Challenges and Opportunities For Safe Water Supply in Mozambique

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ABSTRACT

In Mozambique, despite considerable investments in the promotion of drinking water supplies, the access to quality water of sufficient quantity for the majority of people is still far from optimal. Current official figures report that nearly half of the country´s population and about 45 per cent of urban residents do not have access to safe water. As a result of poor performance or absence of public water services, in most areas, informal private operators supply water to the most of underserved populations. Management of drinking water quality is inadequate and is affected by limitations at production and distribution level.

This research included an analysis of drinking water supply aspects of Mozambique with the view to contribute to the understanding of the factors affecting present drinking water supply and the challenges facing the water governance sector in developing and maintaining sustainable drinking water supplies. Emphasis was put on identifying critical factors affecting production and management of drinking water quality.

The analysis of water quality aspects shown that present limitations in water safety and water quality are due mainly to lack of adequate treatment, inadequate management of distribution and lack of knowledge among operators. The quality of water sources used for drinking water production is very similar to that of many other parts of the world and the methods used for water treatment are, suited for production of excellent treated water quality. However, poor knowledge and inefficient operation of treatment processes causes drinking water production to be ineffective.

Methods of improving drinking water treatment were also investigated. For reasons of sustainability, low cost treatment methods were selected. Pre-treatment with up-flow roughing filtration and use of natural coagulants (*Moringa Oleifera*) for water treatment were the methods tested. The results proven that if properly incorporated in the drinking water treatment strategy of the country, these methods can provide a viable and sustainable alternative for improved drinking water production.

Service quality aspects of informal private operators were also analysed. It was concluded that they provide a reliable alternative for access and for expansion of service delivery to areas lacking piped water supply. It was also concluded that present human health risks for consumers relying on these services are comparable to that of formal water supplies. However, the lack of an inclusive regulatory framework to this type of service providers limits the possibilities for regulation of their activities. Therefore, regulation aspects around formal and informal service providers formed part of the research and a proposal for expanding the existing regulatory framework was presented. Licensing and regulatory functions needed are presented.

The main conclusion of this study is that two major factors affect drinking water supply in Mozambique specifically; limited service coverage and; limitations in water safety and water quality caused by lack of adequate treatment, poor management of water distribution and lack of knowledge among operators. The main contribution of this study is to the water governance sector of Mozambique and it refers to the various possibilities offered by methods tested during this study, for sustainable improvement of drinking water production. In addition, the findings of the discussion of the drinking water supply situation looking not only at quantity but also at quality aspects of service delivery as was done in this study, will hopefully help the sector redefine its strategy of addressing drinking water supply in Mozambique.

CONTENTS

APPENDED PAPERS

This thesis is based on the following papers, which will be referred to in the text by their Arabic numerals. The papers are appended at the end of the Thesis.

Paper 1 Matsinhe, N.P.; Juizo J.; Persson, K.M. and Rietveld L.C. (2008). **Challenges facing drinking water production in Mozambique – A review of critical factors affecting treatment possibilities.** *Submitted to journal Water Science and Technology.*

Paper 2 Matsinhe N.P.; Juizo J. and Persson, K.M. (2008). **The effect of intermittent supply and household storage on the quality of drinking water in Maputo**. *Submitted to Water Science and Technology – Water supply.*

Paper 3 Matsinhe, N.P.; Juizo J.; Rietveld L.C. and Persson, K.M. (2008). **Water services with independent providers in peri-urban Maputo: Challenges and opportunities for long-term development**. *Water SA, Vol. 34, No. 3, pp 411-420*.

Paper 4 Matsinhe N.P.; Juizo J.; Macheve, B. and dos Santos, C. (2007). **Regulation of formal and informal water service providers in peri-urban areas of Maputo, Mozambique**. *Journal Physics and Chemistry of the Earth, Vol. 33, No. 8-13, pp 841-849.*

Paper 5 Matsinhe N.P. and Persson, K.M. (2008). **Hydraulic flocculation with up-flow roughing filtration for pre-treatment of surface water prior to conventional rapid sand filtration**. *Submitted to Environmental Science and Engineering.*

Paper 6 Arnoldsson, E.; Bergman, M.; Matsinhe N.P. and Persson K.M. (2008). **Assessment of drinking water treatment using Moringa Oleifera natural coagulant.** *Watten, Vol.64, pp 137-150.*

RELATED PUBLICATIONS

Conference Proceedings

Matsinhe N.P.; Quessoni J. (2005): Influência da Reserva Domiciliar na qualidade da Água consumida na cidade de Maputo. *4^{th} Congresso Luso-Moçambicano de Engenharia, 29 August -1 September 2005, Maputo, Mozambique.*

Matsinhe N.P.; Persson K.M. (2006**):** Opportunities to improve the drinking water quality of Maputo-Mozambique. *International Congress on Integrated Water Research Management and Challenges of the sustainable development, 23-25 May 2006, Marrakech, Marroco.*

Juizo D.; Matsinhe N.P. (2006): Water Services in peri-urban areas of Maputo with private sector participation. 7^{th} *WARFSA/WATERNET/GWP-SA symposium, 1-3 November 2006, Lilongwe, Malawi.*

Matsinhe N.P.; Juizo J.; Berta M and Clara dos Santos (2007): Regulation of formal and informal water service providers in peri-urban areas of Maputo, Mozambique. 8^{th} *WARFSA/WATERNET/GWP-SA symposium, 31 October - 2 November 2007, Lusaka, Zambia.*

Supervised Master Thesis

Malin Kajsa and Anna Linquidist (2004). The effect of intermittent supply and storage in the quality of drinking water in Maputo. *Department of Water Resources Engineering, Faculty of Engineering, Lund University, TVRL 2005: 7.*

Anna Gustafsson and Maria Johansson (2006). An Investigation of nutrient levels along the Mbuluzi River- A background for sustainable water resources management. *Department of Water Resources Engineering, Faculty of Engineering, Lund University, TVRL 2006:9.*

Arnoldsson Emelie, Bergman, M. (2007). Assessment of drinking water treatment using Moringa Oleifera natural Coagulant. *Department of Water Resources Engineering, Faculty of Engineering, Lund University, TVRL 2006: 7*

1. INTRODUCTION

1.1 Background and identification of the Problem

The provision of adequate water supplies is essential in order to meet basic human needs and to address poverty, and promote economic development, health and hygiene. Water supply has a long history in this respect, and the rationale for its improvement has always been the need to protect public health, to reduce mortality and morbidity in the population, and to promote economic development, especially in the developing world.

During the last four to five decades, many cities in the developing world, particularly African cities, have experienced rapid population growth but, water and sanitation infrastructure has lagged behind. Despite considerable investments made in the development of water supply infrastructure, the progresses that have been registered in many of those places have been slow. Achieving the target set in the United Nations Millennium Declaration of halving the proportion of the population without access to potable water supplies by 2015 remains therefore a challenge (OECD, 2007). The *Global Water Supply and Sanitation Assessment 2000*[1] estimated, for instance, that in 2002, about 1.1 billion people worldwide lacked access to adequate water supplies, and that those lacking services were chiefly in Asia and Africa. In absolute terms, Asia has the highest number of underserved citizens, but proportionally this group is larger in African countries (WHO/UNICEFF, 2006) where, an estimated 27% of the population did not have access to potable water. Levels of service by world population, defined as access to piped water was estimated to be 47% while, in Africa, this figure was only 24%.

The situation in Mozambique does not differ significantly from that reported in many other African countries. Coverage estimates obtained from the *Mozambique Demographic and Health Survey* (WHO/UNICEF, 2006); indicate that in 2003, 72% of the urban population, corresponding to about 37% of the country's total population, had access to adequate drinking water supplies. This figure in rural areas was only 28%. The proportion of residents with access to piped water through household connections was far less, corresponding to only 18% of the urban population and to less than 2% in rural areas (WHO/UNICEF, 2006).

Despite massive investments in the development and extension of the infrastructure for drinking water supply in Mozambique, service provision to a large number of urban settlements is still far from optimal, mainly because the investments have focused on increasing water production and water availability, while little attention paid to other, equally important aspects of service delivery such as, the quality of the services and water quality. Added to this, lack of adequate strategies for strengthening, institutional capacity and human resources, and for securing financial arrangements needed to guarantee the long-term sustainability of the infrastructure, had worsened the situation. The consequences of this situation are many, and include:

- Inadequate coverage of piped water supplies in most (if not all) urban centres of the country. Poor quality of piped water supplies due to factors such as intermittency, flow and pressure fluctuations, and frequent discontinuities of service provision;

[1] Later updated by UNICEFF in September 2002

- difficulties in ensuring water of acceptable quality due to a lack of, or malfunctioning of ,treatment facilities, and sub-optimal operation of treatment processes at existing treatment facilities due to factors such as technological and operational constraints and lack of supplies;

- difficulties in maintaining acceptable treated water quality during transport, storage and distribution; and

- Proliferation of alternative service providers in the informal water market in an environment where licensing and regulatory tools for service providers are still lacking.

The aim of this study was to contribute to the overall understanding of the status of the drinking water supply in Mozambique and the challenges facing the water supply governance sector in developing and maintaining sustainable drinking water supplies. The study focuses on the quality aspects of urban water supplies with the emphasis on the identification of critical factors affecting water treatment, the sustainable production of drinking water, and the management of drinking water quality by formal and informal service providers. The starting point for this work was the recognition that investments in the development of urban water supplies have generally focused in increasing water availability, rather than other dimensions of water supply services, such as water quality, service continuity, equity and reliability, which are now recognized as important factors in the long-term planning of investments in this sector.

1.2 Objectives of the research

The main objective of this research was to analyse the drinking water supply system in Mozambique, based not only on the quantitative aspects but also on qualitative aspects of drinking water supply. Some of the critical factors affecting drinking water production and the problems and challenges facing the sector in supplying potable water in sufficient quantities in the long term are discussed, and methods of improving the situation evaluated. Given the wide range of aspects to be covered, the following research questions were defined to help address the objectives of the study.

1. Which key factors currently affect drinking water production and the management of drinking water quality in the context of urban water supplies in Mozambique?

2. Given the present status of urban water supplies, what alternatives are there for subserviced consumers to overcome the inconveniences caused by a lack of, or inadequate, piped water supplies? In addition, which factors affect the current and long-term sustainability of service provision through alternative service providers?

3. Given the prevailing situation regarding drinking water production and the management of drinking water quality, which options exist to improve the efficiency of drinking water production in order to secure safe and sustainable drinking water supplies in the long term?

1.3 Overall methodology

In order to address the research questions outlined above, the study was divided into a number of steps as follows.

1. The identification of factors affecting the overall production of drinking water in the country. This included the investigation of source and treated water quality, the evaluation of treatment methods and performance efficiencies in a number of waterworks, as well as the evaluation of procedures used to assess raw and treated water quality and to control processes during water treatment. This step helped address the first research question.
2. The assessment of the quality of water supplied by formal and informal service providers, and the identification of factors contributing to water quality deterioration during distribution. The quality of drinking water provided by the formal network in Maputo and alternative service providers operating in the various neighbourhoods of Maputo was used in this investigation to help address the first and second research questions.
3. The assessment of the main characteristics of water supply services in peri-urban Maputo, the quality and organization of the management of services and the challenges facing alternative service providers in providing water of sufficient quality and quantity in the long term. In addition to this, the possibility of expanding the reach and influence of the existing regulatory framework to cover alternative service providers was also evaluated. The results of these assessments were used to address the second research question.
4. The evaluation of methods to improve drinking water treatment and the sustainability of drinking water production through low-cost treatment technologies. The results of pilot-plant experiments and laboratory testing were used to address the issue of the sustainable development of drinking water treatment, i.e., the third research question.

1.4 Thesis structure and appended papers

This thesis consists of a summary and six appended papers. In the summary the overall status of the drinking water supply in Mozambique is discussed based on a review of past studies, reports and related papers. This review, which focused on the organization of the drinking water sector and on the methods used for the production and distribution of drinking water in Mozambique, provided the background necessary to address the research questions explored in this study. The major findings obtained during individual studies conducted as part of this research are also presented in the summary.

This thesis describes research mainly concerning the water supply services in the city of Maputo. However, the results are used to infer the overall situation of drinking water supply in the country and to discuss the main challenges facing the drinking water governance sector in developing and maintaining safe and sustainable water supply services in the long term. The individual studies focused on quantity and quality aspects of the formal and informal water supply services, drinking water production methods and factors affecting water treatment and possible methods for improvement. Research results have also been presented at international conferences as well as in the appended papers.

In **Paper 1** a critical review is presented of the main factors affecting current drinking water production in Mozambique. Given that most drinking water supplies use surface water for drinking water production, the water quality of six rivers used for drinking water production was analysed and the critical factors affecting treatment possibilities identified. The performance efficiency of three major waterworks in the country was also analysed.

In the study presented in **Paper 2**, the quality of drinking water in the supply network of Maputo was analysed, and the factors causing water quality deterioration during distribution investigated. Field work was conducted in an area of central Maputo to investigate the overall quality of drinking water in the Maputo water supply network.

Paper 3 and **Paper 4** describe the analysis of the quantity and quality of water supply services provided by formal and informal service providers. **Paper 3** addresses the main challenges facing alternative service providers, notably small-scale independent providers (SSIPs) in supplying water of sufficient quality in sufficient quantities in the long term. Potential human health risks associated with the consumption of water provided by SSIPs were also investigated. The study described in **Paper 4** is based on the findings presented in **Paper 3** concerning the activities of alternative service providers in peri-urban Maputo. **Paper 4** discusses aspects of service quality in the informal water market and the possibility of expanding the reach and influence of the regulatory framework for formal water services to also cover SSIPs.

Paper 5 presents the results of experimental work conducted to investigate methods of reducing turbidity and improving suspended solids removal with the use of up-flow roughing filters for hydraulic flocculation and conventional rapid sand filtration for final treatment. In **Paper 6** a comparative study of coagulation efficiency using extracts of the natural coagulant, *Moringa oleifera* (*M. oleifera*) and aluminium sulphate in the treatment of surface water is presented. In this study, standard jar-test experiments were used to investigate the potential of using seeds of *M. oleifera* instead of aluminium sulphate, and to assess the optimal dose and conditions for their use. The use of *M. oleifera* together with coarse to fine sand filtration, and the possibility of using *M. oleifera* at small-scale treatment plants were also investigated.

2. OVERVIEW OF THE DRINKING WATER SUPPLY SECTOR OF MOZAMBIQUE

2.1 Background on the study area

Mozambique is located in the south-eastern part of Africa bordering the Mozambique Channel, between South Africa and Tanzania. It lies between coordinates 18° 15′S and 35° 00′E (Figure 1) within a typically tropical/subtropical region, where the climate is under the influence of the equatorial low-pressure zone with a NE monsoon in the warm season. The climate according to the Köppen classification system is tropical rain savannah, with mean average temperatures between 25 °C and 26 °C in the low-lying coastal areas and lower temperatures in the higher areas.

Figure 1 Map of Mozambique showing geographic location of the country and the location of major cities. Source: Google maps.

Because of the influence of the NE monsoon, rainfall is mainly restricted to the warm season between October/November and April. The rainfall varies considerably within the country, ranging from over 2400 mm/year in the northern parts of the country to only 300 mm/year in the southern parts, particularly in the Chicualacuala area near the border with Zimbabwe in the Limpopo River basin (Ferro & Bouman, 1987). In terms of water balance, the region is generally classified as having a negative water balance, according to the Budyko aridity coefficient[2] (DNA, 1999).

The case study area described in this thesis concerns the Mozambican capital city of Maputo and the adjacent city of Matola, both of which are served by the same water supply system. The capital city is characterized by three kinds of districts, namely an area with high-rise buildings, the so-called ‘cement city’, a few inner suburbs built before independence in 1975, and the outer neighbourhoods of the peri-urban areas consisting mainly of informal settlements built during the unstable periods that followed independence.

[2] Synopsis of Water Resources of Mozambique (1999)

In similarity to many other parts of the developing world, the peri-urban areas of the city of Maputo have developed without proper urban planning, due mainly to rapid population growth and lack of financial resources for investments in infrastructure and, as a result, many of these areas today face severe difficulties regarding access to public utilities such as water, sanitation and electricity. While the residents of the neighbourhoods located near the cement city have access to piped water through overstretching the formal network, their water supply is unreliable due either to a lack of pressure in the nearby grid, or because they are located beyond the reach of the formal network. In many of these areas, the lack of an adequate supply of piped water has prompted the emergence of a multiplicity of alternative providers, among which small-scale independent providers and household water resellers, presently constituting the most reliable source of water for a large proportion of un-connected residents. Taking the city of Maputo as an example, SSIPs presently account for the water supply to nearly 32 % of households in the city, compared with roughly 62 % of households that relies on the formal network (Gumbo, 2004; Seureca & Hydroconseil, 2005). The remaining 6 % rely on other kinds of supply.

The situation in the city of Maputo is very similar to that in other cities in the developing world, where alternative service providers are reported to play an important dominant role in serving unconnected residents. It has been estimated, for example, that SSIPs supply as much as half the urban population in some countries of Asia, and nearly a quarter of the urban population of Latin America (Kariuki & Schwartz, 2005; OECD, 2007). In African countries, nearly half of urban dwellers are believed to rely on alternative service providers for at least a portion of their drinking water (Collingnon & Vézina, 2000). The list of examples in Africa includes the cities of Bamako, Cotonou, Conakry and Dar es Salaam, where alternative service providers are the main source of drinkable water for more than 60 % of households, and cities such as Abidjan, Nairobi and Ouagadougou, where they are reported to serve 22 % to 28 % of unconnected households (Reweta & Sampath, 2000; Collingnon & Vézina, 2000;).

2.2 Overview of the legal and institutional framework

In Mozambique, water supply services are the mandate of the National Directorate of Water-DNA, under the Ministry of Public Works and Housing. DNA is the primary agency responsible for water resources policy making, planning and management, and for ensuring the provision of water supply and sanitation services throughout the country.

In 1995 the first National Water Policy (NWP) was approved, which has since then guided water sector reforms. In line with the objectives of the NWP, the government was relieved of the task of the actual implementation of water supply services to focus on policy making and planning of the management of water supply services (DNA, 1995). Special attention is devoted to improvements in water supply services, the encouragement and regulation of the involvement of private service providers, and the participation of beneficiaries in the management of water supply services such as that provided through public standpipes.

As part of the reforms in the drinking water supply sector, the Government of Mozambique established the Framework for Delegated Management of Water Supply in 1998 (Decree Numbers 72, 73 and 74:9 of December 1998), which created the legal basis for the delegation of operation and management of public water supply services to independent private entities through concessions, leasing or management contracts (Zandamela, 2002; Gumbo et al., 2003; Sal-consultores, 2005). The main institutions involved in the Framework are: the Ministries of

Public Works and Housing, of Planning and Finance and of State Administration, the National Directorate of Water, the Water Supply Investment and Assets Fund (FIPAG), the Council for the Regulation of Water Supply (CRA), the Co-ordinating Forum for Delegated Management, the municipal authorities and private operators (Figure 2).

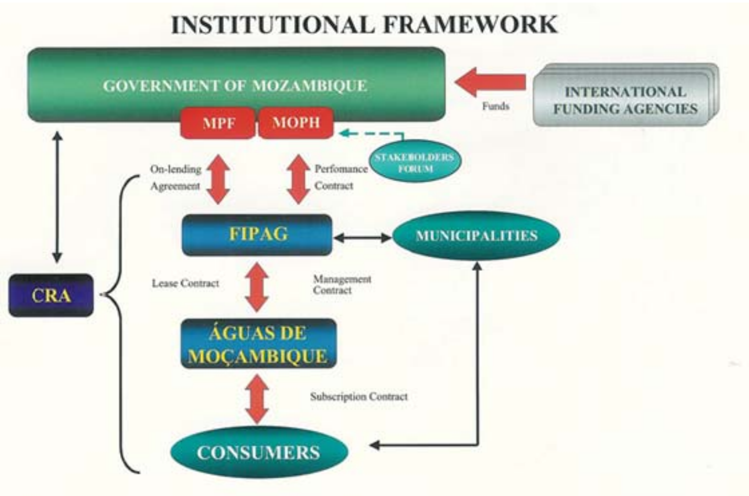

Figure 2 Overview of the Framework for Delegated Management of Water Supply in Mozambique. Source: Sal-Consultores 2005).

The FIPAG was created to take over the fixed assets and the duties and obligations for water service delivery in five major cities of Mozambique, previously serviced by state water companies. The CRA was created with the objective of regulating private sector contracts under the rubric of the framework. As such, CRA is an independent regulating body designed to ensure a balance between service quality, the degree to which it meets consumer interests, and the economic sustainability of the water system. It mediates the interests of the main private service providers and the lessor (FIPAG) aiming to reconcile them through the mechanism of tariff setting. The geographical limit of CRA's influence is therefore defined by the boundary of the area of each contracted concession.

Private sector participation in water supply in Mozambique started in 1999 when the first private operator, Águas de Moçambique-AdeM, was awarded a 15 years contract to provide services to the cities of Maputo and Matola, and management contracts for the cities of Beira, Quelimane, Nampula and Pemba (Zandamela, 2002; Gumbo et al., 2003). In 2004, the government decided to expand the framework for delegated management to include four southern cities of Mozambique. The water supply systems of the cities of Xai-Xai, Chokwé, Inhambane and Maxixe were integrated and delegated to the Dutch company Vitens (OECD, 2007). CRA increased its ambit to cover also these cities. In 2006, a further expansion of the delegated management took place in the central region of Mozambique and five more towns were included.

In areas outside the cities with delegated management of water supply, as well as in rural areas, DNA still retains full control of water systems (OECD, 2007) but the operation and management of the water systems is secured by public or state-owned entities. According to the DNA manual for the management of piped water systems in cities without delegated management, service regulation is to be the task of district or municipal regulatory commissions, which have yet to be established. These institutions will be responsible for tariff and service monitoring, implementing regulations, evaluation and analysis of information and conciliation of consumer interests with those of the operator and the DNA (OECD, 2007; Seureca & Hydroconseil 2005)

2.3 Drinking water supply options and choice of technology

The drinking water supply of Mozambique is functionally divided in two sub-sectors; the urban sub-sector supplying piped water in large urban centres, and the rural water supply sub-sector, which provides rural water supplies mainly through boreholes with hand pumps and some piped water to small towns and villages.

Rural water supplies are generally groundwater based. According to statistics (WHO/UNICEFF, 2006) nearly 63% of the country's total population have rural water supplies, only 2 % of which have access to piped water supplies. Most rural water supply is by point water sources, namely boreholes and hand pumps. Coverage estimates in these areas are generally assessed according to accessibility to point water sources, a daily water demand of 20 litres per person per day, and a maximum distance to the nearest water point of 500 m. Piped water supplies in small towns and villages are mainly by public standpipes and yard connections.

Urban water supplies are generally surface-water based with service provision generally secured by piped water supplies. Although the coverage for the urban population in Mozambique is estimated to be 72 %, urban water supplies in Mozambique are available to only 37 % of the total population of the country, of which only 18 % have access to water through house connections (UNICEFF, 2006). Surface water from rivers is mainly used for drinking water production. In Table 1, an overview is given of the current situation regarding raw water sources and treatment methods for the piped water supply in 10 major cities of Mozambique.

Piped water is generally supplied at three levels of service: house connections, yard connections or public standpipes. The distribution of consumers by level of service varies from town to town. Taking Maputo as an example, a survey carried out in 2007 indicated that the proportion of residents with access to piped water through house connections was 42%. The figure for yard taps was 35% and for public standpipes 23% (Seureca & Hydroconseil, 2005).

Table 1 Typical design of drinking water treatment plants of 10 major towns of Mozambique. (SW = surface water; GW = groundwater).

Town	Estimated water demand by 2008 (m^3/day)[1]	Type of raw water source	Type of treatment	Operating capacity (m^3/day)[2]
Lichinga	2 947	SW+ large reservoir with selective intake	Conventional with pressure filters	2 160
Pemba	9 487	GW–borehole field	Conventional with cascade aeration + direct filtration	10 000
Nampula	14 762	SW+ large reservoir with constant intake	Conventional-standard[3]	13 500
Nacala	6 568	SW+ large reservoir with constant intake	Conventional with pressure filters	5 700
Quelimane	13 320	GW–borehole field	Slow sand filtration	4 200
Tete	7 116	GW–borehole field	Conventional with cascade aeration + direct filtration	5 100
Beira	30 000	SW–direct intake from a sugar cane irrigation channel	Conventional-standard with lamella type settling basins	19 200
Xai-Xai	8 600	GW–dune aquifer	Disinfection with granular chlorine	6 000
Mocuba	2 279	SW–direct intake from river	Conventional standard + pressure filters	1 000
Maputo-Matola	240 000	SW–direct intake from river	Conventional standard	172 800

[1] According to estimates from DNA.

[2] design capacity according to plant operators.

[3] conventional standard = pre-chlorination, chemical coagulation, flocculation, sedimentation, rapid sand filtration and disinfection.

2.4 Drinking water treatment methods and quality criteria

Regarding drinking water production, conventional treatment, consisting of chemical coagulation, flocculation, sedimentation, rapid sand filtration and disinfection, is most commonly used. In these methods coagulation is used to reduce the repulsive forces responsible for the stability of colloidal dispersions while flocculation is used to enhance particle transport and aggregation, and the eventual formation of suspensions suitable for separation with sedimentation and filtration. Sedimentation does the bulk of the liquid-solid separation while filtration, usually deep bed filtration, is used as a polishing step. Particle destabilization and aggregation therefore largely determine therefore, the efficiency of water purification (Hammer et al., 2004; Polasek, 2007; Lawrence et al., 2007). Disinfection, usually with the help of chlorinated compounds is used to kill bacteria and to provide acceptable levels of residual chlorine to prevent post-contamination (WHO, 2004). Additional processes in conventional treatment may include pre-chlorination to assist the removal of algae and dissolved organic matter and conditioning for alkalinisation and corrosion control.

Conventional treatment is generally regarded as the most effective method of producing drinkable water from surface water sources. However, the efficiency of the method depends on various factors, among which are the quality of the raw water and its variation. For example, when flocculation is used for the treatment of water with low turbidity, the process is said to be kinetically poor if it cannot be accomplished with operational modifications that may include the use of coagulant aids or coagulation-direct filtration processes (Chuang et al., 1997; Polasek & Mult, 2005). High values of turbidity affect the efficiency of coagulation processes, and can cause blockage of filters leading to the demand for frequent cleaning of filters and clarifiers, which increases the cost of water production.

Conventional treatment is also unsuitable for the removal of high concentrations of organic matter, algae and impurities resulting from anthropogenic pollution. High concentrations of natural organic matter-NOM, for instance, influence alum speciation in coagulation processes (Volk et al., 2000; Viraraghavan & Srinivasa, 2004; Sharp et al., 2005), and NOM is a precursor of disinfection by-products-DBPs (Ruehl, 1999). The presence of algae can cause several problems to drinking water production depending on the algal species and their concentration (Bauldin et al., 2006). These problems can impact the plants operation and the quality of treated water. Algae impacts for instances, the performance of filters (Polasek & Mult, 2005), reduces the efficiency of flocculation processes, and can alter the nature of organics, thus influencing processes designed to remove NOM (Cheng et al., 2003; Leikens, 2004; Qin et al., 2006). Algae can also be the source of unpleasant taste and odour (WHO, 2004; Bauldin et al., 2006).
Other methods of treating surface water include the use of the so-called non-conventional methods whereby slow sand filtration is used as the primary treatment process and roughing filtration (mostly horizontal roughing filters) used for pre-treatment (Huisman, 1984; Smet & Visscher, 1990; Sanchéz et al., 2006). Most advanced methods include for example, treatment with membranes and desalinization plants (Hammer et al., 2004; Lawrence et al., 2007). For groundwater supplies faced with problems of excess iron and manganese, the most commonly used method of treatment is aeration followed by direct filtration. Water disinfection is also used mainly to maintain levels of residual chlorine suitable for prevention of post- contamination.

The objectives of drinking water treatment are generally translated into drinking water quality standards, which should be met at treatment plants. These standards are generally specific to each country or region, but most countries have based their standards on the WHO Guidelines for drinking water (WHO, 2004). The Mozambican standards (MISAU, 2004) were also developed based on the WHO Guidelines.

2.5 Alternative water supplies

Service provision through alternative water supplies is generally by groundwater-based, small piped water supplies usually developed by small-scale independent service providers. Consumer access is generally by public standpipes, but many independent providers report to offer services also through house connections and yard taps. The evolution of household level water strategies into independent service providers is, in most cases, unplanned. Most owners of such systems constructed them to provide water for themselves, but at the insistence of neighbours allow private connections or sell water through yard connections, thus slowly developing into small-scale water vendors. Also, because the profit from selling water helps them offset their investment and running costs (break-even in about 2-3 years), many of them eventually turn into professional service providers.

Taking the city of Maputo as an example, a survey carried out in 2005 (Seureca & Hydroconseil 2005; Boyer, 2006) indicated that around 240 SSIPs existed in Maputo, which were reported to provide services to as many as 32% of unconnected households in peri-urban Maputo. Around 65% of these SSIPs were reported to have been established since 2001 (Figure 3). During the same period, service levels were reported to have risen from public taps only to house connections, yard taps and private standpipes (Sal-Consultores, 2005). Today, some 32% of SSIPs operating in peri-urban Maputo are reported to have more than 100 house connections.

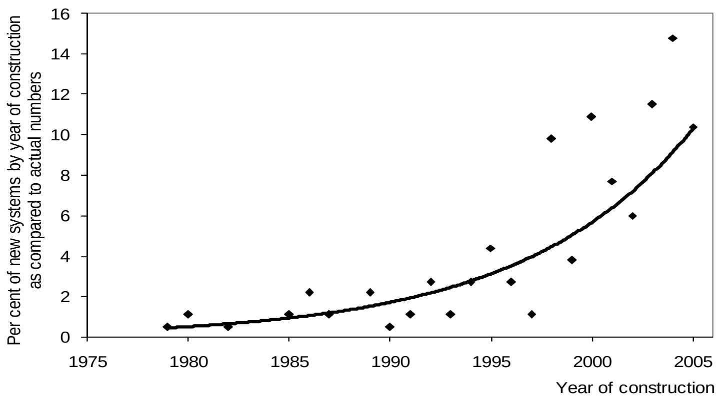

Figure 3 Evolution of small-scale independent Providers (SSIPs) in Maputo-Mozambique

Most alternative providers, although located within the official boundaries of the main cities and, in some cases within contracted concession areas, they are currently not formally regulated. Reasons for that are the lack of legislation and an administrative framework that could be used to grant licences or regulate their activities.

3. METHODOS

3.1 Field work

This thesis is based mostly on field work and laboratory testing. Field work was carried out to assess the quality of drinking water from formal and informal service providers, and to assess the potential of the regional aquifer used by independent service providers operating in the region of Maputo. Field work was also used to evaluate the quality of water supplied by independent service providers and to evaluate the efficiency of drinking water treatment in a number of waterworks used for case studies. Detailed descriptions of the methodology and the results obtained through field work are presented in **Papers 1** to **4**. Laboratory work was used mainly to evaluate the efficiency of drinking water treatment using alternative and low-cost treatment methods. The low-cost treatment methods tested were hydraulic flocculation with up-flow roughing filtration, and the use of extract from *M. oleifera* seeds for coagulation of surface water. The methodology and results are presented in detail in **Papers 5** and **6**.

3.2 Sources of data and choice of water quality variables

The data used in this work were obtained through field work, and from historical sources available at the DNA, regarding mostly river water flows and water quality. The results of studies conducted in some of the river courses investigated were used to assess river water quality. Historical data from plant operators and data collected through field work were used to assess the quality of drinking water provided by formal and informal service providers in the city of Maputo, and also to assess the performance of the waterworks at Maputo and Beira and Nampula.

The parameters used to define overall river water quality were: turbidity, total hardness, pH and total alkalinity, organic matter content, indicator organisms and phosphates (related to algae growth). Rivers chosen for the study were: the Limpopo, Umbelúzi and Maputo rivers in south Mozambique, the Púngue River in central Mozambique and the Monapo and Licungo rivers in north Mozambique. Turbidity, pH, alkalinity and organic matter were used to describe the efficiency of drinking water treatment.

Before use, the data on river water quality obtained from the DNA databases were checked for their analytical accuracy by performing charge balance tests on the data on ionic species. These tests were used to eliminate erroneous or suspicious observations from the original data sets. A charge balance error of ±15 % was accepted due to the limited size of available data sets. Around 53 % of the data sets analysed regarding the Licungo River and 24.5 % from the Umbelúzi were rejected due to unreliable values of various water quality parameters and charge balance errors greater than 25 %.

The data used to assess the quality of drinking water in the Maputo network were: residual chlorine, bacteria, turbidity and solids. Temperature, residence time and the condition and cleaning of household tanks were used to make the final assessment of drinking water quality following storage at household level. These data were also tested for statistical significance. In this way, all pair-wise data collected before and after household storage were checked for statistical significance using a method that consisted of determining a confidence interval for the difference between two expected values **$l(\mu_1 - \mu_2)$**; if this interval does not cover zero the difference is regarded as being significant between two homogeneous groups. A 95 % confidence interval (**$p=0.05$**) was used in all tests. Chemical and physical parameters measured in samples taken from the network and after household tanks were compared, with an independent sample T-test. The T-test was also used to compare residual chlorine in samples with and without bacteria. The T-test is not valid for turbidity, free residual chlorine, total residual chlorine or nitrate, since the statistical variances of the two groups were not comparable, and the Mann-Whitney U-test was used instead. The presence and absence of bacteria in samples taken before and after storage were also compared using the Mann-Whitney U-test.

The presence of faecal bacteria and nitrates, and the electrical conductivity and salinity were the parameters used to assess the quality of water from alternative service providers. The electrical conductivity (EC) was measured with the purpose of evaluating the influence of sea water intrusion on the quality of borehole water. Results of borehole pumping tests were used to complement this analysis. Emphasis was placed on the potential for groundwater contamination due to over-exploitation of the aquifer system.

3.3 Situation analysis with respect to drinking water treatment and efficiency of drinking water production

The situation analysis with respect to drinking water treatment and the efficiency of drinking water production was based on the evaluation of the results regarding treated water quality from a number of treatment works and their compliance with internationally accepted drinking water quality standards. The analysis also included the assessment of operational procedures within these waterworks, with emphasis on the operation of coagulation-flocculation processes and procedures for the control of raw and treated water quality during treatment. The waterworks studied were based on the standard design of conventional treatment, also being the best-equipped waterworks in the country, and also those where records were kept of water quality, or the quality could be assessed.

3.4 Situation analysis with respect to drinking water quality

Drinking water quality was assessed through field studies conducted in an area of central Maputo and on the evaluation of the quality of the source water used by alternative service providers in peri-urban Maputo. Analysis of drinking water quality from the piped network was motivated by the fact that water distribution in Maputo, and in many other towns of Mozambique, is generally intermittent, a *modus operandi* that is often associated with quality problems, due to the ingress of contamination during periods of low or no pressure in the grid (Tokajian & Haswa, 2003; Totsuka et al., 2004) and reduced disinfection capacity due to long residence times in pipes and reservoirs (Kiéné et al., 1998; Hua et al., 1999; Powell et al., 2000; Vreeburg & Boxall, 2007). Also, consumers faced with intermittent supplies often develop their own ways to cope with this, for example, by constructing household tanks which add to the factors responsible for drinking water quality deterioration.

In order to carry out this evaluation, water samples collected before and after household tanks were analysed with regard to their physic-chemical and bacteriological characteristics. The condition of household tanks was also assessed through observations and interviewing the owners. Aspects of interest included the overall condition of the tanks, construction materials, tank dimensions and consumer practices regarding cleaning and disinfection. The results of time-dependent chlorine decay tests using samples of treated water were used to estimate the magnitude of chlorine depletion during storage, and to estimate chlorine decay rates for treated water. The method used, which is often referred to as the “bottle” or jar-test (Powell et al., 2000), consists of recording the chlorine concentrations, at fixed time intervals, of the water collected in jars. The results of these tests were compared with the results of calculations performed with data provided by the service provider and data generated during field work. Estimates of chlorine decay rates were based on a first-order decay reaction.

The results of the evaluation of the quality of source water used by alternative service providers were used to identify the present and long-term challenges facing alternative service providers in supplying water of sufficient quality and quantity in the long term, and to assess possible human health risks associated with the consumption of water from these providers. Borehole pumping tests, the results of which were interpreted using the graphical method of Jacob (Kruesman & Rider, 1991) were used to evaluate not only the potential of the regional aquifer but also the long-term vulnerability of the aquifer system to external contamination. Samples from thirty-five wells were used to assess borehole water quality. A total of ten pumping tests were performed to assess the hydrological potential of the aquifer system.

3.5 Laboratory testing

Laboratory testing was performed with the purpose of investigating methods of improving the turbidity reduction achieved with conventional treatment. The methods tested were up-flow roughing filtration for hydraulic flocculation and the use of *M. oleifera* seed extract for the coagulation of surface water. Pilot-plant experiments were carried out to determine the optimal dosage and filtration conditions for hydraulic flocculation with up-flow roughing filters and the suitability of the suspensions formed for removal by subsequent rapid sand filtration. River water was used for the experiments. Turbidity reduction, head loss development and velocity gradients in the roughing filter were the parameters used to evaluate the performance of the pilot plant.

Coagulation experiments were performed using standard jar test experiments with solutions prepared from aluminium sulphate and *M. oleifera* seed extracts, the results of which were used to compare coagulation efficiencies and the effects on turbidity reduction and the chemistry of the treated water. The optimal dosage of coagulant was investigated for different levels of turbidity, and the properties of treated water were monitored. The use of *M. oleifera* seed extract together with coarse to fine sand filtration, and the possibility of using *M. oleifera* at small-scale waterworks was also investigated.

4. RESULTS AND DISCUSSION

4.1 Source water quality and methods of treatment

4.1.1 Surface water quality

Papers 1 and 3 present a discussion of source water quality and methods of conventional drinking water treatment. Turbidity, suspended solids, natural organic matter, bacteria, the presence of algae and other aquatic plants were identified as raw water quality variables of major concern for drinking water production (Paper 1). Because most rivers used for drinking water production are of torrential regime, these impurities not only occur at high concentrations but there are also wide seasonal variations.

The removal of these impurities, particularly turbidity, is essential during water treatment for the production of safe drinking water. Turbidity itself is not a major health concern, but affects water acceptability and is generally related to other quality variables (e.g. colour, total suspended solids, algae and bacteria), some of which are of major concern for human health (WHO, 2004). The overall condition of water with respect to turbidity therefore influences the levels at which some of these variables occur in natural waters and also the treatment processes needed to produce drinking water. When these levels are constantly low, simpler and less expensive treatment processes can be used, but when these levels are constantly high, more complex and expensive treatment processes are required. The worst scenario, however, is when the levels vary greatly, as the treatment process must be sufficiently flexible to treat the varying quality of the raw water.

Figure 4 shows a typical example of river water turbidity for a number of rivers used for drinking water production in Mozambique, where it can be seen that river water turbidity is generally high at all locations, and also that it varies considerably during the year.

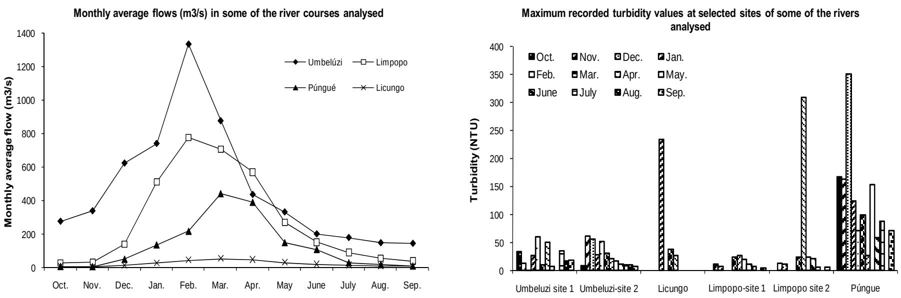

Figure 4 *Average monthly flows (m3/s) and maximum values of water turbidity (NTU) recorded at selected sites of rivers used for drinking water production of some cities in Mozambique such as the city of Maputo (Umbelúzi River), Beira (Púngué River) and Mocuba (Licungo River). Data source: DNA database.*

The relatively low values of maximum turbidity observed at some of the locations investigated (Umbelúzi and Limpopo-site 1) are due to the effect of major hydraulic works (man-made reservoirs) located upstream of the sampling locations, where solids and turbidity are reduced by sedimentation. From the data shown in Figure 4 it can also be seen that river water turbidity generally shows a good correlation with river water flow, and thus with the hydrology and rainfall pattern of the region.

Physical parameters such as water pH and temperature do not affect water acceptability, and are not of concern regarding health, but they have a major influence on water quality parameters such as bacteria and algae growth. Average river water temperatures in Mozambique are generally between 20 °C and 25 °C and the raw water pH generally between 6.0 and 9.0. Because high temperatures are generally accompanied by heavy rainfall and high river water turbidity, the combined effect of these factors provides ideal conditions for bacterial growth and algae blooming. The common practice of building reservoirs to secure water availability during periods of reduced flow usually worsens the situation because the hot climate characterizing tropical and subtropical regions provides the perfect ecological environment for bacteria and algae blooming (Anderson et al., 1999; Chorus & Bartram, 1999). Added to this natural climatic effect is the enhanced rate of nutrient input that accompanies the growth of towns and the development of irrigated agriculture in the catchment areas around the water courses.

It was concluded that current knowledge concerning river water conditions with respect to the presence of algae and/or eutrophication problems is poor due to a lack of data and detailed studies. Besides some measurements taken at irregular intervals by DNA, which relates to levels phosphorus in river water, the only references that could be found for assessing the potential for river water eutrophication where, a study on presence and removal of cyanobacterial toxins in the water from a reservoir supplied by the Umbelúzi river (Bojcevska & Jergil, 2003), and a further study by Gustafsson & Johansson (2006) on levels of nutrients along the Umbelúzi river. Other study relate to the Limpopo River where, the river water quality was also assessed for presence of phosphorous.

Different references found in literature and proposed by different organizations and authors suggest limits for total phosphorous concentrations in the range 0.1-0.16 mgP/L to avoid euthrophication in river water which are presented in Table 2.

Table 2 Different limits for phosphorous and nitrogen to avoid euthrophication in rivers. Limits suggested by different organizations and authors (* all fresh waters; ** Total P = 0.3262 PO43- (mg/L).

