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# REPORT ON THE SALT PROBLEMS IN LOWER SHIRE REGION, MALAWI.

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## Abstract

This article is meant to be an overview of the current available groundwater quality data in the Lower Shire region in southern Malawi. One of the main problems in this region seems to be salt related problems. Particularly high concentrations of sodium and chloride have been reported for the groundwater in Lover Shire Valley, both as a result of evaporation and dissolution of evaporite minerals. High salinity is problematic because alternative water sources are not readily available. Soil erosion in Malawi is one of the major types of land degradation that poses the biggest threat to sustainable agriculture. Climate change is affecting the water sources in Malawi. With increased frequency and magnitude of floods, groundwater recharge may increase. This is particular a case in semi-arid and arid areas like Lower Shire region, where heavy rainfall and floods are the major sources of groundwater recharge. This paper demonstrates that there are several challenges in the Lower Shire region that require attention. There also is a need for better understanding of the processes leading to salt problems.

**Keywords:** Salinisation, groundwater, climate change consequences, Lower Shire region, Malawi.

## 1. Introduction to the issue of salinisation

### *1.1 The hydrologic cycle and definitions*

#### 1.1.1 Hydrology

Several things can happen to the water when precipitation falls on land. Some of the rain will remain close to the top of the soil and may evaporate, and some of it will be taken up by the roots of plants and then be evaporated through the leaves. This process is called *transpiration*. The term *evapotranspiration* is used for the sum of evaporation and transpiration. Some of the water may infiltrate into the soil, where it migrates laterally toward a stream. This process is called *interflow*. Some of the water may percolate down to the groundwater system. *Overland flow* is the term used when the water is flowing on the surface of the ground, due to too heavy rainfall or poor permeability of the soil. Some of the terms marked in cursive above are illustrated in Figure 1 beneath.

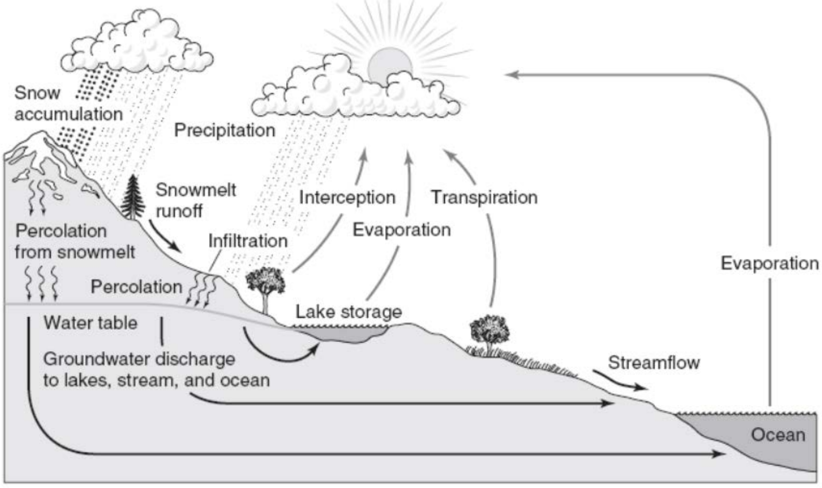


Figure 1: Schematic diagram of the hydrologic cycle. (Buchwald, 2002)

### 1.1.2 Water chemistry

When rainwater comes in contact with soil, its chemistry undergoes drastic changes. As water passes through the soil zone, it acquires solutes from dissolution or partial dissolution of minerals. Other solutes, like nitrogen compounds and phosphate, are extracted from the water by plants. Dissolved Natural Organic Materials are mainly decomposition products from dead organic material, but organisms in the soil can also release soluble organic compounds to the water. This accelerates the breakdown of minerals. During droughts, evapotranspiration removes essentially pure water from the soil. This implies that solutes in the water tend to build up in concentration. They even may precipitate as solid phases. This will be further explained later.

### 1.1.3 Water in streams and rivers

During dry periods, the water in the stream (its base flow) is mainly derived from the permanent groundwater system. In more rainy periods, the base flow will be augmented by contributions from interflow, overland flow and rain falling directly on contributing lakes and the stream channel. The term *runoff* is generally used for the total amount of water leaving an area in streams or rivers. The natural changes in the chemistry of a mass of water as it flows down a river are generally small, compared to the changes that takes place in the soil zone or in an aquifer. The reason is that the water spends a shorter time in the river, and there is also relatively little contact between the water and solid phases. The chemistry of many rivers today is strongly influenced by inputs of domestic and industrial waste.

### 1.1.4 Groundwater

At some distance below the earth's surface there is groundwater that fills all pores, voids, and open cracks. The term *water table* is used for the surface that divides the zone in which the pores are completely filled with water from that in which the pores are partially filled with air. The region below the water table is called *phreatic* or *saturated zone,* while the region above is the *vadose* or the *unsaturated zone.* In some places the unsaturated zone is absent, as is common where there are lakes and marshes, and in some places it is hundreds of meters thick, as is common in arid regions. The behaviour of groundwater systems is generally controlled by the two following terms: *Porosity,* which is the fraction of the soil or rock which is void space, and *permeability,* which is a measure of the ability of soil or rock to transmit fluids. An *aquifer* is a water-saturated rock or unconsolidated materials with sufficient porosity and permeability to be a usable source of water for wells. The piezometric surface is the imaginary surface that everywhere coincides with the piezometric head (the pressure) of the water in the aquifer. Artesian groundwater is an aquifer in which the piezometric surface is above its upper boundary.

Most of the water we observe on the continents is meteoric in origin, that is, it has been derived from the atmosphere as rain or snow in relatively recent geologic times. The term *formation water or connate fluids* is used for water, often saline water, occurring in the pores of a deeply buried sedimentary rock. (Drever, 1988)

## *1.2 Forms and causes for salt accumulation*

### 1.2.1 Evaporation

A major process in the hydrologic cycle is evaporation. On average 68% of the water that falls as rain over the continents is returned to the atmosphere. This is happening either by direct evaporation or transpiration through plants. The net effect of evaporation is to remove pure $H_2O$ from solution, leaving all the dissolved components behind. The concentrations of these components therefore tend to increase in regions with greater evapotranspiration then precipitation. It is therefore only in relatively arid climates that the build-up of dissolved components through evaporation is a major control of water composition. (Drever, 1988) In specific locations, accumulation of salts and alkalinity is especially great due to water confinement, such as depression in the landscape (Figure 2). Evaporation or lateral groundwater flow can move salts deposited by ancient seas, which were later buried under sediments, to the surface. The result is degraded soils. This means that salt problems are not only restricted to soils of arid climates. (McBride, 1994)

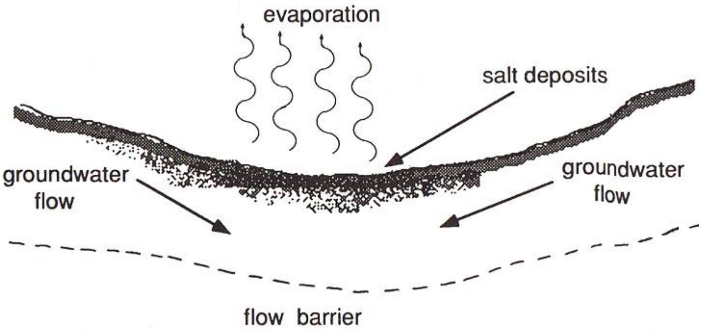


Figure 2: Localized situation conductive to the accumulation of salinity in a semiarid climate (McBride, 1994)

### 1.2.2 Cyclic wetting and drying

An important process in salinification is the complete evaporation of water during dry periods, leading to deposition of all its solutes. The dry period is followed by a wet period with partial re-dissolution of the solutes again. The Hardie-Eugster model, explained in section 1.3.1, is based on the assumption that the dilute water entering an arid basin undergoes continuous evaporation until it becomes a concentrated brine. Further, the water undergoing evaporation occurs in pores of an alluvium or as near-surface groundwater rather than as an open lake. The deposited salts tend to form efflorescent crusts on the ground surface if the water initially was saline. If it was relatively dilute, the salts may be deposited in the ground just below the surface. Another possibility is that the salts may form in the capillary fringe above the water table where the water table is near the surface.

