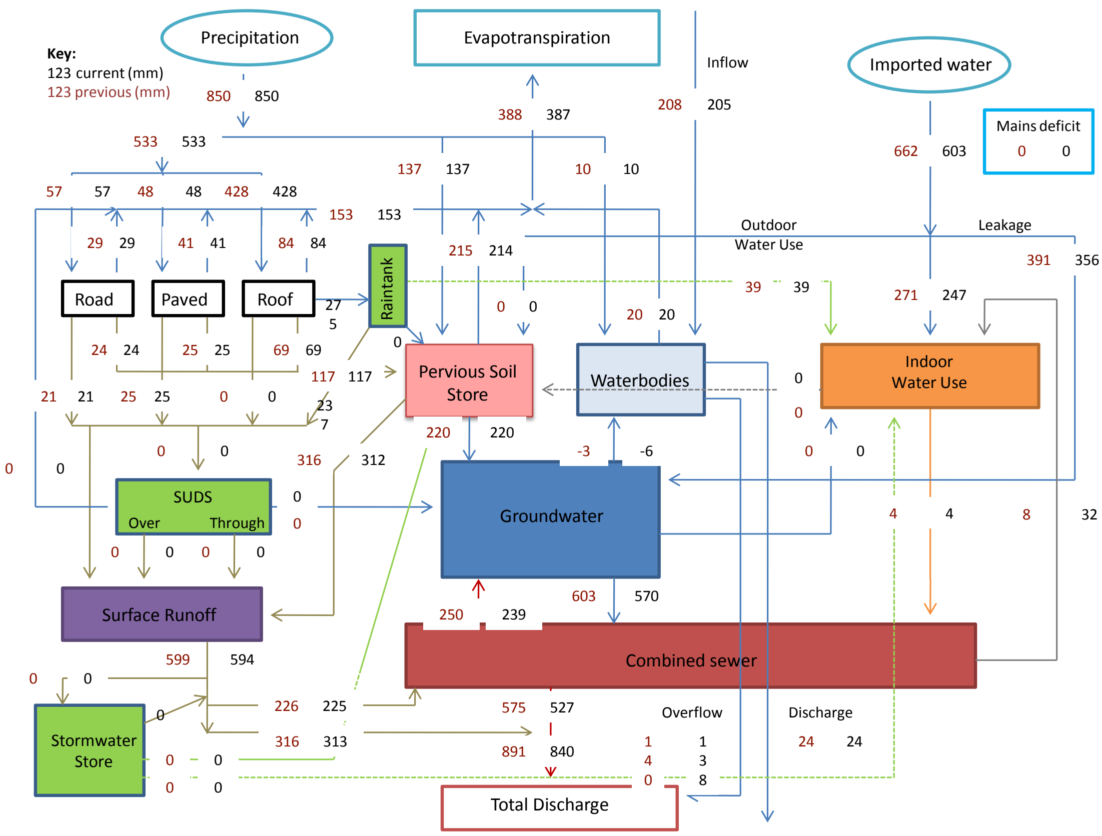


## a) MC Scale SW recycling- Water Flow diagram

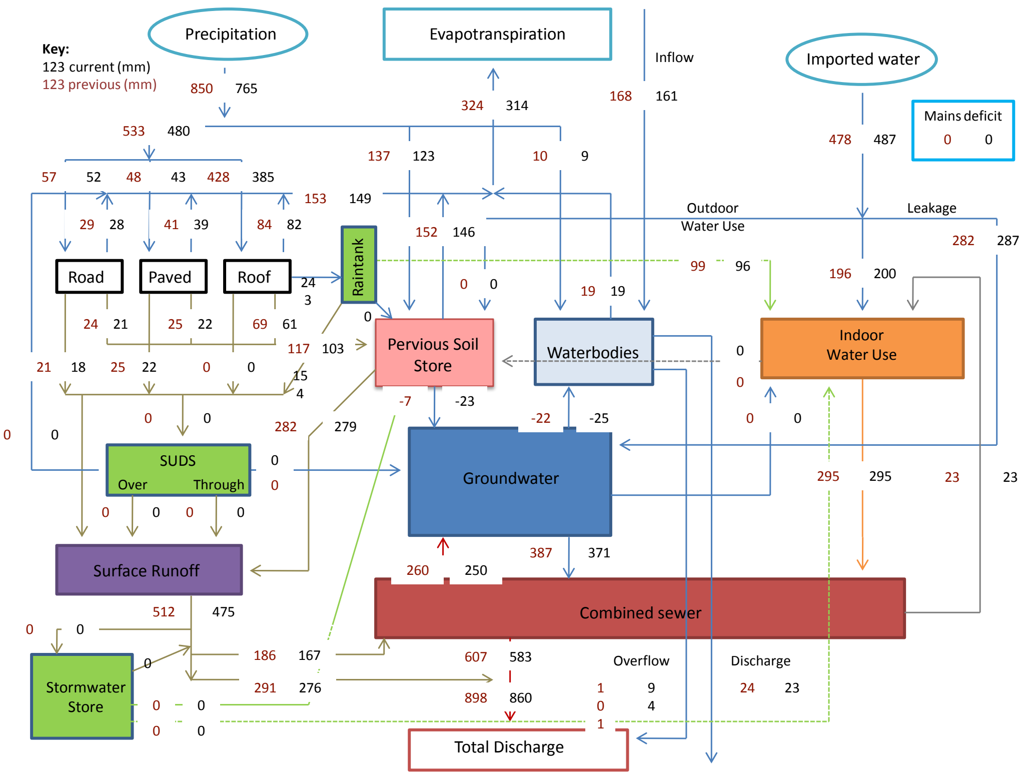



## b) MC Scale WW Recycling Water Flow diagram:



## APPENDIX 8

a) 10 % increase in Rainfall with UB Raintank and UB WW implemented.




b) 10% decrease in Rainfall with UB Raintank and UB WW implemented.