Variable	Limit
Phosphorous	
Tot. P (rivers draining to lakes- U.S.EPA)	0.05 mgP/L
Tot. P (rivers not draining to lakes- U.S.EPA)	0.1 mgP/L
Phosphate (Fytianos et al., 2002)	0.5 mgPO_4^{3-}/L = 0.16 mgP/L
Inorganic P (SAWQG)*	0.005 mgP/L
Nitrogen	
Inorganic N (SAWQG)**	0.5 mgN/L

From the analysis of the data from DNA database it was found that total phosphorous concentrations in the Umbelúzi River could vary from as low as 0.01 mg/L to figures as high as 0.63 mgP/L clearly values higher than the indicative limit of 0.16 mgP/L. This suggests that conditions favourable to euthrophication of Umbelúzi river water may occur from time to time. The results of the study by Bojcevska & Jergil (2006) gave evidences of presence of high concentrations of toxic cyanobacteria in the water of the studied reservoir. However, the study from Gustafsson & Johansson (2006) resulted in much lower values, with average total phosphorous concentration of all measurements of about 0.054 mgP/L. The sampling period used in this study covered, however, a much shorter period of analysis (two months from September to November) and this may explain the difference in results. Yet, the average concentration of phosphorous at all sites investigated was close or exceeded the guideline value for rivers draining into lakes as is the case of the Umbelúzi, which supports the findings from the previous study about the possibility of euthrophic conditions in the river water and, the possibility of presence of algae and cyanobacteria. Problems with algae at the Umbelúzi River were also reported in a latter study by Couto (2004) and more recently by managers of the waterworks of Maputo water supply who report frequent outbreaks of algae at the intake works.

The study on the Limpopo River provided similar results. In this, total phosphorous in the river water were found to vary from 0.03 mgP/L to values as high as 2.0 mgP/L. Two sampling locations were considered for this analysis. Given the origin of the problem, this is a situation that is likely to be encountered in many rivers used for drinking water production, particularly those where intensively irrigated agriculture is practiced upstream of the major intake works.

Chemical properties such as water hardness and alkalinity generally affect water acceptability and water treatment efficiency. Problems with hard or soft water are generally site specific because they depend on the interaction of many factors including the soils and rocks from which the water is derived, which are generally site or region specific (Stumn & Morgan, 1996; WHO, 2004). The water alkalinity is closely related to the concentration of carbonates, bicarbonates and hydroxide ions in the water, therefore it is closely related to water hardness. It influences, for instance, scale formation in the case of hard water and the degree of water corrosiveness of soft water. During water treatment, the pH and water alkalinity affect processes such as coagulation and disinfection. For example, when the alkalinity of the raw water is too high, an excess of destabilizing reagent is generally required to adjust the water pH to optimum reaction values. In contrast, when the alkalinity is too low, it must be increased in order to optimize reaction conditions and improve the overall process efficiency (Polasek & Mult, 2005; Velasco et al., 2007). Knowledge of the water's pH and alkalinity is therefore useful in evaluating the optimum conditions for treatment processes, as well as the final condition of treated water with respect to its corrosive or scaling properties.

Analysis of river water hardness and alkalinity (Paper 1) confirmed the site-specificity of these variables. As can be seen from the results presented in Paper 1, the river water hardness can vary from rather soft to moderately hard at some locations, to slightly hard or even hard at other locations. Related problems for drinking water production are therefore site specific, but in general river water is classified as suitable for drinking water production.

The presence of high concentrations of organic matter is generally a problem in surface water treatment. Organic matter affects treated water quality, especially taste and odour, and the levels of nutrients (e.g. carbon) available for bacterial growth, as well as treatment processes such as chemical coagulation and disinfection (WHO, 2004; Leiknes et al., 2004; Sharp et al., 2005). Source of organic matter in fresh water are, the natural processes in fresh water, such as the decay of organic material from animal and vegetable sources, and human activities, such as sewage disposal and irrigation of agricultural land (WHO, 2004).

Analysis of the data on the presence of organic matter in river water (Paper 1) showed that levels of organic matter at all sites investigated were generally high, and at concentrations that exceed the guideline value for drinking water (2.5 mg C/L measured as DOC). However, the observed levels of organic matter at the sites investigated are not indicative of organic pollution of anthropogenic origin. This mean that when river water is used for drinking water production in Mozambique, water treatment should also include processes to remove organic matter not only because of the need to comply with guidelines for drinking water, but also to increase the efficiency of treatment. Because the levels of organic matter are closely related to river water turbidity and river flow, which are strongly influenced by seasonal variations, problems in water treatment related to the presence of organic matter in river water will also be influenced by seasonal variations in river flows.

4.1.2 Groundwater quality

According to the literature (WHO, 2004), most common groundwater quality problems are associated with contamination by bacteria and nitrates, high levels of salinity caused mainly by sea water intrusion, iron and manganese, and water hardness, generally associated with calcium and magnesium dissolved in the water.

The major source of nitrates in groundwater is the natural decay of nitrogen-enriched organic material and human activities such as sewage disposal, on site-sanitation and the accumulation of organic material from improper solid waste handling (Boulding & Ginn, 2003; WHO, 2004; Schmoll et al., 2006). Sewage disposal and on-site sanitation are also important sources of groundwater contamination with bacteria. In both cases, factors such as hydraulic load, rainfall patterns, soil type and depth to the water table determine the rate and extent of the transport of contaminants to the groundwater. Sandy soils, for example, are particularly vulnerable to bacteria and nitrate leaching into the groundwater because of the limited attenuation they provide (Lee and Bastmeijer, 1991; Thompson et al., 2007; Dzwairo et al., 2006).

Most groundwater sources contain some amount of dissolved iron or manganese arising from contact with minerals that contain such minerals (e.g. pyrite). When present in drinking water, iron and manganese not only cause a bad taste but also staining of pipes and clothing. Calcium and magnesium, which cause hardness, are found in groundwater that has come into contact with certain rocks and minerals, especially limestone and gypsum. Drinking water quality problems caused by hard or soft water have already been discussed in Section 4.1.2 of this thesis, and include scale formation and the corrosion of pipes and other appurtenances used in drinking water supply. Problems of high salinity in groundwater are generally the result of sea water intrusion (coastal aquifers) or high total dissolved solids resulting from contact with certain rocks and minerals from which the groundwater is derived. The WHO guideline for the EC of drinking water is 1 500 µs/cm.

Groundwater sources in Mozambique are generally of good quality. However, there are some well-known cases of groundwater of poor quality, for example, the area north of Inhambane Province where the regional aquifer is known to have high total dissolved solids, which gives the water brackish or hard characteristics (Ferro & Bouman, 1987). Also, some alluvial aquifers are known to have problems arising from excess iron and manganese. The most well-known example is the aquifer system used for drinking water supply to the city of Pemba in northern Mozambique, where iron and manganese concentrations in excess of 4.0 mg/L and 0.4 mg/L, respectively, have been repeatedly reported in several previous studies conducted to assess drinking water quality in Pemba. Other examples of iron- and/or manganese-enriched aquifers are the aquifer systems used for drinking water supply to the cities of Quelimane and Tete in central Mozambique.

The analysis of groundwater quality described in this thesis focused on the quality of groundwater sources used by alternative service providers in peri-urban areas of Maputo (Paper 3). The aquifer system used in the case study is part of a large Meso-Cenozoic sedimentary basin that covers the entire area south of the River Save, which is related to a rift system extending between Madagascar and Africa. This system extends from Port Dundford in South Africa to Quelimane in the central part of Mozambique. Karoo basalts and rhyolites, dated to be Permic and Jurassic, form the basement of the system, while Cretaceous to Tertiary flat deposits or deposits with nearly horizontal slopes overlay the Karoo sediments. These deposits are mostly of marine origin and were formed during transgression periods. Sand dunes or quaternary sand deposits cover the entire study area.

The aquifer is divided into two main units; a sandy aquifer or phreatic aquifer, and a deep aquifer of sandstones and limestone (Burgeap, 1961). According to findings from studies by IWACO (IWACO, 1983; IWACO, 1985) later confirmed by Juizo (1995) and SWECO (2004), the separation between the two aquifers is not clearly defined, and for large-scale exploitation of groundwater, the two aquifers can be regarded as a single unit.

As discussed in Paper 3, the groundwater sources used by alternative service providers in the region of Maputo are generally of good quality and virtually free from microbial and organic contamination. Thirty-five boreholes were used to assess groundwater quality in this aquifer system. Two major factors were identified as contributing considerably to this situation, namely: limited hydraulic loads of contaminants due to low population densities (< 100 inh./ha) and the availability of a relatively thick unsaturated zone (> 30 m), where attenuation of contaminants still occurs at sufficient levels. Signs of borehole water contamination with coliform bacteria were, however, found in about 29 % of tested boreholes. About 9 % of tested boreholes showed the presence of faecal bacteria. Low living standards, poor borehole construction and somewhat high hydraulic loads were suggested as probable causes of the high incidence of bacteria in such boreholes, which suggests that the potential for groundwater contamination due to one or a combination of these factors is high.

Borehole water contamination by nitrates was also found to be low in the case study area. Although they varied considerably, from values as low as 3 mg/L to about 35 mg/L, the nitrate concentrations at all sites investigated were found to be below the WHO guideline value of 45 mg/L. Factors contributing to this situation were found to be similar to those determining the levels of contamination by bacteria, i.e. low hydraulic loads due to low population densities and the availability of a rather thick unsaturated zone where biological denitrification may occur. Analysis of the spatial distribution of nitrate concentrations in more densely populated neighbourhoods located within or adjacent to the case study area (Paper 3) indicated, however, that nitrate levels in groundwater can reach values as high as 500 mg/L, suggesting that the potential for groundwater contamination with nitrates may became a real threat to groundwater exploitation in more densely populated areas.

Although the case study area is located near the coast where the potential for salinity problems due to sea water intrusion is high, the levels of groundwater salinity (measured as EC) were found to be low, and within acceptable limits for drinking water supply. Studies conducted in the past (IWACO, 1985) in the same area indicate, however, that the potential for salinity problems in this region is high, and more severe in some parts of the case study area (particularly areas located south-west of the city) when compared to others. Cases of brackish water have also been reported in some areas located north-east of the city and close to the Maputo bay, which all fall outside the areas of high potential for brackish water according to results presented by IWACO (1985). This implies that, while the results of the investigations carried out in this work suggest that the majority of sites investigated do not experience problems of brackish water, the situation may change very rapidly due to the high vulnerability of the aquifer system (coastal aquifer) to sea water intrusion.

4.2 Drinking water treatment methods: current practices and treatment efficiency

When used for drinking water, surface water must be treated. Water derived from naturally protected sources (e.g. groundwater), on the other hand, can be used without extensive treatment provided that it is disinfected at least for safety reasons. The intention of drinking water treatment is to produce water that is safe for human consumption and suitable for domestic use. The quality of water at source determines the type and extent of treatment needed and the input required to perform the task economically and efficiently. Highly polluted water, as is the case in most surface water sources, is usually unsuitable for human consumption and requires extensive treatment prior to utilization.

Various aspects of drinking water treatment in Mozambique are discussed in Paper 1. As can be seen, conventional treatment is the method used for most drinking water production. Most treatment plants employ pre-chlorination, chemical coagulation, flocculation and sedimentation, followed by rapid sand filtration and disinfection with chlorine. Modifications to the basic design also exist, and these involve the use of package units incorporating all the physical processes (flocculation, sedimentation and filtration) into one single unit, and the used of aeration and direct filtration mostly for groundwater supplies (see Table 1).

The overall assessment of drinking water production in Mozambique indicates that the situation today is generally inadequate. The worst situations are found in small and medium-sized water supplies, where the combined effect of poor water quality at source and operational and logistic limitations makes drinking water production far more difficult and inefficient. Based on the three waterworks where the results of drinking water treatment could be analysed (Table 3), it was concluded that the quality of treated water does not always conform to acceptable drinking water quality standards, since turbidity and levels of organic matter in the treated water are generally high and exceed recommended limits.

Although the mean values of turbidity in treated water (Table 3) are generally below the tolerable limit of 5 NTU, the absolute limit of 1 NTU recommended for instance, for effective disinfection with chlorine (WHO, 2004; Thompson et al., 2007), is seldom attained. At the waterworks in Nampula, the situation is even worse, and the turbidity of treated water is frequently reported to be above the maximum tolerable limit of 5 NTU. Besides limiting the possibility of effective disinfection, high values of water turbidity are also known to contribute to the release of undesirable by-products of water treatment such as residual aluminium, which is associated with human health hazards (Alzheimer's disease). In order to maintain levels of residual Al^{3+} below the health guideline standard of 0.2 mg/L, turbidity residuals of less than 0.15 NTU are generally required (Thompson et al., 2007), and these are clearly not attained in most drinking water treatment plants in Mozambique.

Table 3 Results of water treatment at three waterworks in Mozambique (Rwater = raw water; Twater= treated water; -, not measured, Min. = minimum recorded; Max. = maximum recorded; STD = standard deviation; N= number of samples analysed)

Quality variable	**Turbidity (NTU)**		**Org. matter (mgO_2/L)**		**pH**		**Alkalinity (mg/L)**		**Res. Cl^- (mg/L)**
Umbeluzi waterworks									
	R_{water}	T_{water}	R_{water}	T_{water}	R_{water}	T_{water}	R_{water}	T_{water}	T_{water}
Min.	2.9	0.7	2.0	0.8	6.3	6.5	98	41	0.3
Max.	80.6	7.3	6.4	4.8	8.1	7.9	240	230	2.8
Mean	6.7	3.1	4.0	2.7	7.4	7.4	160	152	1.4
STD	6.6	0.9	0.8	0.7	0.20	0.2	14.2	18.7	0.4
N	359	358	351	350	357	358	353	351	333
Beira waterworks-old									
Min.	13.5	0.2	-	-	6.4	6.2	-	-	-
Max.	326	28.0	-	-	7.6	7.6	-	-	-
Mean	49.9	2.5	-	-	6.8	6.7	-	-	-
STD	31.1	3.3	-	-	0.1	0.2	-	-	-
N	310	303	-	-	309	307	-	-	-
Beira waterworks-new									
Min.	11.8	2.3	4.7	2.0	6.4	6.1	58	52	-
Max.	25.9	6.5	6.4	3.2	6.9	6.3	78	82	-
Mean	17.0	4.2	5.6	2.81	6.6	6.2	64.9	61	-
STD	4.6	1.1	0.7	0.4	0.2	-	7.4	9.6	-
N	9	9	8	8	9	9	9	9	-
Nampula waterworks									
Min.	11.7	6.5	4.0	3.2	7.2	6.6	26.9	25.0	-
Max.	47.0	16.8	6.0	4.6	7.9	7.8	38.4	57.6	-
Mean	25.0	10.9	4.8	2.9	7.4	7.2	31.3	39.3	-
STD	13.8	3.3	0.7	0.5	0.3	0.4	3.1	9.6	-
N	10	10	10	10	10	10	10	10	-

Levels of organic matter in treated water were also found to be high and frequently in excess of the target level of 2.5 mg/L (WHO, 2004). The treated water on the other hand, is generally over-chlorinated (see Table 3). High levels of residual chlorine, combined with the high levels of organic matter and water turbidity mean that taste- and odour-forming compounds, as well as disinfection by-products, may develop frequently following treatment. The potential of human health risks due to bacterial growth is also high, as organic matter can act as a source of nutrients for bacteria during the transport, storage and distribution of water. Chemical parameters such as pH and alkalinity that affects the corrosive and scaling properties of water and, thus the suitability of the water for domestic use were generally found within acceptable limits for corrosion control (pH > 6.5; alkalinity > 61 mg/L).

From the analysis of results of drinking water treatment (Papers) it was concluded that, while methods currently used for drinking water treatment are generally suited for the production of water of excellent quality from existing sources, poor quality of the raw water and seasonal variations in water quality make drinking water treatment generally costly, technically demanding and heavily dependent on the availability of consumables (e.g. chemicals) and skilled personnel to operate the plants. Factors identified as having a significant effect on the performance of water treatment plants are: (i) inadequacy of existing infrastructure and operational procedures for water treatment, (ii) inconsistent operation of essential chemical processes due to malfunctioning of equipment or temporary lack of consumables and, (iii) lack of guidelines for specific contaminants (e.g. DBPs), which mean that water treatment is aimed only at those variables for which guidelines have been established.

The chemical coagulation and flocculation stage seems to be the unit operation most affected by the above-mentioned factors, not only because it depends greatly on the availability of supplies, but also because careful adjustment of the operational parameters, notably the raw water pH and alkalinity, is generally required ensuring high efficiency. Figure 5 shows annual records of coagulation processes at the Maputo waterworks, in which it can be seen that the process is performed with reagent dosages of alum and polymer that vary widely within same ranges of raw water turbidity and alkalinity.

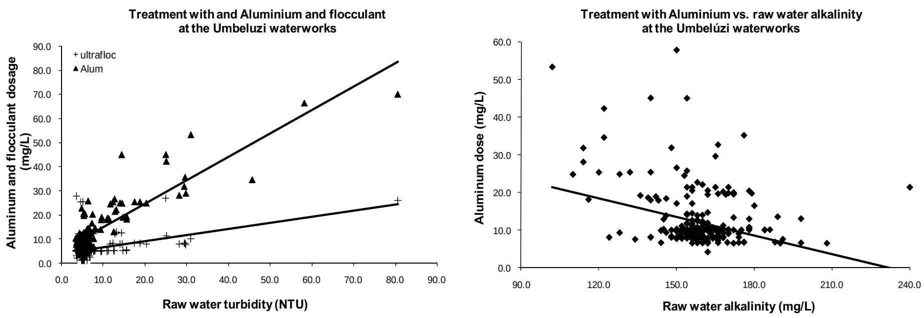

Figure 5: *Treatment with aluminium and coagulant aids at the Umbelúzi waterworks and its relation to raw water turbidity (NTU) and alkalinity (mg/L). Data refers to one full year (2005) operation of chemical coagulation at the treatment works. Source of data: FIPAG (2005).*

Since effective operation of coagulation processes generally requires optimization of the pH, usually between 6.5 and 7.0, and the addition of hydrolysing coagulants generally alters the water alkalinity, coagulation using different coagulant doses in the same range of raw water turbidity and alkalinity mean that deviations from the optimum reaction pH for coagulation may occur frequently and affect the overall coagulation efficiency. The consequences of inefficient coagulation are many, and include wastage of chemicals, excessive production of sludge and increased treatment costs. The most important, however, is the resulting poor performance of subsequent stages of treatment (sedimentation and filtration) and overall poor quality of the treated water.

In the discussion of drinking water treatment results (Paper 1) it was also noted that chemical processes essential to maintain acceptable standards of water treatment are frequently discontinued, and that the control of raw and treated water quality is rather inconsistent. Proper control of raw and treated water quality is essential to establish operational procedures and to assess the performance of drinking water production. Operation in this rather inconsistent way has certainly had an effect on the efficiency of drinking water production.

4.3 Coverage and service quality

4.3.1 Coverage and service quality provided by formal service providers

The quality of water supply services can be defined using various criteria. These include coverage, service continuity and pressure, water quality, and the degree of responsiveness of service providers to consumer's complaints. Service coverage of piped water supplies in Mozambique is discussed in the introduction of this thesis. The service quality provided by formal service providers is discussed in Paper 2, using the network of Maputo as an example. Emphasis was placed on drinking water quality. The reason for choosing this service quality indicator was the fact that water supply services in Maputo, and many other urban centres of Mozambique, are intermittent, despite the known inconveniences resulting from such disruptions.

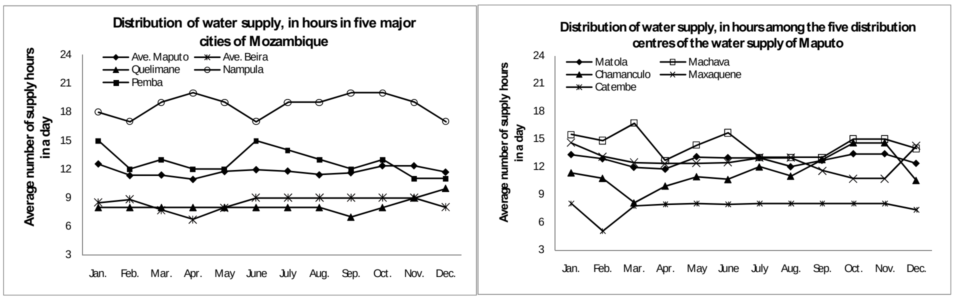

Figure 6 *Distribution of water supply, in hours, in five major cities of Mozambique (left) and among distribution centres of the water supply to the city of Maputo (right). The data on Maputo and Beira water supplies was taken as average of distribution hours among existing distribution centres. All data refers to year 2004. Source: FIPAG (2005).*

Intermittent supply is employed in many parts of the world as it is believed to help reduce leakage in old or badly maintained pipe networks, help raise awareness of water conservation among consumers, and help reduce the per capita demand, compared with continuous supplies, leaving, in theory, room for savings in investment and operational costs. Many recent studies (Tokajian & Hashwa 2003; Coelho et al., 2003; Totsuka et al., 2004; Kajsa & Lindquidist, 2006; Vreeburg & Boxall, 2007) indicates, however, that intermittent supplies are linked to a number of inconveniences to consumers among which, water shortages caused by reduced flow, low or lack of pressure in the networks, quality problems resulting from the ingress of contaminated water, and water quality deterioration resulting from prolonged storage.

As seen from figure 6, water supply and distribution in Maputo is also intermittent and the reason for this is the need to reduce leakage during distribution (Gumbo, 2004; Zandamela, 2000). Methods commonly used by consumers to overcome problems caused by intermittency are, the reliance on services delivered by alternative providers and the construction of extra household tanks for those having piped connections. Both alternatives are, however, associated with considerable water quality problems resulting either from exposure to unsafe water supplies, the ingress of contamination, or water quality deterioration during storage.

Analysis of drinking water quality in the network of Maputo (Paper 2) showed that drinking water in Maputo is not always safe for human consumption, due mainly to the occasional presence of bacteria. Both faecal coliforms and *E. Coli* were found in reservoirs at distribution centres and taps in the network. The reasons for this was a combination of factors that includes the condition of pipes, ingress of contaminated water during periods of low or no pressure, long retention times in pipes and reservoirs in the distribution network, and the condition and maintenance of household tanks. Some contamination was found to occur before or at the reservoirs of the distribution centres, clearly suggesting the ingress of contamination during periods of low or no pressure.

Storage was found to significantly affect drinking water quality at household level. Samples collected before household tanks generally had better quality than those collected after the tanks. Factors contributing to this were found to be long storage times, poor maintenance of household tanks and the ingress of contaminants. Since residual chlorine, used to maintain a certain disinfection capacity in water, decreases naturally with time long storage times, particularly at household level, were found to significantly affect water quality. As can be seen from the results presented in Paper 2, and in figure 7, storage at household level increased the risk of the presence of faecal coliforms in water by more than 100 %. These results are in agreement with those of other researchers (Coelho et al., 2003; Totsuka et al., 2004), who also found positive correlations between mean bacterial counts, pH, temperature and particularly storage time. The disinfection capacity in the network was generally found to be high, which partially explains why bacteria counts in the network were generally low.

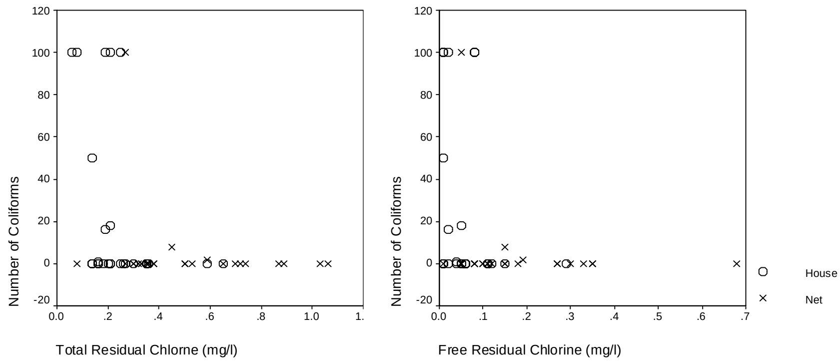

Figure 7: *Presence and coliform bacteria in samples taken before and after storage at household level.*

Although based on a limited number of samples, sediments in household tanks were also found to potentially contribute to water quality deterioration. Most household tanks were found to be over-dimensioned. This, combined with frequent discontinuities in the supply of water to the household tanks provides the ideal conditions for the settling of turbidity-causing particles and sediments build-up. The combined effect of sediments in tanks, low water disinfection capacity and long retention times provides the ideal conditions for bacterial growth in the network and household tanks. The intermittent mode of operation of the water network in Maputo has, therefore, been pointed out identified as one of the critical factors affecting service and water quality in Maputo. The most serious consequence of intermittency in Maputo is the deterioration of water quality in network reservoirs and household tanks.

4.3.2 Coverage and service quality provided by informal service providers

Coverage and quality of the services provided by alternative service providers are discussed in Papers 3 and 4. Water supply services offered mainly by small-scale independent providers in peri-urban Maputo were used as an example. For the purpose of assessing service quality, services were ranked according to three levels of quality: bad, reasonable and good. The following three quality indicators were ranked: water price at private standpipes as compared to public standpipes, promptness of standpipe attendants and neighbourhood authorities to respond to consumer's complaints, and access to services by individual consumers as measured by the number of hours with pressure and open access to consumers at private and public standpipes. For the assessment of water quality, borehole water used by independent service providers was investigated regarding bacterial and organic contamination (*E. coli* and/or faecal coliforms and contamination with nitrates) and salinity (through EC measurements).

Analysis of the coverage aspects from alternative service providers (Paper 4) gave a clear picture of the role played by independent providers and their importance in service provision to unconnected residents in large urban centres. Alternative service providers are known to cater for as many as 32 % of households in Maputo (Sal-consultores 2005; Seureca & Hydroconseil 2005), while 62 % of households rely on services provided by formal service providers.

Regarding the quality of their services, although alternative providers charge more per unit volume of water than the formal service provider, their services are generally appreciated by consumers, mainly because they are more readily available and met their expectations more rapidly. Regarding the quality of water provided by independent providers (Paper 3) it was found that today, the quality of groundwater tapped by independent providers is virtually free from microbial and/or organic contamination and is thus safe for human consumption and domestic use. However, there were obvious exceptions, for example, high levels of salinity, caused by sea water intrusion or the vulnerability of the aquifer system to sea water intrusion, making the water from individual boreholes or specific locations unsuitable for human consumption.

The quality of water that is ultimately delivered to consumers depends not only on the quality of water at source, but also on the treatment and storage methods applied following abstraction. External factors, such as those resulting from storage conditions and the condition of pipe networks, greatly affect the quality of the water. In an investigation of the quality of water from this type of service providers it was found that the water from a number of systems operated by independent providers was of inferior quality with respect to its microbial quality (Kajsa & Lindquist, 2005). About 50 % of samples analysed from a data set consisting of 158 records had bacteria counts in excess of guideline values.

Given that the quality of water at source is virtually free from contamination as was concluded in Paper 3, a possible cause of the deterioration of water quality following abstraction is external contamination, e.g. during storage, and the ingress of contamination during distribution. The conditions during water treatment and storage following abstraction from the source seem to contribute greatly to this situation. As noted in the discussion of Paper 2, none of the independent providers interviewed reported that they regularly treated the water before distribution. Thus, raw water is only treated when problems are detected during monitoring checks conducted intermittently by the Ministry of Health via its Water, Food & Hygiene Department.

5. CHALLENGES AND OPPORTUNITIES FOR SAFE WATER SUPPLY IN MOZAMBIQUE

Major problems affecting drinking water supply in Mozambique are; inadequate service coverage, poor reliability and inferior water quality. These problems are common to large and small to medium size water supplies, but the latter face more serious problems because of limited financial capacity for investments in new or upgraded infrastructures. The lack of adequate piped water supplies is viewed as prompting consumers, particularly those living in the surroundings of the main cities, to find alternatives to cope with water shortages by relying on services offered by alternative providers, most of which in the form of small-scale independent providers-SSIPs. These services are presently not formally regulated, yet the quality and reliability of services seem to be generally better than that offered by formal service providers (Paper 3). Lack of reliable piped water supply services is also viewed as prompting consumers to find ways of coping with water shortages by constructing household tanks, most of which are today claimed to be one of the root causes for water quality deterioration at household level (Paper 2).

Drinking water production and management of drinking water quality is generally inadequate in Mozambique. The discussion of source water quality aspects (Paper 1) and those of treatment methods and efficiencies have indicated that problems exist at almost all systems using surface water (mostly river water) for drinking water production. Conventional treatment is mostly used for surface water treatment and drinking water production. The worst situations are found in small and medium-sized water supplies, where the combined effect of poor water quality at source and operational and logistic limitations makes drinking water production far more difficult and inefficient.

Overall, the quality of water at source is suited for drinking water production with conventional treatment but, factors such as poor water quality at source and seasonal variations and operational and logistic constraints makes drinking water production difficult, ineffective and to depend heavily on skilled personnel and reliable supplies to operate efficiently the plants. Critical variables of surface water quality are turbidity, bacteria, NOM and algae and aquatic plants. Groundwater sources used for large water supplies (e.g. to the city of Pemba) do not face problems of organic contamination, but in here, problems with excess iron and/or manganese and, sometimes, water hardness are the typical problems of large scale drinking water production from groundwater sources.

Regarding the management of drinking water quality, the intermittent mode of operation of most piped water supplies in Mozambique is viewed as one of the critical factors affecting and water quality. The most serious consequence of intermittency is deterioration of water quality due to ingress of contamination during periods of low or no pressure and prolonged storage in the network, reservoirs and household tanks (Paper 2). These problems are common to services offered by alternative service providers as well as those offered through formal piped water supplies. Regarding the services offered by alternative service providers most, if not all, tap their water from groundwater sources which are now assessed as virtually free from contamination (Paper 3). However, this situation may change in future either due to over-exploitation of aquifer systems or increased hydraulic loads of contaminants caused by increased population densities.

In view of the above, major challenge facing the drinking water supply sector and institutions of the water governance framework in Mozambique is, to develop sustainable drinking water supplies, capable of supplying quantity water of acceptable quality to residents, industry and commerce in most urban centres of the country.

5.1 Meeting targets in drinking water production and coverage

In sections 4.3.1 and 4.3.2 of this thesis a discussion was held on coverage aspects around formal and informal service providers from where it was concluded that coverage levels from either type of services are still far from optimum. In many cases, present operational capacity is beyond required demands and expected growth. Added to that, existing infrastructure, particularly the water distribution infrastructure, cannot be extended to reach the rapidly expanding neighbourhoods of urban centres.

To meet targets in drinking water production and coverage, considerable investment is needed in the development of additional infrastructure or extension of existing ones. This is an unrealistic option in many places in Mozambique because of the limited financial capacity to invest in all components of the drinking water supply infrastructure. Meeting targets in drinking water production and coverage requires, therefore, a well established strategy whereby, the priority is given to investments in areas that are more likely to bring short term benefits and meet expectations of consumers and water governance authorities.

In the discussion of the drinking water production aspects (Paper 1) it was concluded that, although most drinking water supplies are presently operating beyond required capacities, actual production levels are close to required demands, suggesting that the priority for investments is on improvements of water quality, water distribution and service coverage when compared to bulk water production. Options to improve drinking water production and water quality requires investments aimed not only to restore and expand partially production capacities at existing treatment works, but also, to improve operation of treatment processes and efficiency of drinking water production. Critical aspects around this matter are discussed in section 4.4.2 of this thesis.

Improvements in water distribution and service coverage can be achieved either by physically expand existing networks and improve operation and management of water quality during distribution or by developing small-scale distribution networks designed to provide services to areas presently located outside the range of coverage of formal distribution networks. The latter is a strategy currently being explored to expand service coverage in the area of Maputo whereby, state-funded groundwater based distribution networks are being developed in the peri-urban areas of the city, for further delegation of operation and management responsibilities to local-based private operators (Paper 4). SSIPs presently running self-financed water supply systems will be involved as well.

SSIPs have a long history of acceptance by donors and governmental authorities as viable alternatives to managing and expanding public services (Paper 3 & 4) and this can be capitalized by the water supply governance authorities of Mozambique to help expand service coverage to presently underserved areas. In view of this, water governance authorities in Mozambique are asked to mobilize resources for developing such alternative water supplies, and develop mechanisms for the involvement of SSIPs; through management contracts within specified service areas inclusive those falling within formally contracted service areas under the rubric of delegated management. Franchising models whereby an official provider (either a private operator or a public entity) acts as the main franchisor and the independent providers as the franchisee may also be explored given the potential they have to simultaneously improve service delivery and local economic development (Wall, 2006). Since most SSIPs are currently not formally regulated, the challenges facing the water governance authorities in this respect are also related to formalization and regulatory aspects which are further discussed in section 5.5 of the thesis.

5.2 Meeting drinking water quality targets

Drinking water treatment aspects and quality criteria are discussed in Papers 1, 5 & 6 of this thesis. From the discussion in Paper 1 it was concluded that, most common source of drinking water production in Mozambique is surface water and that, most commonly applied method of drinking water production is conventional treatment. Drinking water quality standards to be met during water treatment are those developed by the Ministry of Health (MISAU 2004), based on the WHO Guidelines.

The first place where drinking water quality standards have to be met is at the outlet of water works. Analysis of drinking water treatment results (Paper 1) have shown, however that treated water quality from the water works studied did not always conform to acceptable drinking water quality standards. Turbidity and levels of organic matter in the treated water were generally high and exceeded recommended limits of the guidelines. The waterworks studied are the best-equipped waterworks in the country, thus the ones where, in theory drinking water treatment should have to be performed up to required standards. The situation in other, less equipped waterworks is, therefore, likely to be worse. Factors identified as having a significant effect on the performance of water treatment plants were: (i) inadequacy of existing infrastructure and operational procedures for water treatment, (ii) inconsistent operation of essential chemical processes due to malfunctioning of equipment or temporary lack of chemicals and, (iii) lack of guidelines for specific contaminants (e.g. DBPs), which mean that water treatment is aimed only at those variables for which guidelines have been established.

The main challenges facing water governance authorities in this respect is to assure that currently applied methods of drinking water production are capable of producing treated water that conforms to national and internationally accepted water quality standards (particularly those which are health-related) and that consumers are provided with the best possible water quality. As noted in Paper 1 and in section 5.1 of this summary, improvements of drinking water production require interventions at the level of source water quality and at design and operation of drinking water treatment processes. Practical aspects to be considered are:

- The need to guarantee proper selection, design and operation of drinking water treatment infrastructure so that, existing or to be constructed infrastructure is capable of dealing with commonly found raw water quality problems vis a vis current drinking water quality standards.

- The need to guarantee that the selection and management of raw water sources is done in such a way that existing treatment infrastructure is capable of dealing with corresponding raw water quality aspects,

- The need to guarantee that the quality of treated water at the outlet of treatment plants and further on during transport and distribution always conform to specified guidelines and that consumers are provided with safe water from the physical chemical and bacteriological points of view. The latter includes the effective removal of b*acteria, viruses* and other health-related pathogens.

- The need to guarantee that water disinfection with chlorine and other chemical processes used during water treatment do not become source of contaminants from treatment chemicals such as residual Aluminium and disinfection by-products.

- The need to develop knowledge and skills to deal with particular raw water sources such as raw water sources potentially polluted with organic contaminants of anthropogenic origin.

Various possible methods exist to attain these objectives and these were discussed in Paper 1. A process approach similar to the illustration in Figure 8 was proposed which is viewed with potential to bring immediate and significant changes in the actual scenario of drinking water production.

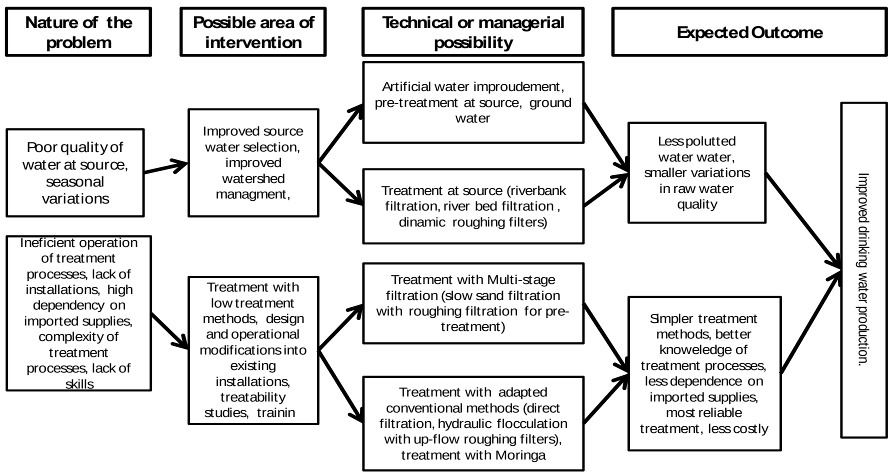

Figure 8 Process approach to improve overall drinking water production in Mozambique

Surface water quality in Mozambique is generally assessed as suited for treatment with conventional methods (paper 1); however, the possibility of abstracting less polluted water from existing sources may generally help improve drinking water production. Methods that can be used to meet this objective are, the use of artificial lakes and pre-treatment at source (e.g. through river bank infiltration) particularly if required flows are small. Problems with large reservoirs in tropical regions were discussed in Paper 1 and in section 4.1.1 of this summary and refers mainly to the risk of algae blooms, and presence of other toxic cyanobacteria and, sometimes, changes in the chemical composition of raw water (e.g. alkalinity) which can turn drinking water treatment even more complex and costly (Cheng et al. 2003; Baudin 2006).

Possible methods to improve design and operation of drinking water treatment were discussed in Paper 1 and technical options investigated in Papers 5 and 6. According to the discussion in Paper 1, improvements in the design and operation of drinking water treatment should aim the reduction of inefficient operations, which were found to result from variations in the raw water quality and inadequate operation of treatment processes. For reasons of long term sustainability, methods proposed for improving drinking water production put emphasis on the so-called low cost treatment methods, of which, roughing filters and coagulation-direct filtration processes were the methods investigated.

Extensive research on these methods (Ingallinella et al., 1998; McConnachie et al., 1999; Polasek & Mult, 2002; Mahwi et al., 2004) have proven that if properly incorporated into existing treatment schemes, they can help improve treatment efficiency and overall production capacity at relatively low investment and operational costs. Roughing filters are particularly advantageous because they can handle large variations in raw water turbidity without compromising overall treatment efficiency (Mishra & Breemen 1987; Smet & Visscher, 1990; Sánchez et al., 2006). Coagulation-direct filtration processes are also advantageous because they combine particle aggregation and separation in one single unit thus, giving room for large savings in investment costs. Coagulation-direct filtration processes are also advantageous because they demand lesser amounts of destabilizing reagents when compared to traditional coagulation-flocculation-sedimentation.

The results of experimental work on roughing filtration, presented in Paper 5, have proven that use of roughing filtration for hydraulic flocculation following chemical coagulation of surface water can provide a viable and flexible alternative to improve turbidity and solids removal by conventional rapid sand filtration. As seen from results presented in Paper 5, use of an up-flow roughing filters for hydraulic flocculation (contact-filter) resulted in the formation of suspensions which were completely retained by subsequent rapid sand filtration with minimum head loss developed in the filter bed of both units (Figure 9). The pilot plant used in the experiments was tested with the up-flow roughing filter operated at filtration velocities comparable to that of rapid sand filters yet, without signs of clogging or reduced efficiency of the up-flow filter. Best performances were attained with the pilot plant run at filtration velocities of about 6.0 m/h which are suitable for full scale operation of rapid sand filters. Coagulant doses were 25 % less than the amount required if conventional coagulation-flocculation was used.

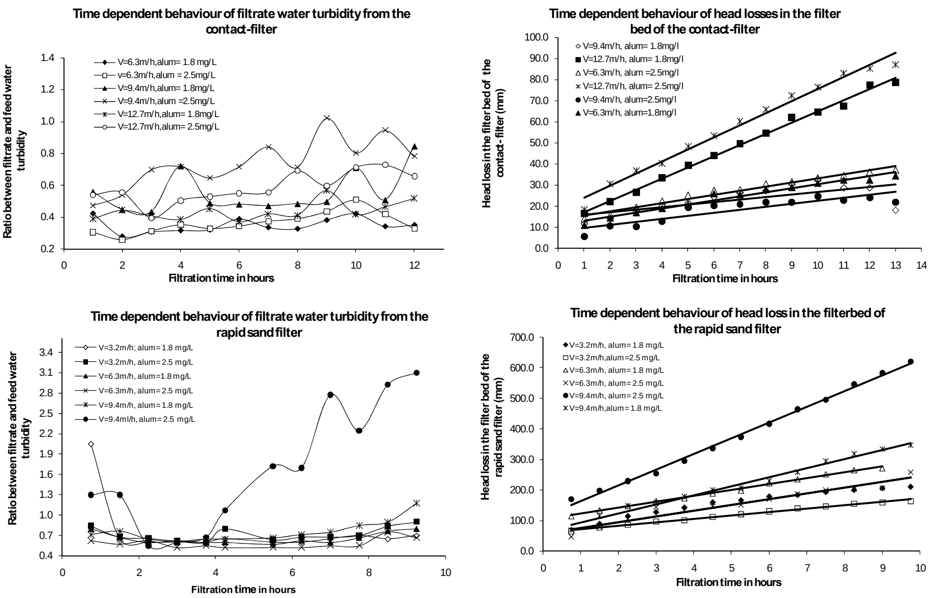

Figure 9 *Time dependent behaviour of filtrate turbidity (NTU) and head losses (mm) during filtration experiments with hydraulic flocculation in a multi-layer up-flow roughing filter followed by single media rapid sand filtration. Average raw water turbidity was of about 20 NTU. Information about filtration velocities and alum dosages applied is also shown.*

These results were in line with findings from other researchers (Mishra & Breemen, 1987; Mahvi et al.,2004; McConnachie et al., 1999,) about the possibilities of using roughing filtration for hydraulic flocculation prior to conventional rapid sand filtration (direct filtration processes). As seen in the results presented in Paper 5, the quality of feed water transferred to rapid sand filter following was generally better than that laving the gravel bed of the contact filter which suggests that apart from a partial removal of particles in the gravel bed, additional removal of particles took place in the supernatant water above the gravel bed (Figure 10).