The end result of an evaporate-solution cycle is water that contains only ions that precipitate as highly soluble salts. It has lost ions that precipitate as less soluble compounds. The chemistry of the resultant solution is not strictly controlled by solubility; it is also controlled by the kinetics of dissolution of the precipitated phases.

(Drever, 1988)

### 1.2.3 Solonetz and solonchaks soils

The definition of a salt affected soil is a soil that has been adversely modified for the growth of most crop plants by the presence of soluble salts, exchangeable sodium or both. Saline or solonchaks soils refer to those showing a concentration of soluble salts which results in lowering the soil moisture potential due to osmotic effects. Under such conditions, plants suffer from osmotic drought and hindrance to normal water and nutrient uptake. Sodic (alkali or solonetz ) soils refer to those soils characterised by the presence of sufficient exchangeable sodium and high pH to interfere with the growth of most crop plants. (U.S.S.L., 1954)

### 1.2.4 Saltwater intrusion in costal areas

Under natural conditions there is a flow of freshwater towards the sea. This limits the landward encroachment of seawater. But with the development of groundwater withdrawal and subsequent lowering of the water table or the piezometric surface, the dynamic balance between fresh and seawater is disturbed. Seawater is then permitted to intrude unstable parts of the aquifer. Figure 3 is an illustration of this phenomenon. Saltwater intrusion is a common problem in the Mediterranean countries. (Domenico and Schwartz, 1998)

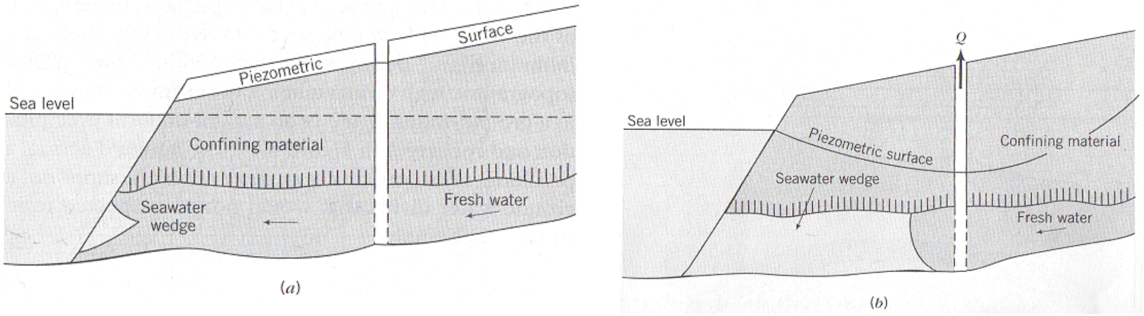


Figure 3: Hydraulic conditions near a coastline (a) not subject to seawater intrusion and (b) subject to seawater intrusion with an advancing seawater wedge.
(Domenico and Schwartz, 1998)

### 1.2.5 Flooding

Flooding from rivers or the sea takes place across natural landforms (floodplains and coastal plains) that have a characteristic geomorphology and geological make-up. Water flowing downstream carries along particles from geological structures in its path. These particles are materials like clay, silt, gravel, and sand. The deposit the stream leaves behind is called alluvium. When the stream is flowing downhill it carries most of the sediment along with it, but when it reaches a plain, it deposits it. This sediment tends to make the flat area, or plain, fertile. A floodplain is also called an alluvial plain.

Geological maps can show why flooding not necessarily occurs in every part of a valley floor. For example some river terraces, being relatively upstanding areas in a floodplain, act as natural obstacles to flooding and their higher parts may remain dry. Alluvium, on the other hand, tends to be low-lying and will at least partially flood during a major event. Even the narrow alluvial tracts of small tributary valleys can be prone to flash flooding. On a catchment scale, the capacity of the ground to absorb water is directly related to the underlying geology. For example, clay-rich rocks and some Quaternary deposits are impermeable, as are the soils developed on them. Such geological terrains will thus be susceptible to rapid run-off, enhancing the potential for serious flooding downstream, during high rainfall events. (BGS, 2007)

## *1.3 The chemistry of sodification*

### **1.3.1 The Hardie-Eugster model** (Drever, 1988)

During evaporation, all the solutes in the water are eventually deposited as solid phases, presumably in the order predicted by the Hardie-Eugster model shown in Figure 4.

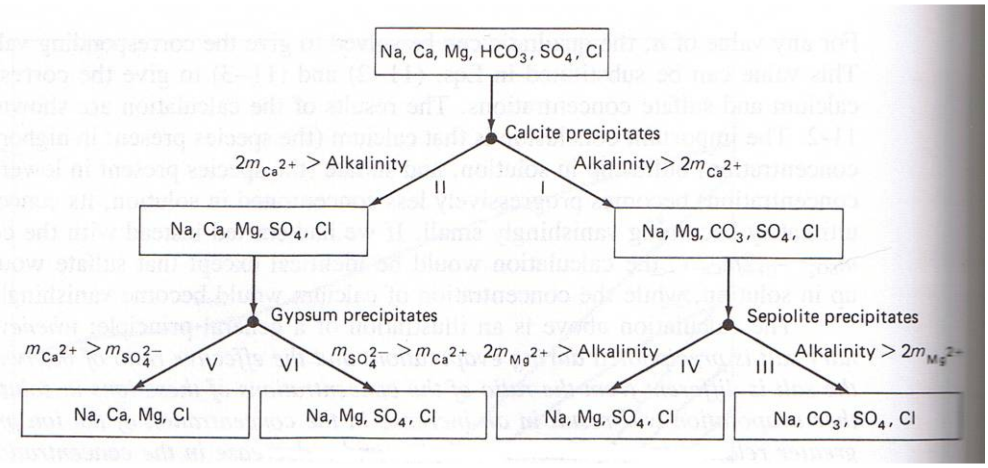


Figure 4: Some of the possible paths for the model evaporation of natural waters. (Drever, 1988)

This model interprets the chemistry of waters undergoing evaporation in terms of a succession of chemical divides. With almost all natural waters, the first mineral to precipitate, and hence to cause the first chemical divide, is calcite ($CaCO_3$). Essentially all the calcium will be removed from solution during evaporation if the calcium concentration, on an equivalent basis, is less than the alkalinity. The solution will tend toward an alkaline carbonate brine. (Path I, Fig. 4) If calcium concentration is greater than alkalinity, essentially all carbonate species will be removed from solution. In this case, the solution will tend toward a nearly neutral sulphate or chloride brine. (Path II, Fig. 4) Following path I, the next chemical divide is caused by sepiolite ($Mg_4Si_6O_{15}(OH)_2$) precipitation. This involves two species, $Mg^{2+}$ and $H_4SiO_4$. The solution will tend toward a carbonate-free sulphate or chloride brine, if the magnesium concentration is greater than remaining alkalinity. (Path IV)
Following path II, the next mineral that is likely to precipitate is gypsum ($CaSO_4$). If the calcium concentration remaining after calcite precipitation is greater than the sulphate concentration, the resulting brine will have chlorides of Na, Ca and Mg as the major solutes. If the sulphate concentration is greater than that of remaining calcium, the resulting brine will have chloride and sulphate as major anions and sodium and magnesium as major cations.

According to James I. Drever in the book The Geochemistry of Natural Waters (Drever, 1988), the most important conclusions that may be drawn from the Hardie-Eugster model are that brines should be chemically simple, containing relatively few ions as major species. Further, the composition of the final brine is determined by the composition of the dilute water from which the brine was derived. It should also be mentioned that this model is an oversimplification of the real world.

When water flows through a porous medium, exchange reactions take place between ions in the water and ions adsorbed on the medium. Also neutral species, notably $H_4SiO_4$ may be adsorbed on solid surfaces. Except at very high concentrations, potassium ($K^+$) and sodium ($Na^+$) do not form any salts. Calculations like those of Hardie and Eugster predict that $K^+$ and $Na^+$ should simply build up in solution during evaporation. However in practice, $K^+$ is almost always found to be depleted relative to $Na^+$ in saline waters. According to Drever, it was only when the water was flowing underground that the $K^+$ removal took place while it did not happen in a lake. If a soil, in which the exchange sites are largely occupied by $Ca^{2+}$, is exposed to a relatively saline water, monovalent ions would be able to displace divalent calcium. Biological uptake of potassium seems to be less important than adsorption in regulating potassium concentrations in saline waters. In ion-exchange reactions involving clay minerals or zeolites, potassium is removed from solution. The calcium released in exchange for sodium probably precipitates as a carbonate within the medium. In many regions that are now arid, the exchangeable cation is often initially calcium.

### 1.3.2 Weathering and alkalinity

Human activities, including the application of poor quality irrigation water, fertilizers, and waste water to land, can accelerate the process of salt accumulation and soil degradation. Historically, salt-related problems of irrigated agriculture have been responsible for the loss of much productive land in semi-arid parts of the world. Even in the absence of these localized inputs, salts accumulate in soils that are not subjected to frequent leaching. The source of these ubiquitous salts is mineral weathering.

$$Mg_2SiO_4 + 4H_2O \rightarrow 2Mg^{2+} + Si(OH)_4 + Na^+ + 4OH^- \qquad (1)$$

$$2NaAlSi_3O_8 + 11H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 4Si(OH)_4 + Na^+ + OH^- \qquad (2)$$

Equations 1 and 2 reveal as a general rule, that the hydrolysis of primary silicate minerals is a non reversible process at earth-surface conditions that generates alkalinity. In a more humid climate, acidity will be consumed. Conversely, oxidation of primary minerals containing elements in the reduced state can be acidifying. This is shown below in Equation 3. Acidity is also generated through biological processes in the soil by the release of $H^+$ in exchange for base cation nutrients.

$$2FeS_2 + 7O_2 + 2H_2O \rightarrow 2Fe^{2+} + 4SO_4^{2-} + 4H^+ \qquad (3)$$

The oxidation of $Fe^{2+} \rightarrow Fe^{3+}$ which will be precipitated as $Fe(OH)_3$, is also lightly to happen. This reaction will produce much acidity. The equations 1 and 2 are called *weathering processes* and the net effect is generating alkalinity. In soils of arid and semi arid climates, the alkalinity can accumulate.

The source of this alkalinity is the silicate anion liberated from the mineral by hydrolysis of the structure. This anion is a strong base, reacting with protons from solution to form a weak tetravalent acid with pK values of 9.9, 11.8, and 12.

$$SiO_4^{4-} + 4H^+ \rightarrow Si(OH)_4 \qquad (4)$$

Reaction 4 generates alkalinity in the form of $OH^-$ ions if the protons are provided by water dissociation. In natural soil systems, $OH^-$ reacts further, with $CO_2$ dissolved in the water to convert the alkalinity into the carbonate or bicarbonate form. (Equation 5)

$$OH^- + H_2CO_3 \rightarrow H_2O + HCO_3^- \quad (5)$$

The cation associated with the alkaline carbonate anion becomes critical in limiting the severity of alkalinity in soil solution. Any alkalinity that accumulates does so in the form of carbonate or bicarbonate salts due to the huge amount of $CO_2$ in soils. $Mg^{2+}$ and $Ca^{2+}$ carbonates are not very soluble, but $Na^+$ and $K^+$ carbonates dissolve readily in water to form solutions with very high pH.

$$\begin{aligned} &Na_2CO_3 \rightarrow 2Na^+ + CO_3^{2-} \\ &CO_3^{2-} + H_2O \rightarrow HCO_3^- + OH^- \quad (6) \end{aligned}$$

Thus, soil waters rich in $K^+$ and $Na^+$ are more likely to become alkaline than soils rich in $Ca^{2+}$ and $Mg^{2+}$. (McBride, 1994)

**Table 1: Solubility of Carbonates in Cold Water.**

| Carbonate | Solubility(g/L) |
|---|---|
| $CaCO_3$ | 0,014 |
| $MgCO_3$ | 1,76 |
| $Na_2CO_3$ | 71 |
| $K_2CO_3$ | 1120 |

(McBride, 1994)

## *1.4 Environmental problem*

### 1.4.1 Irrigation consequences

When water is used for irrigation, it always results in some evaporation. This may cause accumulation of salts in the soil and /or an increase in the salinity and sodium content of the soil water in the top soil. High salt content in the soil decreases soil fertility. Sufficient irrigation water should be applied to wash the salts to a depth in the ground deeper than the roots. Thus- combating salinity build-up demands large volumes of irrigation water and may cause salinity problems in shallow groundwater or nearby surface water. (Drever, 1988)

### 1.4.2 The effects of salt-degraded soils on plants

Salinity, sodicity and alkalinity are three hazards of salt-degraded soils to plants. Table two shows how soils are classified.

**Table 2: Classification of saline and sodic soils**

EC denotes electrical conductivity. ESP denotes the Exchangeable Sodium Percentage, a measure of the alkalinity hazard.

| | EC (mS/cm) | ESP (%) | Typical pH | Structure |
|---|---|---|---|---|
| Saline | >4 | <15 | <8,5 | Good |
| Sodic | <4 | >15 | >9,0 | Poor |
| Saline-sodic | >4 | >15 | >8,5 | Fair-Good |

(McBride, 1994)

High salinity lowers the free energy of water in soil solution, thereby reducing the ability of the plant roots to extract water from the soil. This is an osmotic effect that becomes significant only in extremely saline soils. More important effects of soil salinity are likely to include particular ion toxicity effects (e.g., $Na^+$ and $Cl^-$) and nutritional imbalances (e.g., excessive $Na^+$ or $K^+$ uptake relative to $Ca^{2+}$ and $Mg^{2+}$). Beyond the potentially toxic accumulation in plant tissue, sodicity presents a physical limitation to plant growth due to the dispersing effects of exchangeable $Na^+$ on clays and organic colloids. Although dispersion is suppressed in saline-sodic soils by high salt concentrations, clay swelling and dispersion result. This counts if the excess salt is removed by leaching. The consequences of dispersion are colloid migration, the clogging of soil pores, and dramatic reduction in the rate at which water can percolate through the soil. Because dispersed soils have very poor structure, problems like cementation, surface crusting, and soil erosion becomes the result. Furthermore, humus can deposit at the surface during the evaporate loss of water from the soil. This happens because humus becomes dispersed in sodic soils, and gives some soils a dark appearance. Historically the name “Black soils” has been used to describe such soils.