This mean that if properly designed a contact filter using roughing filters can perform simultaneously as a flocculation and sedimentation basin which, in theory, opens room for large savings in investment costs in the event of construction of rehabilitation of drinking water treatment plants. Added to that, is the fact that the pilot plant could be operated at dosages of chemical reagent that were some 25 % less than the amount required if conventional treatment was used which means that saves are also possible in relation to operational costs of drinking water production.

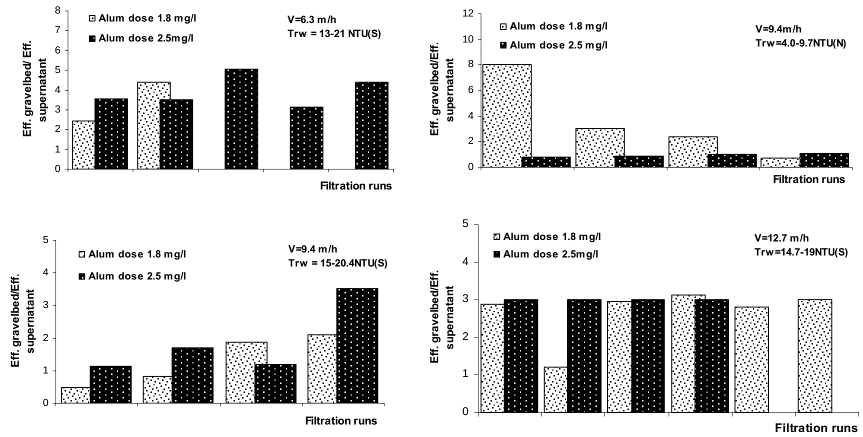

Figure 10 *Relative contribution of gravel bed and supernatant layer in turbidity removal in the contact filter: (N) = natural turbidity; (S) = synthetic turbidity; Eff. = efficiency (%. Information about filtration velocities and alum dosages applied is also shown*

Because drinking water production in Mozambique is also affected by constraints related to the temporary lack of supplies essential for effective operation of chemical processes (coagulants), methods of improving chemical treatment by using natural coagulants (*M. Oleifera*) as a substitute to metal salts were also tested. Results obtained (Paper 6) coincide with findings from other researchers (Ngabigengesere & Narasiah, 1998; Katayon et al., 2005) about the advantages of using the natural coagulant for drinking water treatment notably that:

- treatment with *M. Oleifera* does not affect the chemistry of treated water,
- treatment with *M. Oleifera* produces lesser amounts of sludge as compared to coagulation with metal salts,
- *M. Oleifera* has the possibility of production at local level and at relatively low costs.

Use of *M. Oleifera* for water coagulation has, however the disadvantage of increasing the concentration of nutrients and COD in the treated water. These findings were confirmed during the experiments with *M. Oleifera* the results of which were presented and discussed in Paper 6. Accordingly most efficient treatment was found when using aluminium sulphate for coagulation of water, however, treatment with *M. oleifera* could also produce treated water of excellent quality. Methods used to extract the active agents from the *M. oleifera* included: extraction with tap water, extraction with distilled water and, extraction with distilled water followed by oil extraction. High turbidity removals were obtained when the active agents were extracted using tap water. Extraction methods affected therefore *M. oleifera* performance but not the final chemistry of the treated water.

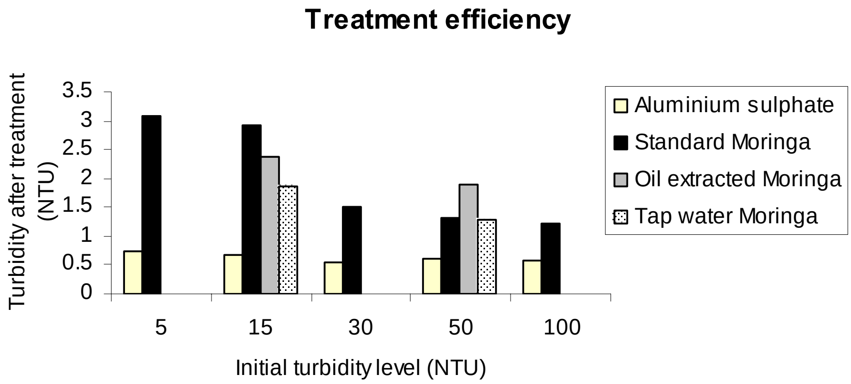

Figure 11: *Treatment efficiency with Moringa and Aluminium sulphate. Comparison of optimum dosage of coagulant and treatment efficiency (turbidity removal) for different levels of raw water turbidity. Results from jar-test experiments.*

Treatment of water coagulated with *M. oleifera* with up- flow roughing filter used for hydraulic flocculation and rapid sand filtration used final treatment was also tested. The results were compared to those obtained when alum sulphate was used for coagulation instead. Treatment with aluminium sulphate resulted in a better effluent quality but, the treated water when *M. oleifera* was used was also of acceptable quality. Treated water turbidity when *M. oleifera* was used was within acceptable limits for drinking water production (less than 2 NTU) and the increase of head losses in the filters was not higher for *M. oleifera* when compared to aluminium sulphate.

From the results obtained with the experiments with *M. oleifera*, it was concluded, that treatment with *M. oleifera* can be a simple, cheap and sustainable solution to substitute aluminium sulphate during water coagulation, particularly in small waterworks. Overall, it can be said that tap water extracted *M. oleifera* and treatment with flocculation followed by direct filtration processes are alternatives that can be explored in the event of expansion or construction of small waterworks.

5.3 Management of drinking water quality

In previous sections of this thesis, a discussion was held on drinking water production aspects of Mozambique, the critical aspects affecting treatment possibilities and the possibilities of improving drinking water treatment efficiency through adoption of low cost treatment options. Methods discussed considered improvements of source water quality (e.g. through best watershed management practices and pre-treatment at source) and improvements in design and operation of drinking water treatment processes.

Drinking water quality management may be established through a combination of protection of water sources, control of treatment processes and management of the distribution and handling of water. It has generally five key components:

1. The water quality targets;
2. A system assessment to determine whether the water supply chain (up to the point of consumption) as a whole can deliver water of a quality that meets the above targets;
3. A monitoring of the control points in the supply chain that are of particular importance in securing drinking water safety;
4. Management plans documenting the system assessment and monitoring; and describing actions to be taken under normal and incident conditions. This includes documentation and communication; and
5. A system of independent surveillance that verifies that the above are operating properly.

Formally water supply agencies have a basic responsibility to provide safe water and would be expected to develop and implement management plans to address points 2 through 4 above. These management plans should address all aspects of the water supply, focusing not only on control of water production and treatment but also on the delivery side of drinking water.

While the priority in most water supplies is the need to comply with drinking water quality standards at the outlet of the waterworks, the quality of water that finally reaches consumers is not always the same as that leaving the treatment works. External factors such as post-contamination due e.g. to ingress of contamination, and water quality deterioration due to prolonged storage in pipes, reservoirs and household tanks, are known to largely impact the final quality of water delivered to consumers. This mean that, while compliance to drinking water quality standards at production level is important, the management of drinking water quality following treatment is equally important in the global effort of meeting drinking water quality targets. Main challenges facing water governance authorities of Mozambique in this respect, is the need to secure that treated water is of good quality at any time and location downstream the treatment facilities and that consumers are provided with the best possible water quality.

Management aspects of drinking water quality in Mozambique were discussed in Paper 2, using the network of Maputo as an example. Factors identified as having a significant impact on water quality deterioration in the network were: ingress of contamination during periods of low or no supply and prolonged storage in pipes and household tanks. The intermittent mode of operation of the network of Maputo was found to largely contribute to the problems. Because intermittent supplies are used not only in Maputo but in almost all urban settlements of Mozambique, the drinking water quality situation of other cities where existing pipe works are in poorer conditions will be similar or even worse than that encountered in Maputo.

This mean that besides efforts to increase drinking water availability in the main towns, the main challenges facing water governance authorities in this respect is the need to implement actions aimed at reducing inconveniences resulting from intermittent supplies thus, eliminating factors responsible for water quality deterioration following treatment. Since, moving from the present condition of intermittent supplies to conditions of continuous supplies is a long term goal that requires massive investment, simpler and less costly actions can be implemented which includes: increasing public awareness on the health risks associated with practices commonly used to overcome water shortages caused by intermittent supplies, improve water quality management practices (e.g. through a review of water re-chlorination strategies) and improve household water management practices (e.g. through mandatory rules for construction and location of household tanks).

5.4 Role of alternative service providers

Urban water supply services by alternative service providers were discussed in Papers 3 and 4. From the discussion in Paper 4, it was concluded that they provide a valuable contribution in overcoming the problems resulting from inadequate service coverage particularly in peri-urban areas experiencing rapid population growth. In the discussion, it was also concluded that the demand for their services is driven not only by demand for services in areas presently lacking or with unreliable piped water supplies but also by the incapacity of formal providers to respond to the water demand of their service areas. This situation is unlikely to change in the near future. Moreover, SSIPs have recently been recognized by water governance authorities as important partners in the global effort of expanding service coverage with piped water supplies. As noted in Paper 4, the strategy adopted is based on public private partnership arrangements whereby the public sector transfers part of its responsibility of service delivery to self-financed or formally delegated private actors, among which SSIPs, while keeping the political responsibility for the services.

The typical design of water systems constructed by SSIPs or those constructed by water governance authorities for further delegation of operational responsibility to private operators is based on groundwater sources which mean that, the potential of regional aquifers used to develop such systems and the associated quality problems are key elements for the long term planning of service delivery expansion with alternative service providers. Moreover, most systems of this type are constructed within moderate to densely populated areas where, sewers do not exist and sanitation is mainly provided through septic tanks, cesspits and dry-pit latrines (Paper 3). Under these conditions, seepage from on-site sanitation represents the most serious source of widespread pollution (both point and diffuse) to the aquifer systems. Construction and completion details of the boreholes that will be connected to such systems are also crucial factors in that they may increase the risk of groundwater contamination by creating localized pathways for ingression of pathogens (Schmoll, 2006; Godfrey, 2005) or by shortening the distance and time required for pathogens to reach the groundwater table (Argoos, 2001). The extent and risk of groundwater contamination will depend, however, on many factors among which, the degree of attenuation of contaminants during percolation through the unsaturated zone and, eventually, through the aquifer system (Lewis et al., 1981; Sugden, 2006).

The expansion of service provision with the involvement of self-financed or formally delegated alternative providers is, therefore, associated to quality and quantity problems that may undermine the long-term sustainability of the proposed strategy. These problems were discussed in Paper 3 and possible measures to diminish risks of failure of the proposed strategy identified. One of such measures is the establishment of clear regulatory tools that will enable water governance institutions frame the activity of alternative providers and enforce the adoption of more stringent protective measures for boreholes constructed to provide public services and for construction and management of small-scale water supply systems. This include for example:

- Regulated procedures for borehole design and location in order to minimize risks of groundwater contamination. Emphasis should be put on aspects such as wellhead protection, positioning of filter screens and the location of boreholes in relation to existing pit latrines. A minimum radius of influence of 25 m from pit latrines is generally accepted in Mozambique.

- Mandatory rules for direct protection of boreholes used for drinking water supply (e.g. a 5x5 m surrounding fence)
- Mandatory rules for all type of alternative providers regarding chlorination of the water before distribution.

In the discussion of urban water supply services (Paper 4), it was also concluded that, as for today, the activity of alternative providers is not formally regulated and that reforms are needed in the existing legal and regulatory framework so that matters concerning service quality and protection of consumer´s interests can be addressed. Critical aspects around this matter are discussed in the next section of this thesis.

5.5 Regulation and legal aspects around formal and informal service providers

Legal and regulatory aspects of urban water supplies in Mozambique are discussed in section 2.2 of the thesis and in Paper 4. In Paper 4, the main aspects of regulation of water supply services in an environment where formal and informal service providers coexist were discussed using the city of Maputo as an example. It was concluded that, while regulation aspects around formal water supply services are clearly defined, the situation concerning alternative service providers is still unclear. This was found to limit the possibilities of expanding the existing regulatory framework in a way to make it inclusive of all forms of service provision in urban environments. Given that alternative providers generally operate in areas where the majority of the urban poor lives, the existing situation of regulation of urban water supply services was also found to limit the possibilities of establishing mechanisms to protect unconnected consumers with regard to matters such as water pricing and water quality thus, undermining the ultimate goal set by the water governance framework of servicing the poor.

As noted in Paper 4, in cities with delegated management of water supply, a management model for peri-urban water supplies has been developed by the water governance authorities that, in theory, should address pro-poor aspects in the existing regulatory framework. This management model was, however, found to have a number of limitations to meet its objectives because:

- The model is based on a contractual agreement between standpipe attendants of the public service and the main service provider. As such, the model is not applicable to other forms of service provision (e.g. from the informal water market). The model does not open room for the establishment of mechanisms to protect unconnected consumers in aspects related for instance to water pricing and water quality.

- There is lack of legal basis for issuing licenses to authorize other types of service providers to operate within the lease area and hence their inclusion in the standpipe management model.

- There is lack of clarity concerning the roles of municipalities and neighbourhood authorities in the management of water services in areas covered by the framework. This result in a lack of clarity and possible conflicts of interest of the role they have to play as system managers and system regulators.

- Lower water governance institutions of the framework (e.g. e.g. municipal and neighbourhood level authorities) have a weakened position to perform in an unbiased fashion their regulatory tasks. Neighbourhood level authorities are also involved in the selection and nomination of standpipe attendants and in the management of the finances of the standpipes therefore, tasks of management, supervision and regulation are generally not separated.

The most serious challenge facing water governance authorities in this respect is therefore the need to establish mechanisms that will allow the expansion of the existing regulatory framework to cover also the informal water market. As noted in Paper 4, the first step in this respect is the definition of a clear licensing framework with which, all actors involved in the provision of water supply services will be obliged to comply. Aspects to be taken into consideration in this respect are also discussed in Paper 4 and include:

- The licensing framework should be inclusive of all forms of alternative service providers regardless of their position in relation to formally contracted concessions.

- The financial and social sustainability of services provided through public standpipes should be maintained because it is through this type of service provision that the majority of urban poor get access to piped water. Actors of the presently informal water market should therefore be complementary and not competitors to the public service,

- The issuing of licenses for water resale activities should follow a real demand as expressed by consumers,

- To reduce the risk of inconsistent and unsustainable services due to managerial constraints, the issuing of licences for actors of the presently informal water market should follow proven managerial capacity of potential candidates.

Since one of the major weaknesses identified in the existing regulatory framework is the lack of clarity concerning the position and role played by institutions of the lower water governance framework in the management of water supply services, the proposed licensing framework should also consider a decentralization of certain regulation activities to institutions of the lower level of the water governance framework. Emphasis should be put on separating the supervision and regulatory roles played by these actors. With CRA playing the role of normative agency, and the Municipalities playing the role of the licensing authority, the water governance framework will have greater leverage to ensure compliance. In areas without delegated management of water supply the normative role will be played by district or municipal regulatory commissions. Furthermore, at neighbourhood level, clarification of communication lines from the community level upwards to the institutions at higher level of the governance framework is required. Partnerships with Non Governmental Organizations-NGOs, Community based organizations-CBOs and the municipality are also needed to develop information channels and communication campaigns to inform consumers of their rights and options for recourse or assistance.

6. SUMMARY AND CONCLUSIONS

This thesis had two main purposes: to analyze water supply services in Mozambique and critical factors affecting provision of safe and reliable drinking water supply services and, to investigate methods of improving the situation and challenges facing the sector to secure safe and sustainable drinking water supply in the long run. This was done by analyzing drinking water supply aspects based not only on quantitative aspects but also on qualitative indicators such as the quality of drinking water, and the reliability of water supply services. Critical factors affecting drinking water production were also analysed and methods to improve the situation evaluated. Legal and regulatory aspects of drinking water supply were also discussed.

From the analysis presented and the results obtained, the following answers were given to the research questions of the thesis.

Which key factors currently affect drinking water production and the management of drinking water quality in the context of urban water supplies in Mozambique?

Analysis of drinking water production aspects have shown that as for today, drinking water treatment is not done up to the standards due to a combination of factors that includes; poor water quality at source, lack of functional installations and poor performance of processes within existing installations. Most commonly used source of raw water for drinking water production is river water and for treatment, conventional methods are mostly used.

The quality of water from rivers in Mozambique is very similar to that encountered in many other parts of the world, where drinking water production is done up to standards with treatment methods that are similar or even simpler than those used in Mozambique. Methods used for drinking water treatment and sources used for drinking water production are, therefore, suited for production of water of excellent quality.

Factors identified as having a significant effect on drinking water production in Mozambique were ranked in two categories namely: source water quality related factors and, operational and technical related factors. Source water quality factors refers mainly to the seasonal variations in river water quality which makes drinking water treatment to be generally costly and technically demanding because the treatment process must be sufficiently flexible to treat the varying quality of the raw water. Chemical coagulation and flocculation seem to be unit operations mostly affected by such variations because for best efficiencies, careful adjustment of operational parameters is generally required. Inefficient performance of coagulation-flocculation generally leads to inefficient performance of subsequent clarification processes thus, to inefficient production of drinking water. Technical and operational related factors refers mainly to: (i) inadequacy of existing infrastructure and improper operation of treatment processes due to lack of knowledge among plant operators, (ii) inconsistent operation of essential chemical processes due to malfunctioning of equipment and temporary lack of consumables and, (iii) lack of guidelines for specific contaminants (e.g. DBPs), which means that water treatment is aimed only at those variables for which guidelines have been established. Overall, technical and operational related factors have more impact on drinking water production.

Management of drinking water quality is also deficient. Present limitations in water safety and water quality results from lack of adequate treatment and inadequate strategies for operation of water distribution (intermittent operation) which leads to frequent deterioration of treated water quality. Factors identified as having a significant impact on water quality deterioration were; ingress of contamination and water quality deterioration due to prolonged storage in pipes and reservoirs. The intermittent mode of operation of water distribution has, therefore, been identified as one of the critical factors affecting water quality following treatment. Besides leading to frequent fluctuations in pressure, intermittent supplies are known to force consumers to find ways of coping with intermittency by constructing extra household tanks. Pressure fluctuations contribute largely to ingress of contamination while, household water storage contributes to water quality deterioration due to prolonged storage.

Given the present status of urban water supplies, what alternatives are there for subserviced consumers to overcome the inconveniences caused by a lack of, or inadequate, piped water supplies? In addition, which factors affect the current and long-term sustainability of service provision through alternative service providers?

Methods found by subserviced consumers to meet their water demands comprehends the reliance on services provided by alternative service providers. Service provision with alternative providers is generally assessed as good in matters related to coverage, service reliability and accessibility to consumers. The quality of water from sources used to provide services is also assessed as safe for human consumption and domestic use. Yet, the quality of water that is ultimately delivered to consumers depends not only on the quality of water at source, but also on the treatment and storage methods applied following abstraction. External factors, such as those resulting from storage conditions and the condition of pipe networks, greatly affect the quality of the water. These are common problems to water services provided through formal water supplies which mean that consumers relying on alternative providers are exposed to the same level of human health risks as those relying on formal water supply services.

Service provision with the help of alternative providers is not likely to change in the near future mostly because of increasing demand for their services. Moreover, alternative service providers have recently been recognized as strategic partners for service provision expansion in areas presently lacking formal water supplies. The typical design of water systems run by alternative providers is based on groundwater flow, therefore, the potential of regional aquifers used to construct such systems and the associated quality problems are key elements for the long term planning of service delivery expansion through alternative providers. Factors such as over-exploitation of the aquifers and increased hydraulic loads of contaminants due to increased population densities will certainly impact their capacity of providing quality water of sufficient quantity in the long term.

The long term sustainability of service provision expansion with the help of alternative providers is also faced with possible threats associated to their actual legal status. Main challenges facing water governance authorities in this respect are the need to establish mechanisms that will allow the formalization of alternative providers and the expansion of the existing regulatory framework to allow for the enforcement of more stringent protective measures around water supply services offered through this segment of providers.

Given the prevailing situation regarding drinking water production and the management of drinking water quality, which options exist to improve the efficiency of drinking water production in order to secure safe and sustainable drinking water supplies in the long term?

The evaluation of drinking water production aspects of Mozambique has indicated that drinking water treatment is deficient. Poor quality at source, inadequate infrastructure and, inconsistent or inadequate operation of water treatment processes were factors identified as affecting largely drinking water production. Possible methods to improve the situation were investigated and found to require improvements both in the management of source water quality and in the design and operation of treatment processes within the actual context of skills, logistics and managerial capacity. For reasons of sustainability, low cost treatment technologies, among which, roughing filtration and coagulation-direct filtration processes with up-flow roughing filtration used for hydraulic flocculation were investigated given their potential to increase overall production capacity and treatment efficiency at relatively low investment and operational costs.

These methods were found to be particularly advantageous because they can handle large variations in raw water turbidity without compromising overall treatment efficiency. Also, because they generally combine particle aggregation and separation in one or few unit large savings in investment costs can be attained through elimination of sedimentation and flocculation basins usually required in conventional treatment. Coagulation-direct filtration processes are also advantageous because they demand lesser amounts of destabilizing reagents when compared to traditional coagulation-flocculation-sedimentation.

Use of natural coagulants such as the seeds of the *M. oleifera* tree for water coagulation at small scale treatment plants was also investigated and the results compared to those obtained when using aluminium sulphate for the same purpose. Although most efficient treatment was found when using aluminium sulphate, treatment with *M. oleifera* could also produce treated water of excellent quality. Use of *M. oleifera* for water coagulation was found therefore an realistic alternative to conventional methods in small to medium size water supplies, presuming that an adequate amount of plantations are established. Use of *M. oleifera* and treatment with flocculation followed by direct filtration processes are, therefore, alternatives that can be explored in the event of expansion or construction of small waterworks.

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Appendix. Papers

I

CHALLENGES FACING DRINKING WATER PRODUCTION IN MOZAMBIQUE- A REVIEW OF CRITICAL FACTORS AFFECTING TREATMENT POSSIBILITIES

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ABSTRACT

This paper discusses the drinking water production situation of Mozambique and critical factors affecting treatment possibilities. The River water quality of six important rivers is analysed and some of the critical factors affecting treatment possibilities identified. Treated water quality of three major waterworks of the country is also analyzed and the results used to infer from the overall situation of the country. High turbidity values occurring typically during rainy periods, presence of bacteria, natural organic matter and, sometimes, presence of algae were identified as water quality variables of major concern for drinking water production. Seasonal variations in river water quality make drinking water production costly and technically demanding. Treatment processes should therefore be designed for the worst water quality case. Technologically and operationally related aspects also impact drinking water production. The situation is critical in small to medium size water supplies where lack of financial capacity limits the possibilities for investments in costly production methods. Methods of improving the situation are also discussed. This includes pre-treatment at source and technical improvements through incorporation of low cost treatment processes into already existing plants. If properly incorporated, these methods are proven to increase overall production capacity at relatively low investment and operational costs.

Keywords: drinking water production**,** surface water; conventional treatment; roughing filtration; coagulation -direct filtration

INTRODUCTION

Drinking water production in Mozambique depends mostly on river water. Most rivers are of torrential regime, thus associated with seasonal flow and water quality variations. When used for drinking water production surface water must be treated. Turbidity, suspended solids, natural organic matter (NOM), and pathogenic bacteria are generally the quality variables of major concern. Impurities resulting from human activities can also be present and impact the raw and treated water quality and sometimes, the complexity of drinking water production (WHO, 2004). Conventional treatment is the most widely used method of removing impurities from surface water supplies. In its simplest form, it involves chemical coagulation, flocculation, sedimentation and filtration followed by disinfection (Hansen, 1988; WHO

2004). Additional treatment may include pre-chlorination to assist the removal of algae and dissolved organic matter and conditioning for alkalinisation and corrosion control. Conventional treatment consisting of chemical coagulation, flocculation, sedimentation filtration and chlorination is also used in Mozambique. Because of many reasons, however, most drinking water treatment plants are presently incapable of producing treated water of acceptable quality. This is particularly true in small to medium sized water supplies where the combined effect of poor water quality at source, operational and logistic constraints and limited financial capacity makes drinking water production far more ineffective.

This paper examines the overall situation of drinking water production in Mozambique and critical aspects affecting treatment possibilities. The raw water quality of six important rivers used for drinking water production is analyzed. Results of drinking water production from three major waterworks of the country are analyzed and used to infer from the overall situation of drinking water production in the country. Methods of improving the situation are also discussed with emphasis put on small to medium size water supplies.

METHODS

Selected rivers

Six rivers were selected rivers for the study. These are, the Limpopo, Maputo and Umbelúzi Rivers located in South of Mozambique, the Púngué River located in central Mozambique and the Monapo and Licungo Rivers located north of Mozambique. The Umbelúzi, Púngué and Monapo rivers are used for drinking water production of three largest cities of Mozambique namely, Maputo, Beira and Nampula cities.

Selected waterworks

Results of treated water quality from the waterworks of Maputo, Beira and Nampula were used in the study. These are the waterworks where records of water quality determinations exist or could be assessed. The three waterworks are constructed based on conventional methods.

Source of data and selection of water quality parameters

Data used in the study were obtained from three major sources namely historical data gathered by the national water authority (DNA) for the Licungo and Umbelúzi rivers and results from controlled studies on the Limpopo and Maputo rivers. Records of raw and treated water from plant operators at Beira and Umbelúzi waterworks were also used. Field work conducted between March and April 2008 was used to gather additional data on Púngué and Monapo rivers.

Before use, the data obtained from DNA databases were checked for their analytical accuracy through charge balance tests performed with the data on ionic species. These tests were used to eliminate faulty or suspicious observations from the original data sets. A charge balance error of ±15% was accepted due to the limited length of available data sets. Around 53% of the data sets analyzed for the Licungo River and 24.5% from the Umbelúzi were rejected due to unreliable figures of different water quality parameters and charge balance errors higher than 25%.

Turbidity, hardness, pH and alkalinity, organic matter, indicator organisms, phosphate (related to algae growth) were used to assess the overall condition of river water. To assess drinking water treatment results, turbidity, pH, alkalinity and organic matter were used. Turbidity was selected because it impacts treated water acceptability and the performance of unit operations during treatment. Turbidity is also related to presence of microorganisms (WHO, 2004). The water hardness was selected because it impacts water acceptability and water treatment. The water pH and alkalinity were selected because they impact chemical processes (e.g. coagulation, chlorination) during water treatment. The water alkalinity also helps assess the degree of water corrosiveness following treatment.

Organic matter was selected because it influences the quality of treated water, especially the levels of nutrients available for bacteria growth. Organic matter can also interfere with treatment processes. The guideline value for treated water is 2.5 mgC/ℓ measured as DOC (WHO, 2004). Presence of bacteria was selected for obvious reasons of human health protection and algae were selected because they impact treatment processes (e.g., filtration) and have the potential to release toxins of health concern.

RESULTS AND DISCUSSION

Typical river water quality

Typical values/ranges of river water quality variables compiled from existing studies and data bases of selected rivers are presented in Table 1. For comparison, the Mozambican guidelines (MISAU, 2004) for drinking water are included.

Physic-chemical quality

For all six water sources analyzed, turbidity and total suspended solids concentrations are generally found within ranges that exceed the guideline values for drinking water even when they occur at their lowest concentrations. The river water turbidity also experience seasonal variations typical of river courses of torrential regime. Figure 1, gives an example of typical variations of river water flow and turbidity in four out of the six rivers analyzed. As seen, the river water turbidity can vary from figures lower than 10 NTU during the dry season, to figures above 300 NTU during rainy periods.

The relatively low values of maximum turbidity at Umbeluzi and Limpopo (site 1) rivers are due to the sampling sites being located downstream major hydraulic works (man-made reservoirs) where most solids and turbidity is reduced due to sedimentation. Analysis of data shown in Table 1 suggests a similar pattern with respect to suspended solids concentrations. Data used in this respect is from Limpopo, Púngué and Umbelúzi Rivers.

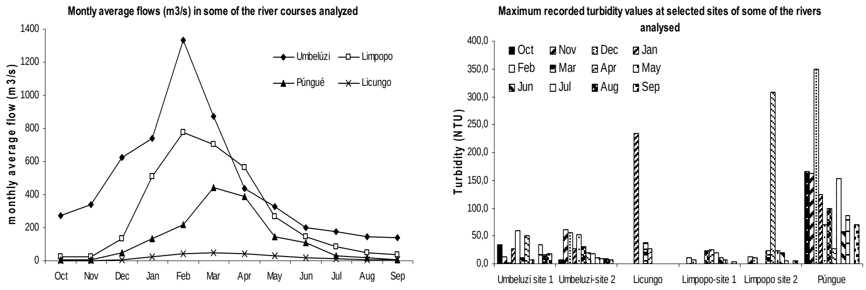

Figure 1 *Average monthly flows (m^3/s) and maximum values of water turbidity (NTU) recorded at selected sites of rivers used for drinking water production of some cities in Mozambique such as the city of Maputo (Umbelúzi River), Beira (Púngué River) and Mocuba (Licungo River). Data source: DNA database.*

Physical parameters such as water pH and temperature do not affect water acceptability, and are not of concern regarding health, but they have a major influence on water quality parameters such as bacteria and algae growth. Average river water temperatures in Mozambique are generally between 20 °C and 25 °C and the raw water pH generally between 6.0 and 9.0. Because high temperatures are generally accompanied by heavy rainfall and high river water turbidity, the combined effect of these factors provides ideal conditions for bacterial growth, algae blooming and the release of taste- and odour-forming compounds (Zamxaka et al., 2004; Chorus & Bartram, 1999). Added to this natural climatic effect is the enhanced rate of nutrient input that accompanies the growth of towns and the development of irrigated agriculture in the catchment areas around the water courses.

Chemical properties such as water hardness and alkalinity generally affect water acceptability and water treatment efficiency. Problems with hard or soft water are generally site specific because they depend on the interaction of many factors including the soils and rocks from which the water is derived, which are generally site or region specific (Stumn & Morgan, 1996; Lawrence et al., 2007). The water alkalinity is closely related to the concentration of carbonates, bicarbonates and hydroxide ions in the water, therefore it is closely related to water hardness. It influences, for instance, scale formation in the case of hard water and the degree of water corrosiveness of soft water (Polasek & Mult, 2005; Polasek, 2007; Velasco et al., 2007). During water treatment, the pH and water alkalinity affect processes such as coagulation and disinfection. Knowledge of the water's pH and alkalinity is therefore useful in evaluating the optimum conditions for treatment processes, as well as the final condition of treated water with respect to its corrosive or scaling properties.

From the results in Table 1, it is clear that the river water quality can be change from conditions of rather soft to moderately hard (Total hardness between 10 and 100 mg/ℓ) in some rivers (e.g. Licungo, Maputo and Púngué) while, in others (e.g. Limpopo and Umbelúzi) it varies from conditions of slightly hard to hard (100> total hardness < 440 mg/ℓ). Therefore, the type and magnitude of river water quality problems with respect to these quality variables is site specific. River water quality is however within acceptable limits for drinking water production.

Analysis of river water quality with respect to presence of organic matter could only be done for the Licungo, Limpopo and Umbelúzi Rivers. As seen in Table 1, levels of organic matter in river water are generally higher than the guideline value of 2.5 mgC/ℓ of the guidelines (MISAU, 2004). Also seen in Table 1 is that the river water quality also experience seasonal variations in respect to this quality variable. These were attributed to variations in river flow and water temperature. Yet, observed levels are not indicative of organic pollution of anthropogenic origin.

Table 1 Typical values of river water quality in Mozambique and drinking water standard requirements (MISAU, 2004). For Maputo river mean values of data sets used are presented with standard deviations values indicated between brackets.

Water quality constituent	Reference	Typical value/range							Mozambican guidelines (Misau 2004)
		Licungo (intake)	Limpopo (site 1)	Limpopo (site 2)	Maputo (site 1)	Maputo (site 2)	Púngue (intake)	Umbeluzi (intake)	
pH	-	5.3-8.1	6.7-9.7	6.7-9.3	8.2	8.0	6.0-8.5	6.7-8.7	6.5-8.5
Temperature	^{0}C	22-26.5	19 -32.0	22-32.8	-	-	18-35	21-26.5	-
Total dissolved solids	TDS (mg/l)	-	149-1930	123-1052	-	-	-	370-410	1000
Total suspended solids	TSS (mg/l)	-	7.3-384.0	3.6-288	-	-	1.7-106	-	-
Turbidity	NTU	5.5-234	5.8-308.0	10.1-362	16.6 (7.0)	18.2 (19.5)	5.0-33.0	3.8 -173.0	5
Total Hardness	$mgCaCO_3/l$	8.0-30.0	107-446	108-340	115.6 (101.5)	95.5 (27.8)	16-227	137-165.0	500
Total Alkalinity	$mgCaCO_3/l$	20-120	-	-	-	-	24-43	139-160.0	-
E. Conductivity	EC (ms/m)	120-410	26-337	25-185	24.8 (7.9)	39.0 (11.5)	40-88	550-630.0	1500
Manganese	Mn (mg/l)	-	0.05-0.36	0.02-0.31	-	-	-	0.01-0.03	0.1
Total iron	Fe (mg/l)	0.01-2.86	0.1-14.6	0.14-12.5	-	-	0.02-1.07	0.04-0.18	0.3
Nitrate	NO_3 (mg/l)	0.2-0.33	0.03	0.03	5.8 (4.4)	6.9 (3.9)	0.03-4.16	0.01-0.5	50
Nitrite	NO_2 (mg/l)	0.02-0.32	0.03	0.03	0.06 (0.06)	0.05 (0.06)	0.03-0.24	0.01-0.03	3
Total Phosphorous	(mgP/l)	-	0.05-2.0	0.03-1.98	-	-	-	0.01-0.63	-
Total coliforms	cfu/100 ml	-	-	-	-	-	-	>1000	1-10
E.Coli	cfu/100 ml	-	66-250	32-870	-	-	-	36-350	None
Faecal coliforms	cfu/100 ml	-	-	-	-	-	-	18-300	None
Total organic Carbon	TOC (mgC/l)	-	0.7-9.2	0.7-15.2	-	-	-	-	2.5
Bioch.O. Demand	(mg/l	-	0.5-3.6	0.5-2.5	-	-	-	-	-
Dissolved Organic C	(mgC/l)	0.5-7.8	0.7-10.1	0.7-8.8	-	-	-	2.0-6.4	-

Microbial quality

Data on microbial quality of river water could only be assessed for Limpopo and Umbelúzi rivers. Average monthly values of total coliforms and faecal bacteria are presented in Table 1 for the Umbelúzi river, whereas for the Limpopo River, results of *E.Coli* determinations are presented. The data regarding faecal bacteria counts in Umbelúzi river water was further plotted against turbidity and time (Figure 2). As seen from Table 1 and Figure 2, presence of faecal bacteria in river water is constant and generally high during the whole year. The data on presence of faecal bacteria in river water were also found to show good correlation to river water turbidity (0.5 < R < 0.8) and less with water temperature (0.3 < R < 0.9).

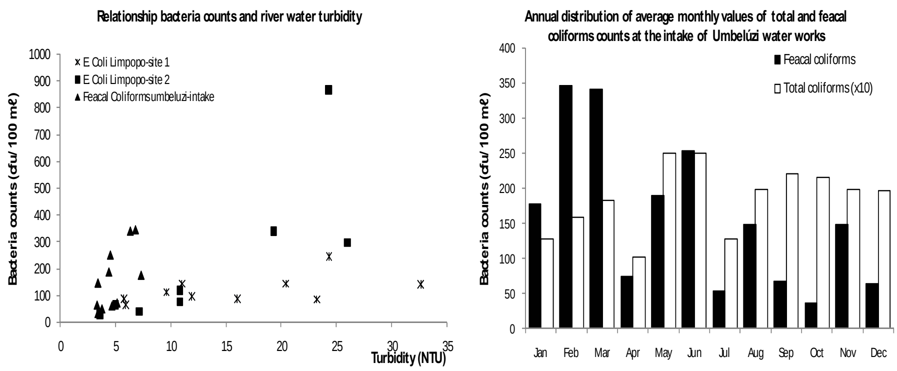

Figure 2 *Monthly records of data related to contamination with bacteria at the intake of the Umbeluzi River and relationship with river water turbidity (left). Also illustrated is the pattern concerning incidence of bacteria in river water during the year (right).*

Biological characteristics

Presence of algae and aquatic plants were the parameters used to assess the biological quality of river water. Studies to investigate presence of algae in river water could only be found for the Umbeluzi and Limpopo rivers. The two studies assessed during this work involved the Umbeluzi (Bojcevska & Jergil, 2003; Gustafsson & Johansson (2006)) and the Limpopo rivers. The study from Bojcevska & Jergil, (2003), focused on the presence and removal of cyanobacterial toxins in water taken from an impounding reservoir supplied by the Umbelúzi River. The study from Gustafsson & Johansson (2006), focused on presence of nutrients, among which phosphorus, as an indicator of the potential for river water eutrophication. In the study on the Limpopo River the water quality was assessed for presence of phosphorous. Some results of measurements of levels phosphorus in river water taken by DNA at irregular intervals were also used.

Average phosphorous concentrations as measured by Gustafsson & Johansson (2006) in the Umbelúzi River are of about 0.054 mgP/L whereas; the data from DNA database indicates figures in the range 0.01-0.63 mgP/L. The study on the Limpopo River provided values of phosphorous in the river water in the range 0.03 mgP/L-2.0 mgP/L (see Table 1). Different references found in literature and proposed by different organizations and authors suggest limits for total phosphorous concentrations in the range 0.1-0.16 mgP/L (Table 2) to avoid euthrophication of river water.

Table 2 Limiting concentrations of Phosphorous and nitrogen to reduce risk of river water euthrophication. Limits suggested by different organizations and authors (* all fresh waters; ** Total P = 0.3262 PO_4^{3-} (mg/L).

Constituent	Limit
Phosphorous	
Tot. P (rivers draining to lakes- U.S.EPA)	0.05 mgP/L
Tot. P (rivers not draining to lakes- U.S.EPA)	0.1 mgP/L
Phosphate (Fytianos et al., 2002)	0.5 mgPO_4^{3-}/L = 0.16 mgP/L
Inorganic P (SAWQG)*	0.005 mgP/L
Nitrogen	
Inorganic N (SAWQG)**	0.5 mgN/L

As seen from Table 1, phosphorous concentrations in the Umbelúzi River could reach values higher than the indicative limit of 0.16 mgP/L. This suggests that euthrophic conditions might occur from time to time in the Umbelúzi River. The study from Bojcevska & Jergil (2006) gave evidences of presence of toxic cyanobacteria present in the reservoir water.

The study from Gustafsson & Johansson (2006) provided lower values. However, this study had a sampling period covering a shorter period of analysis (from Sept. to Nov.) which can explain the difference in the results. Average values measured by Gustafsson & Johansson were however close to or exceeded the critical value proposed in Table 2 for rivers draining into lakes as is the Umbelúzi River which support the statement made before that euthrophic conditions might occur frequently in the river. Problems with algae at the Umbelúzi River were been reported in a past study by Couto (2004) and more recently by managers of the waterworks of Maputo water supply who report frequent outbreaks of algae at the intake works.

The results for the Limpopo River are similar to the results on the Umbelúzi river (Tot. phosphorous concentrations in the range 0.03-2.0 mgP/L). Two sampling locations were used for this analysis. Given the origin of the problem, similar conditions are expected in many other rivers used for drinking water production, particularly those where intensively irrigated agriculture is practiced upstream the major intake works.

Typical design of drinking water treatment in Mozambique

In Table 3, a summary is given of the most common design of drinking water treatment plants in Mozambique. As seen, most water supplies rely on surface water for drinking water production and conventional methods for water treatment. Most treatment plants are built with pre-chlorination, chemical coagulation, flocculation, sedimentation, rapid sand filtration and disinfection with chlorine. Modifications to the basic design comprehend the use of package units incorporating all physical processes (flocculation, sedimentation and filtration) in one single unit and the used of aeration and direct filtration processes mainly for ground water supplies.

Table 3 Typical design of drinking water treatment plants of 10 major cities of Mozambique

Town	Estimated water demand by 2008 (m^3/day)[1]	Type of raw water source	Type of treatment	Operating capacity (m^3/day)[2]
Lichinga	2 947	SW+ large reservoir with selective intake	Conventional with pressure filters	2 160
Pemba	9 487	GW–borehole field	Conventional with cascade aeration + direct filtration	10 000
Nampula	14 762	SW+ large reservoir with constant intake	Conventional-standard[3]	13 500
Nacala	6 568	SW+ large reservoir with constant intake	Conventional with pressure filters	5 700
Quelimane	13 320	GW–borehole field	Slow sand filtration	4 200
Tete	7 116	GW–borehole field	Conventional with cascade aeration + direct filtration	5 100
Beira	30 000	SW–direct intake from a sugar cane irrigation channel	Conventional-standard with lamella type settling basins	19 200
Xai-Xai	8 600	GW–dune aquifer	Disinfection with granular chlorine	6 000
Mocuba	2 279	SW–direct intake from river	Conventional standard + pressure filters	1 000
Maputo-Matola	240 000	SW–direct intake from river	Conventional standard	172 800

[1] According to estimates from DNA.
[2] design capacity according to plant operators.
[3] conventional standard = pre-chlorination, chemical coagulation, flocculation, sedimentation, rapid sand filtration and disinfection.

As it is seen from Table 3 most waterworks are operated below or very close to required demands. The only exception in the Table, are the waterworks for Pemba.

Typical Results of drinking water treatment

Water quality

In Table 4 an example is given of treated water quality from the waterworks of Maputo, Beira and Nampula. The data used is based on annual records from year 2004.