Alkalinity of soil solutions can also create toxicity for plants. Typically the alkalinity is in the form of $HCO_3^-$ and $CO_3^{2-}$. These anions are known to reduce the availability of Fe to plants. Additionally, the high pH is likely to reduce the availability of other micronutrients like Zn and Mn as well. There is also some evidence that Al toxicity might contribute to poor plant growth in alkaline soils. Al solubility increases at high pH, according to Equation 7.

$$Al(OH)_3\,(s) + OH^- \rightarrow Al(OH)_4^- \tag{7}$$

(McBride, 1994)

### 1.4.3 The extent of the water problem on a global, regional and local scale

The lack of water is an acute problem in large parts of the world. In addition the quality of the water is often bad leading each year to that over 5 million people die due to water pollution. Many illnesses have often water as the source of contamination. The distribution of water is unequal in the world today, both geographical and with the seasons; in some deserts it can be years between each rainfall, but in the mountains of Himalaya, there can be over 10 metres annual precipitation. The dry areas of the world constitutes one third of the earths land area, according to Figure 5.

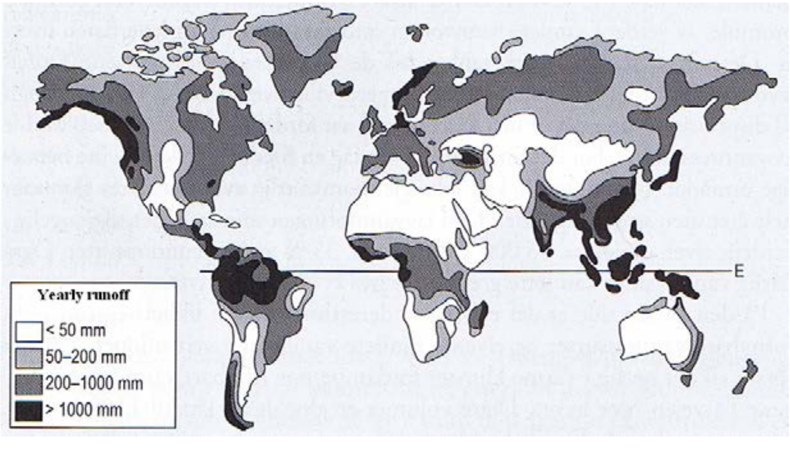


Figure 5: Annual runoff. (Tollan, 2002)

The situation is even more complicated by people living in cities. In 2008, the world reaches an invisible but momentous milestone: For the first time in history, more than half its human population, 3.3 billion people, will be living in urban areas. By 2030, this is expected to swell to almost 5 billion. Large cities with 10 million inhabitants are becoming a reality, especially in Asia. By 2030, the towns and cities of the developing world will make up 80 per cent of urban humanity. (UNFPA, 2007) It is an economically and technical problem to obtain clean water for these cities. To obtain enough water and secure the domestic system is also a challenge.

Over half of the earth’s population is dependent on groundwater as water source. Globally, 70% of all water consumption is used for irrigating. China and India are the two countries that irrigate the most. During the “green revolution” in the 1960-1980’s there was a great increase in the use of groundwater for irrigating. New high yielding plants needed more water, and new technology for well boring was developed. The increasing prize for the energy needed to pump the groundwater has not stimulated to high efficiency in the water use. This is because in many countries the energy prizes in agriculture is strongly subsidized, e.g. in India.

The world’s population has doubled between 1960 and 2000 from 3 to 6 billions, and the water consumption from ca. 2000 to 4000km$^3$ per year. The competition for water will increase. Many stress-factors attached to population density, like deforestation, soil destruction and more deserts, are affecting the water resources. Peoples individually consumption will also increase. This is due to the standards of personally comfort, and because the water demanding technology in the households is increasing.

Conflicts arise when the water is unequally distributed or is reduced in quality. One example that can be mentioned is Egypt, Ethiopia and Sudan which are all arguing over the water in the river Nile. Another example can be that Libya is overusing fossil groundwater in aquifers that also belong to Chad, Sudan and Egypt. An example from Europe is the water from the river Tajo that runs through Spain and into Portugal. The water does not always respect frontiers. Many countries are almost totally dependent of runoff from a neighbour country to be able to cover its water demand. (Tollan, 2002)

It is predicted that in the coming decades, one of the biggest global resource problems will be access to clean freshwater. One billion people had no access to clean drinking water from public supply in the year 2003. Probably, between 2 and 7 billion people are going to live in water scarce countries in the middle of this century. (Appelo and Postma, 2005)

# 2 Case study: The Lover Shire region.

## *2.1 A brief description of Malawi*

### 2.1.1 Geography

Malawi is one of the poorest countries in the world. It is located in south-eastern Africa. As seen in Figure 6, it is bordered by Mozambique on the east and southwest, by Tanzania on the north and north east, and by Zambia on the west and northwest. Malawi has a broad range of vegetation types and geographical features for being a small country. Woodlands, tropical rain forests, open savannah, high altitude grasslands and scrub are all found in the country. There are high plateaus in the north, and lowlands in the centre stands around Lilongwe. The Zomba Plateau and Mulanje Massif are mountains in the Shire Highlands, while Lower Shire Valley lies only just above sea-level (altitude 35 to 105 metres). (UNDP, 2005) This is the southern most point in Malawi and is the region that will be studied in this report. The surface area of Malawi is comprised by more than 20% water (MOWSWD, 1994), and contains the third biggest lake in Africa - Lake Malawi. The only outlet to this lake is the Shire River, which flows southwards to join the Zambezi River in Mozambique on its journey to the Indian Ocean.

Figure 6: Map of Malawi. (Grapic Maps, 2007)

The human pressure upon the natural environment is very serious, with more and more of the country being put under cultivation of maize and cash crops. Areas are also being cleared for human habitation. Increased need for firewood also constitutes a threat for the woods.

### 2.1.2 Climate

Malawi is lying entirely within the tropics, and has a sub-tropical climate. There are three seasons, the dry and hot period from August to November, the wet and hot period from December to April, and the cool and drizzly period from May to August. The rainy season lasts from November to April. Rainfall is strongly affected by topography and prevailing-wind direction. The Rift valley is arid. Both tropical and sub-tropical crops, such as maize, tobacco, groundnuts, cotton, fruits and vegetables grow in Malawi. (UNDP, 2005) Around 20% of the land is arable, though only an area of 560 square kilometres is irrigated. (CIA, 2003) Monthly average temperature is 21-30ºC in the Lower Shire Valley, compared with temperatures around 10-16 ºC in the Nyika uplands. (BGS & WA, 2004)

### 2.1.3 Population data

The current estimated population is 13, 6 million inhabitants, with 46% under the age of 15 years. The population growth rate is 2,38%. Life expectancy at birth is 43 years of age. These numbers have taken into account the effects of excess mortality due to AIDS. (CIA, 2003) National literacy stands at 50% for females and 72% for males. This estimation is based on people over 15 years of age that can read and write. The total population's literacy is almost 63%. (CIA, 2007)

### 2.1.4 Economic conditions

The largest economical sector is agriculture. The principal exports are tobacco, sugar, coffee and tea. Maize is the dominant subsistence crop and covers 80% of all cultivated land. The earlier dictator Banda forced the peasants to grow maize to avoid competition for the great landowners. A major activity around the lakes is fishing. Livestock farming is underdeveloped. Currently, less than 4% of the Malawians have access to the electricity grid. Wood is the main source of energy. (UNDP, 2005) The government faces many challenges, including developing a market economy, improving educational facilities, facing up to environmental problems, dealing with the rapidly growing problem of HIV/AIDS, and satisfying foreign donors that fiscal discipline is being tightened. (CIA, 2007)

### 2.1.5 Social conditions

Two thirds of the Malawians live below the poverty line; i.e. they are living on less than $1 per day. This means that most people are unable to meet their food requirements. Most farmers in Malawi are smallholder farmers who can not afford to buy commercial fertilisers and improved seed. As such most of them depend on government input subsidy programme for farm inputs. (DMS, 2007) Further, many people are still using unimproved water sources despite some progress. (Mutangadura et al., 2005). When water is available it is often of poor quality, thus contributing to a range of health problems including diarrhoea, intestinal worms and trachoma. Most rural water supply is provided by groundwater which is abstracted from hand-dug wells, springs and hand pumped boreholes. In the urban areas, most public supply is derived from surface-water sources. (UN, 1989)

## *2.2 Description of Lower Shire region*

### 2.2.1 Geology

It is in the southernmost part that Lower Shire area is located. According to Figure 7, this area consists mostly of Quaternary alluvium, but also Permo-Trias Karoo sediments, a little area of Cretaceous- Pleistocene sediments and another area consisting of Precambrian crystalline basement rocks.

The sediments of Cretaceous to Pleistocene age include poorly-indurated (poorly-hardened) sandstones, marls, clays and conglomerates with some evaporites.

The Karoo age deposits are mainly sandstones, marls and conglomerates with some coal seams. They are usually well-indurated with calcite cements.

Much of the alluvium arises from erosion of rock material from the Rift Valley escarpment slopes. The sediments are partly faulted as tectonism along the Rift Valley is still active. The Quaternary deposits consist of unconsolidated mixed clays, silts, sands and gravels. Along the shore of Lake Malawi, these reach up to 60 m thick but are up to 150 m thick in the Lower Shire Valley. (BGS & WA, 2004)

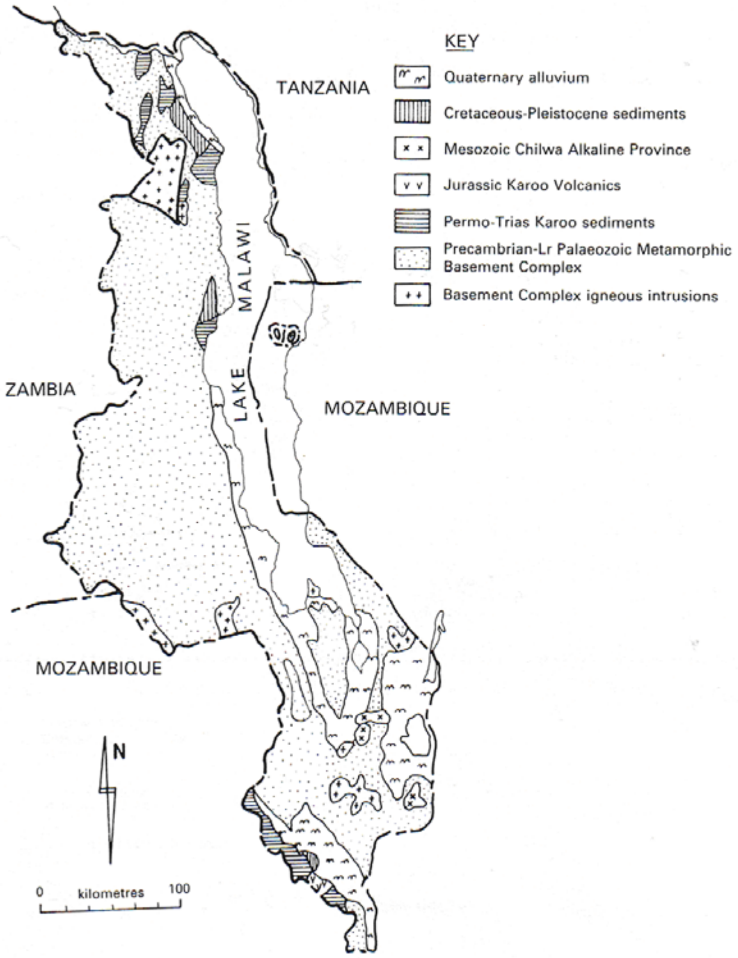


Figure 7: Geological map of Malawi.
(Lewis & Chilton, 1989)

### 2.2.2 Ground- and surface waters

Malawi has three major groundwater zones (Figure 8):

- The Rift Valley Zone, which includes the Lake Malawi rift and the upper and lower sections of the Shire Valley. It is separated by the Rift Escarpment zone of tectonic origin from the High Plateau.
- The Lower Shire Valley.
- The High Plateau zone weathered rock products and fractured rock.

Chemical analyses of borehole groundwater show that sodium bicarbonate is the major dissolved solid in the Lower Shire Valley, while both calcium and sodium bicarbonate are the major dissolved solids in the Rift Valley zone. Dissolved sodium and chlorine are prevalent along the west bank of the Lower Shire. (Kalenga Saka, 2006) As described in section 2.1.2, there are dry periods which make the surface water unavailable for considerable parts of the year. Consequently, aquifers provide the most reliable potable water supplies for the majority of rural communities. Aquifers also make easier agricultural development of dry areas like Lower Shire area. The quality of the groundwater is affected by surface water, and therefore the problem with dissolved solids in the groundwater is exacerbated during the rainy season.

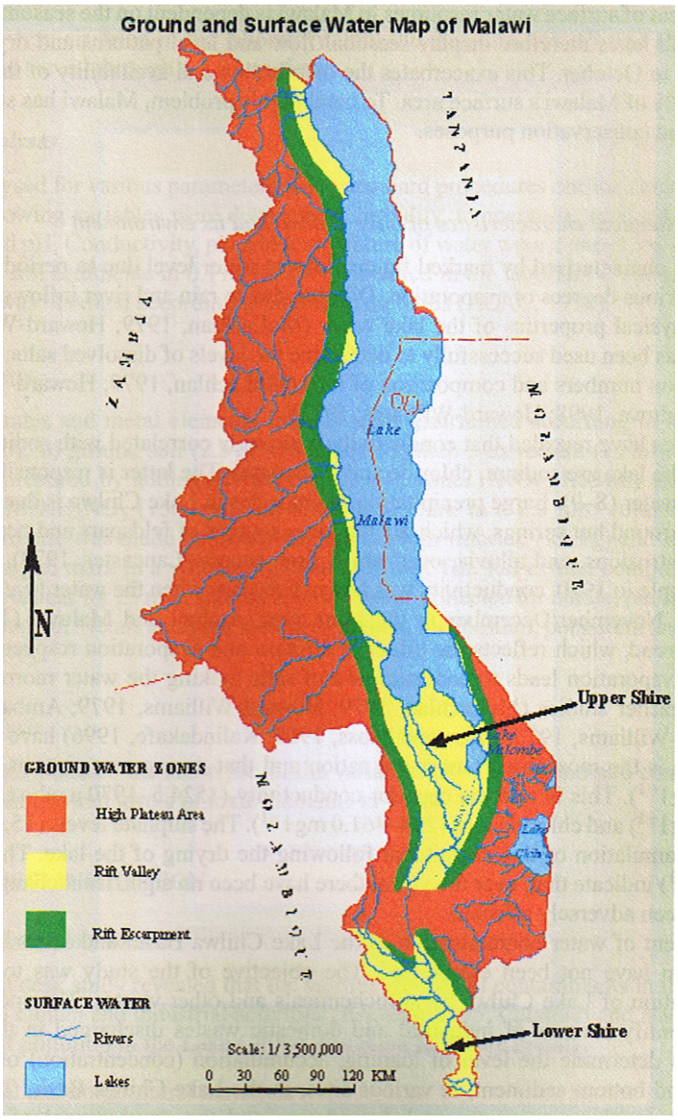


Figure 8: Distribution of ground- and surface water in Malawi.
(Kalenga Saka, 2006)