Table 4 Results of water treatment at three waterworks in Mozambique (R_{water} = raw water; T_{water}= treated water; -, not measured, Min. = minimum recorded; Max. = maximum recorded; STD = standard deviation)

Quality variable	Turbidity (NTU)		Org. matter (mgO_2/L)		pH		Alkalinity (mg/L)		Res. Cl^- (mg/L)
Umbeluzi waterworks									
	R_{water}	T_{water}	R_{water}	T_{water}	R_{water}	T_{water}	R_{water}	T_{water}	T_{water}
Min.	2.9	0.7	2.0	0.8	6.3	6.5	98	41	0.3
Max.	80.6	7.3	6.4	4.8	8.1	7.9	240	230	2.8
Mean	6.7	3.1	4.0	2.7	7.4	7.4	160	152	1.4
STD	6.6	0.9	0.8	0.7	0.20	0.2	14.2	18.7	0.4
Nr. Of records	359	358	351	350	357	358	353	351	333
Beira waterworks-old treatment plant									
Min.	13.5	0.2	-	-	6.4	6.2	-	-	-
Max.	326	28.0	-	-	7.6	7.6	-	-	-
Mean	49.9	2.5	-	-	6.8	6.7	-	-	-
STD	31.1	3.3	-	-	0.1	0.2	-	-	-
Nr. Of records	310	303	-	-	309	307	-	-	-
Beira waterworks-new treatment plant									
Min.	11.8	2.3	4.7	2.0	6.4	6.1	58	52	-
Max.	25.9	6.5	6.4	3.2	6.9	6.3	78	82	-
Mean	17.0	4.2	5.6	2.81	6.6	6.2	64.9	61	-
STD	4.6	1.1	0.7	0.4	0.2	-	7.4	9.6	-
Nr. Of records	9	9	8	8	9	9	9	9	-
Nampula waterworks									
Min.	11.7	6.5	4.0	3.2	7.2	6.6	26.9	25.0	-
Max.	47.0	16.8	6.0	4.6	7.9	7.8	38.4	57.6	-
Mean	25.0	10.9	4.8	2.9	7.4	7.2	31.3	39.3	-
STD	13.8	3.3	0.7	0.5	0.3	0.4	3.1	9.6	-
Nr. Of records	10	10	10	10	10	10	10	10	-

As seen in the Table, treated water quality not always conform to the guidelines (WHO) particularly in relation to turbidity and organic matter concentrations. The mean values of treated water turbidity of Maputo and Beira waterworks are generally below the tolerable limit of 5 NTU, but the absolute limit of 1 NTU of the guidelines is hardly attained. Treated water turbidity from Nampula waterworks, has always been recorded higher than the absolute limit of 5 NTU. Mean values of organic matter in the treated water were, in all cases, reported higher than the target limit of 2.5 mg/l. When looking at results from the Umbelúzi waterworks, it is clear that the treated water is frequently over chlorinated. Other chemical parameters such as treated water pH and alkalinity were generally found within acceptable limits for corrosion control (pH > 6.5; alkalinity > 61 mg/ℓ) at Umbelúzi waterworks and slightly out of the range in Beira and Nampula.

Operation of drinking water treatment

Table 5 gives an example of operational data of chemical processes at the Umbelúzi waterworks. The data in Table 5 comprehend the range and average dosages of chemicals applied and the average number of days in a month when chemical treatment was not performed. As can be seen, chemical processes within this plant are frequently discontinued. Reasons pointed for that are: the malfunctioning of dosing equipment or the lack of chemicals.

In Figure 3 an example of annual (2004) records of operation data on chemical coagulation at Umbelúzi waterworks is presented from where it is seen that the process was performed with reagent dosages (alum and polymer) that vary considerably within the same range of raw water turbidity and alkalinity. An almost linear relationship is observed between raw water turbidity and chemical reagent dosages which suggest that, the selection of reagent dosages was based on a linear relationship with the river water turbidity.

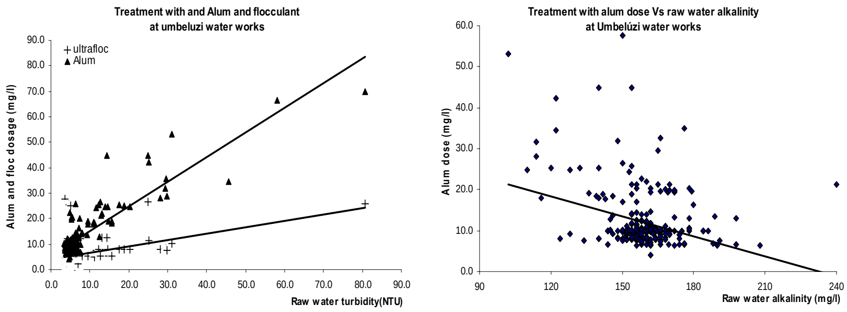

Figure 3: *Treatment with aluminium and coagulant aids at the Umbelúzi waterworks and its relation to raw water turbidity (NTU) and alkalinity (mg/L). Data refers to one full year (2005) operation of chemical coagulation at the treatment works. Source of data: FIPAG (2005).*

From the data shown in figure 3 it is clear that alum doses were somewhat unrelated to both raw water turbidity and alkalinity and also that, they varied significantly within the same range of raw water quality values. The raw water pH and alkalinity had also varied considerably during the period of analysis, from conditions of rather soft (Total alkalinity < 100 mg/ℓ) to slightly alkaline (Total alkalinity > 240 mg/l).

Table 5 Range and average values of dosages applied for chemical treatment at Umbelúzi water works. Also indicated, is the average number of days in a month during which chemical treatment was disrupted due to lack of supplies or mal-functioning of equipment.

Chemical Process	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Set.	Oct.	Nov.	Dec.
Chemical coagulation												
Alum dosage (mg/l)												
Average	22.3	17.5	12.6	19.5	8.7	8.0	10.2	10.0	10.0	11.2	8.4	
Range	6.4-70.0	4.1-57.7	7.8-53.2	11.2-42.4	7.6-11.8	7.1-10.2	8.1-12.4	8.1-11.4	7.4-11.8	9.9-24.4	4.8-10.4	4.8-10.4
No. days disruption	4	2	0	0	0	0	0	0	0	0	0	0
Polymer dosage (mg/l)												
Average	1.7	1.5	0.5	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.3	
Range	1.2-2.8	1.2-2.5	0.4-1.0	0.3-1.1	0.5-0.6	0.3-0.9	0.3-0.6	0.4-0.6	0.2-0.6	0.3-0.8	0.1-0.5	
No. days disruption	22	18	0	0	0	0	0	0	0	0	0	0
Pre-chlorination												
HTH dosage (mg/l)												
Average	2.8	2.8	0.8	1.4	0.8	0.7	1.1	1.1	0.8	0.5	-	-
Range	1.5-3.8	0.8-3.6	0.3-1.6	0.3-2.7	0.3-1.6	0.3-1.6	0.3-1.8	0.3-2.2	0.3-1.4	0.4-0.5	-	-
No. days disruption	0	8	17	18	21	22	21	22	26	29	30	30
Post-alkalinisation												
Lime dosage (mg/l)												
Average	3.6	3.9	3.7	2.7	1.9	1.7	1.7	1.4	1.7	2.0	1.4	-
Range	3.4-3.9	3.3-5.3	3.5-4.1	1.4-4.5	1.4-4.1	1.4-2.9	0.7-3.7	1.4-1.5	1.4-2.7	1.4-4.8	1.4-1.5	-
No. days disruption	25	24	23	17	10	13	16	23	16	20	19	30

Consequences for drinking water production

Treatment possibilities with conventional treatment

Treatment possibilities by conventional treatment depend on a number of factors including:

- the concentration of the chemical in the raw water;
- control measures employed throughout the drinking-water system;
- nature of the raw water; and
- treatment processes already installed.

If a guideline value cannot be met with the existing system, then additional treatment may need to be considered, or water should be obtained from alternative sources. From the six water sources studied, it is clear that river water is generally of inferior quality, thus unsuitable for consumption without prior treatment. Table 6, adapted from literature (WHO, 2004) summarizes the treatment achievability by conventional treatment built according to the standard design from where it is seen that with the commonly found designs of drinking water treatment plants in Mozambique, conditions exist for the production of excellent treated water quality from existing surface water sources.

Table 6 Treatment achievability by conventional treatment [a,b]

Typical raw water quality variable	Unit process			
	Pre-chlorination	**Coagulation/Flocculation Sedimentation**	**Rapid Sand Filtration**	**Chlorination**
Turbidity & solids	No eff.	>80%	>80%	No eff.
Faecal Bacteria[c]	>80%	Lim. eff	Lim. eff	>99.9%
Natural O. matter	50% or more	50% or more	No eff.	No eff.
Algae cells	No eff.	50% or more	Lim. eff	No eff.
Cyan bacteria cells	No eff.	>80%	No eff.	No eff.
Algae derived toxins	Lim. eff	No eff.	No eff.	>80%
Iron[d]	No eff.	50% or more	>80%	No eff.
Manganese[d]	No eff.	50% or more	>80%	>80% (<0.05)
Drawbacks	DBPs,	Insoluble Al, turbidity breakthrough if inefficient, NOM and extraneous organics impacts efficiency	Performance related to efficiency of previous processes	DBPs

Adapted from WHO, 2004
b The table includes only those quality variables of concern for drinking water production in Mozambique.
c 3 log removal (>99.9% removal) by rapid filtration with coagulation and sedimentation:
d pre-oxidation or aeration required:

As seen from the table, treatment processes arranged according to the design of drinking water treatment plants in Mozambique can lead to the production of treated water of excellent quality from existing surface water sources. It is also learn from the table that, if properly designed and operated, chemical coagulation, flocculation and sedimentation are the unit operations of the standard design of conventional treatment that does the bulk of the removal of impurities such as turbidity and solids, organic matter, algae and cyanobacteria cells. These are raw water quality variables identified as having a significant impact on drinking water production in Mozambique. Critical processes in the treatment chain are coagulation-flocculation. Poor performance of these processes results generally in poor performance of subsequent stages (sedimentation and filtration) and thus, of overall drinking water production. Effective operation of coagulation and flocculation is therefore essential to meet desired standards of drinking water treatment.

Factors affecting treatment possibilities

Quality variables of major concern for drinking water production were identified as turbidity and suspended solids, dissolved organic matter, bacteria and in some cases, presence of algae (Table 1). Iron and sometimes manganese may also be present and pose some challenges for drinking water production. It is also seen from Figure 1 that most surface water sources experience seasonal flow variations that impacts both the physic-chemical and microbiological quality of river water.

Because most turbidity causing particles have their stability defined by surface charge, their removal from water is best attained with coagulation processes based on charge-neutralization mechanisms (Polasek, 2005; Stumn & Morgan, Lawrence et al., 2007). When the raw water turbidity is high the optimum pH-range for coagulation is between 4.5 and 5.5 but when the raw water turbidity is low, the unavailability of high concentration of particles to promote inter-particle contacts requires the formation of amorphous hydroxides onto which the fine particles will enmesh (seep coagulation). The optimum pH-range for coagulation in this case is between 5.5 to or 6.0 or even higher (Polasek & Mult, 2005).

Most constituent of organic matter are of an acidic character, therefore their removal by destabilization-aggregation processes should also be performed at an acidic pH-range, preferably between 4 and 6.5 (Polasek & Mult, 2005; Sharp et al*.*, 2005; Qin et al., 2006). Optimum coagulation conditions for removal of natural organic matter-NOM are, therefore, similar to those required for low turbid waters however, at higher reagent dosages and lower pH-values (Velasco et al., 2007; Volk et al., 2000; Ruehl, 1999; Eikebrook, 1999).

Algae generally behave like turbidity therefore their removal from water can be made effective through destabilizing-aggregation mechanisms similar to those applied for removal of turbidity (Polasek & Mult, 2005). At low concentrations, algae can be removed by interception onto precipitates of the destabilizing reagent i.e. at an optimized pH-reaction for coagulation between 5.5 and 6.5. At high concentrations, immobilization or even destruction by means of pre-oxidation is required.

The effective purification of water takes place at a particular pH which depends on the nature of impurities to be removed and the particular condition of raw water with respect to its pH and alkalinity. Therefore, it is necessary to establish the optimised pH value at which all kinds of impurities present in the water will be removed with the highest attainable efficiency. Looking at data presented in Table 1, it is seen that the river water pH and alkalinity can vary significantly, suggesting that, careful adjustment of the water pH is required to maintain effective operation of coagulation-flocculation processes.

The addition of chemical coagulants usually alters the water pH and alkalinity, however, the extent to which the optimum pH-reaction for effective coagulation is attained depends on various factors among which the raw water natural alkalinity and the amount of chemical reagent applied. When the raw water turbidity is high and the water pH is just above neutral this can be easily be accomplished thanks to the high amounts of reagent usually required however, when the raw water turbidity is low, the optimum pH-reaction may, in many occasions, be unattained due to the buffer effect of alkalinity water.

The two factors that significantly influence the overall efficiency of coagulation in water treatment are, therefore the dosage of the destabilizing reagent and the reaction pH. When the purification process is aimed at removing a single pollutant, for instance turbidity, then a dosage at which maximum turbidity removal is attainable, is the optimum dosage for operation of the process. This is the common practice used in Mozambique for selection of operational dosages. When, on the other hand the purification process is aimed at removing a mixture of different impurities (e.g. when removal of organic matter and algae is also required), then the purification process must take place under optimised reaction conditions at which residual concentration of each contaminant is below its permissible limit.

As noted in the previous discussion, the optimum range for each impurity requires different dosages and different reaction pH values which means that the optimized operational dosage should be selected from within ranges that are coincident for all individual contaminants. This requires from plant operators not only a clear knowledge of the condition of the raw water but also enough skills because, if incorrectly done, the removal of some of impurities of the water may be negatively affected. For example, during periods of low turbidity the optimum dosage for operation of coagulation can be easily adjusted to incorporate also removal of organic matter without compromising significantly turbidity removal, however, during periods of high turbidity and particularly when the river water alkalinity is low, the operation of coagulation based on optimum coagulant dosages for removal of NOM (sweep coagulation) mean that the efficiency in turbidity removal may be adversely affected.

Looking at the data presented in figure 3, it is clear that the operation of coagulation is often performed with reagent dosages that vary considerably from within the same range of turbidity and pH-alkalinity in the raw water. This suggests, that very often, the optimised pH-reaction for effective operation of coagulation is not attained. This, impacts overall coagulation efficiency and consequently the performance of subsequent processes. Looking at data presented in Tables 5, it is also clear that, very often coagulation is discontinued due, to lack of chemicals or mal-functioning of equipments which also undermine effective drinking water treatment. The consequences for drinking water production are; ineffective operation of treatment processes and the production of treated water of inferior quality.

The data presented in Table 4 is very illustrative of the situation. Although the treated water turbidity is generally below the tolerable limit of 5 NTU, the absolute limit of 1 NTU recommended in the guidelines is seldom attained. It is also seen from Table 4, that the treated water is generally over chlorinated. This combined to high levels of organic matter in the treated water means that, taste and odour forming compounds as well as disinfection-by-products-BDPs may develop following treatment. Also, presence of high levels of organic matter in the treated water may increase the potential for human health risks due to bacteria growth in distribution and storage facilities.

Methods of improving the situation

The main challenges facing drinking water production in Mozambique have been identified as; poor water quality at source and frequent variations and the need for rather complex and costly operations to maintain standards of drinking water production. Improvements to the situation require therefore, improvements in the quality of raw water and in the design and operation of drinking water treatment processes. Various possibilities exist to attain these objectives which can be summarized as depicted in Figure 4 below.

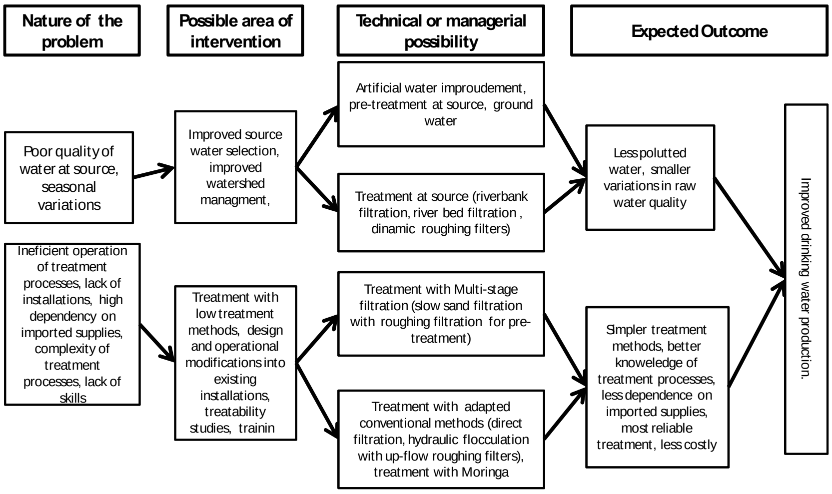

Figure 4: Process approach for sustainable improvement of drinking water production in Mozambique.

Because turbidity and bacteria are partially reduced in large reservoirs, abstraction of raw water from large reservoirs (natural or man-made) is one feasible option to get less polluted water for drinking water production. Large reservoirs suffer, however, the threat of eutrophication due to high temperatures. Care should therefore be taken when opting for this solution to minimize risks of increasing production costs and complexity of water treatment. As a rule, water containing organic contamination resulting from algae propagation is more difficult to treat with traditional methods of conventional treatment. When required flows are small (e.g. small to medium size water supplies), river bank infiltration also provides a feasible alternative to get less polluted water for drinking water production.

Improvements or modifications to existing designs should be aimed at two major objectives: (i) smooth variations in raw water quality and (ii) reduce inefficient operations within treatment plant designs. Examples of methods technically suitable are; roughing filtration and coagulation-direct filtration processes. Extensive research conducted on this methods (Smet & Visscher, 1990; Ingallinella et al., 1998; Bauer et al., 1998) have proven that if properly incorporated into existing plants they can improve treatment efficiency and production capacity at relatively low investment and operational costs. Coagulation-direct filtration processes are particularly advantageous because they combine particle aggregation and separation mechanisms in one single unit.

CONCLUSIONS

Turbidity, bacteria, natural organic matter, and sometimes algae and aquatic plants were identified as river water quality variables of major concern for drinking water production. These impurities often occur in high concentrations and experience large seasonal variations that make treatment methods costly complex and technically demanding. Conventional treatment consisting of chemical coagulation, flocculation, sedimentation filtration and chlorination is mostly used in Mozambique. While suited for production of high quality drinkable water from surface water sources, in Mozambique, poor water quality at source, compounded by seasonal variations in river water quality and poor or inadequate operation of treatment processes leads to the production of treated water that often fail to comply to required standards.

The first place where drinking water quality standards have to be satisfied is at the outlet of the treatment plants. However, in a large number of treatment plants of Mozambique (inclusive Maputo waterworks) these standards are not fully achieved. Factors contributing to that includes: (i) inadequacy of existing infrastructure and operational procedures for water treatment (ii) inconsistent operation of essential chemical processes due to mal-functioning of equipments or temporary lack of supplies and, (iii) lack of guidelines for specific contaminants (e.g. DBPs) which makes water treatment practices to target only those variables for which, guidelines have been established.

Methods of improving the situation require either improvements in the quality of raw water or improvements in the design and operation of treatment processes. Though linked to potential problems with algae, abstraction of raw water from large reservoirs is an option technically suited to get less polluted water for drinking water production. When required demands are small, river bank infiltration also helps reduce loads of contaminants carried with the raw water.

Improvements/modifications to the existing design of the water treatment plants with the view of smoothening variations in raw water quality can also help minimize inefficient operations within treatment plants. Roughing filters, and coagulation-direct filtration processes are all technical options potentially suited to improve treatment efficiency and increase overall production capacity at relatively low investment and operational costs.

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II

THE EFFECTS OF INTERMITTENT SUPPLY AND HOUSEHOLD STORAGE IN THE QUALITY OF DRINKING WATER IN MAPUTO

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Abstract A serious problem arising from intermittent supplies is the associated high level of contamination and public health hazards resulting either from ingress of contaminated water or from prolonged storage. This paper discusses the overall condition of the drinking water quality of intermittent water supplies in Mozambique. The network of Maputo is used as an example. Records of water quality determinations from different locations in the network are used to assess the final quality of water at consumer's taps. Chlorine residual levels measured in reservoirs and results of bulk chorine decay tests performed with samples of treated water are used to estimate chlorine decay constants (k_b) at different locations of the network and to predict the influence of retention time in the final quality of water. Presence of bacteria, low disinfection capacity and long residence times in the network and reservoirs are the main factors affecting the final quality of distributed water. Post-contamination due to ingress of contaminated water and prolonged storage in reservoirs is high. The intermittent operation of the distribution network is therefore inadequate to guarantee safe drinking water.

Keywords: intermittent water supply, household storage, chlorine decay, water quality Maputo,

INTRODUCTION

The provision of safe drinking water is essential in maintaining the quality of life in all communities. During the last decades, the demand for improved supplies in the Third World has been increasing considerably due to rising per-capita incomes, rising standards of living, and population increase (Reweta & Sampath, 2000). While the pressure on existing supplies increased with time, the development of additional sources and/or extension of existing supplies have been an unrealistic option for many places of the developing world due to financial constraints.

The solution frequently applied in such places is the adoption of intermittent supplies. Intermittent supplies, however, are associated with quantity and quality problems, occasionally linked to fatal health hazards (Totsuka et al., 2004). Despite considerable negative impacts, intermittent supplies are used in many parts of the world, especially in arid and densely populated areas of the developing world.

Totsuka et al., (2004) point out that more than 90% of the population served by piped water supply in South Asian countries receives water during less than 24 hours/day. In most African countries, conditions are worse. According to the same author, in Zaria (Nigeria), only 11% of consumers with a piped supply receive water one day in two while, in Mombasa (Kenya), the average number of service hours is of about 2.9 hours/day. For Dar-es Salaam (Tanzania), Reweta & Sampath (2000) indicate that the main supply to the town provides less than 1% of the required demand, forcing residents to depend heavily on alternative supplies. The long list of examples also includes many countries in The Middle-East.

The most critical consequence of intermittent supply is the risk of water contamination due to ingress of contaminated water and the consequent public health hazards. Other consequences include, inequitable water distribution, inconveniences to consumers and added costs of water supply due to the need of additional facilities such as storage tanks and pumps (Totsuka et al., 2004).

Unequal distribution of water forces consumers to find their own ways to cope with intermittency by constructing household tanks. However, contamination of drinking water in household tanks is a second important health risk. Totsuka et al., (2004) report water quality tests carried out in Istanbul (Turkey) which revealed that 24% of samples taken from consumer storage tanks were found positive for coliforms compared to only 4% positive samples taken from the pipe network. Tokajian & Haswa (2003), reporting results from a controlled study in Beirut (Lebanon), have found a positive correlation between mean bacterial counts and pH, temperature and storage time.

Intermittent supplies can also promote bacterial regrowth in the network during stagnant hours and consequent biofilm detachment when the supply is restablished. These events were found to greatly impact the water quality distributed in a controlled study run in a suburb of Nablus Palestine, Coelho et al., (2003). Bacteria counts were about eight times higher during the first five minutes of supply compared to the overall water quality.

Water supply and distribution in a large number of Mozambican cities and villages is also intermittent. Existing transport and distribution networks are old; suffer from high levels of leakage, limited hydraulic capacity and limited coverage, caused by city demand increases and city growth. The average number of supply hours in the majority of the cities is of less than 12 hours (Gumbo et al., 2003). The purpose of this work is to evaluate the effect of intermittency and household storage on the quality of drinking water distributed in Maputo.

MATERIALS AND METHODS

The study Area

Maputo is the largest city of Mozambique and the city capital of the country. The town is supplied by piped water from a system consisting of a single source in the Umbeluzi River, treatment by conventional treatment, transport through a 28 km transmission main, and distribution through a reticulated network of approximately 840 km (Gumbo, 2004). Five distribution centres (DCs) exist of which three are located in series along the main supply line (Matola at about 10 km from the water works, Chamanculo at 20 km and Maxaquene at 28 km). The others are Machava DC located some 17 km from the water works, and Alto-Maé DC located at about 24 km.

The supply from the water works is done 24 hours a day, but the distribution to the different consumption zones is intermittent because of low pressure in the system and the need to minimize losses (Gumbo et al., 2003). Many consumers of the city of Maputo have therefore, built extra household tanks to cope with water shortages. A large proportion of these tanks are built on ground level from where stored water is further pumped to roof tanks or supplied directly to taps in the households.

Data collection

The drinking water quality in Maputo was investigated through analysis of data provided by the service provider and data collected through fieldwork. The data from the service provider covered the period 2001-2004 but only data from 2004 was used for the analysis. Due to incompleteness of the data with respect to bacteriological data, the analysis of bacteriological aspects of distributed water was done using data from 2003.

Residual chlorine, bacteria, turbidity and solids are the parameters used for the analysis of the water quality in the network. Temperature, residence time and the condition and treatment of reservoirs and household tanks are used to make the final assessment of the quality of drinking water in Maputo. Reference locations are: the water works (treated water), distribution centres (DC), household tanks and taps in the network.

Fieldwork took place during 7 weeks in November/December 04. Water samples taken from different locations in the network were analyzed for physic-chemical and bacteriological characteristics. During the fieldwork, samples were collected twice a week (Mondays and Wednesdays) usually between 7.30 a.m. and 2.00 p.m. Four sampling points were visited each day where, water samples were collected pair wise on taps located before and after household tanks. The taps used to collect samples for bacteriological analysis were cleaned with cotton and ethanol before sampling. In addition, the taps were left open for about 1 minute before sampling.

During sampling of household reservoirs, the condition of the tanks was assessed through observation and interviews to owners. Aspects of interest included, the overall condition of the tanks, construction materials and dimensions, consumers practices regarding the cleaning of reservoirs and consumer's concerns about water quality.

Time dependent chlorine decay tests were performed with samples of treated water. The method used (often referred to as 'bottle" or "jar test", (Powel et al., 2000)) consisted of recording chlorine concentrations at fixed time intervals from bottles previously filled with sample water. The tests were used to estimate the magnitude of chlorine depletion with time and to estimate chlorine decay rates (K_b) for treated water. The results of the tests are compared to results of calculations done with data provided by the service provider and that generated during the fieldwork. Existing or measured data on residual chlorine was used to estimate chlorine decay rates at selected locations of the network with emphasis put on household tanks and reservoirs of distribution centres. Chlorine decay rates estimations where based on a first order decay reaction.

Estimates of the total residence times in the network, reservoirs and household tanks are used to discuss the results of calculations of chlorine decay rates.

Measurements

Temperature, pH, TDS, conductivity, free and total residual chlorine, was measured directly in the field while turbidity, bacteria and solids were measured in the laboratory. All Temperature readings were taken with a standard mercury thermometer (accuracy of ± 1^0C) and TDS, pH and Electrical conductivity (EC) were measured with pocket Wagtech digital meters. Free and Total residual chlorine (FRC, TRC) were measured with the DPD (diethyl-p-pheneylene diamine tablets) colorimetric method with colour measurement through a portable digital photometer (Wagtech 5000) calibrated at 520 nm wavelength.

Turbidity and alkalinity were measured a few hours later in the laboratory. A Hach turbidity meter DR 2500 was used for turbidity readings. Alkalinity was measured with a simplified titration method described in the Standard Methods for the Examination of Water & wastewater, (20^{th} edn., 1998). All bacteriological analyses were done at the laboratory of the Ministry of Health using the membrane method described in the standard Methods for the Examination of Water & Wastewater. The parameters measured were total bacteria, faecal coliforms and *E.coli*. Sediments sampled in at least three reservoirs were analyzed for solids (total, volatile and fixed solids). The method used for analyzing solids followed the Standards Methods for the Examination of Water & Wastewater (20^{th} edn., 1998).

All pair wise data was checked for its statistical significance. The method used consisted of making a confidence interval for the difference of two expected values $I(\mu_1 - \mu_2)$; if this interval does not cover the zero it is regarded to be a significant difference between two homogeneous groups. A 95% confidence interval ($p=0.05$) was used in all tests.

Chemical and physical parameters measured in samples taken from the network and after household tanks were compared, with an independent sample T-test. The T-test is a parametric comparative test used to show if a difference exists between two homogenous groups. For turbidity, free residual chlorine, total residual chlorine and nitrate the test was not valid since the variance of the two groups were not equal. The Mann-Whitney U-test was used instead. Presense and absense of bacteria in samples taken before and after storage were also compared with a Mann- Whittney U-test. The T-test was also used to compare residual chlorine in samples with and without bacteria.

RESULTS AND DISCUSSION

Residual Chlorine

For assessing chlorine residual levels in the network of Maputo, about 1192 records of the operator database and 26 records of determinations done during the fieldwork were investigated. The records from the operator database contained only values for TRC while that of the fieldwork included also data for FRC. The results of the assessment for TRC, indicate levels of residual chlorine in the network and water leaving reservoirs of DCs, mostly above the lower limit 0.25mg/l (**Table 1**).

Typically, the allowable minimum is 0.2 mg/l (WHO, 2004). The Mozambican standards for total residual chlorine are 0.25 -1.0 mg/l in the net and 1.5 mg/l at the water works (MISAU, 2004). In the specific case of Maputo water supply where a private company (Águas de Moçambique-AdeM) has been awarded a 15 years lease contract to manage the water supply for the city, the contract standards indicate limits only for free residual chlorine between 0.2-1.0 mg/l.

Table 1. Total and Free residual chlorine and Turbidity in the network, reservoirs of DCs and household tanks of Maputo water supply

Location	Residual Chlorine									Turbidity				
	Nr. records	Total Residual chlorine				Free Residual chlorine				Nr. records				
		Ave.	Max	Min	Std	Ave.	Max	Min	STD		Ave.	Max	Min	STD
Treated water (db)	338	1.58	2.49	0.87	0.37					338	3.22	7.64	1.81	0.59
Net (db)	1192	0.69	2.0	0.13	0.32	-	-	-	-	-	-	-	-	-
Net (fw)	27	0.50	1.1	0.08	0.25	0.17	0.68	0.01	0.14	30	2.00	6.00	0.60	1.50
DC-Matola (db)	320	0.98	3.0	0.20	0.44	-	-	-	-	320	2.52	11.20	1.15	0.73
DC-Machava(db)	345	0.97	3.0	0.15	0.40	-	-	-	-	341	2.39	9.19	0.81	0.73
DC-Chamanculo(db)	343	0.98	2.5	0.15	0.41	-	-	-	-	341	2.31	6.99	0.78	0.67
DC4-Alto Maé(db)	343	0.81	2.5	0.15	0.36	-	-	-	-	340	2.30	7.36	1.08	0.58
DC5-Maxaquene(db)	345	0.63	1.9	0.11	0.30	-	-	-	-	342	1.76	6.73	0.79	0.59
H-reservoirs (fw)	26	0.24	0.65	0.06	0.14	0.06	0.29	0.01	0.06	30	1.40	3.50	0.7	0.6

The data on TRC levels of water leaving reservoirs of DCs also show average TRC levels decreasing as the distance from the water works increases even though, the water is re-chlorinated at some DCs located along the main supply line (Matola and Chamanculo).

Analysis of records for TRC and FRC using sampled data reveals much lower values for FRC in the network and household reservoirs with 77% of samples falling below the target limit of 0.2 mg/l. TRC levels were in general 0.26 mg/l lower after reservoirs while, FRC was 0.11mg/l lower. A statistically significant difference ($p < 0.01$) between levels measured before and after household tanks has been observed.

Analysis in different parts of the network thus suggests that the disinfection capacity in the network is rather high when evaluated with TRC levels. The same analysis done on basis of FRC suggests, however, a different scenario with chlorine residual levels (0.17 mg/l) very close to the lower limit recommended for an effective disinfection of the water.

Turbidity

The results of the analysis (see **Table 1**) suggest mean values of about 3.22 NTU for treated water and mean values between 1.8-2.5 NTU for water leaving DCs. The data from the operator's database did not contain data on turbidity levels in the network but the results of the sampled data suggest mean values of 2.0 NTU. From **Table 1** it is clear that at all measured sites turbidity levels were most of the times above the WHO desired limit of 1.0 NTU and that in few occasions the WHO limit of 5 NTU was exceeded. The absolute limit of 20 NTU stated in the contractual limits of the water company of Maputo was, however, never exceeded.

Overall, turbidity levels at all investigated sites show rather large variations between extreme values with occasional increases of turbidity levels of the water leaving some of the reservoirs of DCs. This was reported in the reservoirs of the DCs of Chamanculo and Alto Maé but not in the reservoirs of Maxaquene DC.

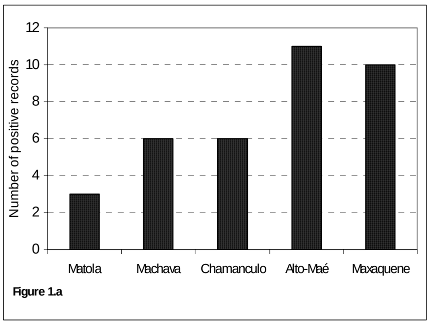
This suggests the possibility of occasional loads of turbidity-causing particles entering the reservoirs, causing sediments to build up during periods of low demand and further release with the water leaving the reservoir during periods of high demand. Sources of turbidity causing particles can be pipe and fitting corrosion, lining erosion, biological growth, chemical reactions and external contamination that may occur during operations such as pipe repairs (Vreeburg & Boxall, 2007). The formation and growth of particles is, however, a very complex process, which is currently poorly understood but factors such as contact times, contact surface, and hydraulic conditions are likely to play an important role in controlling these processes (Vreeburg & Boxall, 2007).

Bacteria

Presence/absence of bacteria was investigated using records from both the service provider and the additional field survey. The operator's database had records of samples of treated water, reservoirs at DCs and reservoirs and taps of the network. Samples taken during the fieldwork considered two locations at each sampling point namely taps before and after household reservoirs. Around 503 records taken from the operator's database (148 from reservoirs at DCs and 355 from taps and household tanks) were investigated for presence of bacteria. The fieldwork produced another 60 records.

The results suggest that both faecal coliforms and *E.coli* were found frequently in reservoirs of distribution centres, network taps and household tanks. The records on treated water did not contain data on presence/absence of bacteria. In the reservoirs of DCs, bacteria were found in about 24% of the records investigated.

The levels of contamination were generally low (<10cfu/100 ml), but occasionally reached high values (up to 165cfu/100ml). Analysis of records from reservoirs of DCs also suggests that the DCs located first along the main line had the lowest incidence of bacteria counts when compared to DCs located further along (**Figure 1a**.).



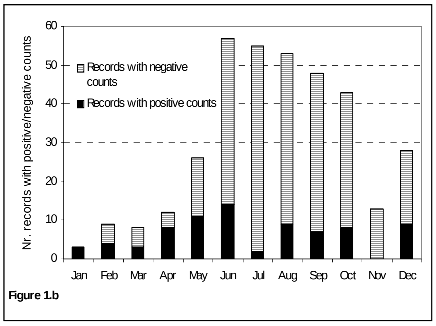


Figure 1. Incidence of bacteria in reservoirs of DCs (**Fig. 1a**) and taps of the network (**Fig. 1.b**).

The data from the operator's database suggest, additionally, that on the network between the DCs and the households tanks, around 20% of the investigated samples were found contaminated with bacteria. The annual distribution of cases with positive counts of bacteria over the total number of records investigated in the distribution network is show in **Figure 1b**.

The incidence of positive samples is evenly distributed throughout the year, which suggests that contamination with bacteria is a rather persistent problem in the network. A similar analysis done with records of the fieldwork suggests that coliform bacteria were found in thirteen out of the sixty samples collected (22% of samples taken). Six out of the thirteen samples found with bacteria had bacteria counts over 100 cfu/100ml. Coliform bacteria was generally found in samples collected after household tanks (**Figure 2**). Ten out of the thirteen samples found with bacteria were collected after household tanks.

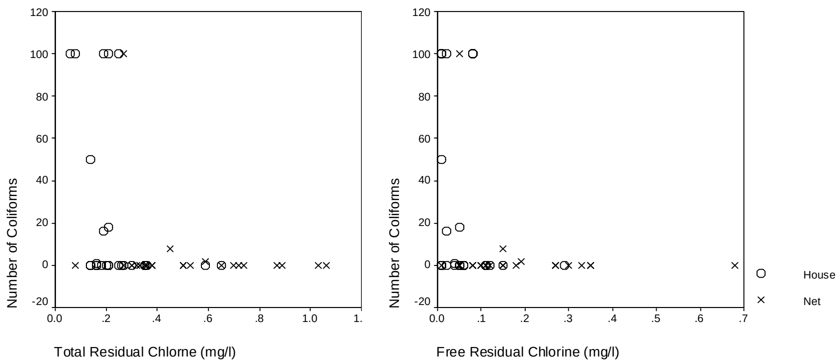


Figure 2. Presence of Coliform bacteria in samples taken before and after household tanks.

Because these samples were collected from seven different locations in the network, in three cases bacteria were found at least twice during the study. The results of the fieldwork also indicate that bacteria were only found in samples collected from reservoirs with rather low concentrations of residual chlorine (see **Figure 2**). TRC was generally low in the influent of distribution centres in those days when faecal coliforms were found. *E.coli* was found three times in the network when the concentration of FRC was between 0.05 and 0.19mg/l. These levels of FRC should be sufficient for disinfection (WHO, 2004). This suggests that recent contamination of the drinking water took place.

One of the major reasons for bacterial contamination in pipes and reservoirs of distribution networks is insufficient disinfection capacity due to insufficient residual chlorine. Since chlorine decays over time, increased retention time by either storage or prolonged periods of interruption of supply increases the risk of occurrence of bacteria at points of water consumption. Biofilm formation and bacteria growth may also be occurring during periods of low or no pressure and further biofilm (containing bacteria) detachment when the supply is restart (first flush effect).

The network of Maputo is left under pressurized more often than the transport main between distribution centres (at least once a day), therefore, ingress of contaminated water may occur more frequently. The network is however, left under pressurized only few hours/day so, the time for biological growth between flushes is short. Problems with biofilm formation play, therefore, a minor role with respect to contamination with bacteria.

Sediments

Sediments may increase the rate of chlorine decay in pipes and reservoirs, decrease the disinfection capacity and act as a source of nutrients for bacterial growth (WHO, 2004). Sediments resulting from particle accumulation are in fact know to have a relation with biological activity since, one-12% of the organic matter in the particles may consist of bacterial biomass. This make sediments resulting from particle accumulation an important factor in hygienic safety of drinking water (Vreeburg & Boxall, 2007).

Sediments taken from few tanks in the network were investigated for factors known to influence chlorine decay rates in the reservoirs and to contribute for microbial growth (**Table 2**).

Table 2. Solids concentration in water collected from household reservoirs

Reference site	Total solids (mg/l)	Volatile solids (mg/l)	Fixed solids (mg/l)	VS/TS
3	411.0	133.0	278.0	0.32
7	631.0	166.0	465.0	0.26
3	464.0	112.5	352.0	0.24

The VS/TS fraction is used as an indication for the organic matter content. The results (see **Table 2**) show amounts of 24-32% of organics present in the sediments. The organics can potentially serve as nutrients for microbial growth or exert an extra demand of chlorine in tanks and reservoirs. According to findings from literature, the existence of large variations in turbidity will be the predominant causes of sediments build up in reservoirs.

Apart from increasing the rate of chlorine decay, sediments build up in reservoirs decreases the disinfection capacity as bacteria can hide inside the particles and escape from the effect of chlorination. The fact that the water stays relatively long in reservoirs may also increase the potential for biofilm formation (on the walls of reservoirs) and bacterial growth.

Chlorine decay & retention time

Chlorine decay constants calculated according to first order decay models for different parts of the network are resumed in **Table 3**. Mean values of total residual chlorine in the influent and effluent of reservoirs were used in the calculations. The values of retention time in reservoirs of DCs were calculated from average figures of water consumption as provided by the operator and the net volume of reservoirs of the specific distribution centers.

For household storage tanks, retention time was calculated based on an average daily consumption equivalent to an average of 4,4 persons/house (INE, 1999) and a per capita water demand of 120 l/p.d as pescribed in the national standards (DNA, 2003) for water consumption. Though the vary significantly in sizes, household tanks were assumed to have a capacity of 1.0 m^3. Results of calculations of average retention time in reservoirs and estimated constants for residual chlorine decay are resumed in **Table 3**. Chlorine decay rates vary significantly in different parts of the network which suggests that the extent of chlorine decay varies in the system.

Table 3: Chlorine decay constants (K_b (l/h)) in different parts of the network.

Location	Average Chlorine concentration inlet C_0(mg/l)	Average Chlorine concentration effluent C_e(mg/l)	Average retention time (hours)	K_b (1/h)
Treated water[a]	1.58	-	-	0.603
DC-Matola	1.17	0.98	12.5	0.016
DC-Chamanculo	1.20	0.97	37,2	0.006
DC-Alto Maé	0.95	0.81	11.8	0.015
DC-Maxaquene	0.887	0.63	10.1	0.035
H-reservoirs (TRC)	0.5	0.24	48	0.015
H-reservoirs (FRC)	0.17	0.06	48	0.022

Note: [a] obtained from time dependent chlorine decay test R = 0.903

The results of chlorine residual tests performed with samples of treated water are also resumed in **Table 3**. Compared to the results obtained for different reservoirs in the network, the rate of chlorine consumption in the treated water is much higher than that observed in reservoirs of DCs and households. This is expected pattern since, the treated water is re-chlorinated in two points along the main line (Matola and Chamanculo) before reaching the reservoirs at DCs located downstream. According to findings from Kiéné et al., (1998) and Fang et al., (2000), chlorine decays more rapidly in freshly chlorinated water when compared to water that has been re-chlorinated.

The rate of chlorine decay in DCs and household reservoirs appears to be generally high and to vary significantly (between 0.006 and 0.035 l/h). This suggests that there may be external factors (e.g. biomass builds up, particles mixed with turbidity) that influence the decay rates.

Condition and treatment of household tanks

The materials mostly used for construction of household storage tanks is concrete, plastic (pre-fabricated black-PVC tanks) and asbestos cement. The capacity of concrete and asbestos cement tanks ranges from 0.25 m^3-4.5 m^3, while that of plastic tanks ranges from 0.5m^3-1.5m^3 (**Table 4**). The maintenance of the tanks is often poor, cleaning and disinfection is hardly done and in many of them lids was missing or was locked for long periods meaning that they are hardly opened for cleaning, maintenance and repair work.

Most of the tanks are oversized for the average demand/family, which, according to estimations based on an average of 4.4 persons/household @ 120 l/p.day, lies between 0.5 and 0.6 m^3/day. This result in relatively long storage times, excessive depletion of residual chlorine and the possibility of bacterial growth and biofilm formation due to insufficient disinfection capacity and bad condition of tanks.