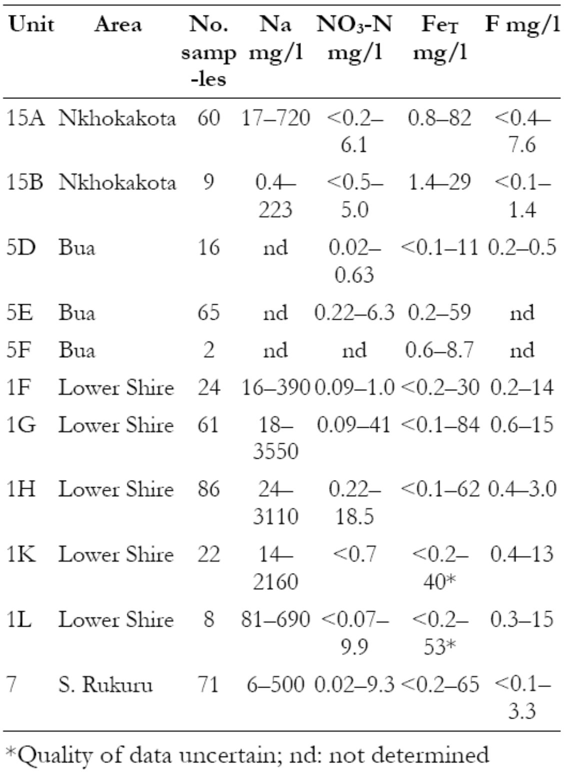
Since the Karoo sediments are usually well cemented, they have low porosity (UN, 1989) and therefore their aquifer potential is restricted. Groundwater is usually present only in fractures. In the Lower Shire Valley, groundwater levels in this aquifer are typically 20–30 m below surface (UN, 1989). The less well-indurated Cretaceous sediments have greater potential as an aquifer. The Quaternary alluvial deposits generally form a good resource for water supply. (BGS & WA, 2004)

## *2.3 Available data*

### 2.3.1 Overview of the groundwater quality

The chemical quality of groundwater in the aquifers of Malawi has been little documented. From the limited information available, groundwater compositions appear to be spatially variable and highly dependent on aquifer lithology. One of the main problems affecting the groundwater appears to be high salinity. This is particularly the case in groundwater from the alluvial deposits of the Lower Shire Valley.

Table 3: Range of concentrations of selected parameters in groundwater from Malawi. (Bath, 1980) $Fe_T$ is total (unfiltered) iron.



| Unit | Area | No. samp-les | Na mg/l | $NO_3$-N mg/l | $Fe_T$ mg/l | F mg/l |
|---|---|---|---|---|---|---|
| 15A | Nkhokakota | 60 | 17–720 | <0.2–6.1 | 0.8–82 | <0.4–7.6 |
| 15B | Nkhokakota | 9 | 0.4–223 | <0.5–5.0 | 1.4–29 | <0.1–1.4 |
| 5D | Bua | 16 | nd | 0.02–0.63 | <0.1–11 | 0.2–0.5 |
| 5E | Bua | 65 | nd | 0.22–6.3 | 0.2–59 | nd |
| 5F | Bua | 2 | nd | nd | 0.6–8.7 | nd |
| 1F | Lower Shire | 24 | 16–390 | 0.09–1.0 | <0.2–30 | 0.2–14 |
| 1G | Lower Shire | 61 | 18–3550 | 0.09–41 | <0.1–84 | 0.6–15 |
| 1H | Lower Shire | 86 | 24–3110 | 0.22–18.5 | <0.1–62 | 0.4–3.0 |
| 1K | Lower Shire | 22 | 14–2160 | <0.7 | <0.2–40* | 0.4–13 |
| 1L | Lower Shire | 8 | 81–690 | <0.07–9.9 | <0.2–53* | 0.3–15 |
| 7 | S. Rukuru | 71 | 6–500 | 0.02–9.3 | <0.2–65 | <0.1–3.3 |

*Quality of data uncertain; nd: not determined

### 2.3.2 Nitrogen species

The WHO guideline value for nitrate (N) in drinking water is 11.3mg/L. Sporadic high concentrations were apparent in the groundwater from the Lower Shire Valley though even here, $NO_3$ – N concentrations were mostly less than 5 mg/L. Many of the measured concentrations were below the detection limits (<0,7 mg/L). (Table 3) Low values of nitrate imply minimal pollution inputs, although the analyses referred to are relatively old. It is unclear to which extent they reflect modern groundwater compositions. (BGS & WA, 2004) High nitrate levels in the groundwater can be a result of irrigation practices. (Conrad et. al., 1999)

Deterioration of water courses through pollution from agricultural runoff, sewage and industrial wastes are concerns for surface-water quality, but there is currently little information available to assess their impact on groundwater resources.

The significance of denitrification[1] has also not been quantified. This may be an important process in some of the Quaternary alluvial aquifers where conditions are likely to anaerobic. Such aquifers are to be found in the Lower Shire area. (See section 2.2.1) No data are available on the concentrations of other nitrogen species (nitrite, ammonium) in groundwater from Malawi. (BGS & WA, 2004)

### 2.3.3 Salinity

Particularly high concentrations of sodium and chloride have been reported for the groundwater from the Lower Shire Valley (Bath, 1980), both as a result of evaporation and

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[1] Bacterially-mediated removal of nitrate from groundwater under anaerobic conditions.

dissolution of evaporite minerals. Most boreholes close to the river and with shallow water tables have saline groundwater compositions. Chloride concentrations up to 400mg/L and sodium up to 3600mg/L have been reported. (Bath, 1980) Further away from the river, the saline groundwater results from the dissolution of evaporate minerals such as halite (NaCl) and gypsum ($CaSO_4 \cdot 2H_2O$). In groundwater alluvial deposits close to the edge of the Karoo sediments (Figure 6), chloride concentrations up to 2100mg/L and sulphate up to 2400mg/L were recorded. High salinity is problematic because alternative water sources are not readily available. The vertical variation in groundwater salinity in the Shire Valley may be significant, but has not yet been studied. (BGS & WA, 2004)

### 2.3.4 Fluoride

There were reported high fluoride concentrations in the Lower Shire Valley, up to 15mg/L in some samples. (Table 3) Hydrothermal sources of fluoride are likely in this active Rift zone. (BGS & WA, 2004)

### 2.3.5 Iron

UN (1989) gave ranges for total iron in groundwater from both weathered basement rocks and alluvial sediments as 1-5 mg/L. In Lower Shire Valley, there have been reported concentrations of iron up to 84 mg/L. (Bath, 1980) However, the ranges quoted reflect compositions of unfiltered water samples and therefore represent total iron (including particulate iron) rather than dissolved iron. As such, the concentrations will vary considerably according to the turbidity of the water and the degree of flushing (pumping) of the well before collection. Nonetheless, the total concentrations reported may be indicative of the concentrations in water used for domestic purposes.

High concentrations of dissolved iron can occur under acidic or reducing conditions. There is no evidence for strongly acidic groundwater in Malawi, but anaerobic conditions could exist in some aquifers, particularly in the alluvial deposits of the Lower Shire Valley. (BGS & WA, 2004) Some studies have suggested that the high iron concentrations in Malawian groundwater derive from corrosion of metallic pump and pipe parts rather than from the aquifer. These sources are difficult to distinguish. Both are possible, but mineral sources within the aquifer are considered more significant. Nonetheless, some improvements in water quality with respect to iron have been reported following replacement of ferrous casing with a PVC alternative. (Chilton & Smith- Carington, 1984; Lewis & Chilton, 1989)

The high concentrations observed in the groundwater are not likely to be detrimental to human health. Still, the effects on water colour and taste create problems. High iron concentrations are one of the main causes of well abandonment in Malawi. (Bath, 1980)

### *2.4 Future climate predictions*

#### 2.4.1 Temperature

According to IPPC fourth assessment report, it is very likely that all land regions will warm in the 21st century. In Africa, warming is very likely to be larger than the global annual mean warming throughout the continent, with drier subtropical regions warming more than the moister tropics. Mean temperatures in Lower Shire region have increased by 2.3% (Phiri et al, 2005)

#### 2.4.2 Precipitation and droughts

Rainfall in southern Africa is likely to decrease in much of the winter rainfall region and western margins. (IPCC, 2007) Increased inter-annual variability has, however, been observed in the post-1970 period, with higher rainfall anomalies and more intense and widespread droughts reported (e.g., Richard et al., 2001; Fauchereau et al., 2003). In different parts of southern Africa (e.g., Angola, Namibia, Mozambique, Malawi, Zambia), a significant increase in heavy rainfall events has also been observed (Usman and Reason, 2004). A concrete example is when heavy rain caused flooding in the Lower Shire Region in January 2007. It was the districts Chikwaka and Nsanje in southern Malawi that were most affected. This area has many rivers, and the Shire River overflows in the wet season. Some of the consequences were crops destroyed, houses collapsed and animals swept away. (DREF Bulletin, 2007) Severe droughts occurred in the 1991/1992 and 1994/1995 growing seasons (November -April). (MNREA, 2002) Climate models update for the period November to January 2008 indicate that Malawi will experience normal to above normal total rainfall amounts with an increased chance of floods. (DMS, 2007)

Analysis of the water balance shows that evapotranspiration exceeds annual rainfall.
This result implies that the excess water used for evapotranspiration is obtained from the groundwater. (MNREA, 2002)

The extent to which current regional models can successfully downscale precipitation over Africa is unclear, and limitations of empirical downscaling results for Africa are not fully understood. (IPCC, 2007)

## 3 Discussion

### *3.1 Parallels*

#### 3.1.1 Makgadikgadi Pan complex in Botswana

The high levels of salinity along with nitrate pollution are the most common groundwater quality concern in Botswana. Elevated salinity levels render groundwater unsuitable for human and livestock consumption, particularly in the semi-arid Kalahari region. The most affected areas are associated with mining, but there are also instances where elevated concentrations appear to stem from geological formations. (Vogel et al.,2003) Around the Makgadikgadi Pan complex, which is one of the largest saltpans in the world, groundwater salinity proved to be of gravest magnitude. Data showed that the groundwater was highly saline (TDS > 10 000 mg/L) and hyper saline (TDS > 45000 mg/L) in places. A linear correlation analysis suggested that halite (NaCl) dissolution was the mineral source of both sodium and chloride for the vast majority of groundwaters. A considerable amount may originate from wind-blown salts from the evaporative deposits of the Makgadikgadi Pan complex. (Wood et al., 2004)

### 3.1.2 Ghanzi in Botswana

Due to extremely large precipitation, flooding occurred in large parts of the Ghanzi area in the 1999/2000 rainy season. Cattle also died. Such exceptional conditions modify the general recharge patterns in the area. The conceptual hypothesis is that salts that had collected in specific parts of the unsaturated zone during drier seasons were leached into the subsurface. Following a high recharge event, it appears that most of the high salinity water was removed either through pumping or diluted by natural migration. As a result, groundwater salinity and nitrate concentrations at nearly all the affected boreholes returned to lower levels within three to four years. (Tredoux and Talma, 2006)

### 3.1.3 Wadi El-Natrun area in Egypt

In This area in Egypt, soils are affected by the quality of the irrigation water. Sodium chloride is the dominant salt, and sodium saline irrigation water (-5000 ppm) is the main factor for salinity formation. (El-Mowelhi, 2007)

## *3.2 Consequences*

### 3.2.1 Nature and societal response

As the climate is changing together with population growth, one can expect not only increased deforestation, but also increased poaching in parks and game reserves, soil erosion, overgrazing, overfishing and in general over-exploitation of the available resources. Soil erosion in Malawi is one of the major types of land degradation that poses the biggest threat to sustainable agriculture and also leads to contamination of water and soil resources. (DREA, 1994) Ecologically delicate marginal areas such as hillsides and steep slopes are being cleared for cultivation. As a general rule of thumb, Africa’s ecology is fragile. Owing to their fragility, African soils (those of Malawi included) can withstand only a number of years of continuous use or non-stop use. After that, mineral leaching, hard panning and soil erosion set in. Increased deforestation is a problem not only because forests provide for the nation’s fuel requirements, but forest cover also protects steep slopes and upper river catchment areas from the effect of soil erosion, flash flooding and low rainfall infiltration in the soil. Overgrazing is a consequence due to increase in livestock production. Malawi has been affected by lack of food and undernourishment, and this make the Malawians vulnerable to many diseases, i.e. AIDS. People are forced to use intensive methods in agriculture so that more food can be produced. Socioeconomic consequences like migration, deserted villages and unemployment are also results that can be seen. (Kalipeni, 1992) Changes in rainfall have resulted in changes in the growing seasons as well as in crops grown. For example, maize used to be grown in November, but it is now being grown in December. Clearly, farmers are now uncertain of when to plant. (Khamis, 2006)

### 3.2.2 Impact on groundwater recharge

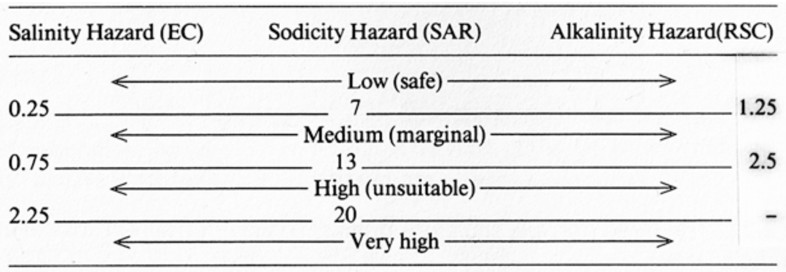
Since climate changes now is a reality of life on earth, the interest in determining impacts on climate change on groundwater is growing rapidly. However, there has been very little research on the impact of climate change on groundwater. (Alley, 2001) Climate change affects not only the volume of rainfall, but also the frequency, duration and intensity of rainfall events, which is described in section 2.4.2. The frequency of rainfall events will affect antecedent soil moisture conditions. Infrequent events are less likely to cause saturated conditions. The drier top soils before the rainfall event may allow increased infiltration but decreased recharge. This is depending on the soil type and structure. Increased event intensity and duration may have the opposite effect. (Cavè et al., 2003) With increased frequency and magnitude of floods, groundwater recharge may increase. This is particular a case in semi-arid and arid areas where heavy rainfall and floods are the major sources of groundwater recharge. Bedrock aquifers in semiarid regions are replenished by direct infiltration of precipitation into fractures and dissolution channels, and alluvial aquifers are mainly recharged by floods (Al-Sefry et al., 2004). Although rising watertables in dry areas are usually beneficial, they might cause problems, e.g., in towns or agricultural areas (soil salinisation and wet soils). Climate change is likely to have a strong impact on the salinisation of groundwater due to increased evapotranspiration. This is the case in Malawi. (IPCC, 2007) Indirect impacts on groundwater resources may also arise from climate change impacts on vegetation and human activities e.g groundwater abstraction patterns. Declining rainfall will affect groundwater storage over both short and long term. Decreased recharge will lead to lowering of the groundwater table, and increase both drilling and pumping costs for groundwater users. (Cavè et al., 2003)

## *3.3 Recommendations*

### 3.3.1 Amelioration of salt-degraded soils

Salt degraded soils, are as earlier mentioned, typically associated with semiarid and arid climates. Irrigation water is often a factor in their formation or reclamation. Water of poor quality can degrade soils, and water of good quality can improve them. Water quality is measured by the degree of salinity, sodicity and alkalinity, as shown in table 4. RSC means the residual Sodium Carbonate Value. SAR means the Sodium Adsorption Ratio and is based on the concentration of $Na^+$, $Ca^{2+}$ and $Mg^{2+}$ in solution.