Table 4: Location, condition and treatment of household tanks

Ref. house	Location	Net volume (m^3)	Average number of users	Average retention time (days)	Material	Physical condition	Encountered maintenance problem
1	Ground	2.0	6	2.7	Asbestos cement	Fairly good	Tank cover broken. Ingress of contaminants possible.
2	Roof	0.5	5	0.8	Plastic	Good	Lid locked. Access for cleaning and maintenance limited
3	Roof	0.5	7	0.4	Plastic	Good	Lid locked. Access for cleaning and maintenance limited
4	Roof	1.0	6	1.4	Plastic	Good	Lid locked. Access for cleaning and maintenance limited
5	Under ground	6.0 (2x3.0 m^3 e.a.)	8	6.3	Concrete	Fairly Good	One tank with a broken lid. Second tank with lid locked. Access for cleaning and maintenance limited. Ingress of contaminated water possible.
6	Underground	4.5	10	3.8	Concrete	Good	Lid locked. Access for cleaning and maintenance limited
7	Roof	3.0	5	5.0	Concrete	Good	None.
8	Ground	1.0	5	1.7	Asbestos cement	Bad	Tank cover heavily corroded. Ingress of pollutants and contaminated water possible
9	Roof	1.0	6	1.4	Plastic	Good	Lid locked. Access for cleaning and maintenance limited.
10	Roof	1.0	6	1.4	Asbestos cement	Good	None
11	Roof	1.0	7	1.2	Asbestos cement	Good	Dirty inside the tank. Biofilm developing on the walls of the tank
12	Ground	1.0	6	1.4	Asbestos cement	Fairly good	Cover missing. Exposed to ingress of contaminants
13	Ground	0.5	6	0.7	Asbestos cement	Good	Cover missing. Exposed to ingress of contaminants
14	Ground	2.0 (2x1.0 m^3 e.a.)	10	1.7	Asbestos cement	Fairly good	One tank with a broken cover. Second tank with cover locked. Access for cleaning and maintenance limited. Ingress of contaminated water possible.
15	Ground	0.5	7	1.2	Asbestos cement	Fairly good	Tank cover heavily corroded. Ingress of contaminants possible
16	Ground	0.5	6	0.7	Plastic	Good	Lid locked Access for cleaning and maintenance limited
17	Roof	9.0 (6x1.5 m^3 e.a.)	30	2.5	Concrete	Good	Access ladder heavily corroded. Access for cleaning and maintenance limited
18	Ground	2.0 (2x1.0 m^3 e.a.)	6	2.8	Asbestos cement		Covers missing. Exposed to ingress of contaminants.
19	Ground	1.0	5	1.7	Asbestos cement		Cover missing. Exposed to ingress of contaminants

According to results of this study, the average free residual chlorine levels downstream household tanks showed a decrease (**Figure 3**) of about 60% during storage (from 0.167mg/l to 0.061mg/l).

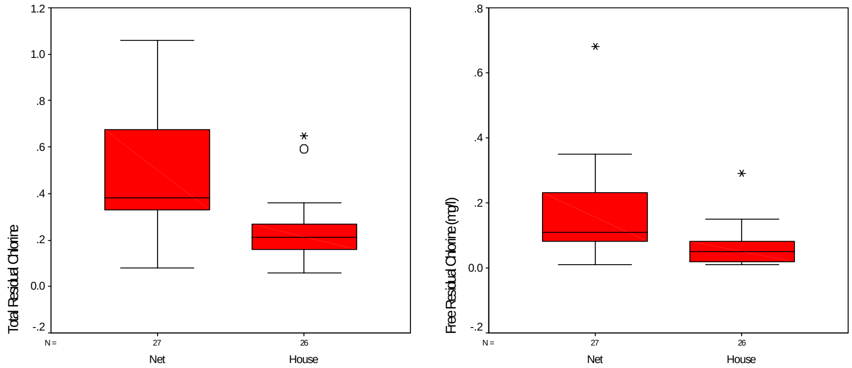


Figure 3: Total and free residual chlorine before (net) and after storage in household tanks (o=outliers, *=extremes).

Free residual chlorine in the majority of household reservoirs is therefore far lower than recommended limits. This finding is in line with conclusions from earlier studies by Coelho *et al*. (2003) and Tokajian & Haswa (2003), who found a strong relationship between storage time and bacterial growth as residual chlorine decreased. The combined effect of intermittency and household storage usually increases retention times, with the observed consequences for chlorine concentrations and occurrence of bacteria.

CONCLUSIONS

The results of this study suggest that the drinking water quality in Maputo is generally not safe for human consumption due to the presence of bacteria. The water quality deteriorates gradually, from the treatment works to the distribution centres, further on into the network, and finally in the household tanks. The reason is a combination of factors such as condition of pipes, ingress of contaminated water when the network is without pressure, long retention times in the network and reservoirs, and condition and treatment of storage tanks.

Both faecal coliforms and *E.coli* were found frequently in reservoirs of DCs and in the network. Apparently, some contamination occurs before or at reservoirs of DCs, which suggests contamination due to ingress of contaminants during periods of low or no pressure. The intermittent mode of operation of the network of Maputo water supply is therefore, pointed as the most critical factor causing contamination in the network.

Storage is influencing the water quality either because of retention time or because of poor management and ingress of contaminants. Long storage times seem to be the major factor of water quality deterioration, particularly in household tanks. Storage increased the risk of occurrence of faecal coliforms in the water with more than 100%.

Though based on a limited number of samples, sediments in household tanks are found to potentially contribute to water quality deterioration. Turbidity of the water entering the reservoirs is generally high. Because the majority of household reservoirs are over- dimensioned and the network is operated intermittently, conditions exist for the settling of turbidity-causing particles and sediments build up.

The combined effect of sediments and low disinfection capacity and long retention time, results in favourable conditions for bacterial growth.

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III

Water services with independent providers in peri-urban Maputo: Challenges and opportunities for long-term development

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Abstract

Water service delivery to most residents of peri-urban areas of greater Maputo depends largely on alternative service providers, mostly in the form of small-scale independent providers (SSIPs). This paper discusses the present and long-term challenges facing SSIPs in supplying quality water of sufficient quantity in peri-urban Maputo and possible human health risks associated with the consumption of water provided by SSIPs. Extensive water sampling and analyses were conducted to evaluate the physicochemical and bacteriological quality of water provided by independent providers and the associated human health risks. Borehole pumping tests, the results of which were interpreted using the graphical method of Jacob, were used to evaluate the regional aquifer potential, the long-term impacts of its exploitation and the aquifer vulnerability to external contamination. From the results of borehole pumping tests it was concluded that the present yields are in average 33% lower than estimated safe yields and that larger than present yields therefore can be exploited. The aquifer vulnerability to external contamination (e.g. by *E. coli* and nitrates) is low, mainly because of low hydraulic loads and the existence of a rather thick (10 to 30 m) sandy unsaturated stratum where bacteria die-off and biological denitrification probably occurs. However, the aquifer vulnerability to sea sea-water intrusion is high. Currently, the health risks posed to consumers relying on services provided by SSIPs are small; even so, 13 out of 35 controlled boreholes had either total coliform or faecal coliform levels higher than the WHO standard. In the long run SSIPs may face more serious water quality problems due either to over-exploitation of the aquifer system or increased hydraulic loads resulting from increased population density.

Keywords: water supply services, peri-urban areas, small-scale independent providers, water quality, public health

Introduction

Most cities of developing countries are characterised by two distinct set-ups, namely the formally built ‘cement areas’ and the nearly rural types of neighbourhoods, the so-called peri-urban settlements, of metropolitan areas. The latter are usually slums, lacking every form of urban planning, where the majority of the urban poor lives. The development of this type of settlements is often not included in the official plans for urban development of the main cities, a fact that often causes difficulties in terms of planning, implementation, provision and maintenance of public services (Bolay and Rabinovich, 2004). To access potable water supplies, most residents of such neighbourhoods rely on alternative service providers such as small-scale independent providers (SSIPs), often acting as investors, developers and/or managers of water kiosks and small-scale piped water systems.

Of the various forms of small-scale service provision, SSIPs have long been accepted by donors and governmental authorities as a viable alternative to developing, managing and expanding service coverage in remote and underserved areas. In the field of water supply, SSIPs are estimated to reach as much as half of the population in some countries (Kariuki and Schwartz, 2005), while up to a quarter of the urban population of Latin America and nearly half of urban dwellers in African countries rely on SSIPs for at least a portion of their drinking water supply (Collingnon and Vézina, 2000). The list of examples in Africa includes the cities of Bamako, Cotonou, Conakry and Dar es Salaam, where SSIPs are reported to be the main source of drinkable water for more than 60% of households, and cities like Abidjan, Nairobi and Ouagadougou, where SSIPs are reported to reach 22% to 28% of unconnected households (Collingnon and Vézina, 2000). The city of Maputo is no exception.

SSIPs have operated in Maputo since the beginning of the 1980s, but they have only become widely established as from 2000. Estimates from a survey carried out on SSIPs in greater Maputo indicate that by 2005, more than 240 groundwater-based small piped systems run by SSIPs existed in the municipalities of Maputo and Matola (Seureca & Hydroconseil, 2005). Around 65% were reported to have been established within the last 5 to 8 years with roughly 43% built between 2002 and 2005 (Fig. 1). During the same period, service levels rose from public taps only to services provided also through house connections, yard taps and private stand pipes (Sal-Consultores, 2005). Today, some 32% of SSIPs are reported to have more than 100 house connections.

Most SSIPs, even though located within the boundaries of greater Maputo and furthermore within the lease area of a private operator – Águas e Moçambique (AdeM) – contracted to provide services to the city of Maputo, are currently not for-

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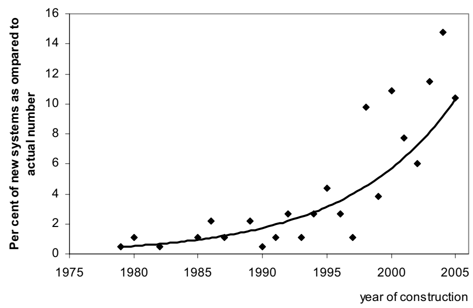

Figure 1
Statistical distribution of SSIPs in Maputo and Matola Municipalities by year of construction (adapted from: Seureca & Hydroconseil, 2005)

mally regulated. This is partially due to the lack of legal bases or legislation frameworks that could be used to issue licences or regulate their activities.

The evolution of household-level water strategies into SSIPs has in most cases been unplanned. Most owners of systems had built those to provide water for themselves, but because of insistence from neighbours they ended up allowing for some private connections or selling water in small quantities (20 to 25 ℓ) and thus slowly developing into water vendors. Also, because the benefits of selling water helped providers offset the investment and running costs (break-even expected within 2 to 3 years), many of them eventually turned into professional service providers.

The rapid increase in SSIP number in the neighbourhoods of greater Maputo has always been driven by demand, particularly in areas where a formal network is lacking. In such neighbourhoods, SSIPs have the dominant role in service provision and are reported to reach as many as 32% of unconnected households (Seureca & Hydroconseil, 2005; Salomon, 2007). This situation is not likely to change in the future, mainly because the physical expansion of the formal network is unlikely to ever match the speed at which new suburbs emerge in the city. Moreover, SSIPs have recently been recognised and accepted as key partners in the recently launched (2006) 'Maputo Water Supply Project', which among other aspects foresees the development of complementary groundwater- based systems and the involvement of small local private operators in the management of service provision.

In this study, the long-term challenges facing SSIPs with regards to supplying quality water of sufficient quantity to unconnected residents of peri-urban Maputo have been assessed based on an analysis of the present situation with respect to the quality of water, the hydrogeological set-up of the aquifer system used by SSIPs and the potential for quality and quantity problems associated with the proliferation of SSIPs. The focus of the study was on the source water quality, potential yields vis-à-vis present and future demands, and the best strategy to locate and monitor boreholes under a scenario of the continuous growth of SSIPs.

Materials and methods

The study area

Maputo is the capital of Mozambique and is situated on the Indian Ocean coastline. The city is characterised by three distinct set-ups, namely the area with high-rise buildings of the so-called old 'cement city', a few inner suburbs built before independence from the Portuguese in 1975, and the outer neighbourhoods consisting mainly of informal settlements.

During the unstable period after independence, exacerbated by the civil war that raged in the country for almost a decade, many families who fled the rural areas in search of security in the cities were allowed to settle in the outskirts of Maputo, where proper urban planning was lacking. With the introduction of municipal reforms in 1998, the city of Maputo was divided into two municipalities namely, Maputo and Matola. Furthermore, the administrative boundaries of the newly created municipalities were re-drawn and most of the neighbourhoods previously considered as informal settlements now became part of the new municipalities.

Without proper planning and investments, however, most of the new neighbourhoods today face severe limitations concerning access to adequate municipal/public services such as water, sanitation and electricity. When it comes to piped water supply, while the residents of the neighbourhoods located near the 'cement city' can still access the piped grid through overstretching the formal network, the residents of the outer neighbourhoods face more restrictions in piped water access, due to lack of pressure in the nearby grid or because the network cannot be sufficiently extended to reach their neighbourhoods.

These problems have not only led to enormous disparities concerning the access to piped water supply but also prompted the emergence of alternative service providers (e.g. SSIPs) who presently constitute the most reliable sources of water for the majority of the under-served urban poor. Today, roughly 38% of households in Maputo rely either on SSIPs (32%) or other types of alternative sources (6%) for their water supply, compared to the roughly 62% of households supplied through the formal network (Gumbo, 2004; Seureca & Hydroconseil, 2005).

Pumping tests and water quality measurements

Pumping tests

Borehole pumping tests were performed to assess the hydrogeological potential of the aquifer system used by SSIPs. A total of 10 pumping tests were performed on an equal number of boreholes distributed within the study area. Attempts were made to establish an evenly distributed grid of test boreholes covering the entire study area. Some problems arose while performing this task, i.e.:

- **Access limitations**. Owners were requested to interrupt their services temporarily to allow for installation of flow meters and other equipment required for the tests, and to run the actual tests. Due to possible disturbances to their services, some owners were not willing to participate; thus, new boreholes had to be identified near to previously selected boreholes in order to maintain the desired level of coverage of the study area.
- **Poor system condition**. In many cases the pipe casing was poorly done, making it difficult and costly to install the equipment for running the pumping test. Therefore, all tests were carried out using pumps already installed in the boreholes. This also limited the possibilities of running the tests with a three-stage pumping rate as is common practice. Instead, a single-stage pumping rate followed by a recovery test was used.
- **Reliability of power supply**. The area suffered from frequent power outages. The borehole locations thus had to

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be chosen on the basis of power reliability. Boreholes reported to be located within an area subject to a high rate of power cuts, as indicated by the owners, were not included in the list of test sites.

Despite the above-mentioned constraints, 10 different sites for the pumping tests were identified. The pumping tests consisted of a well drawdown test with a single stage pumping rate followed by recovery tests. Water levels were measured by divers in all tested wells with an accuracy of ± 1 cm. Discharge rates were determined using a flow meter connected to the rising main of each well. The test results were used to determine the aquifer transmissivity, the borehole-specific yield and borehole productivity.

Water quality measurements

Thirty-five sampling wells were used to assess borehole water quality. Samples of borehole water were collected and further analysed for nitrates and bacteria (*E. coli* and faecal coliforms).

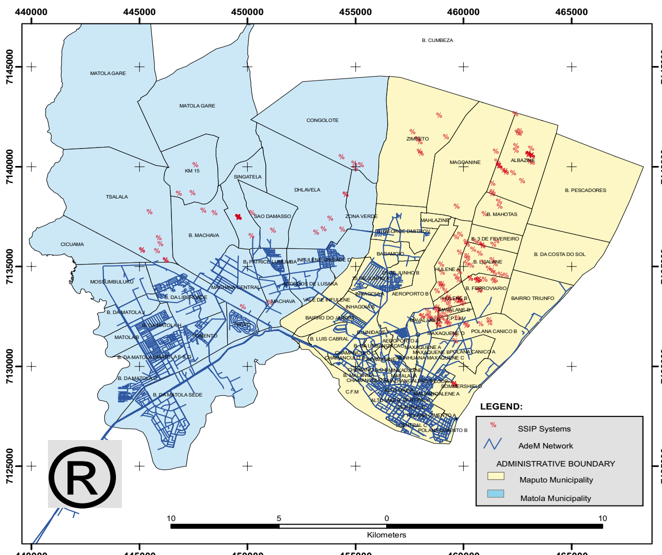

Figure 2
Distribution network of greater Maputo and distribution of water systems run by SSIPs

EC (electrical conductivity) and pH were measured in the field using handheld digital meters from Wagtech International Ltd., and temperature was measured using a standard mercury type thermometer. EC measurements were carried out with the purpose of evaluating the influence of sea-water intrusion on the quality of borehole water.

Nitrates and bacteria were analysed at the AdeM laboratory following procedures described in *Standard Methods* (1995). Bacteriological analyses were carried out using the membrane method. Although a total of 35 boreholes were used to investigate borehole water quality with respect to nitrates, the results from just 12 boreholes were used, due mainly to unreliable results obtained from one of the laboratories involved. The nitrate concentrations reported by Avignon Hydrogeological Laboratory in France were the results used in this study.

Results

Present condition of peri-urban water supply services

The Maputo water supply system is presently run by AdeM, a private operator rendering services through a 15-year lease signed in 1999 as part of the implementation of the framework for delegated management of water supply (Zandamela, 2002; Gumbo et al., 2003; Gumbo, 2004). As a consequence, FIPAG (Fund for the Investment and Property of Water supply) was created to take over as owner of the fixed assets of water supply of 5 major cities of the country; also CRA (the Water Supply Regulation Council) was created for regulation of private sector contracts within the framework. The lease area of AdeM spans across the entire area of the two municipalities while the existing network is limited to the most urbanised areas (Fig. 2).

Demand for services provided by SSIPs

From Fig. 2 it is evident that the lack of formal services in large areas of peri-urban Maputo has prompted the proliferation of private service providers who operate either as the sole service providers in their neighbourhoods or in competition with AdeM. In a survey conducted as part of this study, some 187 SSIPs of Maputo and Matola, who were reported to be responsible for some 192 small-scale piped systems, were interviewed. About 84.4% of providers interviewed said they offered services through house connections and yard taps while 15.6% offered services through standpipes.

The density and distribution of SSIPs in peri-urban areas of the city more or less follows the population density (see Fig. 2). The highest population densities are in the north-eastern part of the city (in the neighbourhoods of Albazine, Mahotas, Hulene, Laulane and Mavalane) and in the new expansion zones located north-west of the city, namely in Zimpeto, Ndhlavela, Bunhiça, Singatela and Tsalala.

The quality of services provided by SSIPs is highly appreciated by residents of peri-urban areas; therefore, the demand for their services has always been high. This has been confirmed through studies carried out for CRA in 2005 (Seureca & Hydroconseil, 2005) and further updated in 2006 (Salomon, 2007); these studies indicated that more than 75% of consumers interviewed were satisfied with the services offered by SSIPs.

SSIPs source water potential

Geological settings

The study area is part of the large Meso-Cenozoic sedimentary basin which covers the area south of the Save River and is related to the rift system between Madagascar and Africa. This system extends from Port Dundford in South Africa to Quelimane in the central part of Mozambique. Karoo basalts and rhyolites, dated Permic and Jurassic, form the basement of the system. Cretaceous to Tertiary flat deposits or deposits with nearly horizontal slopes overlay the Karoo sediments. These deposits are mostly of marine origin and were formed during transgression periods. Sand dunes or quaternary sand deposits cover the entire study area.

Characterisation of the aquifer system

The aquifer system of the region of Maputo is divided into two major units: the sandy aquifer or phreatic aquifer and a deep aquifer of sandstones and limestone with fresh- water, regarded as having good hydraulic potential (Burgeap, 1961). At a local level, the aquifer potential is substantially different for the two aquifers; however, the deep aquifer is the best in terms of strategic groundwater exploitation. The separation between the two aquifers is not clearly defined but for large-scale exploitation of groundwater, the two aquifers can be regarded as a single unit according to findings of IWACO (1983) later confirmed by studies by IWACO (1985), Juizo (1995) and Sweco & Associates (2004).

Groundwater potential

The results of the borehole pumping tests are presented in Table 1. The pumping test results were interpreted using the graphical method of Jacob (Kruesman and Ridder, 1991). The objective was to infer the following parameters characteristic of the groundwater potential: aquifer transmissivity, borehole specific yields and borehole productivity.

For all tested boreholes, the plotted drawdown curve adjusted to the semi-log law (Table 1). This indicates that the aquifer system should be classified as a porous media aquifer in which fractures do not play an important role in the overall aquifer permeability. The aquifer transmissivity was found to be between 40 and 520 m^2/d, which is a reasonably high value for a single sandy aquifer with a depth to the water table of between 10 and 30 m (Table 1).

Borehole specific yield depend on the aquifer setup, but also on the borehole equipment (length and other characteristics of filter screens) and the quality of the gravel pack. Specific yield (discharge for a 1 m^3/h yield) values calculated for the 10 tested boreholes are also presented in Table 1. These were further compared to historical data of the same boreholes and also from nearby boreholes in order to identify possible yield reductions with time. According to the results in Table 2, estimated specific yields for all tested boreholes were found to be within the range of 0.2 to 4.0 m^3/h·m; these are rather high values for sand aquifers and for low-cost boreholes probably constructed without a gravel pack. The long-term productivity of the tested boreholes calculated from the aquifer transmissivity and borehole specific yields is also shown in Table 1. An estimated borehole lifetime of approximately 3 years and a continuous pumping rate of 24 h/d with a maximum drawdown tolerance of ± 10 m were assumed. The results indicate that all tested boreholes can be exploited to a higher yield than the present one without running into risks of over-exploitation of the aquifer system. The total potential yield for the 10 tested boreholes was 1 772 m^3/d. Eighty per cent of the tested boreholes could be exploited within the range of 100 to 300 m^3/d.

Water quality assessment

Microbial contamination

A total of 35 samples were taken from water provided by SSIPs and analysed for microbial contamination. Results of bacteriological analysis for those sites where bacteria counted in excess of recommended guidelines are resumed in Table 2. Accordingly, 14 out of the 35 sites investigated revealed total coliform counts above prescribed guidelines for human consumption (<3 cfu/100 mℓ), while at four sites, total counts of *E. coli* and faecal coliforms indicated moderate to high levels of contamination by faecal bacteria. In these, faecal bacteria counts were reported to range from as low as 10 cfu/100 mℓ to as high as 240 cfu/100 mℓ, while *E. coli* was found to be present at least at three sites.

The sites with the highest incidence of contamination with faecal bacteria were located in two neighbourhoods north-west of the study area (Sigantela and São Damaso) but also in one neighbourhood located north-east of the study area (Albazine). The results of the microbial analysis with respect to total coliform counts were further mapped (Fig. 3) to indicate the spatial dispersion of contaminated boreholes within the study area. Accordingly, the borehole at Singatela was the one showing the most critical situation in terms of bacterial contamination.

TABLE 1
Productivity and potential yield of tested boreholes

Ref. site	Total depth (m)	Depth to water table (m)	Discharge testing (m^3/d)	Measured drawdown (ΔS; m)	Spec. yield 10^3 sec (S_{1000s})	Trans-mis-sivity (m^2/d)	^{a}Qexpl $_{10\ m}$ (m^3/d)
Site 1	25	9.9	32	0.133	6.38	44	41
Site 2	30	12.3	64	0.137	2.46	85	145
Site 3	55	16.9	74	0.120	5.35	113	106
Site 4	30	17.3	77	0.123	1.43	115	245
Site 5	30	16.2	55	0.083	3.58	122	104
Site 6	48	27.4	59	0.073	2.81	147	130
Site 7	35	6.7	28	0.022	0.24	232	304
Site 8	48	27.1	89	0.067	2.50	243	211
Site 9	44	24.6	30	0.017	1.07	332	131
Site10	45	18.5	66	0.023	0.75	518	355
Present yield (m^3/d)			**575**	Potential yield (m^3/d)			**1 772**

[a] *Safe yield for 10 m drawdown after 3 years of continuous pumping*

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TABLE 2
Microbial contamination analysis results of boreholes from which positive counts were reported

Ref. site	Location	Bacteria counts (cfu/100 mℓ)			Guideline standard (MISAU, 2004)	
		Total coliforms	Faecal coliforms	*E. coli*	Total coliforms	Faecal coliforms
Site 1	Romão	9	0	0		
Site 2	Albazine	4	0	0		
Site 3	Abazine	43	9	0		
Site 4	Albazine	460	28	4		
Site 5	Albazine	4	0	0		
Site 6	Zimpeto	15	0	0	< 3	0
Site 7	Dlavele	39	0	0		
Site 8	Dlavele	20	0	0		
Site 9	S. Damanso	150	28	1		
Site 10	Singatela	240	240	13		
Site 11	Tsalala	4	0	0		
Site 12	M. Socimol	23	0	0		
Site 13	Khongolote	4	0	0		

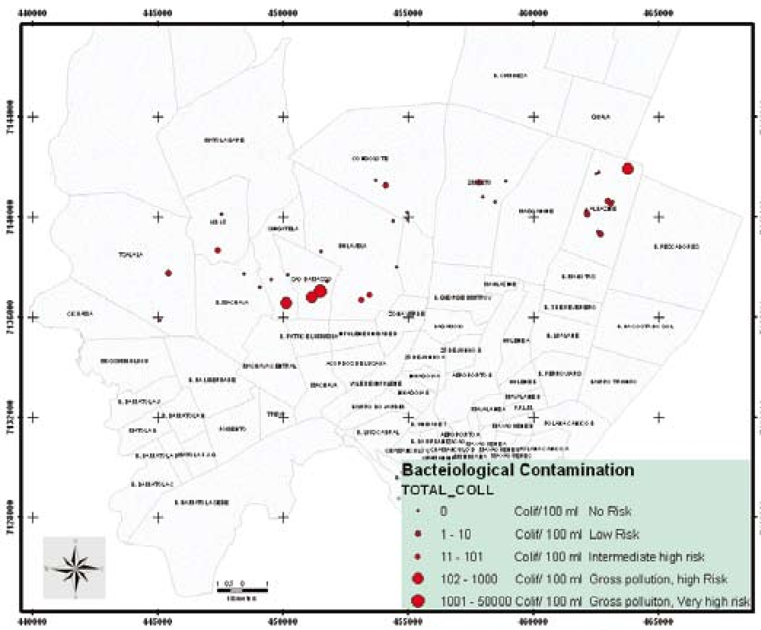

Figure 3
Bacteriological contamination analysis results (total coliforms) of the tested boreholes

Contamination with nitrates

To assess the degree of borehole water contamination with nitrates, results from 12 tested boreholes were used. The locations of sampled boreholes were mapped in Fig. 4. Accordingly, nitrate concentrations in all sampled boreholes were rather low and below the target limit of 45 mg/ℓ set in the guidelines for drinking water quality (WHO, 2004). Reported concentrations ranged from values as low as 3 mg/ℓ to a maximum of 31 mg/ℓ for all tested wells.

The highest nitrate concentrations were reported in boreholes located in areas long established as residential areas (suburbs) of the city of Maputo and thus having moderate to high population densities. These are areas where sanitation is mostly provided by means of cesspits and dry-pit latrines. The area north of the dotted line in Fig. 4 shows the new expansion zones of the cities of Maputo and Matola, and is therefore characterised by low population densities. Here, sanitation is also offered in the form of cesspits and pit latrines. The analysis of the spatial distribution of nitrate concentrations as indicated in Fig. 4 suggested the existence of three distinct areas, namely:

- An area with the lowest levels of nitrates (< 6 mg/ℓ), located mainly in neighbourhoods with low population densities (the northern part of the study area, consisting of the neighbourhoods of Congolote, Zimpeto, Singaleta, São Damasso and KM 15). This also includes areas reported to have a rather shallow groundwater table where the unsaturated zone is relatively thin.
- An area with medium levels of nitrates (10 to 20 mg/ℓ), located mainly in neighbourhoods with moderate to high

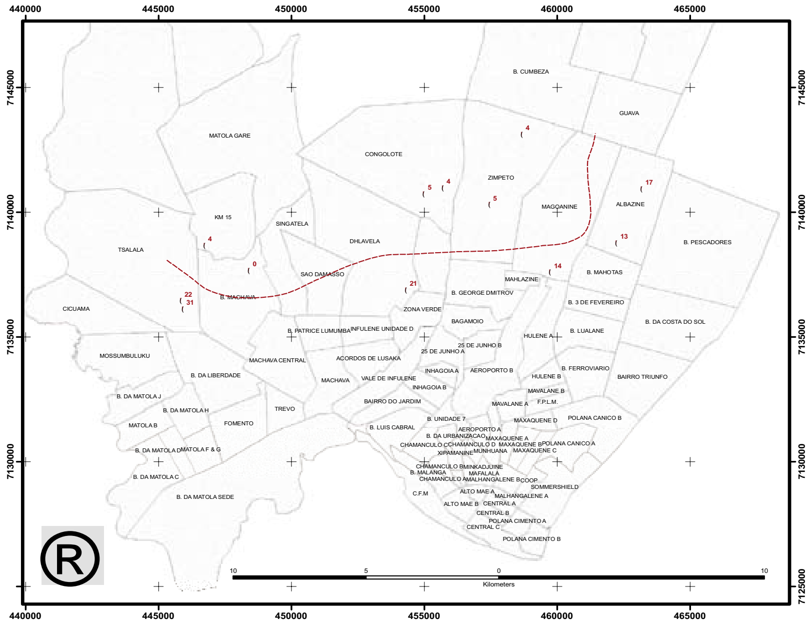

Figure 4
Nitrate concentrations (mg/ℓ) within the study area

population densities (namely the north-eastern neighbourhoods of Magoanine and Albazine), in the aquifer of which a relatively thick unsaturated zone and depth to the water table are reported to exist.

- An area with the highest nitrate levels (20 to 32 mg/ℓ) located mainly in densely populated neighbourhoods (Dlavela and Tsalala).

Electrical conductivity and water salinity

Sea-water intrusion is a very common problem when it comes to groundwater extracted in coastal areas. When aquifers are depleted by high-yield exploitation, sea-water intrusion may occur and the quality of water with respect to its taste is thus compromised. When sea water invades coastal aquifers, the interface position between fresh and brackish water is a function of aquifer properties, pumping rate and aquifer recharge potential. In order to assess the levels of salinity of borehole water used by SSIPs, EC measurements were carried out on samples from 35 boreholes located further north of the study area. The results were mapped and are presented in Fig. 5. Accordingly, only 3 sites were reported to show EC levels in excess of the guideline for drinking water of 1 500 mg/ℓ and hence potentially to contain brackish water. Two sites were located north-west of the study area while the third was located to the north-east.

Discussion of results

Because of the formal water network not reaching most of peri-urban Maputo, SSIPs have, over the past few years, become an integral part of the supply chain of services to the suburbs of greater Maputo. They play the predominant role in service provision to such areas, and the quality of their services is highly appreciated by consumers. Most independent providers operating in greater Maputo are currently unregulated, but important steps have already been taken to change that situation. These include studies commissioned by CRA for the development of regulatory tools to frame their activities, and the joint efforts by CRA and municipal authorities for the formalisation of independent providers (OECD, 2007). SSIPs have also been included as key partners in the recently launched 'Maputo Water Supply Project'. The demand for services provided by SSIPs is therefore not likely to decrease in the near future. Quality and quantity problems associated with future expansion are likely to constitute the main challenges for the long-term sustainability of SSIP activities.

The typical design of water systems run by SSIPs is based on groundwater abstraction. Consequently, the potential of the regional aquifer system is a key element in the long-term planning of intervention of SSIPs. From the results of borehole testing presented in Table 2, it is clear that most boreholes used by SSIPs are of limited depth (< 60 m) and also, that they tap water at relatively shallow depths to the water table (< 30 m), probably from within the sandy aquifer. The pumping test results also indicate that present yields are generally lower than estimated potential yields (0.2 to 0.4 m^3/h.m); consequently, borehole water can be exploited at even higher yields without risking over-exploitation of the aquifer system. This implies that, within reasonable limits of expansion of small-scale service providers and proper location of boreholes, the risks of an eventual depletion of the aquifer system are small. Also, because the two major units comprising the aquifer system of Maputo can be regarded as one unit (IWACO, 1983; IWACO, 1985; Juizo, 1995; Sweco & Associates, 2004), the yield properties in case of larger abstraction rates will also be determined by the deeper aquifer, which is regarded as having better hydraulic properties and being suitable for large-scale exploitation. In fact, the deeper aquifer is regarded as the main supplementary source for the water supply

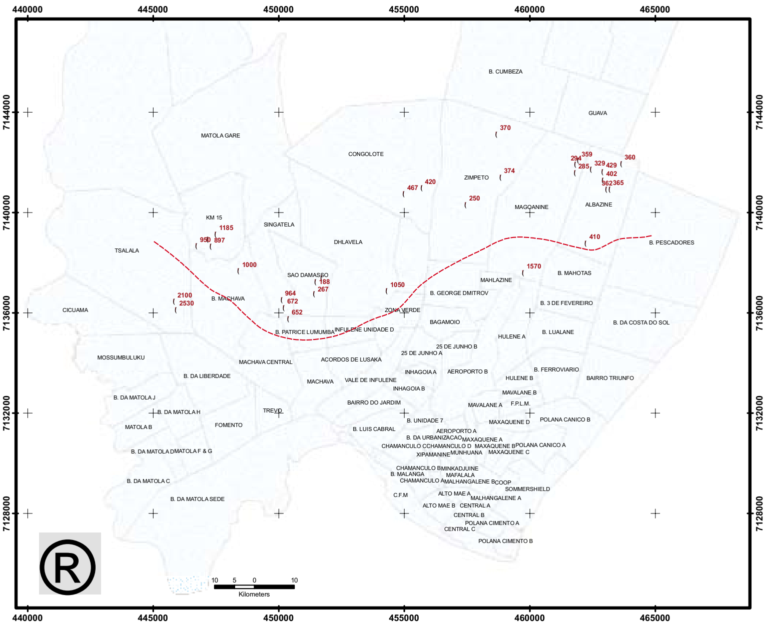

Figure 5
EC levels within the study area (μS/cm). The dotted red line represents the 1 200 μS/cm boundary. All areas located north of the dotted line are suitable for borehole installation.

to the city of Maputo, particularly to the neighbourhoods located north of the city centre.

The results of groundwater quality assessment suggest that, as for today, the quality of water tapped by SSIPs generally conforms to guideline standards (MISAU, 2004; WHO, 2004) with respect to the parameters investigated and therefore poses no constraints on use at domestic level. Yet, none of the independent providers said they treated the water, except when instructed due to problems detected during monitoring intermittently conducted by the Ministry of Health via its Food & Hygiene Department. In fact, the Ministry of Health (MISAU) has in its database about 220 boreholes, the water quality of which is to be regularly monitored; 83 of these are private boreholes run by SSIPs.

The analyses of microbiological quality indicate that, with few exceptions, water from the majority of privately owned systems is virtually free from faecal contamination, as proven by the absence of *E. coli* as well as faecal coliforms in more than 90% of samples investigated. This suggests that as for today, there is no widespread bacterial contamination of the aquifer system used by SSIPs.

Most SSIPs are located within moderately to densely populated residential areas, where sewers do not exist and sanitation is mainly provided through septic tanks, cesspits and dry-pit latrines; therefore, seepage from on-site sanitation represents the most widespread and serious source of pollution (both point and diffuse) to the aquifer system. Since pathogens can survive for many days while percolating the unsaturated strata and eventually through the aquifer system (Sugden, 2006), the major concern regarding poor sanitation is direct migration of pathogenic bacteria and viruses to underlying aquifers and neighbouring groundwater sources (Lewis et al., 1981).

The extent and risk of groundwater contamination depend, however, on many factors, one of which is the degree of pathogen attenuation during percolation through the unsaturated zone and, eventually, through the aquifer system. Some studies (Sugden, 2006; Argoos, 2001; Schmoll et al., 2006) indicate that pathogen attenuation is generally most effective in the uppermost layers of the unsaturated zone, where biological activity is greatest and where the presence of protozoa and predatory organisms, rapid changes in soil moisture and temperature as well as competition from established microbial communities help reduce the level of pathogens in that particular zone and, consequently, in the groundwater.

The distance between the base of pit latrines and water table (also known as soil infiltration layer) plays an important role in the die-off of pathogens. As noted by Sugden (2006) and Schmoll et al. (2006), a soil infiltration layer depth of between 5 and 10 m is sufficient for reducing contamination of the water table by pathogens to acceptable levels.

Because most SSIPs tap their water at depths to the water table of greater than 10 m and pit latrines are built with depths of 1.0 to 1.5 m, sufficient depth is maintained through the unsaturated zone to prevent pathogens from reaching the groundwater table. The horizontal distance between pit latrines and water wells will also have an impact on levels of contamination.

The soil type and permeability characteristics of the unsaturated zone and aquifer system are also important factors, since they impact residence times in the unsaturated zone and prevent the passage of bacterial pathogens into the subsurface. High soil permeability is associated with high risks of pathogens reaching the groundwater table. According to the literature (Schmoll, 2006; Lee and Bastermeijer, 1991), residence times of about a month are long enough to free groundwater sources from pathogens naturally. Long residence times in the unsaturated zone are associated with low risks of groundwater contamination. Seasonal variations of the groundwater table, e.g. due to rainfall, increase the risk of pathogens seeping into the groundwater. Godfrey et al. (2004), Pujari (2007) and Howard et al. (2003)

have all reported significant increases in faecal contamination of groundwater following rainfall events.

Construction and completion details of boreholes are also crucial factors in that they may increase the risk of groundwater contamination by creating localised pathways for ingression of pathogens (Schmoll, 2006; Godfrey, 2005) or by shortening the distance and time required for pathogens to reach the groundwater table (Argoos, 2001). The deeper the filter screen, for example, the longer the time required for pathogens to reach the aquifer system and the higher the die-off rate.

The results of the geohydrological characterisation of the aquifer system used by SSIPs in Maputo suggest that the aquifer system does not have any natural barrier against pollution; this means that contaminants disposed of on the surface or seeping from pit latrines can percolate relatively freely across the unsaturated stratum and readily reach the groundwater system. The results of this study indicate, however, that the incidence of contaminated wells is rather limited, which suggests that either the load of contaminants is rather limited or that the ingress of pathogens is still being sufficiently attenuated in the unsaturated strata underlying the aquifer system. Yet, 13 out of the 35 tested boreholes had either total coliform or faecal coliform levels higher than the WHO standard which suggest that other paths of contamination may probably have occurred.

The most critical situation with respect to faecal contamination was found to be related to an open hand-dug well (in São Damanso) where faecal coliform counts as high as 240 cfu/100 mℓ were reported. Open hand-dug wells are usually constructed in areas with relatively shallow groundwater tables, where the proximity of the groundwater table facilitates the transport of contaminants; consequently, contamination with bacteria could be widespread. For example, a study conducted in rural Zimbabwe (Dzwairo et al., 2006) has shown that pit latrines constructed at less than 2.0 to 3.0 m above the water table affected the groundwater quality at lateral distances of up to 25 m. However, it appears as though this is not necessarily true; in the very few cases where contamination with bacteria was reported, the problem appeared to be related to borehole construction and siting rather than to percolation of contaminants. This is in line with findings from a study by Howard et al. (2003) on water quality variations in shallow protected springs in Kampala, who concluded that improving the sanitary finishing of wells and of local environmental hygiene is more important to protect groundwater quality than controlling wide-spread construction of on-site sanitation facilities. The situation of the contaminated wells identified in this study should therefore not be considered as representative of all SSIPs located within the study area, nor as a common critical aspect of this type of water systems.

The area located north-east of the city (Albazine) where moderate to high levels of bacterial contamination were also reported, is a densely populated area. The depth to the water table, as measured in nearby boreholes where pump tests were performed (sites 8 & 9), suggests that rather thick strata of the unsaturated zone exist (> 25 m). The problem here is attributed either to poor borehole construction or high hydraulic load from pit latrines. Improper location of pit latrines may also be a contributing factor. The area also experiences high recharge conditions and relatively good permeability rates (IWACO, 1985); hence, there is a high potential for bacterial contamination due to percolation. Low living standards, poor borehole construction and high hydraulic contaminant loads are therefore the most probable causes of the high incidence of bacterial contamination reported in these boreholes.

The presence of nitrates is a common groundwater problem (WHO, 2004). Although nitrogen may occur naturally in groundwater, the main sources of groundwater pollution are human activities such as agriculture, sanitation (pit latrines) and accumulation of organic material from improper solid waste handling (Boulding and Ginn, 2003; Schmoll et al., 2006; WHO, 2004). The WHO guideline for the presence of nitrates in drinking water is 45 mg/ℓ. The peri-urban area of Maputo is lacking formal waste collection services and sanitation is mainly provided by dry-pit latrines. Dwellers, on the other hand, usually burn their waste in the garden, thereby reducing the source of diffuse pollution from solid waste handling and leaving seepage from pit latrines as the main source of nitrogen that could potentially pollute the groundwater.

High levels of nitrate are a major problem for bottle-fed infants, as the risk of methaemoglobinaemia increases when nitrate concentrations rise above 50 mg/ℓ (WHO, 2006; Thompson et al., 2007). Factors such as hydraulic loads, soil type and depth to the water table determine the rate and extent of nitrate transport into the groundwater. Sandy soils are particularly vulnerable to nitrate leaching into the groundwater because of the limited attenuation they provide (Thompson et al., 2007). Rainfall also affects nitrate transport into aquifer systems. If the water table is too shallow, there is a great risk of high concentrations of nitrate occurring after a relatively short time, particularly after heavy rainfall.

The results of nitrate analyses for sampled boreholes (Fig. 4) suggest that nitrate levels were always below the WHO guideline value of 45 mg/ℓ for drinking water. Accordingly, three distinct areas can be distinguished:

The area north of the study area where the lowest nitrate concentrations (< 6 mg/ℓ) were reported, covers mainly neighbourhoods with low population densities and thus with relatively low hydraulic loads potentially harmful to the groundwater. It includes zones where the unsaturated zone is rather thin (less than 10 m) and so features a limited capacity for attenuating any nitrate loads leaching from pit latrines. This leaves hydraulic loads as the main factor determining the levels of nitrates in the groundwater, thereby supporting the idea that, presently, levels of groundwater contamination in this area are determined principally by population density.

The area with moderate concentrations (10 to 20 mg/ℓ) is located mainly in neighbourhoods with moderate to high population densities and where a relatively thick stratum of the unsaturated zone exists. The moderate levels of nitrates observed in this area are probably the result of moderate hydraulic loads from pit latrines, combined with a rather limited capacity of the unsaturated zone for preventing the ingress of pollutants due to its relatively high permeability. The area with the highest nitrate concentrations (20 to 30 mg/ℓ) is located in densely populated neighbourhoods. High hydraulic loads from cesspits and pit latrines are certainly the major nitrogen contributor to the groundwater system.

The spatial distribution of nitrate concentrations in the study area thus suggests that population density and the characteristics of the unsaturated zone are the main factors determining present nitrate levels in the groundwater. Present contamination levels were still below critical levels for safe use of the groundwater, a state of affairs that was believed to result from:

- Still limited hydraulic loads due to low population densities (< 100 persons/ha) even in areas considered as densely populated
- Relatively thick soil infiltration layers in areas where the majority of boreholes were located and where biological denitrification may possibly occur.