Table 4: Characterization of water based on its potential to degrade soil properties



| Salinity Hazard (EC) | Sodicity Hazard (SAR) | Alkalinity Hazard(RSC) |
|---|---|---|
| | Low (safe) | |
| 0.25 | 7 | 1.25 |
| | Medium (marginal) | |
| 0.75 | 13 | 2.5 |
| | High (unsuitable) | |
| 2.25 | 20 | - |
| | Very high | |

(McBride, 1994)

Continuous application of irrigation water in dry land water management will ultimately cause the soil to inherit any undesirable chemical characteristics of the applied water. The soil will gradually come to a new equilibrium that is set by the properties of the irrigation water. Irrigation water with a high SAR value applied continuously to a nonsodic soil would ultimately raise the exchangeable ESP.

In order to improve salt-degraded soils in arid climates, the salts have to be removed by irrigation and drainage. The irrigation water must have acceptable values of EC, SAR and RSC. These values are described in Table 4. EC multiplied by the water volume is roughly proportional to total salt in the drainage or irrigation water. In a steady-state situation, the soil is neither accumulating salt nor losing salt. The salt coming into the soil dissolved in irrigation water, $Q_{\text{Irrigation Water}}$ must equal the quantity of salt escaping in drainage water, $Q_{\text{Drainage Water}}$, or equivalently:

$$EC_{\text{Irrigation Water}} * V_{\text{Irrigation Water}} = EC_{\text{Drainage Water}} * V_{\text{Drainage Water}} \qquad (8)$$

During a dry season, when rainfall is low, irrigation water provides virtually all of the water that enters the soil. The steady state situation, along with the situations in which salts are accumulating or being lost from the soil profile, is diagrammed in Figure 8.

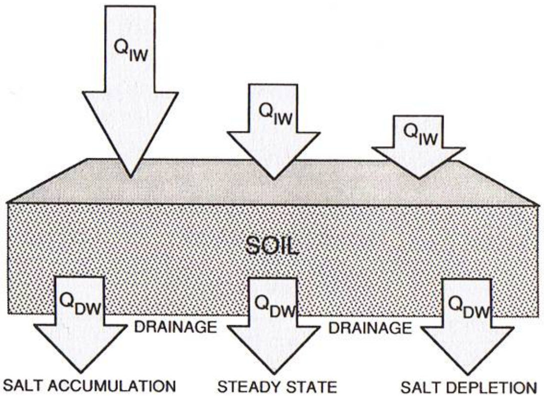


Figure 8: The three possible situations of mass balance for salts in soils of arid and semiarid climates. (McBride, 1994)

The salinity of the irrigation water determines whether salt build-up in the soil can be avoided by the application of a sufficient volume of irrigation water. It might be found that 80% of the irrigation water is lost at the soil surface by evaporation and transpiration. Only 20% of the applied water is drainage water. This situation counts in a steady-state situation where the soil moisture level is not changing.

$$\frac{EC_{IW}}{EC_{DW}} = \frac{V_{DW}}{V_{\mathrm{IW}}} = 0{,}2 \qquad (9)$$

Equation 9 counts for the situation described above. The salt concentration, or EC, in the drainage water must be five times greater than in the irrigation water. $V_{DW}/V_{IW}$ is the *leaching ratio* or *leaching requirement* because it specifies the minimum volume of irrigation water needed to prevent salt build-up. If a greater volume of irrigation water with good quality than the leaching ratio is applied, the salt levels in the soil would actually decrease. The reason why this is difficult to achieve is because such water is often expensive, or/and there is a lack of it.

It should also be mentioned that saline-sodic soils are likely to disperse when the excess soluble salts are leached out. Further, sodic soils may be impermeable to such leaching from the start. Flocculating agents like gypsum ($CaSO_4$) should in practice have been applied to the soils before the salts are leached out.[2] Agents like elemental sulphur or sulphuric acid neutralize alkalinity. They can therefore be beneficial amendments fore the more alkaline salt-

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[2] Agglomeration of individual particles in water suspension to form visible aggregates, which then settle out by gravity, is called flocculation.

degraded soils. When alkalinity is neutralized, the pH would be in a more acceptable range for plant growth. (McBride, 1994)

### 3.3.2 Land use change

Before the penetration of Africa by Europeans, the Africans had developed a unique system to preserve the environment. This was the shifting of cultivation and mixed cropping. Essentially, in this system a family clears or slashes and burns a peace of wooded area. This ashes act as fertilizer for the next years or so. Different types of crops are grown concurrently on the same plot, and this protects the soils from turning into laterite, brick-like soils. After three years they would move on to another piece of land, while the former stands fallow to regenerate. However, such a system requires a reasonably low population density. (Kalipeni, 1992) According to Ministry of Natural Resources and Environmental Affairs in Malawi (2002), the climate change scenarios developed show that new adaptation options need to be considered and incorporated in the crops sub-sector:

- Changes in cultivated land area in line with projected climate change
- Changes in crop types
- Changes in crop location

The role of land use and land-cover change is one area that should be further explored. (IPCC, 2007)

### 3.3.3 Irrigation practices

Groundwater has a history of local mismanagement in the form of overdraft and contamination due to ignorance and lack of regulation. Irrigation in arid areas of the world provides two essential agricultural requirements: a moisture supply for plant growth which also transports essential nutrients; and a flow of water to leach or dilute salts in the soil. Irrigation also benefits croplands through cooling the soil and the atmosphere to create a more favourable environment for plant growth. (Walker, 1989)

Some irrigation systems can be both expensive to construct and operate, other systems can have high labour requirements. The quality of the water will also affect the irrigation practices. A poor quality water supply must be utilized more frequently and in larger amounts than one of good quality. (Discussed in section 3.3.1) Individuals, groups of individuals, and often the state must join together to construct, operate and maintain the irrigation system as a whole. Many of the irrigation projects are often financed by outside donors and lenders. (Walker, 1989) According to MNRERA 2002, some of the changes in crop management strategies should be:

- Use of irrigation water and fertilisers
- Control of pests, weeds, parasites, and diseases
- Soil drainage and erosion control
- Crop husbandry practices

Although the government within the Water and Sanitation sector in Malawi has initiated a number of projects aimed at increasing access to portable water and sanitation facilities, there is still a long way to go. Some improvements have though been made in boreholes, piped – water, gravity schemes, extending water supply capacity, conserving and managing water resources and sanitation. (Malawi Government, 2005)

# 4 Conclusions

It is predicted that in the coming decades, one of the biggest global resource problems will be access to clean freshwater. Probably, between 2 and 7 billion people will live in water scarce countries in the middle of this century. Lower Shire area, along with many other regions in the world, is facing several challenges when it comes to groundwater issues. The region is experiencing rapid population growth, and combined with bad economy and climate changes, the inhabitants are facing several problems.

Climate change is likely to have a strong impact on the salinisation of groundwater due to increased evapotranspiration. Indirect impacts on groundwater resources may also arise from climate change impacts on vegetation and human activities. Smallholder farmers have been exposed to increased droughts and floods, which are affecting food security. It can seem as the poor is getting poorer.

It is recommended that the role of land use and land-cover change should be further explored. Another area that also should be further explored is irrigation. The government within the Water and Sanitation sector in Malawi has initiated a number of projects aimed at increasing access to portable water and sanitation facilities, but there is still a long way to go also in this area.

Since two thirds of the Malawians live below the poverty line, they need help from rich industrialized countries to secure and protect their groundwater resources. Political will and action is required to stop pollution and contamination of groundwater from occurring further. Further research on the impacts of climate variability and change on groundwater is needed together with better understanding of the processes leading to salt problems.

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