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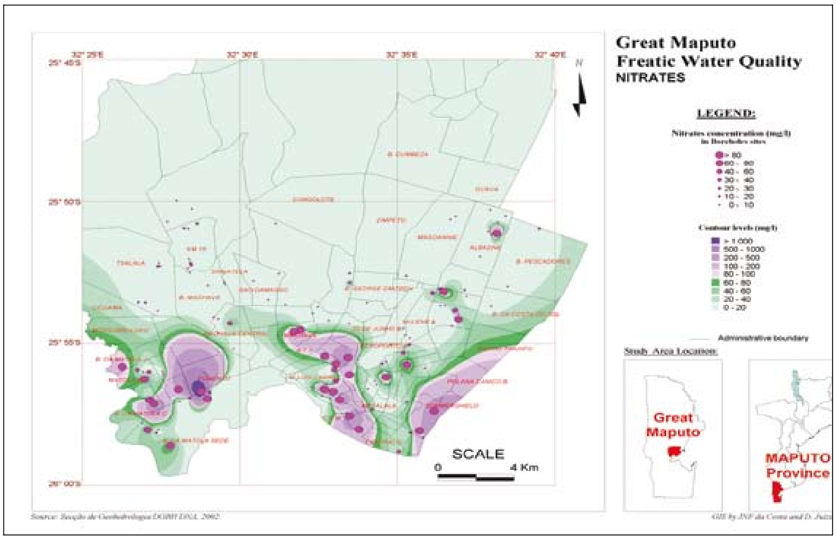

Figure 6
Nitrate concentrations in the neighbourhoods of Maputo based on historical data

An analysis of the spatial distribution of nitrate concentrations based on historical data collected in other, more densely populated neighbourhoods of Maputo (Fig. 6) indicates that nitrate levels in groundwater can be as high as 500 mg/ℓ, which means that contamination by nitrates is a real threat in some neighbourhoods. This is also confirmed by results of similar studies done in other parts of the study area (IWACO, 1984; Juízo, 1995) where nitrate levels of as high as 300 mg/ℓ in the groundwater were reported.

Sea-water intrusion is a common groundwater quality problem in coastal areas. The WHO guideline for EC in drinking water is 1 500 as/cm. Studies with the purpose of assessing the problem of sea-water intrusion in the Maputo and Matola areas (IWACO, 1985) have concluded that such problems are more severe in the south-western part of the city (Matola, Fomento, Cicuama) than in other parts of the city. The occurrence of brackish water has, however, been recorded in some other areas located north-east of the city and close to the Maputo bay, namely the 'bairros' Pescadores, Costa do Sol and Hulene A. While the results of the present study suggest that, as for today, the majority of surveyed sites do not face problems with brackish water, the nature of the geological formations suggests that the area is vulnerable to sea-water intrusion, particularly if the aquifer system should become over-exploited.

Conclusions

SSIPs have become an integral part of the water services delivery chain to the peri-urban areas of greater Maputo, where they are reported to reach as much as 32% of the population. They are presently expanding rapidly to cover new or already established neighbourhoods, not only because of increasing demand resulting from the lack of formal services in such areas but also because they have recently been recognised as important partners for expanding service coverage to reach unconnected residents. The expansion of services with the help of both self-financed and formally delegated small-scale service providers, however, comes with a number of issues deserving urgent attention, among which their capacity for providing quality water of sufficient quantity in the long run.

An analysis of the potential of the aquifer system from which SSIPs tap water to render their services suggests that present yields in general are lower than estimated safe yields and that borehole water can be exploited at higher than the present yields without running into risks of over-exploitation of the aquifer system. This implies that, within reasonable limits of expansion and proper location of boreholes, the expected increase in the number of SSIPs will not lead to an eventual depletion of the existing aquifer system. Yet, care must be taken to ensure that quality problems will not arise due to increased abstraction rates.

So far, the quality of water used by SSIPs to provide services has been virtually free from microbial and organic contamination. Two major factors contribute to this, namely limited hydraulic loads due to low population densities and relatively thick strata of the unsaturated zone, where attenuation of contaminants still occurs at sufficient levels. Yet, 13 out of 45 tested boreholes had total coliform levels above the WHO recommended standard and 4 had faecal coliforms in excess of the standard. Low living standards, poor borehole construction and high hydraulic loads were the probable causes of the high incidence of bacterial contamination in those boreholes.

Nitrate concentrations in all boreholes tested were below the recommended standard of 45 mg/ℓ. However, the situation may change in future, either due to over-exploitation of the aquifer system or to increased hydraulic loads resulting from increased population density.

No problems with brackish water were reported in large parts of the studied area, but in future this could become a serious problem because of the high vulnerability of the aquifer system (coastal aquifer) to sea-water intrusion.

While the potential for development of SSIPs is high, based on demand and the characteristics of the aquifer system, the long-term sustainability of their activities require that efforts be put in place to speed up the already initiated attempts at formalising small-scale independent providers and to establish regulatory tools to frame their activities. In doing so, pressure must be put on authorities to establish mechanisms that will ensure the adoption of more stringent protective measures for boreholes constructed to provide public services, including:

- Regulated procedures for borehole design and location in order to minimise risks of contamination. Special emphasis should be put on aspects such as wellhead protection, positioning of filter screens and the location of boreholes in relation to existing pit latrines. A minimum radius of influence 25 m away from pit latrines is generally accepted in Mozambique.
- Mandatory rules for direct protection of boreholes used as drinking water supply (e.g. a 5x5 m surrounding fence)
- Mandatory rules for SSIPs regarding chlorination of the water before distribution.

Because most independent providers tend to tap water at relatively shallow depths to minimise investment costs, enforcement rules regarding minimum depths of abstraction could also be put in place.

Overall it can be said that SSIPs provide a valuable contribution to overcoming the problems with drinking water supply to peri-urban areas experiencing rapid growth; however, it is imperative that the governmental institutions and already established regulatory bodies put in place mechanisms to reduce the possibilities of future public health risk associated with these systems.

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Regulation of formal and informal water service providers in peri-urban areas of Maputo, Mozambique

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ABSTRACT

Service delivery to large areas of peri-urban Maputo depends largely on alternative informal service providers. These providers are located within the limits of Maputo, in a water supply area that is formally leased to a private operator. Informal service providers therefore operate within the main regulatory body, but their activity is presently unregulated. This paper discusses activities of informal alternative providers in peri-urban areas of Maputo, Mozambique, and opportunities to expand the reach and influence of the main regulatory body to this segment of service providers. The study was commissioned to assist the main regulatory body to setup a strategy to improve the pro-poor focus of the existing regulatory environment and so improve access to potable water for the majority of the under-serviced urban poor. Results of field surveys conducted in selected areas of peri-urban Maputo are presented. The surveys focused on the quality of services, the legal status of independent providers and the organization of water supply services at neighbourhood level. The results indicate that household water resellers and small-scale independent provides are presently an important and indispensable source of access to water for the majority of unconnected residents in peri-urban Maputo and that they are reported to cater for as many as 21% of unconnected households of such neighbourhoods. In the near future, alternative providers will continue to have a dominant role in service delivery in peri-urban Maputo, therefore their legalization and decentralization of certain regulatory functions to the neighbourhood level is required. A neighbourhood based management model is proposed for that purpose. The model is based on a standpipe management model that is broadened to include alternative service providers. The model addresses issues such as water pricing, bidding and compliance strategies, channels for consumer's representation and possibilities of creating neighbourhood-based regulation bodies, which will act as extension branches of the main regulatory body. Sustainability issues around the proposed model are also discussed.

1. Introduction

This paper discusses household water resale activities of alternative service providers and small-scale independent providers (SSIPs) in peri-urban areas of greater Maputo, Mozambique. The work discusses also the opportunities of expanding the reach and influence of the main regulatory body to this segment of providers, who arguably serve the largest portion of Maputo's urban poor. The work was commissioned to assist the regulatory body to setup a strategy to expand its coverage to alternative service providers.

The case paper focuses on peri-urban areas of greater Maputo, Mozambique, where the informal water market plays a dominant role in service provision. These areas are located within the lease area of a private operator contracted to provide services to the city of Maputo, therefore, within the official limits of the main regulatory body. Presently, this regulatory function is restricted only to the main service provider. The main regulatory body has therefore expressed interest to explore the potential of legalizing alternative informal service providers and expanding the reach of the body's regulatory role and influence to this segment of providers. The ultimate objective is to improve the pro-poor focus of the existing regulatory framework and ultimately improve access to potable water to the majority of under-serviced urban poor.

2. Background

In Mozambique, water supply services are the mandate of the National Directorate of Water (DNA), under the Ministry of Public Works and Housing (MOPH). DNA is the primary agency responsible for water resources policy making, planning and management,

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and for ensuring the provision of adequate water supply and sanitation services all over the country.

In 1995 DNA approved the first National Water Policy (NWP) which has since guided water sector reforms. In line with the objectives of the NWP, the government withdrew from the task of direct implementation of water supply services to focus more on policy making and planning of the management of water supply services (DNA, 1995). Among other issues, the policy gives special attention to improvements of water supply services in urban and peri-urban areas, the encouragement and regulation of the involvement of private service providers and the participation of beneficiaries in the management of neighbourhood water supply services such as that provided through public standpipes.

As a response to the objectives of the NWP, in 1998 the Government established the framework for delegated management of water supply (decrees number 72, 73 and 74:9 of December 1998), from which the Water Supply Investment and Assets Fund (FIPAG) and the Council for Regulation of Water Supply (CRA) were created (Zandamela, 2002). The framework created the legal basis for the delegation of operation and management of public water supply services to independent private entities through concessions, lease or management contracts. The main institutions comprising this framework are: the Ministries of Public Works and Housing (MOPH), of Planning and Finance and of State Administration, the National Directorate of Water (DNA), and the Co-ordinating Forum for Delegated Management, FIPAG, CRA, the Municipal authorities, and the private operator. FIPAG is the institution created to take over the fixed assets for water supply and the duties and obligations for water service delivery in five major cities of the country previously serviced by state water companies. CRA is the institution created with the objective of regulating private sector contracts under the rubric of this framework. The geographic limit of the regulator's activities is defined by the boundary of the area of each contracted concession.

The framework has been implemented since 1998 in five largest cities of Mozambique, among them, the city of Maputo (DNA, 1999). In 1999 a private operator, Águas de Moçambique-AdeM, signed a 15 years lease contract with FIPAG to provide services to the city of Maputo and a nearby area called Matola (Zandamela, 2002; Gumbo et al., 2003). Since then, service quality in large areas of peri-urban Maputo improved significantly, however, the situation today, is still far from satisfactory. This has prompted the emergence of a multiplicity of alternative service providers, including small-scale independent providers (SSIPs) and household water resellers, the majority of who operate within the lease area of the main service provider (Seureca and Hydroconseil, 2005). Presently, however, the activity of SSIPs and household water resellers is unregulated.

3. Objectives of the study

The work presented here investigates the main characteristics of the water supply environment in peri-urban Maputo, the quality of services provided by formal and informal providers, the organization of management of peri-urban water supply services and the possibilities of expanding the reach of the regulatory framework to the neighbourhood level.

The focus of the study is on services provided through connected household water resellers and standpipes and household taps connected to groundwater based small piped systems of AdeM and SSIPs. These, generally consist of one or few boreholes connected to one or few water towers and a small distribution network. AdeM also runs few stand pipes connected to the main network. A neighbourhood based management model with its scope broadened to include alternative service providers is proposed to assist the main regulatory body expand the reach of the regulatory framework to the neighbourhood level.

4. The study area

Maputo is characterized by three distinct set-ups, namely the area with high storey buildings of the so-called old "cement city", few inner suburbs built before independence in 1975, and the outer neighbourhoods which consist of informal settlements. During the period after independence and probably exacerbated by the civil war that raged the country for almost a decade, there was high migration of rural citizens to Maputo city. These immigrants were allowed to settle in the outskirts of the city, where proper urban planning was lacking. Temporary licenses were issued for construction of temporary houses but after many years of occupation, the residents of such areas virtually acquired the right to settle and construct permanent houses. With the introduction of municipal reforms started in 1998, the city of Maputo was divided into two municipalities namely, Maputo and Matola. The administrative boundaries of the newly created municipalities were re-drawn and most of the neighbourhoods previously considered informal settlements became now part of the new municipalities.

Without proper planning and investments, however, most of the new neighbourhoods today face severe limitations concerning access to adequate municipal/public services such as water, sanitation and electricity. When it comes to piped water supply, while the residents of the neighbourhoods located near the cement city can still access the piped water through overstretching the formal network, the residents of the outer neighbourhoods face more restrictions to access piped water supply, due to lack of pressure in the nearby network or because the network cannot be sufficiently extended to reach their neighbourhoods.

Besides enormous disparities concerning the access to piped water supply, this has favoured the widespread emergence of informal alternative service providers, among them SSIPs, who presently constitute the most reliable sources of water for the majority of the under-serviced urban poor. Like in many other African cites (Collignon and Vézina, 2000), SSIPs play a dominant role in service provision to unconnected consumers of peri-urban Maputo (Table 1). As shown in Table 1, the situation in Maputo is such that roughly 32% of households rely on SSIPs and 6% on other types of alterna-

Table 1
Access to drinking water in 10 Africa cities[a] and Maputo[b]

	Abidjan (Côte d'Ivoire)	Nairobi city (Kenya)	Dakar (Senegal)	Kampala (Uganda)	Dar es salaam (Tanzania)	Conakry (Guinea)	Nouakchott (Mauritania)	Cotonou (Benin)	Ouagadougou (Burkina Faso)	Bamako (Mali)	Maputo[c] (Mozambique)
Source of water for household use by 1999 (percent of household)											
House connect	76	71	71	36	31	29	19	27	23	17	40
Stand pipe	2	1	14	5	0	3	30	0	49	19	22
SSIPs/traditional sources	22	27	15	59	69	68	51	73	28	64	38

[a,b] Adapted from Collignon and Vézina, 2000 and Seureca and Hydroconseil, 2005.
[c] Figures for Maputo refer to survey done in 2005. All other cities refer to 1999.

tive sources (6%) for their water supply, while 62% of households supplied through the formal network (Gumbo, 2004; Seureca and Hydroconseil, 2005).

It is also within the peri-urban areas of Maputo city where the largest proportion of lowest income groups lives and where unconnected consumers are reported to pay on average about three times more per cubic meter of water than customers with house connections (Sal-consultores, 2005). Yet, these figures are not comparable to other African cities (e.g. Luanda) where residents of informal settlements are said to pay as much as 10,000 times more for water to private vendors than those living in the cement city where piped water is available (Cain, 2004).

The peri-urban areas of the city of Maputo face also limitations in terms of sanitation since no formal sewer systems exist in such areas. Estimates from a survey carried out in 2005 (Sal-consultores, 2005) indicates however that almost 89% of households of peri-urban Maputo have some kind of improved sanitation facility which can be either an improved pit latrines (50%), septic tanks (39%), whereas the rest of households rely on traditional pit latrines or share facilities with the nearby households.

5. Methods

This study was based on field work performed in one of the five urban districts of the Municipality of Maputo. Selection of neighbourhoods for the survey was done with the assistance of the main regulatory body based on the following criteria:

(1) High prevalence of water resale activities either via connected consumers or via SSIPs;
(2) facility for identification of households where water resale is practiced;
(3) existence of large variations in coverage conditions by the main service provider;
(4) representativity or resemblance of conditions of other peri-urban neighbourhoods of Maputo concerning coverage levels and existence of alternative service providers acting in competition with the main service provider.

The neighbourhoods of urban district number 4 were determined to fit the aforementioned criteria and thus chosen as locations for the research. The district consists of 11 neighbourhoods (Fig. 1) of which only two have access to potable water via the formal network. Projections from the Instituto Nacional de Estatística – INE (1999) and data obtained from the local administration indicate that at the time of the survey the district's population was about 282,300 inhabitants.

The survey was conducted between November and December 2007 and consisted of site visits to identify existing conditions of access to potable water supplies and interviews with key

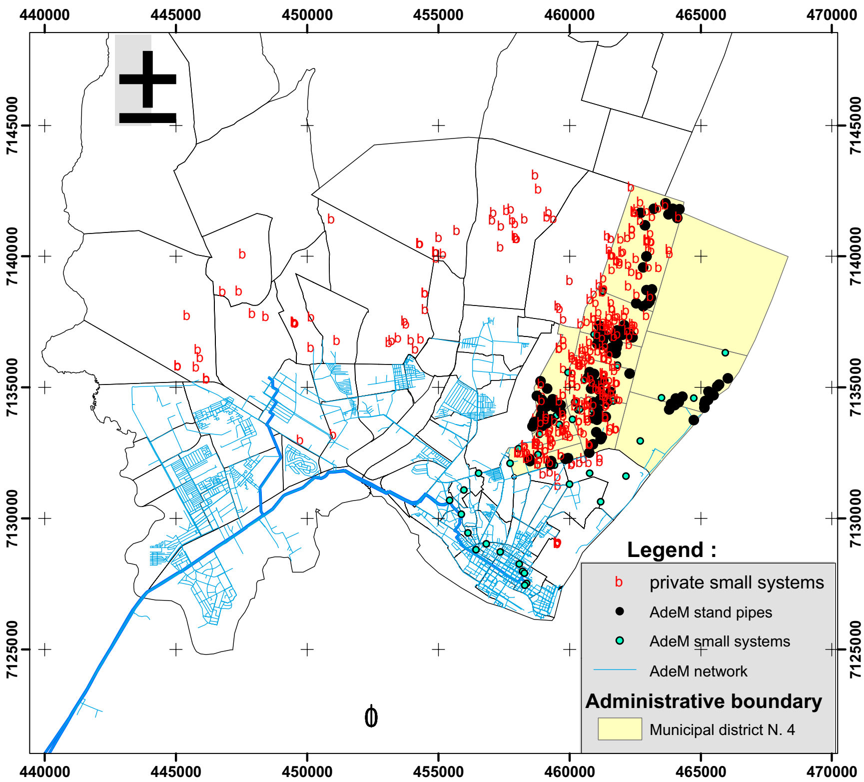

Fig. 1. Urban network of district no. 4 of Maputo city and distribution of small piped systems run by Independent providers.

informants to get an insight on the quality of services offered by different providers, the organization of services and on the level of consumer's satisfaction with respect to services provided. Interviewed people included consumers, owners and stand pipe attendants of small piped systems run by SSIPs, managers and stand pipe attendants of AdeM owned systems and members of water committees (WC), established at neighbourhood level.

Those interviewed included a total of 11 WCs and 249 stand pipe attendants of which 55 were for small-scale piped systems owned by AdeM, 18 for AdeM formal network and 176 of small-scale piped systems owned by SSIPs. In addition, 550 consumers selected randomly at some of the stand pipes visited were interviewed.

6. Results

6.1. Overview of the water supply situation

6.1.1. Access to water services

The survey identified two major sources from which residents of surveyed neighbourhoods get access to potable water supplies. These are standpipes and household taps connected to AdeM formal network and small-scale piped systems, and standpipes and household taps connected to small piped systems owned by SSIPs. Table 2 provides a summary of the number and distribution of standpipes and household taps reported to exist within the surveyed neighbourhood. Table 2 also gives estimates of the proportion of residents depending on the informal water market as compared to those depending on services of the formal provider. As can be seen, about 45% of residents rely on SSIPs to access water and about 13% rely on services provided by AdeM (Salomon, 2007). A large proportion of residents (about 42%) rely on other type of services which includes private wells and household water resellers. From the results in Table 2, it is clear that the informal market plays the predominant role in the provision of water for the majority of residents of the surveyed neighbourhoods.

The results in Table 2 do not include data on the number and distribution of households relying on neighbour-to neighbour water resale to get water. This resulted partially from lack of cooperation from most of the interviewed residents who did not want to expose households practicing household water resale. However, findings from a similar study conducted in a nearby neighbourhood (Boyer, 2006) suggests that neighbour-to neighbour water resale is a long-established and widely-practiced activity in most neighbourhoods and also that it occurs regardless of existing conditions with respect to availability of public standpipes. According to the results of the same study, roughly 69% of unconnected residents depended on neighbour-to-neighbour water resale as their primary source of access to water, while some 57% of residents claimed to have their neighbours as the only viable source of access to water.

6.1.2. Service quality

Water supply service quality is defined using various criteria. These include service continuity, water quality, pressure and the degree of responsiveness to complaints by consumers from service providers. For the purpose of the study, assessment of service quality was based on how consumers evaluated services offered by different providers. A criteria that ranked services according to three levels namely, bad, reasonable and good was used. Ranking was based on three quality indicators namely, water price at public and private standpipes, promptness of standpipe attendants and neighbourhood authorities to respond to consumer's complaints, and the accessibility to services measured by the number of hours with pressure at standpipes and with open access to consumers.

Sixty-nine users of public standpipes and 108 users of privately owned standpipes were interviewed. The survey included also an assessment of how consumer complaints are dealt with by standpipe attendants and on how these are channelled to higher level institutions. The results are shown in Fig. 2 from where it is seen that consumers generally appreciate the quality of services offered by both types of service providers. The public service is better appreciated in terms of water prices and the promptness of standpipe attendants to listen to consumer's complaints, while the private service is best appreciated in terms of service continuity and access to water points.

The results of the survey also revealed also that privately owned standpipes are more readily accessible to consumers, with roughly 90% of them reporting to offer services for more than 8 h per day as compared to 49% of public standpipes offering the same level of accessibility. For many consumers, access to stand pipes and service continuity are the most important aspects to meet their expectations in terms of access to services, particularly for those who can only access the services during the early morning hours or after work.

Private service providers are also viewed by many consumers as the ones that addresses consumer requests and complaints more promptly, particular requests and complaints related to matters such as payment modalities (consumers may get water on a credit basis), negotiation of water prices and the requests for new connections and extensions to the network. The public service,

Table 2
Number and distribution of small piped systems, public and privately owned standpipes and household/yard taps within neighbourhoods of study area

Name of neighborhood	No. of small piped systems		No. of connections from main service provider		No. of connections from SSIPs		Estimated coverage by service provider	
	AdeM	Private	Stand pipes	HC/yard taps	AdeM	SSIPs	AdeM (%)	SSIPs (%)
3 de Fevereiro	2	13	9	0	6	493	1.6	1.9
Albazine	2(1)	17	5	127	11	207	1.1	2.3
Costa do Sol[1]	0	0	18(18)	0	0	0	0.0	0.0
Ferroviário[1]	5(2)	25	13	0	20	2281	2.3	7.6
FPLM[1]	2(1)	7	4	0	9	226	0.7	2.0
Hulene A	3(2)	13	3	0	22	912	0.5	5.5
Hulene B	1	14(11)	17	0	20	1403	3.0	6.0
Laulane	2	37	2	9	22	1864	0.4	7.2
Mahotas	3	51	11	23	29	2541	2.0	9.6
Mavalane A	1	8	2	0	6	453	0.4	1.9
Mavalane B	1	4	4	0	3	180	0.7	0.9
Total	22(6)	189	88	159	148	10,560	12.7	44.9

AdeM stands for the main service provider; HC-house connections.
1 – Neighbourhoods covered by the formal network.
5(2) – In brackets, number of systems/units not functioning.

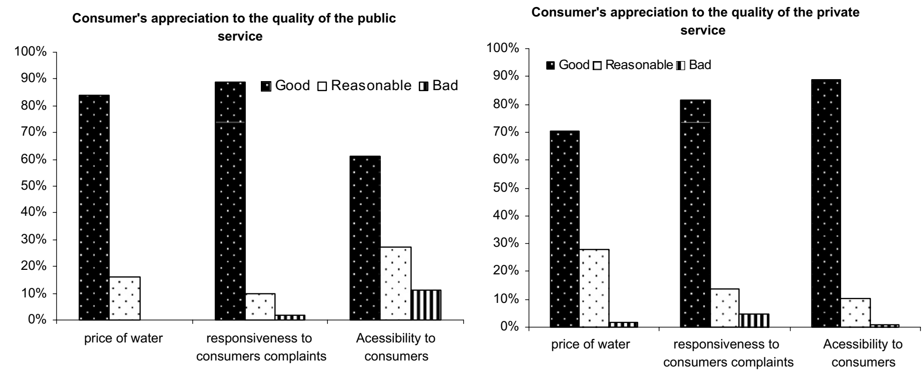

Fig. 2. Consumer's appreciation to the quality of services offered by public (left) and privately (right) owned standpipes. Service quality indicators based on water price at consumer's tap, responsiveness to consumer's complaints and accessibility to water points.

on the contrary is viewed as having limited options to deal with consumer's complaints mainly due to the lack of clarity and legal definition of CRA's role in receiving complaints and in resolving conflicts between consumers and operators/managers. This is compounded by the fact that at neighbourhood level the role of local authorities and institutions of the framework in relation to water supply is not yet clear. The result is that most of the complaints on management issues are taken directly to the standpipe attendants who often convey these to the main service provider (AdeM).

6.2. Overview of the regulatory framework

6.2.1. General framework

The regulatory tasks of CRA, FIPAG, the operator, municipal authorities and neighbourhood-based water committees are presented in Table 3. Though the lease contract for Maputo water supply is signed between FIPAG and the private operator, the regulatory responsibilities are shared between FIPAG, CRA and to a certain extent, the Municipal authorities. Regulations covering quality of services are defined by FIPAG and compliance is monitored by FIPAG and CRA.

Monitoring service quality is done via information provided by operators' progress reports and annual reports on customer complaints, performance audits, and any other information held by the operator or "lessor". The extent of CRA's regulatory intervention in the lease contract, apart from conducting periodic reviews, is limited mainly to an advisory and endorsing role principally in areas related to price regulation and consumer's protection. For price regulation, CRA receives from FIPAG proposals concerning consumer tariff levels and approves these for use by the operator. CRA additionally defines and approves alterations to the tariff structure and of consumer tariffs based on performance indicators agreed to in the lease or management contracts.

The most important area of action of CRA is consumer protection. In this respect, CRA is expected to carry out surveys on consumer opinions concerning service quality and work with consumer associations to study and analyse areas of interest. CRA has an important role in ensuring that the codes of practice for customer relations with the main service provider, in particular customer complaints procedures are reviewed, approved, and complied with and sufficiently publicised to inform consumers of their content.

6.2.2. Operational situation with respect to serving low income-groups

The management of peri-urban services in areas covered by the lease contract is based on a stand pipe management model shown in Fig. 3. The model is specifically designed for services provided through public standpipes and is based on a contractual arrangement between a standpipe attendant and the service provider. As such, the regulations are those provided indirectly via the Municipal authorities whereby, CRA, as the main regulatory body defines (in consultation with Municipality) the regulation norms but the implementation in practice is left to the responsibility of Municipal authorities (Sal-Consultores, 2005). Further delegation of authority can be done to more decentralized actors (e.g. water committees, local associations and other community based organizations-CBOs) via adequate legal instruments such as bye-laws.

At neighbourhood level, the main actors of the standpipe management model are; the water committees (WCs), the standpipe attendant and a representative of the local authorities. Contrary to other situations in the country and elsewhere in the world where

Table 3
Regulation responsibilities for which CRA, FIPAG, AdeM and community water committees are responsible

Service provider	Price regulation	Service quality regulation	Competition regulation	Consumer protection
AdeM	CRA for tariff review and approval	CRA/FIPAG, respectively, for defining and enforcing penalties and performance standards	Bidding process	CRA for approval and ensuring compliance with codes of practice
Small-scale independent providers	None/competition	Competition	None	None
Standpipe attendants	Water committee/ Municipalities	Water committee/AdeM/Municipality	Selection by water committee	Water committee, local authority, Municipality, AdeM, CRA
Water resale	None/competition	None	None	None

Source: SAL-Consultores, 2005

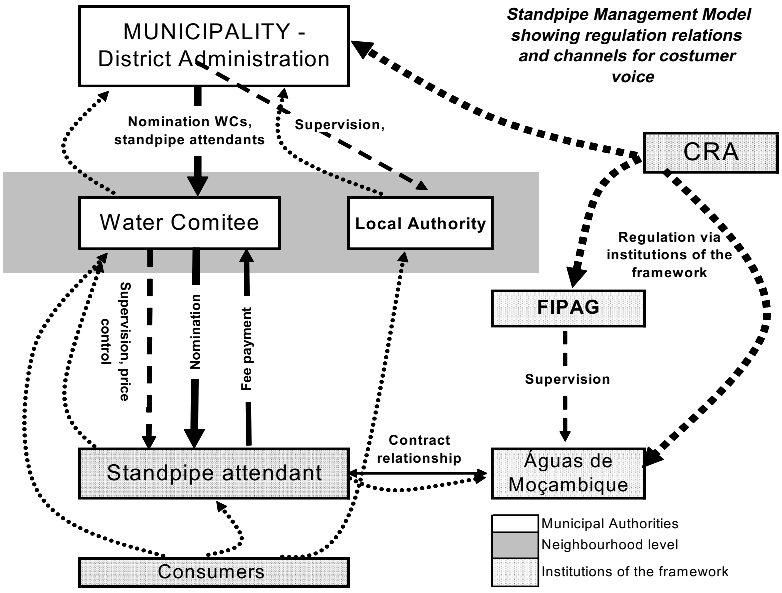

Fig. 3. The existing standpipe management model showing regulation relations and channels for costumer voice. Adapted from Sal-Consultores (2005).

WCs hold full responsibility for water supply in their neighbourhoods which includes collection of user fees and maintenance and repair of water points, in the standpipe management model WCs are only given only a supervisory role.

Analysis of the situation within the surveyed neighbourhoods reveals a number of factors that undermine the full implementation of the standpipe management model and the development of realistic action plans to expand the reach of the regulatory framework to the urban poor. These include

(1) The model is based on a contractual agreement between standpipe attendants of the public service and the main service provider, and is therefore not applicable to other forms of service provision (e.g. neighbour-to-neighbour water resellers and SSIPs). The model does not open room for the establishment of mechanisms to protect unconnected consumers with regards to water pricing and water quality.
(2) The lack of legal basis for issuing licenses to authorise other types of service providers to operate within the lease area and hence their inclusion in the standpipe management model.
(3) The lack of clarity concerning the roles of municipalities and neighbourhood authorities in the management of water services in areas covered by the framework. This can result in conflict of interest of the role they have to play as system managers and system regulators.
(4) A weakened position of WCs to perform in an unbiased fashion their regulatory tasks due to the influence of neighbourhood authorities, and frequently their dependence on revenue from standpipes.
(5) A weakened position of WCs to properly regulate standpipes attendants because they also intervene in the selection and nomination of standpipe attendants and in the management of the finances of the standpipes. As a result, the tasks of management, supervision and regulation are generally not separated.
(6) Difficulties to maintain WCs members always committed to their duties because of insufficient revenue from stand pipes water sale to cover subsidies they are entitled to. In fact, WC-members are a significant financial burden to standpipe attendants.

7. Discussion

7.1. Developmental perspectives for peri-urban water supply

In the near future, informal service providers, mainly SSIPs, are expected to continue to play a dominant role in peri-urban water supply, either because the selling of water is an important source of income for households or because the expansion of the formal network is unlikely to match the speed at which the suburbs of the city will grow.

The current physical expansion of the formal network gives priority to areas with high population densities which are also areas where the majority of informal suppliers exist. This suggests that in the near future, while many of the existing private systems will have to be decommissioned or, otherwise, linked to bulk water supply from AdeM, new market opportunities will certainly develop in areas where the formal network will still be lacking, thus maintaining the status quo with respect to the dominant role played by informal service providers in service provision to peri-urban areas.

Moreover, FIPAG's strategy to expand the network of Maputo water supply considers the development of complementary groundwater based distribution networks to serve the northern part of the city to be contracted out to private operators through management contracts within the lease area of the official provider or in a competitive manner. In the latter case, franchising models whereby the operator acts as the main franchisor and independent providers as the franchisee may also be explored given their potential to simultaneously improve service delivery and local economic development (Wall, 2006).

The potential for development of independent service providers is, therefore, highly favoured by the existing demand for services but the long term sustainability of the activity is threatened by factors such as the lack of a clear regulatory framework and the potential for future water quality problems due to over-exploitation of the aquifer system (Seureca and Hydroconseil, 2005).

While informal service providers are important as a viable alternative to improve water supply services in peri-urban areas of Maputo, the current status under which most of them operate means that they are unprotected by law and hence cannot be properly regulated. Legalization of the informal market and decentralization of certain regulatory activities to the neighbourhood level are therefore important steps in the efforts to improve service delivery to the urban poor.

7.2. Key aspects to be addressed

The first step to meet the demands for an expansion of the reach and influence of the regulatory framework to cover also the informal water market is the establishment of a licensing framework with which all participants of peri-urban water supply will be obliged to comply. In doing so the following need to be taken into consideration:

(i) The licensing framework should be inclusive of all forms of alternative service providers. This includes household water resellers, SSIPs depending on bulk water supply from the main provider and SSIPs depending on their own sources to render services provided that they operate within the Maputo lease area,
(ii) the financial and social sustainability of services provided through public standpipes should be maintained. Household water resellers and SSIPs should therefore be viewed as complementary and not competitors to the public service,
(iii) the issuing of licenses for water resale activities should follow a real demand as expressed by consumers,
(iv) to reduce the risk of inconsistent and unsustainable services due to managerial constraints, the issuing of licenses for household water resale and SSIPs should follow proven managerial capacity of potential candidates.

The issuing of licences for service providers relying on bulk water supply from AdeM shall also consider the problem of the tariff structure applied for bulk water supply. Increasing block tariffs (IBT) developed with the intent of protecting the poor, discourage wasteful consumption and provide opportunities for cross-subsidies is also known to lead to disadvantageous conditions to household relying on water resellers since, such households are forced pay higher unit prices for water than those connected to the network (Wegelin-Schuringa, 1999). In fact, third parties receiving bulk water supply from the main provider for further resale are billed for greater quantities of water at a higher unit cost than non-seller households (Whittington, 1992; Kariuti and Schwartz, 2005; SAL-Consultores, 2005).

Adoption of promotional tariffs based for instance on single-price tariff structure for monthly consumptions of say 30 m^3 billed, for instance, at a rate corresponding to the minimum scale in the tariff structure is more likely to result in affordable prices to the poor and to maintain acceptable profit margins for those practicing the activity. If done otherwise a risk exists that most licensed operators will run into financial problems that obviously will undermine the ultimate goal of servicing the poor. This way of approaching the tariff structure for third parties receiving bulk water supply has also been proposed by Whittington (1992) in his analysis of the water system in Kumasi, Ghana. In that study, Whittington (1992) concluded that the adoption of a single price tariff structure serves the poor far more equitably than the IBT structure.

Together with the establishment of a licensing framework for household water resellers and SSIPs, decentralization of certain regulation activities to the neighbourhood level is required. There should also be a reconsideration of the official view that the influence of neighbourhood authorities and, frequently, their direct benefit from standpipe funds is detrimental to the sustainability of the management of water supply services at neighbourhood level. Emphasis should be put on separating the supervision and regulatory roles currently played by WCs and neighbourhood authorities. On the other hand, the role of the neighbourhood WCs which are conceived as local level arbitration bodies to deal with issues concerning unconnected consumers should be strengthened in order to ensure that these committees operate in an unbiased and independent manner.

At neighbourhood level clarification of communication lines from the community level upwards to the institutions at higher level of the governance framework is required. Partnerships with NGOs, CBOs and the municipality are also needed to develop information channels and communication campaigns to inform consumers of their rights and options for recourse or assistance.

7.3. Proposed management and regulatory model for peri-urban water supplies

Fig. 4 shows a modified version of the standpipe management model with its scope broadened to include informal service providers. This model is proposed for management and regulation of water supply services in peri-urban areas of Maputo.

The model assumes that all service providers operating within the lease area will be connected consumers of AdeM who will benefit from bulk water supply from AdeM or, alternatively, be legally authorised to run their own water sources and piped systems within the lease area under service and quality criteria defined by the operator.

CRA will define operational and performance norms while the Municipality will assume the responsibility for issuing licenses and implementing the regulatory functions. CRA shall make use of the opportunities offered in the lease contract[2] for Maputo water supply which states that the "lessor" may authorise third parties to establish, within the lease area, a system or infrastructure to supply water to areas not already served by the formal network.

Regulation will be conducted directly via the institutions of the framework and indirectly via the Municipal authorities. For indirect regulation, the model further explores some of the opportunities offered by the institutional reforms currently in place within municipalities[3] which require Municipal authorities to have functional committees for liaison with neighbourhood representatives.

Furthermore, the model explores the opportunities offered by the framework for delegated management regarding the position and responsibilities of CRA. The proposed framework foresees the position of a CRA-officer[4] representation in municipalities where CRA is obliged to perform its regulatory tasks. The CRA-officer is therefore the key linchpin in the strategically established partnership between CRA and each municipality.

Among other aspects, the officer's responsibilities include ensuring quality service to the poorly served areas and lower income groups served by standpipes. The officer is also responsible to

[2] Revised concession contract between FIPAG and AdeM (2004) for Maputo and Matola cities.
[3] Municipal legislation concerning water (Municipal laws *n*° 2/97 and 11/97).
[4] Council for regulation of water supply – CRA (decree *n*.° 74/98, December, 1998).

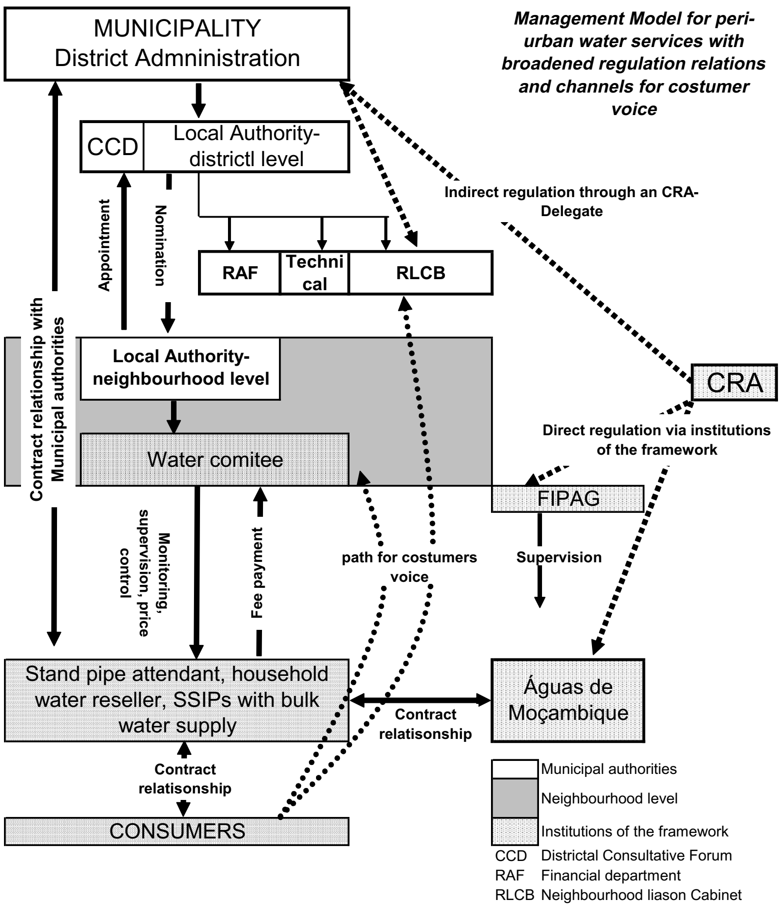

Fig. 4. Proposed model for management of peri-urban water supply with regulation and contractual relations broadened to include alternative service providers.

follow up service provision evaluations in case problems are reported, for example, by calling for meetings with representatives from the private sector, FIPAG, municipality and other relevant government offices in order to verify the reasons for the identified problems.

Since one of the key aspects of regulation is consumer protection, the WCs, the appointed member of local authorities positioned within the liaison committee to be created within the municipality organizational structure and the CRA-officer will provide the necessary platform for hearing consumer's voice and provide feedback from and to the institutions of the framework.

7.4. Sustainability aspects of the proposed model

In the proposed model, WCs are given most of the responsibility for regulation of water supply services at neighbourhood level. The long term sustainability of service regulation based on the proposed model requires that financial means are made available to secure the payment of subsidies to which WC-members are entitled and also their operations. CRA and the municipalities should therefore develop and formalize a system of payment of licenses and regulatory fees in order to secure a sustainable environment of peri-urban water supply regulation based on neighbourhood WCs.

As for today, it is unrealistic to expect that WCs will be able to perform effectively all expected duties due to their limited human capacity. Therefore, long-term support and capacity building is required to reinforce those elements that will ensure that they act independently in pursuing community interests. Issues related to the size of water committees and the possibility of reducing their composition to a single individual operating more or less like a CRA officer shall also be considered.

8. Conclusions

Service delivery to large areas of peri-urban Maputo is largely dependent on alternative informal service providers. Though located within the lease area and therefore within the official competence of the main regulatory body, the regulatory framework is restricted to services of the main service provider. Despite improvements being done to expand the formal network, in the near future, alternative service providers will continue to play an important role in service delivery in peri-urban Maputo either because the selling of water is an important source of income for households or because the expansion of the formal network is not likely to match the speed at which the suburbs of the city will grow. Legalization of informal alternative providers and decentralization of certain regulatory activities to the neighbourhood level is therefore a must.

Formalization of alternative service providers will require a definition by CRA and the municipalities of a framework for issuing licenses and for ensuring the correct implementation of regulatory functions. With CRA playing the role of normative agency, and the Municipality playing the role of the licensing authority, the water governance framework will have greater leverage to ensure compliance.

The long-term sustainability of peri-urban water services regulation based on neighbourhood water committees requires that CRA and the municipalities formalize a system of payments of license and regulatory fees to ensure the long-term functioning of institutions created for the purpose.

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V

HYDRAULIC FLOCCULATION WITH UP-FLOW ROUGHING FILTERS FOR PRE-TREATMENT OF SURFACE WATER PRIOR TO CONVENTIONAL RAPID SAND FILTRATION.

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ABSTRACT

Hydraulic flocculation has been used in many different ways in drinking water treatment for many years. In this paper, the results of experimental work using an up-flow roughing filter for hydraulic flocculation prior to treatment with conventional rapid sand filtration are presented. The objective was to evaluate optimum flocculation conditions with up-flow roughing filtration and the quality of formed suspensions with respect to their filterability. River water was used for the experiments. Turbidity removal, head losses development and velocity gradients in the roughing filter were the parameters used to evaluate the effectiveness of pilot plant processes. Overall turbidity removal in the pilot plant was between 84% and 97%. Removal efficiencies in the up-flow filter were between 18% and 73% and at the rapid sand filter between 77% and 92%. Both units operated under positive pressure. Irrespective of operational conditions established, G-values between 45-190 s^{-1} were attained in the up-flow filter. Best performances were attained when the up-flow filter was operated at the lowest filtrations velocities and alum doses. Overall, the up-flow filter performed both as particle aggregation and separation unit and the quality of formed suspensions was suitable for removal by rapid sand filtration. The method can therefore provide a rather versatile technique for pre-treatment of turbid water prior to conventional rapid sand filtration.

Keywords: water treatment; conventional treatment, roughing filtration; contact-flocculation-filtration*;*

NOMENCLATURE

d_0	filter medium grain size (m)
Eff.	efficiency (%)
G	average shear rate or velocity gradient (s^{-1})
Gt	Camp number [-]
g	gravitational constant ($m\ s^{-2}$)
K_m	filter medium constant [-]
L	effective length of filtration (m)
L_f	depth (height) of filtration layer (m)
NTU	Nephelometric turbidity units
P	power dissipated (watts)
Q	volumetric flow rate ($m^3\ s^{-1}$)
t	time (s)
T_f	mean residence time of fluid flow in filtration layer (s)
T_{res}	residual turbidity (NTU)
T_{rw}	turbidity raw water (NTU)
V	volume (m^3)
v_f	filtration velocity ($m\ h^{-1}$)
ΔH	head loss (m)
ΔH_t	head loss at time t through filtration layer length L_f (m)
ϱ	density ($kg\ m^{-3}$)
η	porosity filter bed [-]
η_t	porosity filter bet at time t [-]
μ	absolute viscosity of water ($kg\ m^{-1}\ s^{-1}$)
ν	kinematic viscosity of water ($m^2\ s^{-1}$)
θ_s	filter media grain sphericity factor [-]

INTRODUCTION

The conventional methods of removing turbidity and solids from raw water generally consist of coagulation-flocculation followed by sedimentation and rapid sand filtration. In these methods chemical coagulation is used to reduce the repulsive forces responsible for the stability of colloidal dispersions while flocculation is used to enhance particle transport and aggregation, and the eventual formation of settleable/filterable suspensions. Filtration (deep bed filtration) is used as a polishing step (Chuang & Li, 1997).

Following destabilization with chemical coagulation, the rate of particle aggregation (flocculation) is governed by the possibility and frequency of collisions between destabilized particles, the efficiency of such contacts and the existence of transport mechanisms (mixing) to get particles close to each other, collide and eventually become attached (Stumn & Morgan, 1996; Lawrence et al., 2007).

Fluid motion for flocculation can be induced either by mechanical stirring or by the energy derived from hydraulic head loss. Mechanical flocculation provides high efficiency and flexibility of operation but is relatively costly in operation and maintenance along with its dependence on the availability of supplies and skilled labour. Hydraulic mixing on the other hand is less costly, can be operated by relatively unskilled personnel but has the restriction of being less flexible to mixing intensity and to flow and water quality variations (McConnachie et al*.,* 1999; Polasek, 2007).

Hydraulic flocculation has been used in water treatment since many years and is particularly well suited for situations of limited financial capacity and skilled labour such as those prevailing in most developing countries. Methods of providing hydraulic flocculation include the use of baffled flocculation channels (Mishra & Breemen 1987; McConnachie et al., 1999), filtration through fixed granular media (McConnachie et al., 1999), and filtration through buoyant media (Vigneswaran & Ngo, 1995).

The methods relying on filtration through fixed granular media are the basis of the so-called flocculation supported filtration processes whereby, coagulant is introduced directly to the raw water inflow immediately prior to the filter inlet (Huisman, 1984; Hansen, 1988; McConnachie et al., 1999). The induced fluid shear resulting from the sinuous flow of the water through the interstices of the filter medium promotes the transport of destabilized particles from the suspension to the grain surface of the filter medium where they eventually become attached by mechanisms of sedimentation, adsorptions and interception (Mishra & Breemen, 1987; Hansen, 1988; Chuang & Li, 1997).

A common design of treatment plants using this concept is the so-called up-flow-down flow filtration. In this method, an up-flow roughing filter (also known as contact filter) is used for hydraulic flocculation prior to filtration with conventional gravity rapid sand filters (Mishra & Breemen, 1987). The primary potential advantage of up-flow/down-flow process is the reduction of capital and operational costs of water treatment which results from the elimination of settling basins and the elimination or significant reduction of dimensions of flocculation tanks (Mishra & Breemen, 1987; Vigneswaran & Ngo, 1995; Chuang & Li, 1997). Other advantages include the reduction in coagulant dosages, decreased sludge production, reduced operation and maintenance needs, and the possibility of maintaining flocculation efficiency regardless of flow and turbidity variations in the raw water.

Previous studies (McConnachie et al., 1999; Ingallinella et al., 1998; Mahvi et al., 2004) concerning the use of roughing filters for hydraulic flocculation, which emphasized the understanding of their performance as compared to conventional paddle flocculation, have demonstrated that the method can provide a rather versatile pre-treatment process capable of handling wide fluctuations in raw water turbidity and operating conditions such as coagulant doses, and filtration rates. McConnachie et al., (1999) reporting results from pilot studies conducted with an up-flow roughing filter operated with M. *oleifera* seed solutions as coagulant, concluded that the unit could treat effectively raw with turbidity as high as 50NTU with minimum head losses generated in the filter. Ingallinella et al., (1998) reporting results of similar studies but using roughing filters operated with aluminium salts as coagulant, concluded that removal efficiencies as high as 90% could be achieved even for raw water with initial turbidity as high as 340 NTU.

The work presented here follows a similar approach. Experimental work was conducted to assess the performance of a pilot plant consisting of an up-flow roughing filter used for hydraulic flocculation and a rapid sand filter used for final treatment in the removal of turbidity from river water. Turbidity removal, head losses development, and velocity gradients in the up-flow filter were the parameters used to assess the pilot plant performance. River water taken from the same source used for drinking water production at a full scale treatment plant servicing the city of Maputo was used to run the pilot plant experiments. Experimental results are therefore compared to those obtained at the full scale treatment plant.

The aim of this paper is to present the main results of the pilot plant experiments. The term 'contact filter' is used in this paper to describe the up-flow roughing filter operated as a hydraulic flocculator.

BACKGROUND

In conventional treatment, mechanical or hydraulic flocculation is used to promote the formation of ideal suspensions in respect to their settling properties or filterability. Suspensions of four different properties can be formed (Polasek & Mult, 2002):

(i) Suspensions that are completely retained in the filter bed at the expense of high head loss during filtration;

(ii) Suspension which generates low head losses but which are poorly retained in the filter bed;

(iii) Suspensions which are poorly retained and generates high head losses and,

(iv) Suspensions which are completely retained in the filter bed and generates a minimum head loss. Suspensions of this type represent the ideal suspensions, the formation of which should be aimed at.

Whether settleable of filterable suspensions are envisaged, the key principle is to induce fluid motion to cause velocity gradients enough to promote particle contacts and aggregation. Two major factors govern the efficiency of flocculation processes (Lawrence et al., 2007; Polasek & Mult, 2005): the intensity and duration of agitation. The mixing intensity is expressed in terms of mean velocity gradient G(s^{-1}), which expresses the energy input into the system. The standard expression for G is

$$G = (\boldsymbol{P}/\mu * V) \qquad (1)$$

Where ***P*** is the power input into the system, **μ** is the absolute viscosity of the water and **V**, the volume of liquid in the reactor. For the work done by the water flowing through a system where hydraulic head loss is involved, the energy input ***P*** is given by

$$P = \varrho * g * Q * \Delta H \qquad (2)$$

with ϱ, the water density, g the gravitational constant, Q the flow rate and ΔH the head loss across the system. Combining equations (1) and (2) results in:

$$G = \sqrt{\frac{\Delta H * g}{v * t}} \qquad (3)$$

Were ν is the kinematic viscosity of the water.

The relationship for G in a porous media is derived from the following equation (Polasek, & Mult, 2002; Lawrence et al., 2007):

$$G = \sqrt{\frac{\Delta H_t * g}{v * T_f * \eta_t}} = \sqrt{\frac{\Delta H_t * g * v_f}{v * L_f * \eta_t}} \qquad (4)$$

The mean residence time through the filter media is based on the model of length over velocity. Since the approach to fluid flow in a packed bed is based on an idealized capillary model based on which the packed media is regarded as a bundle of capillary tubes, to account for the tortuous path of the flow through the filter bed, the effective length of the idealized capillary tubes is related to the porosity of the filter bed and can be calculated as (Huisman, 1984; Chuang & Li, 1997):

$$L = L_f * \eta \qquad (5)$$

The symbols in the right side of Eq. 5 have the same meaning as described in Eq. 4. The mean residence time can therefore be calculated according to the following expression (Chuang & Li, 1997):

$$T_f = L/v_f = L_f * \eta_t / v_f \qquad (6)$$

The porosity of the clogged filtration layer η_t is obtained from Carman-Kozeney equation based on the head loss at specific time t. With K_m taken as 5.0, the expression for the porosity of the clogged filter layer is, according to Polasek & Mult (2002):

$$\Delta H_t = \frac{36 * K_m * v_f * v * L_f * (1-\eta_t)^2}{g * \theta_s^{\ 2} * d_0^{\ 2} * \eta_t^{\ 3}} \qquad (7)$$

MATERIALS AND METHODS

Pilot plant description

The experiments were carried out at the laboratory of Hydraulics of the Department of Civil engineer of Eduardo Mondlane University in Maputo. The pilot plant consists of two Perspex columns, 2.75 m high with an internal diameter of 90 mm. One column was used as a contact filter and the other as a rapid gravity filter. The plant arrangement is depicted in Figure 1.

The contact filter was provided with a 1.25 m filter bed, consisting of three layers of gravel placed in the following manner: bottom layer: broken gravel, 0.25 m high 19.05 mm effective size and porosity of about 55.2 %; middle layer, coarse gravel, 0.55m high, 12.5 mm effective size and porosity of about 54.6% and upper layer, 0.45 m high, fine gravel with 2.78 mm effective and porosity of about 52%. The depth of water above the gravel bed was set at 0.75 m. The column was further provided with a false floor consisting of a metal plate provided with evenly spaced 5 mm diameter holes onto which the gavel bed rested.

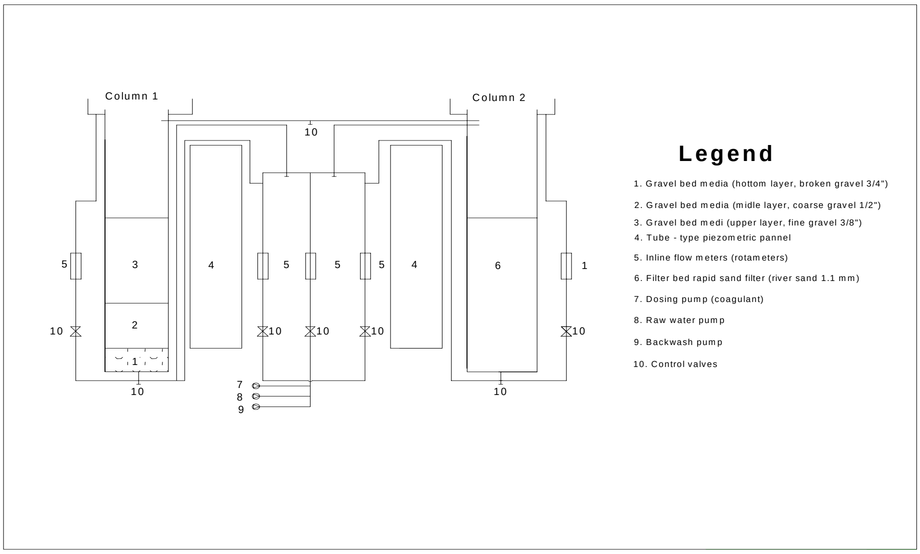

Figure 1 *Schematic diagram of the pilot plant arrangement. Column 1: multi-layer up flow roughing filter; column 2: single media gravity rapid sand filter*

The gravity rapid sand filter was provided with a 1.05 m filter bed consisting of river sand with an effective diameter of 1.10 mm, and a porosity of about 44 %. The depth of water above the filter bed was of about 0.95 m. The filtration column was also provided with a false floor consisting of a metal plate drilled with evenly spaced 1 mm diameter holes onto which the filter bed rested.

Both columns were provided with diametrically opposed connections located 100 mm apart over the height of the column used for water sampling and piezometric head losses readings. The sampling ports consisted of stainless steel tubes extended some 5 mm into the filter bed onto which flexible draw-off tubes where fixed which allowed continuous head loss measurements (via a tube-type pressure gauging) and periodic collection of water samples for turbidity measurements. Roller type clamps were provided on the flexible tubes to allow interruption of flow during periods of no measurement.

Alum prepared as 10% solution of $Al_2(SO_4)_3.18H_2O$ was used for coagulation purposes. The chemical was dosed from a reagent tank to the inlet pipe of the contact filter with the help of a positive displacement pump. Homogenization of the added chemical was achieved by turbulence generated by means of a throttled inlet valve.

All experiments were run at constant filtration velocities maintained through manual flow control attained via inline flow meters (rotameters). The contact filter was however run at filtration rates higher than those used in rapid sand filter therefore; excess water was wasted through overflow pipes located at the top of the columns.

Filtration experiments

A total of thirty four experiments were performed during a period of approximately 6 months from April to October 2007. The raw water inlet to the plant was arranged via a 600 ℓ raw water reservoir connected to a positive displacement gear type pump and a manually operated inline flow controller. The feed water to the contact filter was prepared from two scenarios of coagulant addition (1.8 mg/ℓ and 2.5 mg/ℓ) and raw water turbidity. The effluent from the contact filter constituted therefore the feed water to the rapid sand filter.

During the period of experiments, the river water turbidity was generally low (less than 10 NTU). In order to test the pilot plant also for higher values of raw water turbidity some experiments were conducted with synthetic turbidity water prepared by adding clay to the raw water until levels of turbidity larger than 15 NTU were attained. The pilot plant was further run at filtration velocities of 6.3 $m.h^{-1}$, 9.4 $m.h^{-1}$ and 12.7 $m.h^{-1}$ in the contact filter and of 3.2 $m.h^{-1}$, 6.3 $m.h^{-1}$ and 9.4 $m.h^{-1}$ in the rapid sand filter.

Jar test experiments

Standard jar tests using a Janke & Kunkel jar test apparatus were used to determine the optimum alum doses for the raw water which showed a dosage rate of 2.5 mg Al^{3+}/ℓ as the optimum dosage for maximum turbidity removal if conventional flocculation sedimentation were to be used. The pilot plant was tested also at a dosage rate of about ¾ the optimum dosage.

Sampling and analytical methods

Turbidity and head losses were the main parameters used to assess the performance of the plant. Samples of water for turbidity analysis were taken at different depths of the filter columns at regular time intervals of 45 minutes. The termination criterion was defined as turbidity breakthrough or maximum utilization of the permissible head loss, but because of logistic restrictions all experiments were interrupted after 9 to 10 hours of filtration.

Besides turbidity and head losses, temperature, pH and alkalinity were also used to analyse the raw water quality. These parameters were measured through analytical methods. Temperature, pH and alkalinity were measured prior to the initiation of the experiments. Temperature readings were taken with a standard mercury thermometer (accuracy of ± 1^0C), pH was measured with a handheld digital meter from Wagtech International Ltd., and turbidity via a Hach turbidity meter DR 2500. Alkalinity was determined using a simplified titration method described in the *Standard Methods*, (APHA, 1998, 2^{nd} ed.).

Head loss readings

Head loss readings were taken from both columns using a tube-type differential pressure gauge. Head loss readings were also taken at regular time intervals of 45 minutes.

RESULTS AND DISCUSSION

Raw water physicochemical characteristics

During the experiments the river water turbidity (T_{rw}) was between 4.0 and 9.7 NTU, the pH between 8.0 and 8.4, the total alkalinity between 115.6 and 122 mgCaCO$_3$/ℓ and the temperature between 19 and 31.5 ^{0}C. The quality of the feed water to the filter columns was slightly different, first because some experiments were run with synthetic turbidity water and secondly because the source water was stored for about a day in a closed room before experiments took place. This slightly lowered the water temperature. The main characteristics of the raw and tested water are resumed in Table 1.

Table 1
The range and average (N > 25) values of raw water quality used in this study.

Parameter	Range	Average raw water quality	Average test water quality
Turbidity (NTU)	4.0-22.9[1]	4.7	13.7
Temperature (^{0}C)	19.0-31.5	23.4	21.2
pH	8.2-8.6	8.1	8.4
Alkalinity (mg CaCO$_3$/ℓ)	115.6-122.0	118.0	122.2

[1] synthetic turbidity

Overall performance of the pilot plant

A summary of the results for turbidity removal in the pilot plant is presented in Table 2. For each filtration run, mean values of influent and effluent turbidity are presented. As can be seen from Table 2, turbidity removal in the pilot plant was generally high and reached figures between 84% and 96%. This was independent of the quality of feed water or operational conditions (coagulant dose and filtration rates) established during individual runs.

The rapid sand filter had shown also very good performances. The filtrate quality was in general below the desirable limit of 1.0 NTU of the guidelines for treated water (WHO, 2004) and terminal head losses were, in general below the maximum permissible head loss defined on the basis of the depth of supernatant water (0.95 m) above the filter bed. The rapid sand filter could therefore have been run for longer periods without running into problems of negative pressures in the filter bed.

From Table 2, it is also seen that the filtrate from the rapid sand filter had little variations during individual runs but increased slightly to a mean value of 1.9 NTU when the unit was operated at the highest filtration velocity (9.4 $m.h^{-1}$) and alum doses in the pre-treatment of 2.5 mg/ℓ (runs 19, 21, 22). However, the absolute limit of 5.0 NTU of the guidelines (WHO, 2004), was never exceeded.

The contact filter behaved slightly different. Turbidity removal in this unit was generally lower than in the rapid sand filter (18.7-73.4 %) and the filtrate turbidity experienced large variations during individual runs (see Table 2). This occurred particularly when the unit was run at a filtration rate of 9.4 $m.h^{-1}$ and alum doses in the feed water of 2.5 mg/ℓ (runs 6-12). During these runs, turbidity breakthrough could be observed frequently. Because the sampling port used to tap effluent water from the contact filter was placed some 10 cm above the top of the filter bed, the frequent increases in effluent turbidity were attributed to the effect of gravitational sedimentation that occurred in the supernatant water above the gravel bed. This had a straining effect on the surface above the gravel bed that caused the concentration of flocs to reach its highest values.

This phenomenon, which is similar to the processes taking place in sludge-blanket type clarifiers started to develop right from the beginning of the filtration runs and gradually develop into a thicker and concentrated cloud of particles positioned few centimetres above the gravel bed. In subsequent experiments, the sampling port was lowered to ±1-2 cm above the top of the gravel bed. This allowed the collection of samples not affected by differential settling, hence of lower turbidity values.

The quality of feed water to subsequent rapid sand filtration was in general better than that laving the gravel bed of the contact filter (Figure 2). This suggests that apart from a partial removal of particles in the gravel bed, additional removal of particles took place in the supernatant water above the gravel bed.

Proportion wise the gravel bed performed better than the supernatant layer in the removal of aggregates formed during flocculation. However, for low values of raw water turbidity the effect of gravitational settling had a higher impact in the removal of aggregates particularly when alum dosages of 2.5 mg/ℓ, were applied. This resulted probably from the presence of a large amount of aluminium hydroxide aggregates which were thin enough to flow through the relatively coarse media of the gravel bed, but large and in concentration enough to rapidly develop a sludge blanket in the supernatant above the gravel bed.

The influence of the contact filter to the quality of suspensions transferred to the rapid sand filter appears therefore to have been that of particle aggregation and separation whereby, the gravel bed contributed mostly with particle aggregation and partial separation through mechanisms of particle bridging, and the supernatant water with partial separation through mechanisms of gravitational settling.

Table 2
Summary results of turbidity removal in the pilot plant, contact filter and rapid sand filter.

Run test	Raw water turbidity (NTU)	Filtration velocity[2] ($m.h^{-1}$)	Alum dose (mg/ℓ)	Average turbidity (NTU) contact filter			Average turbidity (NTU) rapid sand filter			Run duration (hr.)	Maximum terminal head loss rapid sand filter (mm)	Overall removal efficiency pilot plant (%)
				Feed water	Filtrate	Removal efficiency (%)	Feed water	Filtrate	Removal efficiency (%)			
33 ÷ 34	16.6-22.9	6.3/3.2	1.8	16.6-17.4	6.1-7.0	57.7-73.4	5.3-6.2	0.7-0.8	87	9	269	96
28 ÷32	13.0-20.9	6.3/3.2	2.5	9.8-17.3	3.7-6.3	63.7-73.2	3.0-4.8	0.7-0.8	78-85	9	204	94-97
1÷ 4	5.7-9.7[1]	9.4/6.3	1.8	8.8-10.7	4.6-5.5	21.4-36.1	3.9-5.4	0.6-0.8	78-87	9-15[4]	937	88-92
15÷18	15.1-16.6	9.4/6.3	1.8	14.3-19.5	5.5-13.5	18.7-65.4	4.0-6.0	0.5-0.7	84-87	6.75-9	272	95-97
6÷9	4.0-4.2[1]	9.4/6.3	2.5	9.0-12.8	5.0-9.7	-[3]	3.7-5.8	0.5-0.7	86-91	9	320	84-89
10÷13	15.4-20.4	9.4/6.3	2.5	19.7-24.8	12.1-20.6	-[3]	6.3-7.0	0.5-0.7	91-92	8.25-9	308	96-97
14, 23÷27	14.7-18.9	12.7/9.4	1.8	12.2-17.3	4.1-9.6	34.6-73.2	4.0-5.9	0.6-1.0	82-87	7.5-9	583	95-96
19÷21	15.0-17.1	12.7/9.4	2.5	14.2-19.8	8.1-12.1	29.4-41.6	7.0-10.4	1.1-1.9	77-84	8.25-9	670	88-93

[1] Tests run with natural turbidity
[2] 6.3/3.2; filtration velocity in the contact filter and rapid sand filter respectively
[3] turbidity breakthrough in the contact filter
[4] filtration experiments 1 and 2 run continuously without filter cleaning totalling 15 hours of continuous operation

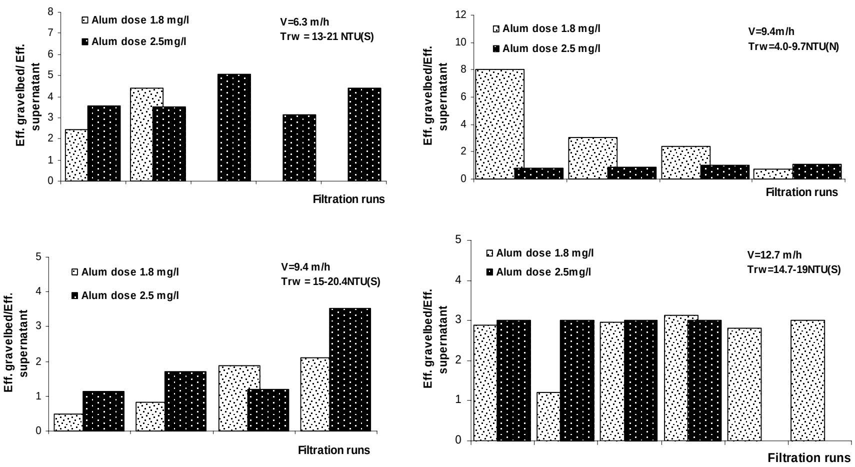

Figure 2 *Relative contribution of gravel bed and supernatant layer in turbidity removal in the contact filter: (N) = natural turbidity; (S) = synthetic turbidity; Eff. = efficiency (%. Information about filtration velocities and alum dosages applied is also shown.*

The performance of the pilot plant was also compared to treatment results obtained at the full scale treatment plant of Maputo water supply (Figure 3). In this plant, conventional coagulation/flocculation sedimentation is used for pre-treatment and rapid sand filtration is used for final treatment. The plant is operated with two parallel production lines. Sludge-blanket clarifiers operated at surface hydraulic loads of 1.6 $m.h^{-1}$ (**line 1**) and 2.4 $m.h^{-1}$ (**line 2**) are used for flocculation/sedimentation purposes. The rapid sand filters are operated at filtration rates of 5.2 $m.h^{-1}$ and 7.1 $m.h^{-1}$ respectively. The data used for the comparison was taken from the operator's database and comprehend results of filtrate turbidity when the pilot plant was operated under similar conditions of raw water turbidity and alum doses used for pre-treatment. As seen in Figure 3, the pilot plant had removal efficiencies comparable to that obtained at the full scale plant and produced a filtrate of better quality.

Performance of the contact filter

Head losses and filtration runs

In Figure 4, the development of pressure drop in the gravel bed of the contact filter is illustrated. The pressure drop increased linearly along with filtration rates and alum dosages which clearly indicate a time-dependent reduction of the gravel bed porosity and an increase in the inter-pore shear stress due to accumulation of particles.

The pressure drop in the contact filter was in all cases of a few centimetres and well below the maximum allowed head loss calculated from the available depth of supernatant water.

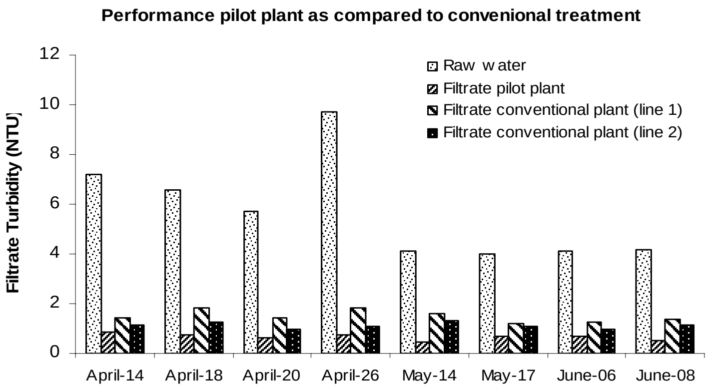

Figure 3 *Performance pilot plant as compared to conventional treatment with coagulation flocculation, sedimentation and rapid sand filtration.*

In up-flow filters, maximum head loss is limited by the danger of uplifting the filtering material which occurs when the soil pressure equals the water pressure (Huisman, 1984). The filtering material properties such as porosity, specific gravity and thickness of the filter bed set the limits. Because the contact filter was provided with a top layer made up of the finest gravel the maximum head loss was limited by the properties of this layer and was calculated as 0.35 m based on the following properties of the filtering material: porosity 52 %; specific density 2.6 kg.m^{-3}; and thickness of about 0.45 m. Accordingly, the contact filter operated under positive pressure during all experiments which means that it could have been run for longer periods and also with a much lower (almost 50%) depth of supernatant water.

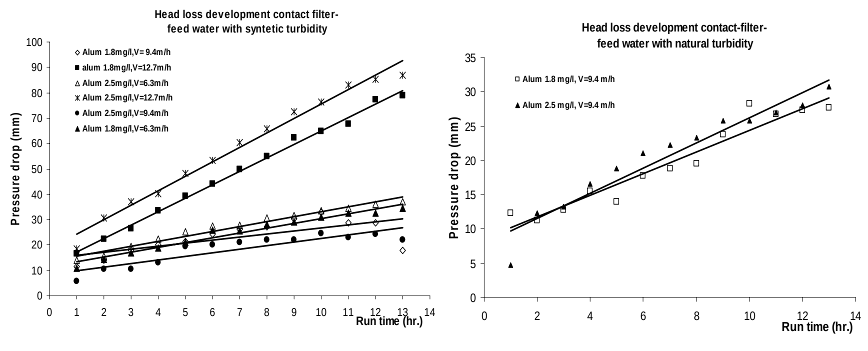

Figure 4 *Time dependent behaviour of head losses (mm) in the contact-filter for experimentsrun with syntetic turbidity (left) and natural turbidity (right). Average raw water turbidity wasin the range 4.0-9.5 NTU. Syntetic feed water had a turbidity of about 20 NTU.*

Analysis of head losses developed when the unit was run at a filtration velocity of 12.7 $m.h^{-1}$ indicates that much higher values were observed and also that the head losses developed more rapidly. This resulted from high fluid shear stress established when the unit was run at such high filtration velocities which may also have promoted high rates of particle aggregation within the gravel bed, eventually associated with high rates of solids retention. This observation coincides with findings from other researchers (Chuang & Li 1997; Ingallinella et al., 1998 and McConnachie et al., 1998) who concluded, that shear stress affects flocculation processes and head loss development. As noted by the same authors, associated with increases in the rate of particle aggregation within porous media, an increase in head losses is expected. The magnitude depends on the induced shear stress but also on the rate of solids deposition/detachment.

The head losses at a filtration velocity of 12.7 $m.h^{-1}$ developed much faster than at 6.3 $m.h^{-1}$ or 9.4 $m.h^{-1}$ but, in contrast, the head losses at 9.4 $m.h^{-1}$ developed slightly lower than at 6.3 $m.h^{-1}$. This unexpected behaviour was attributed to a possible predominance of thin aggregates that could flow easily through the relatively coarse media of the filter bed, thus limiting the rate of solids deposition and consequently the increase in head losses. This also explains the high filtrate turbidity observed with the plant operated at 9.4 $m.h^{-1}$ as compared to operation of the plant at 6.3 $m.h^{-1}$, and similar conditions of raw water turbidity and alum doses. In fact, since flocculation in porous media is predominantly under ortokinetic conditions (Mishra & Breemen, 1987; Chuang & Li, 1997), the conditions with lower filtration velocities and longer retention times resulted in better conditions for the formation of larger aggregates and for increased rate of solids deposition that explains the relatively large head losses in the gravel media.

The quality of feed water with respect to its turbidity seems to have had little influence on head loss development in the contact filter. The differences shown in Figure 4 seem to have resulted from differences in filtration velocities and coagulant dosages applied rather than from differences in the feed water quality. This suggests that irrespective of the feed water quality, the flocculation conditions created within the gravel media resulted in suspensions of relatively similar properties with respect to their filterability. In fact, as noted by Chuang & Li (1997) and Declan et al. (2008) the value of turbidity in suspensions formed during flocculation in porous media is qualitatively proportional to the solids content but inverse of the particle size which means that the filterability of corresponding suspensions is independent of the raw water turbidity.

Turbidity removal

Figure 5 illustrates time-dependent values of filtrate turbidity from the contact filter. To account for variations in raw water turbidity, readings are plotted on the basis of the ratio between the filtrate turbidity and that of the feed water. As shown in Figure 5, the filtrate turbidity decreased slightly during the initial stages of filtration, but soon after that it started deteriorate and to show variations occasionally associated to turbidity breakthrough with filtration time.

The initial decrease in filtrate turbidity was probably due the high solid retention capacity of the clean gravel bed which led to a rapid accumulation of particles during the initial stages of filtration. During subsequent stages, the increase in solids being retained in the gravel bed accompanied by reduction in gravel bed porosity, led to an eventual increase in the inter-pore shear stress which may have promoted particle detachment and turbidity breakthrough with the filtrate. As shown in Figure 5, the highest variations in filtrate turbidity occurred more frequently when the unit was operated at 9.4 and

12.7 m.h^{-1}, suggesting that shear stress affects not only flocculation processes as noted previously, but also particle retention and detachment in porous media.

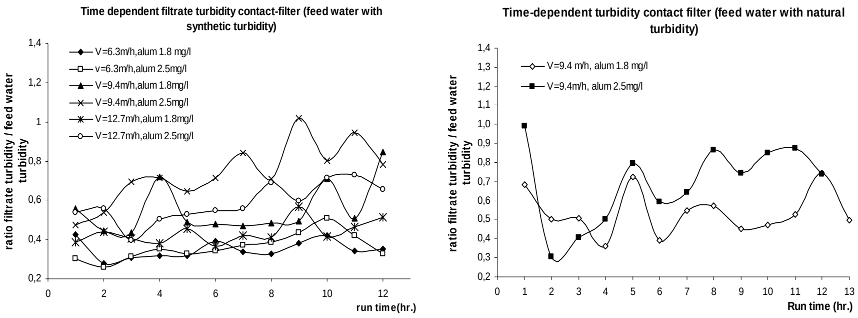

Figure 5 *Time dependent behaviour of filtrate turbidity (NTU) in the contact-filter, for experimentsrun with syntetic turbidity (left) and natural turbidity (right). Average raw water turbidity wasin the range 4.0-9.5 NTU. Syntetic feed water had a turbidity of about 20 NTU. Information about filtration velocities and alum dosages applied is also shown.*

As noted from Figure 5, most efficient treatment was obtained when the unit was operated at a filtration velocity of 6.3 m.h^{-1} and alum doses of 1.8 mg/ℓ. The low performances observed when the contact filter was run at 9.4 m.h^{-1} were associated to poor flocculation conditions resulting from the combined effect of moderate to low agitation intensities and short residence times which, eventually resulted in the formation of aggregates that could flow easily through the relatively coarse media of the contact filter and where not strong enough to withstand the induced fluid shear stresses. Changing the filtration velocity to 12.7 m.h^{-1} resulted in much higher agitation intensities and inter-pore shear stress. This eventually resulted in the formation of thin but much stronger aggregates (despite the short residence times) which, because of their smaller size were mostly retained through mechanism of particle bridging and attachment on the surface of the gravel media but were strong enough to withstand high induced shear stresses.

According to results shown in Figure 5, changing the alum dose from 1.8 mg/ℓ to 2.5 mg/ℓ seems to have had impacted the performance of the contact filter particularly when high filtration velocities were used. As shown in Figure 5, the poorest performances were mostly observed when using alum doses of 2.5 mg/ℓ. Possible reasons for this could be that the aggregates formed when using high alum doses are generally large in size but weak in strength, suggesting that they removal in porous media is largely affected by mechanisms of particle breakage and detachment from the filter grains. Chuang & Li (1997) and Ingallinella et al. (1998) have also reported that flocs formed with high alum doses are generally large in size but weak in strength, thus unable to withstand high inter-pore shear stresses.

Velocity gradients

Velocity gradients (G) and Gt-values calculated from to Eqs. 4 and 7 and the head losses generated across the two upper layers of the contact filter are presented in Table 3. As can be seen, velocity gradients (G s^{-1}) were between 45-120 s^{-1} in the middle layer of the contact filter and between 88 –

190 s^{-1} in the upper layer. The head loss across the bottom layer of the contact filter was in all cases negligible therefore, corresponding G and Gt-values are not presented.

Table 3
Initial and terminal values of G (s^{-1}) and Gt generated at the two uppermost layers of the contact filter.

Filtration velocity ($m.h^{-1}$)	Reference layer	Initial G and G*t* values				Terminal G and G*t* values			
		Alum dose (mg/ℓ)				Alum dose (mg/ℓ)			
		1.8	**2.5**	**1.8**	**2.5**	**1.8**	**2.5**	**1.8**	**2.5**
		Velocity gradients G (s^{-1}) and G*t* values							
6.3	Middle	25	27	967	1006	45	56	1482	1706
	Upper	46	44	1819	1779	88	87	2971	2951
9.4	Middle	41	34	991	906	60	56	1352	1245
	Upper	40	31	1198	997	96	88	2353	1312
12.7	Middle	55	58	1015	1042	110	123	1659	1784
	Upper	64	79	1407	1631	168	192	2867	3128

References from text books (Stumn & Morgan 1996; Lawrence et al., 2007) recommend that mixing for optimum flocculation should generally be of low intensity, with G-values preferably between 20 and 70 s^{-1} and Gt-values between 2 x 10^4 and 2 x 10^5. Below these limits no proper flocculation occurs while, increasing G and *t* values beyond these limits results generally in floc breakage and turbidity breakthrough in subsequent treatment processes. The principle behind these limits is associated to the belief that low agitation intensity favours the formation of large and readily setleable aggregates and that, beyond a certain limit of agitation, floc breakage occurs. However, recent studies from Polasek (2007), arguing the principles behind the so-called customary flocculation suggests that, while slow mixing promotes the formation of large and readily settleable flocs the end result is in fact the formation of flocs that are large in size, but of low density, very fragile and with a tendency to fragment. As noted by the same author, this type of flocs is suitable neither for sedimentation nor for rapid sand filtration. In contrast if the flocculation is performed under high agitation intensities over the entire process until optimum flocculation is reached, the formed flocs are generally more compact and dense. Accordingly, depending on the resultant size of aggregates required, flocculation can take place under high agitation intensities with *G*-values preferably above 50 s^{-1} or low agitation intensities with G-values below 50 s^{-1}.

The high and low agitation intensities involve the same transport mechanism and differ only by the agitation intensity (*G*-value). When micro-flocs are to be formed, high agitation intensities (*G*-values between 100 and 500 S^{-1} are usually preferred while, for large and readily settleable macro-flocs, low agitation (G-values between 5 and 20 S^{-1} is generally preferred. The agitation intensity together with the duration of the process determines the final result. Flocs formed under low agitation and long retention times are generally larger and denser than those formed with high agitation and short contact times (Polasek & Mult, 2005; Polasek, 2007).

From the results shown in Table 3, it is seen that G-values in the contact filter ranged from conditions of moderate to high agitation intensities. Our interpretation to this is that this has favoured the formation of aggregates of different characteristics concerning the size and density but which were removed by sedimentation and attachment onto the surface of the gravel grains. From the results of Table 3, it also appears that best flocculation conditions were attained when the contact filter was run at a filtration rate of 6.3 $m.h^{-1}$. However, due to the small size of the filtering material used in the upper layer of the contact filter, relatively large G-values were established ($G \approx$ 87-96 s^{-1}) in this layer which, eventually contributed to particle breakage. This was independent of the alum dose or filtration velocity applied.

At a filtration velocity of 6.3 $m.h^{-1}$, the combined effect of lower agitation intensities and longer retention times resulted eventually in the formation of large aggregates hence, the highest removal efficiencies attained when compared to other filtration velocities. When the contact filter was operated at 9.4 $m.h^{-1}$ relatively large aggregates were eventually formed but now, the effect of high induced inter-pore shear stress and short retention times may have caused formed aggregates to break and be detached from the grains, thus leading to the highest concentrations of particles in the filtrate. Increasing the filtration velocity to 12.7 $m.h^{-1}$ resulted in agitation intensities that favoured the formation of thin but dense aggregates (Polasek, 2007) which were poorly retained in the gravel media thus, the lowest performances observed at this filtration velocity. The effect of particle breakage and detachment from the gravel grains when the contact filter was run at 9.4 $m.h^{-1}$ and alum doses of 2.5 mg/ℓ seems, however, to have impacted the filtrate quality more seriously.

Performance of the rapid sand filter

Time-dependent filtrate turbidity and head losses from the rapid sand filter are presented in Figure 6. As can be seen the filtrate from the rapid sand filter was always of acceptable quality (T_{res} > 1 NTU). The terminal head losses was , in all cases, below the maximum permissible head loss of 1.35 m, calculated from Carman-Kozeney equation (Huisman, 1984), based on the available depth of supernatant water (0.95 m) and a clogged layer of about 30% the filter bed thickness.

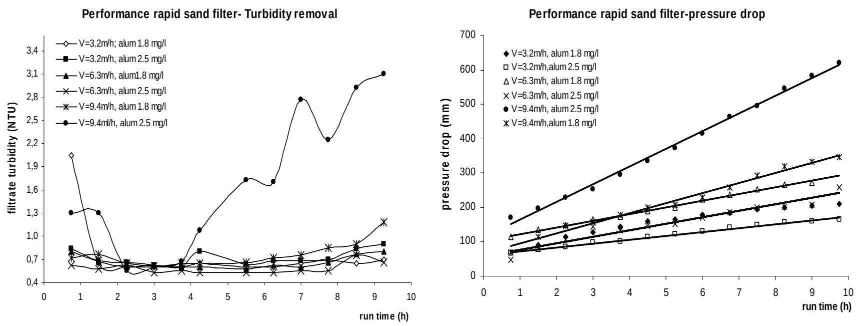

Figure 6 *Performance of the rapid sand filter. Time dependent values of filtrate turbidity (left) and head loss development (right) are presented. Also information on filtration velocities in the rapid sand filter and alum dosages applied in the contact filter is presented.*

Exception is made for the filtration runs done with feed water prepared from filtration velocity of 9.4 $m.h^{-1}$ and alum doses of 2.5 mg/ℓ in the contact filter, during which the filtrate from the rapid sand filter started deteriorate 3 to 4 h, after the beginning of the experiments. This resulted eventually from the high load of fine particles being transferred from the contact filter which, at the corresponding scenario of operation, had the poorest performances as is can be seen from Figure 6.

From analysis of results of head loss development in the rapid sand filter it is seen that the unit always operated under positive pressure which means that longer filtration runs could have been established without running into problems of negative pressures. This also indicates that turbidity breakthrough was the factor determining the duration of filtration runs particularly when filtration velocities higher than 6.3 $m.h^{-1}$ were chosen to run the plant.

From the results shown in Figure 6, it is also seen that head losses in the rapid sand filter developed more or less linearly. This indicates that impurities penetrated uniformly through the depth of the filter bed. This also indicates that irrespective of the performance of the contact filter, the quality of suspensions transferred to the rapid sand filter were generally of similar properties in respect to their filterability. As shown in Figure 6, irrespective of the conditions of operation of the contact filter, the resulting suspensions were in general completely retained in the rapid sand filter and generated minimum head losses. As noted by Polasek (2002) suspensions of this type represent the ideal suspensions, the formation of which should be aimed at during pre-treatment for filtration with conventional rapid sand filters. The optimum combination seems to have been that of operating the contact filter and the rapid sand filter at filtration velocities of about 6.3 $m.h^{-1}$ or lower and alum doses of 1.8 mg/ℓ.

CONCLUSIONS

Results of this study supports claims made by other researchers that the use of roughing filters for hydraulic flocculation provides a viable and flexible alternative for improved turbidity and solids removal by conventional rapid sand filtration.

In this study, the quality of suspensions produced at the contact filter was generally suitable for removal by subsequent rapid sand filtration independent of the operational conditions established (feed water turbidity, filtration velocities and alum doses) at individual filtration runs. Best performances were, however, attained when the contact filter was operated at a filtration velocity of 6.3 $m.h^{-1}$ and alum doses of about ¾ of the optimum dosage obtained from jar test experiments.

Overall performance of the pilot plant performance was in general above 84%. The filtrate from the rapid sand filter was of acceptable quality and consistently below 1 NTU and the units operated under positive pressure during the entire duration of the experiments. Longer than the 9 to 10 hours duration of filtration could therefore, have been established.

Velocity gradients in the contact filter were within limits of moderate to high agitation intensities and were, in general within limits recommended in literature for effective flocculation. Formed aggregates were suitable for removal by mechanisms of sedimentation and particle bridging in the gravel media of the contact filter and dense enough to be removed by mechanisms of sedimentation in the supernatant water above the gravel bed. The remaining flocs could be effectively removed through subsequent filtration.

The contact filter used in this study was designed with the filter bed arranged with the gravel size decreasing in the direction of the flow. This impacted significantly the unit's performance since floc breakage and detachment occurred mainly at the upper and finer layer of gravel bed. Further research is therefore required concerning the optimum composition and arrangement of the gravel media. The use of a relatively large supernatant layer above the gravel bed helped however; reduce significantly particle (turbidity) concentration in the filtrate.

Because filtration velocities used to run the contact filter, were much larger than those recommended for plain roughing filters (Smet & Visscher, 1990; Sánches et al., 2006) large investment and operational costs can be attained by using up-flow roughing filters as hydraulic flocculators. Saves can also be attained in relation to costs with chemical reagents. For optimum operation of up-flow roughing filters used for hydraulic flocculation, the units should however be designed for G-values between 40 and 90 S^{-1} and filtration velocities lower that 6.0 to 7.0 $m.h^{-1}$.

ACKNOWLEDGEMENT

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VI

VATTEN 64: 137–150. Lund 2008

ASSESSMENT OF DRINKING WATER TREATMENT USING *MORINGA OLEIFERA* NATURAL COAGULANT

Värdering av *Moringa Oleifera* för fällning av dricksvatten

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Abstract

In this study, a comparison between *Moringa Oleifera* MO and aluminium sulphate was conducted for coagulation of turbide water using jar test. The optimum coagulant dosage was investigated for different levels of turbidity, and the impact on treated water properties monitored. Use of MO together with direct filtration was also investigated.

Coagulation with aluminium sulphate led to more efficient treatment but MO could also produce water of acceptable quality. On the other hand, treatment with MO did not change the chemistry of treated water and was more efficient for high initial turbidities. Highest removal efficiencies were obtained when MO was extracted using tap water as compared to distilled water and oil extraction. Coagulation with aluminium, followed by direct filtration led also to better performances but in both cases the treated water met WHO water guidelines. Prolonged sedimentation helped improve MO treatment efficiency for low initial turbidities.

MO is found to be a sustainable solution for coagulation in drinking water treatment. The possibilities of using MO together with direct filtration are good and provide a realistic alternative to conventional methods for small to medium size water supplies.

Key words – Moringa Oleifera, drinking water treatment, aluminium sulphate

Sammanfattning

Att minska turbiditeten är en central del vid beredning av dricksvatten från ytvatten, och sker oftast med koagulering och flockning, där polyvalenta metallsalter som aluminiumsulfat används. Studier indikerar att metallsalterna kan ersättas av ett naturligt koaguleringsmedel från det tropiska och subtropiska trädet *Moringa Oleifera* (MO). Dess frön har använts i småskalig dricksvattenberedning i Indien och Sudan i flera generationer. Koaguleringsmedlet är troligtvis ett eller flera protein som agerar likt katjoniska polyelektrolyter.

I denna studie har en jämförelse mellan MO och aluminiumsulfat genomförts i bägareförsök. Den optimala dosen av koaguleringsmedlet undersöktes för olika turbiditetsnivåer, och effekten på vattenkemin kontrollerades. Användning av MO tillsammans med direktfiltrering, samt möjligheterna att använda MO i vattenverk undersöktes också.

Den mest effektiva beredningen för alla turbiditetsnivåer återfanns vid användning av aluminiumsulfat. MO påverkade inte de fysikaliska egenskaperna och var mest effektiv för högre grumlighetsnivåer i råvattnet. Extraktionsmetod för MO-extrakt påverkade inte det beredda vattnets kemiska egenskaper. En förlängd sedimentationstid tillsammans med MO förbättrade reningen och försöket med direktfiltrering var lyckat. Rening med MO och direktfiltrering resulterade i mer effektiv rening än med aluminumsulfat i kombination med direktfiltrering. MO kan anses vara ett förnyelsebart och billigt koaguleringsmedel vid dricksvattenberedning. För bästa resultat bör MO användas tillsammans med direktfiltrering. Om vattenberedningen sker i liten skala är MO ett realistiskt alternativ till konventionella metoder, förutsatt att plantager etableras i tillräcklig omfattning.

1. Introduction

When surface water is used for drinking water production, turbidity removal is an essential part of the treatment process. It is generally achieved using coagulation with metal salts followed by aggregation of particles through flocculation and separation through sedimentation and filtration. Aluminium (e.g. $Al_2(SO_4)_3 \cdot 18H_2O$) and iron salts are mostly used as coagulant reagents. Recent studies (Ngabigengesere & Narasiah, 1998; Katayon et al., 2005) have indicated a number of serious drawbacks linked to the use of aluminium salts such as Alzheimer's disease associated with high aluminium residuals in treated water, excessive sludge production during water treatment and considerable changes in water chemistry due to reactions with the OH^- and alkalinity of water. In addition, the use of alum salts is inappropriate in some developing countries because of the high costs of imported chemicals and low availability of chemical coagulants (Schultz and Okun quoted by Katayon et al., 2005).

A number of studies have pointed out that the introduction of natural coagulants as a substitute for metal salts may ease the problems associated with chemical coagulants (Katayon et al., 2005). Using natural coagulants such as the seeds from the *Moringa Oleifera* MO tree instead of aluminium salts might give advantages, such as smaller costs of water production, less sludge production and ready availability of reagents. There are also some disadvantages such as increased concentration of nutrients and COD in the treated water due to the organic nature of this type of coagulants.

In this paper, the potential of using *Moringa Oleifera* as an alternative to aluminium sulphate for drinking water treatment in Mozambique is evaluated, its limits analyzed and the optimal use and dosage assessed. Standard Jar-test experiments performed with solutions prepared from aluminium and MO seeds were used to compare the efficiency in turbidity removal and the impacts on the water chemistry. Filtration experiments in a coarse to fine media filter were used to compare filtration efficiency of suspensions prepared through coagulation with Al and MO.

The more specific objectives for this study were to:

- Evaluate the optimum dosage of MO for different levels of turbidity, and its removal efficiency at each level.
- Compare the treatment efficiency of MO to that of aluminium sulphate, regarding both treatment efficiency and influence on water quality and characteristics.
- Find a suitable method of preparation for the MO coagulant, and establish a procedure manual for the preparation, use and dosage of MO in order to use it for drinking water treatment.
- Investigate the possibilities of using MO on an industrial scale, regarding availability and reliability of production and distribution.

2. Background

In nature, water is always contaminated with various types of pollutants. Some of them are harmless and sometimes even desired in water whereas others need to be removed before the water can be used for drinking purposes. Physical properties such as turbidity, colour and solids impact the aesthetic appearance of water and its acceptability for consumption. The microbiological quality has a large effect on the taste and smell of water and can sometimes be a large problem in river water. Eutrophication of surface water sources due to nutrients disposal (e.g., from agriculture and wastewater) and physical properties such as pH and temperature, favours algae and bacteria growth and can cause health risks. Bacteria in water can cause illnesses such as typhoid (Salmonella typhus), cholera (Vibrio cholera), and diarrhoea (Giardia lamblia). Faecal coliforms and streptococci indicate contamination from human or animal faeces.

The aim of drinking water treatment is to remove impurities and bacteria in order to meet the quality guidelines for drinking water (WHO, 2004). The design of water treatment process varies between different treatment plants. It also depends on the quality of raw water and the requirements regarding treated water quality. Surface water generally requires more treatment than ground water, since the former is more easily contaminated.

Conventional treatment is mostly used for surface water treatment. It generally involves chemical coagulation followed by flocculation, sedimentation, filtration and disinfection. Common coagulants are aluminium sulphate, ferric chloride, polyaluminium chlorides and synthetic polymers. All of these coagulants have in common the ability of producing positively charged ions when dissolved in water, which can contribute to charge neutralization (Degrémont, 1979; Hammer et al., 2004). The dosage of coagulant depends on several parameters such as type and concentration of contaminants, pH and temperature. The optimal dosage for specific water is defined as the dosage which gives the lowest turbidity in the treated water. Dosage beyond the optimum point will, apart from obvious disadvantages such as increased aluminium/iron content in the treated water, also lead to an increase in turbidity.

If the sedimentation step is omitted, and the flocculated water is led directly to filtration, the process is called direct filtration (McConnachie et al., 1999). A pre-requisite is that the raw water is of seasonally uniform quality with turbidity routinely less than 5NTU. If

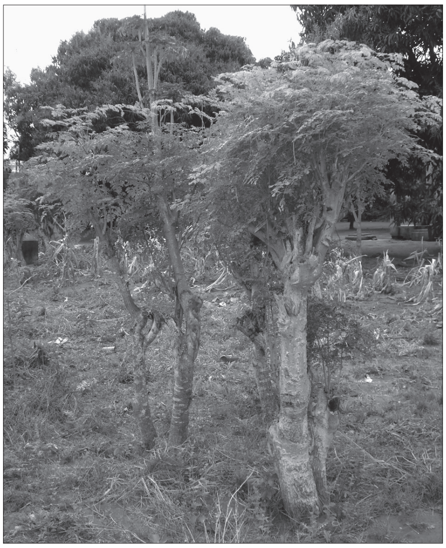

Figure 1. *The Moringa Oleifera tree (left) and dried and shelled seed (above).* *© M. Begman.*

otherwise, pre-treatment is required. This includes pre-treatment with contact basins, flocculation chambers and roughing filters with flocculation processes. The latter can be designed either with a horizontal flow direction (HRF), up-flow (UPRF) or down-flow (DFRF). In all cases, coarse media of decreasing size in the direction of flow is used (Sánchez et al., 2006).

If flocculated water is filtered first in an up-flow roughing filter prior to its final treatment in rapid sand filters the processes is called up-flow-down flow filtration. This method is claimed by researchers (Ingallinela et al., 1998; McConnachie et al., 1999) as capable of producing treated water of quality equal to that of standard coagulation-flocculation followed by sedimentation and filtration, but, at lower investment and operational costs. Surface water treatment can also be treated by slow sand filtration-SSF. In this case, pre-treatment is always needed because SSF cannot handle high turbidity values of the raw water. For pre-treatment roughing filters are mostly used.

When conventional coagulation is used, chemical coagulants such as iron and alum salts are needed but, natural coagulants such as the seeds from the *Moringa Oleifera* tree can also be used. Traditionally, surface water has been treated with the help of herbs as natural coagulants for centuries in India. Ripe seeds of *Strychnos potatorum*, wiry roots of the rhizome of *Vetiveria zizanioides*, seed coats of *Elettaria cardamomum* and leaves from *Phyllantus emblica* have all been recorded to be used for water treatment in past and present times (Sadgir, 2007).

The *Moringa Oleifera* (MO) tree (Figure 1) is a perennial plant that grows very fast, with flowers and fruits appearing within 12 months after planting. The tree grows up to a height of 5–12 meters with branches extending between 30 and 120 cm (Lilliehöök, 2005).

With its origin in India and Pakistan the *Moringa Oleifera* plant was brought to the Africa continent and Sudan, in particularly during the colonial era for ornamental purposes. The natural coagulant found in MO is present in 6 of the 14 species of MO growing in Africa, Madagascar, India and Arabia. Knowledge that MO seeds can purify water is not new; the seeds have been used for water treatment for generations in countries like India and Sudan. For example, the women of Sudan have used the seeds from the MO three for water treatment since the beginning of the 20th century (Schwartz, 2000) through a technique that comprehended the swirling of seeds in cloth bags with water for a few minutes and let it settle for an hour.

Scientifically, the coagulation properties of MO seeds were first confirmed by the German scientist Samia Al azharia Jahn (Schwartz, 2000). The active agent is believed to be a protein, but the exact form of the protein is not yet known. Recent research has identified proteins of sizes ranging from 3 to 60 kDa, all possessing coagulating ability. The protein(s) act as a cationic polyelectrolyte, which attaches to the soluble particles and creates bindings between them, leading to large flocs in the water. Stirring and mixing accelerates the electrostatic flocculation, and the flocs condense the contaminants (Göttsch, 1992).

Extraction of the active agents can be done in several ways but most techniques follow the pattern: dried seeds grained or powdered with or without shells; powder mixed with a small amount of water and, the solution is stirred and filtrated (Ndabigengesere & Narasiah, 1998; Muyibi & Alfugara, 2003; Ghebremichael et al., 2005). The filtered solution is called "crude extract" or "stock solution" and can be used for water treatment without further preparation. Several studies have shown that the use of salt water and/or tap water is more efficient as solvent than e.g. distilled water. Okuda et al. (1999) showed for example that the crude coagulation capacity was up to 7.4 times higher when the active agents were extracted with salty water as compared to distilled water. The reason for this is assumed to be that the coagulating protein is more soluble in water with high concentration of ions (Okuda et al., 2001a). Other studies have focused on purifying the active agent as much as possible and producing a stable protein powder without excessive organic matter. Two separate studies show that the active agents could be purified from the extract using a cation exchanger column, leading to reduced levels of COD in the treated water (Ghebremichael, 2005; Ndabigengesere & Narasiah, 1998). However, a more low-tech way of reducing the organic content is to extract the oil from the seeds with an organic solvent (Ghebremichael, 2005).

The treatment efficiency is dependent on the turbidity of the raw water, as revealed in previous studies by Katayon et al., (2004). MO has also been proven to produce significantly less sludge than aluminium sulphate, which is an advantage especially if the sludge is to be dewatered or treated in some other way before disposal (Ndabigengesere et al., 1994). MO can also be used in combination with other coagulation salts, such as aluminium sulphate (Sutherland et al., 1994).

The coagulation and flocculation ability of the seeds has been investigated in several different studies around the world (Ndabigengesere & Narasiah 1998; Bengtsson, 2003; Muyibi & Alfugara, 2003). These studies have shown that neither pH nor alkalinity nor conductivity was affected during water treatment, but an increase in COD, nitrate and orthophosphate has been observed. Other studies have indicated that treatment with MO is dependent on the pH of the raw water were optimum is above neutral (Okuda et al., 2001b) whereas others say it is independent of raw water pH (Schwartz, 2000).

Storage of seeds and extract and its influence on coagulation properties has also been investigated by Katayon (Katayon et al., 2004; Katayon et al., 2006). Seeds were dried, crushed and stored in different containers and at different temperatures. These studies concluded that the temperature and type of container did not have a significant effect on treatment efficiency but that the duration of storage did. The seeds stored for one month showed better treatment efficiency than seeds stored for longer periods (three to five months). Storage was also found to influence the coagulation properties of the extract and to decrease treatment efficiency with increased duration (Katayon et al., 2006). The study does not discuss the reason for this but it could be assumed that it is due to microbial degradation of the proteins. The study also concluded that the duration of storage of extract should not exceed 24 hours as degradation of active agents is assumed to occur within this time. As noted by Katayon et al., (2004) extract solutions stored for longer than 2 to 3 days had between 73.6 % and 92.3 % lower turbidity removals as compared to fresh solutions.

3. Methodos

3.1. Jar tests experiments

The equipment used for jar test experiments was a Janke & Kunkel jar test apparatus with 5 beakers of 2.0 l capacity each (Figure 2). Each beaker was filled with 1.5 l of test water with identical turbidity. Different volumes of coagulant reagent were added to 4 of the five beakers with the last used as the blank sample. Mixing of the coagulant with water was provided by flash mixing during approximately 3 minutes with propellers set at 120 rpm followed by slow mixing at 40 rpm during approximately 17 minutes. Then the propellers were stopped and the content of the jars left to settle for approximately 30 minutes. After sedimentation, samples were taken for water quality determination.

For each coagulant and turbidity level, three identical jar tests were performed in order to obtain statistically reliable results. However, some of the parameters were only measured during one of these three jar tests and/or

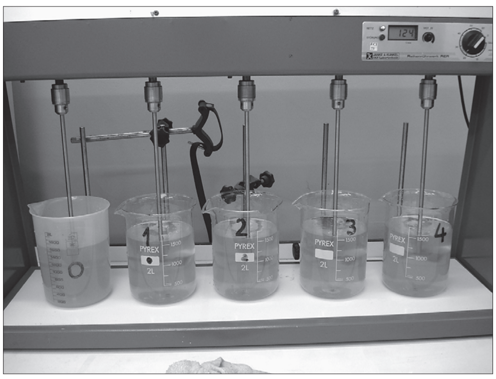

Figure 2. *Jar test equipment.*

in the jar with the optimal dosage, due to restricted time and economic means. If the optimal dosage was not found in the jar test, a new test with new dosage was carried out until the optimum was found.

3.2. Preparation of extract and test water

Dried and shelled MO seeds were obtained from IIAM (Agronomic research institute of Mocambique) via the Department of Chemical Engineering at Faculty of Engineering of Eduardo Mondlane University. The shells were ground to a fine powder using a mortar. The powder was then weighed and dissolved in distilled water to make a 50 g/l solution. The solution was stirred for 30 minutes using a magnetic stirrer, and finally filtrated through a Whatman filter no. 40. A fresh solution was prepared every day in order to avoid ageing effects. Two alternative preparation methods were used, one involving oil extraction from the seeds and the other using tap water instead of distilled water. To extract the oil, the ground seeds were first dissolved in cyclo-hexane, stirred for 30 minutes and then filtrated through a Whatman filter no. 40. The remaining solids in the filter ("press cake") were then dissolved in water, stirred and filtrated according to procedures described previously. The tap water preparation process was identical to the standard method, but with tap water as solvent instead.

Raw water from Umbeluzi river was used for all experiments. During the period of the experiments (September and October) the river water had low values of natural turbidity, therefore most experiments were performed with synthetic turbidity water. This was done by using ordinary clay, obtained from the Geology department of Eduardo Mondlane University. The clay was first ground with a mortar to make the particles as fine as possible, and then added to the water in sufficient amounts to produce the desired levels of turbidity.

3.3. Measurements and analytical methods

Turbidity, suspended solids, temperature, pH, EC (electrical conductivity), total dissolved solids (TDS), alkalinity, COD (chemical oxygen demand), and bacteria were the water quality parameters measured. Turbidity was measured using a 2100P turbidimeter from Hach. In order to increase reliability of measurements, water turbidity readings were tripled and that of settled water, doubled and the average values used as reference values.

Temperature was measured with a standard mercury thermometer (accuracy of ± 1°C) held for 1 minute in the water, and the observed values rounded to the nearest integer. pH and EC were measured using handheld digital meters from Wagtech International Ltd, and TDS was measured using an handheld digital meter TDScan Low-range (0–1990 ppm) from Eutech Instruments. All readings were taken with the digital meters held for 1 minute (or until a stable value was reached) in the sample water.

Alkalinity was measured with a simplified titration described in *Standard Methods* (1998). The samples were titrated with hydrochloric acid using an 725 Dosimat automatic titration equipment from Metrohm. The added volume of acid was noted at the colour changes (from pink to transparent for phenolphthalein and from blue to yellow for the mixed indicator).

COD and bacteriological analyses were conducted by the laboratory at the Ministry of Health in Maputo. For the bacteriological analysis, sterilized bottles were provided by the laboratory. During sampling, the bottles were filled completely to minimise the dissolution of air oxygen, and thereby aerobic degradation, in the samples. Microbial parameters analysed were total coliforms, *faecal* coliforms and *faecal* streptococci.

Suspended solids were also determined using standard procedures described in the *Standard Methods* (1998). The concentration of suspended solids was measured for 6 different levels of turbidity and a calibration curve plot, in order to provide a relationship between turbidity and suspended solids. This was done since the measurement of suspended solids is very time demanding, up to 2 days for each set of measurements, whereas turbidity is measured in less than a minute. With the calibration curve, turbidity values could be easily converted into approximate values of suspended solids concentrations.

3.4. Filtration experiments

Filtration experiments were performed in a pilot scale plant consisting of an up-flow roughing filter followed by single media gravity rapid sand filter. Pre-coagulated water with MO was used as test water. The test water turbidity was of about 30 NTU, and the dosage of MO was set to 50 mg/l. The flow rate was set to 60 l/h through the roughing filter, and 40 l/h through the single media filter. Turbidity and head loss measurements were used to assess the pilot plant performance. Turbidity readings were taken as described previously and head loss readings were taken using a tube-type differential pressure gauge. Turbidity and head loss readings were taken at regular time intervals of 30 minutes.

3.5. Sources of error

The procedure of the experiments was done consistently through the whole study to minimise the sources of error. Possible errors in the study might arise from the lack of calibration for the equipment used in measuring

Table 1. *The range and average quality of the raw water used in this study.*

Parameter	Raw water		Test water[1]	
	Range (historical)	Range (study period)	Range	Average
Turbidity (NTU)	3.8–173	4.6–6.8	5.2–100	36.1
Temperature (°C)	21–27	22–24	21–25	23
pH	6.7–8.7	8.2–8.4	8.2–8.6	8.4
Alkalinity (mg $CaCO_3$/l)	140–160	209.6–211.1	206.4–215.2	212
TDS (mg/l)	370–410	480–490	480–500	490
EC.(µS/cm)	550–630	710–720	700–730	720

[1] synthetic turbidity water

turbidity, pH, conductivity and TDS. The dosage for the flocculation was not done at exactly the same time in each jar, leading to time differences for the mixing of the water. However, the main factors affecting the jar test results are believed to be differences in preparation of raw water and MO extract.

COD and bacteriological analyses were done at the Health ministry. The time passing between filling the bottles with samples and the actual analysis affects the result since organic matter can be degraded if stored too long. The large variation of the results (and large deviation from the values recorded in 2003 and 2006 in the Umbeluzi River) suggests that either the sampling method or analysis procedure were not satisfactory, and that the results are not reliable.

4. Results and discussion

4.1. Raw and test water physio-chemical characteristics

The general physio-chemical quality (range and average values) of the raw and test water is presented in Table 1. All variables were measured at the laboratory, prior to each jar tests experiment.

As shown in Table 1, the raw water quality did not vary much during the period of experiments but analysis of historical data suggests that large variation can be expected, particularly in relation to turbidity. It is also seen from Table 1, that measured values of conductivity, total dissolved solids and alkalinity were generally higher than given values from previous measurements. Since raw water samples were collected from a location just downstream the waterworks where aluminium sulphate and lime are used for coagulation and neutralization the observed increase in raw water pH and alkalinity could be explained by the disposal of sludge and waste water containing $Al(OH)_3$ from the plant. Also, downstream the waterworks, the river is sometimes affected by saltwater intrusion because of its proximity to the river mouth. This may explain the observed increases in EC and TDS. The sludge from the waterworks also contains large amount of ions, which also explains the increase in conductivity and TDS.

Most coagulants perform less effective when the water temperature is low or when the raw water pH and alkalinity experiences fluctuations. Unlike turbidity, these parameters show very small variations during the year. Therefore during preparation of test water these parameters were not changed but the raw water turbidity was. A calibration curve for converting turbidity readings into approximate levels of suspended solids was also developed and is presented in Figure 3.

Accordingly, an almost linear relationship between turbidity and suspended solids is observed particularly when the raw water turbidity is high (>10NTU). The reason for the bad correlation at low turbidity values is probably due to the fact that the total mass of suspended solids in a 200 ml sample when the turbidity is low (less than 10NTU) is very small, around 1 mg, which is dif-

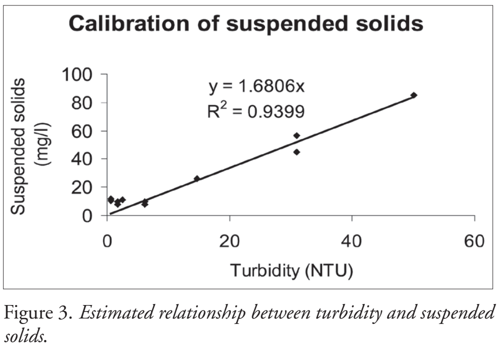

Figure 3. *Estimated relationship between turbidity and suspended solids.*

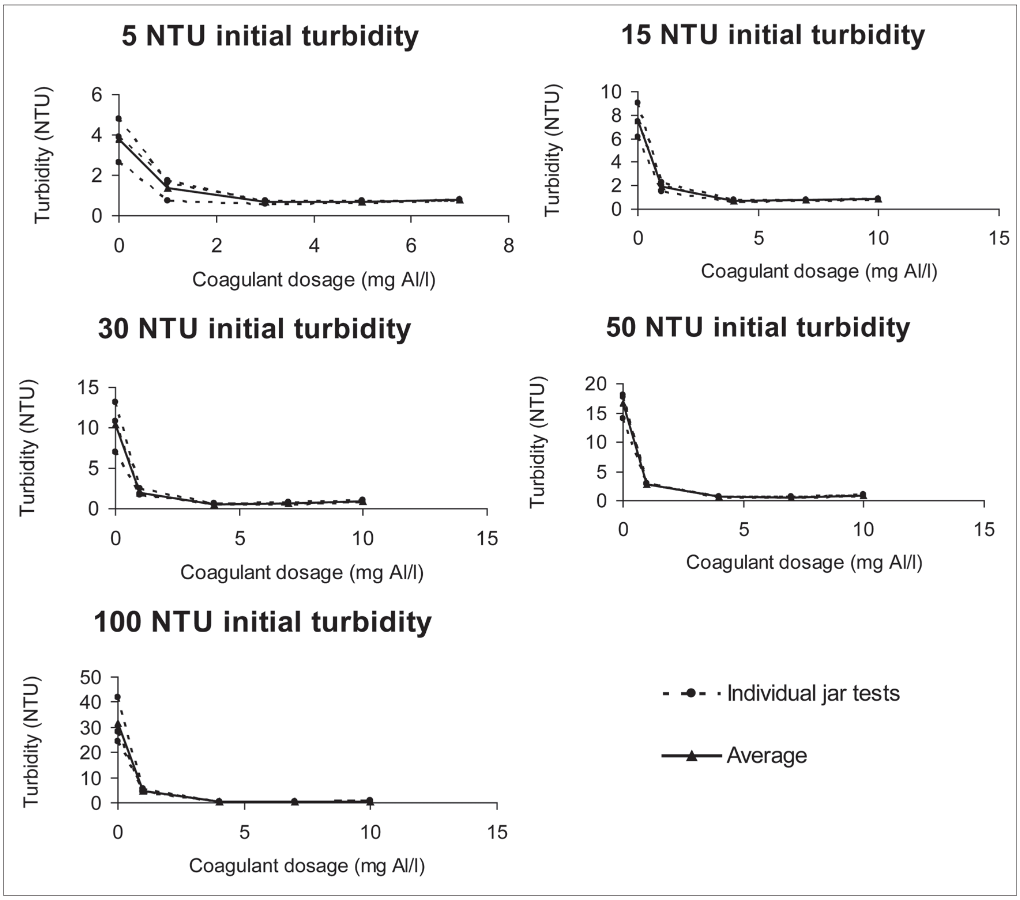

Figure 4. *Turbidity removal for raw water turbidity values in the range 5 to 100 NTU and aluminium sulphate as coagulant.*

ficult to measure with acceptable precision. A larger sample volume would increase the precision, but the measurements were already time consuming and unfortunately there was not enough time to filter larger volumes.

4.2. Optimum dosage and turbidity removal

4.2.1. Coagulation-flocculation with Alum sulphate

Results of optimum conditions of turbidity removal using Aluminium sulphate as the main reagent are presented in Figure 4 from which it is seen that coagulation with aluminium sulphate resulted generally in high removal efficiencies, irrespective of the raw water turbidity. The optimum dosage in all cases was between 3.0 and 4.0 mg Al^{3+}/l, corresponding to approximately 0.1g/l of solid $Al_2(SO_4)_3 \cdot 18H_20$. The coagulant formed large flocs that settled in 30 minutes and lead to a stable outgoing turbidity of 0.5–0.6 at the optimum dosage. The relative standard deviation for outgoing turbidity at optimum was 10–20 %, corresponding to approximately 0.1 NTU.

4.2.2. Coagulation with Moringa Oleifera

Coagulation-flocculation with *Moringa Oleifera* was done with reagent solutions extracted in three different ways. *Moringa Oleifera* extracts prepared with distilled water, was chosen as the standard preparation method to comply with earlier studies and also to reduce the number of unknown parameters in the tests. The other methods considered solutions prepared with distilled

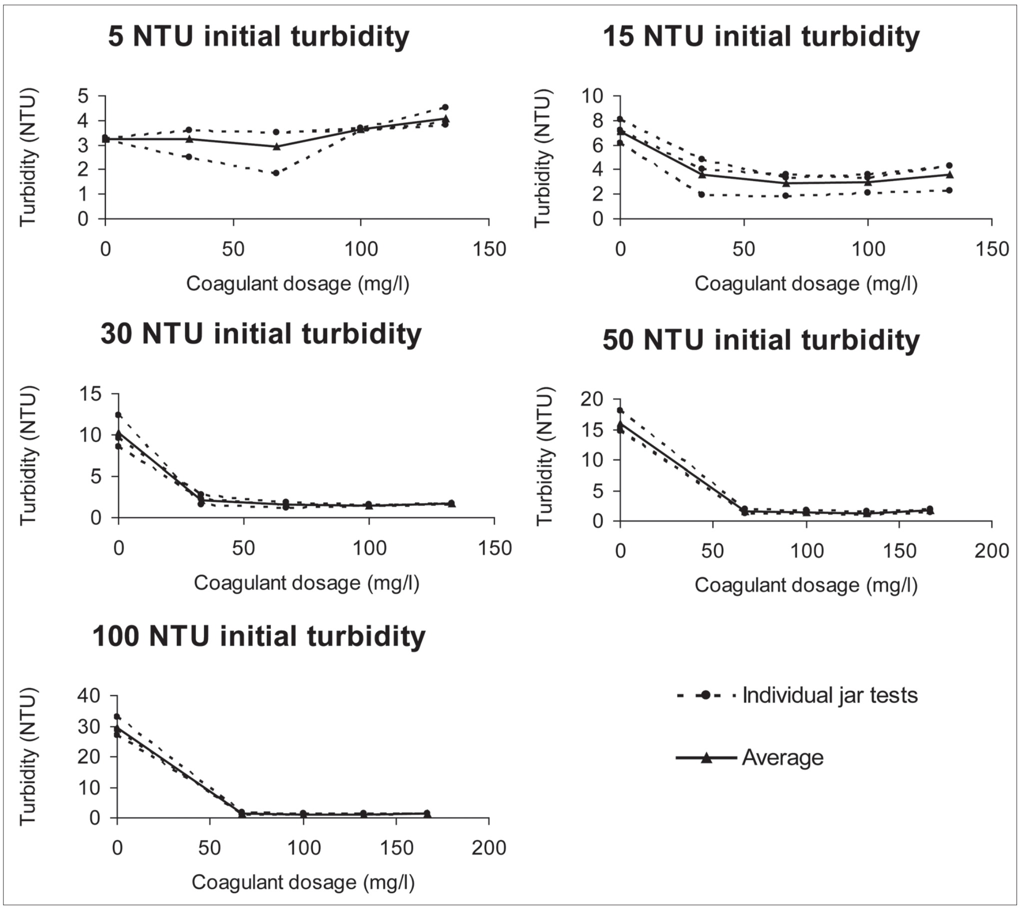

Figure 5. *Optimum dosage and turbidity removal at different levels of raw water turbidity using Moringa Oleifera extract prepared according to standard method.*

water and oil extraction and solutions prepared with tap water.

The results of optimum dosages and turbidity removal with MO prepared with the standard procedure are presented in Figures 5. The coagulant dosage indicates the mass of seeds that were used initially per litres of raw water, not the actual concentration of MO extract in the water. This difference is important to note since, a lot of the seed mass was separated during the filtration step when preparing the extract. The exact concentration of MO in the crude extract is therefore unknown.

For medium and high turbidity levels in the raw water (30–100 NTU), the optimum dosage was found between 40 and 70 mg/l and to more or less increase with increasing raw water turbidity. The outgoing turbidity at the optimum dosage ranged between 1–1.5 NTU. For low values of initial turbidity (5–15 NTU), the process was less effective since an optimum reagent dosage was generally not attained and the lowest outgoing turbidity remained around 3 NTU. Coagulation with MO extracted with distilled water resulted therefore in high removal efficiencies when the raw water turbidity was high but in poor efficiencies when the raw water had low values of turbidity (5 and 15 NTU). In the latter case, the treated water still had high amounts of suspended flocs even after 30 minutes of sedimentation. This indicates that flocs formed were either too small or not dense enough to settle within the 30 min-

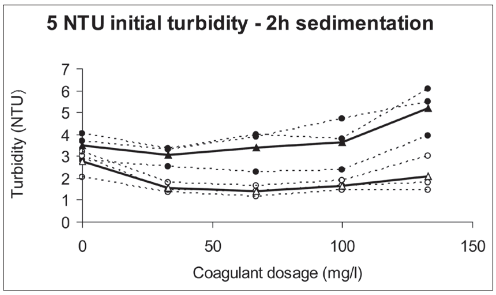

Figure 6. *Residual turbidity after 30 minutes (filled dots) and 2 h of sedimentation (empty dots) respectively, using an initial turbidity of approximately 5 NTU. Dotted lines show individual jar test results while solid lines indicate the average values.*

utes chosen for sedimentation. Complementary test with longer sedimentation time (Figure 6) confirmed this observation and resulted in significantly better removal efficiencies.

The prolonged sedimentation time resulted in an average outgoing turbidity of 1.4 NTU, a significant improvement. The extra sedimentation time indicates that coagulation of low turbid waters, using MO can only be effective if accompanied with long sedimentation times, which, in practical terms means large sedimentation basins.

The results of coagulation with MO prepared with distilled water and oil extraction as well as with tap water are presented in Figure 7. Two different levels of turbidity were tested; 15 NTU and 50 NTU. Preparation with oil extraction was conducted as recommended in previous studies (Ghebremichael, 2005; Narasiah & Ndabigengesere, 1998) which indicate that oil extraction helps prevent increases in COD of treated water. Preparation with tap water was used because it is more convenient for large scale production.

When solutions prepared with oil extraction were used, the average outgoing turbidity was 2.4 NTU, for 15 NTU initial turbidity and 1.9 NTU for 50 NTU initial turbidity at optimum dosage rates of 67 mg/l and 100 mg/l respectively (Figure 7, top). The relative standard deviation at optimum was 10 % for the low turbidity level, and over 50 % for the high turbidity. The latter was due to one jar test with much higher results than the other. The reason for this different result may have been bad coagulation properties of the seeds used to prepare the crude extract that day. The same extract was used in one of the jar tests at 15 NTU, and gave higher outgoing turbidities in that test as well, although not as extremely high as in the 50 NTU jar test. Another possibility is that the extraction process with cyclo-hexane removed

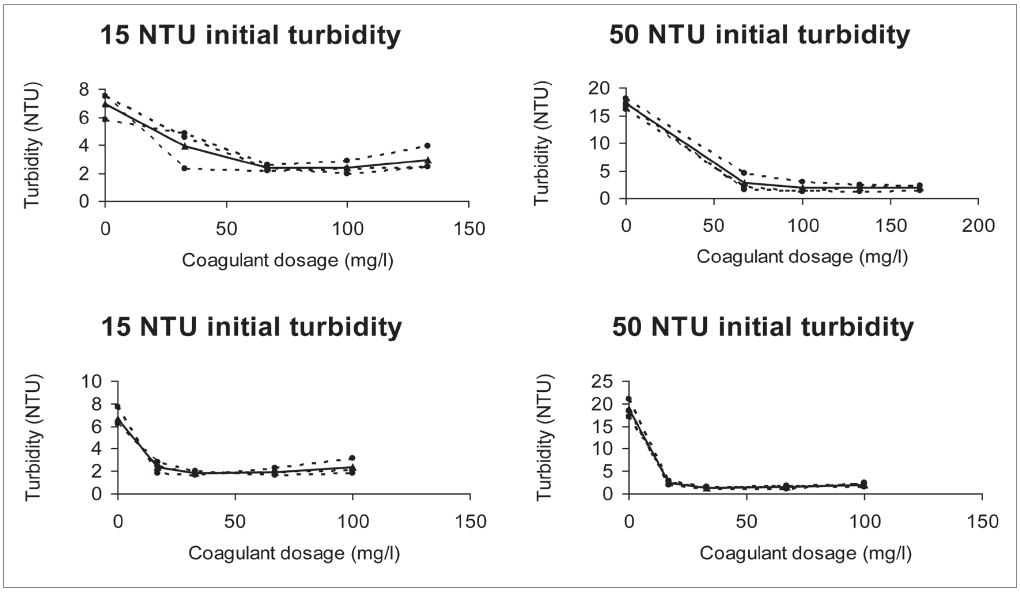

Figure 7. *Turbidity removal efficiency with Moringa Oleifera prepared with oil extraction (top) and tap water (bottom) and initial turbidity in the raw water of 15 and 50 NTU.*

some of the coagulating agents as well, thus lowering the coagulating ability of the crude extract.

When solutions prepared with tap water were used, the average outgoing turbidity was of 1.85 and 1.3 NTU for low and medium turbidity respectively (Figure 7, bottom). Optimum dosage rates were of about 33 mg/l for water with low (15 NTU) and medium (50 NTU) initial turbidity. The standard deviation at optimum was 10–15 %.

4.3. Effect on water quality

The effect of the reagents on some of the treated water quality, notably the water pH, alkalinity and EC is illustrated in Figure 8. As can be seen, coagulation with aluminium sulphate (Figure 8, right) led to a decrease in the water pH and alkalinity and to an increase in conductivity. These trends were confirmed statistically at 0.05 level of significance. These effects are also well known from previous studies (kemira, 2003) and use of aluminium sulphate throughout the world.

At an initial turbidity level of 15 NTU, the results from the COD analyses indicated a modest increase in COD from 1.6 to 2.4 mg O2/l. Bacterial contamination expressed as the number of total coliforms per 100 ml were reduced from >100 to 24. *Faecal* coliforms on contrary, increased from <1 to 18 counts per 100 ml while *faecal* streptococci were found to be >100 counts per 100 ml both before and after treatment. At 50 NTU initial turbidity, the COD decreased from 12.8 to 9.6

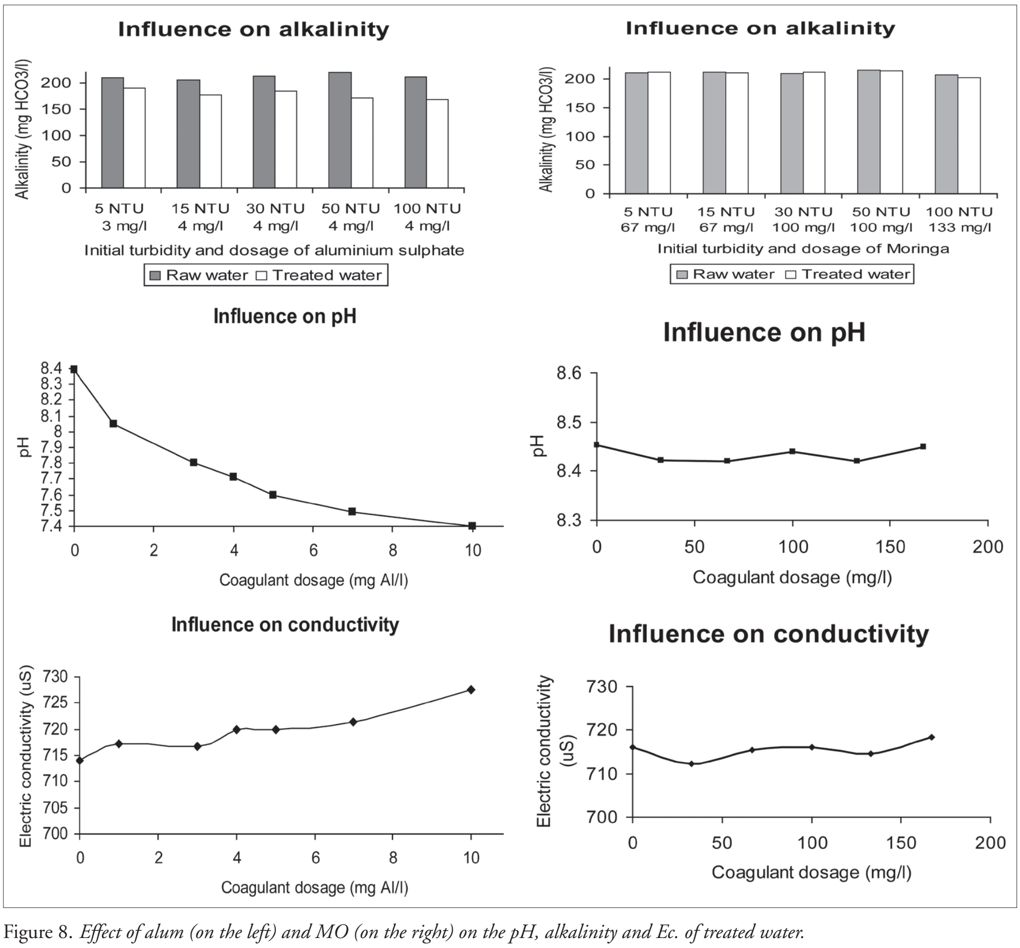

Figure 8. *Effect of alum (on the left) and MO (on the right) on the pH, alkalinity and Ec. of treated water.*

mgO_2/l. Altogether, these results are too few and too diverse to be reliable, and no conclusions can be drawn regarding the effect of aluminium sulphate on COD and on the microbial quality of treated water.

Treatment with *Moringa Oleifera* had no effect on the pH, alkalinity or conductivity of the treated water. The impact on COD levels and on the bacteriological quality of water was evaluated for initial turbidity of 15 and 50 NTU but the results are inconsistent. At 15 NTU, the COD results indicated an increase from 2 mg O2/l to 2.4 mg O2/l after sedimentation at optimum dosage, whereas at 50 NTU the result was a decrease from 40 mg O2/l to 7 mg O2/l. Considering the yearly variations of COD in the Umbeluzi river in 2006, where no value exceeding 9 mg O2/l was reported the high COD levels found in the samples indicates either that readings were misleading or that external sources of organic pollution (e.g. from the clay used to make artificial turbidity) existed.

The COD results from the 15 NTU turbidity level supports however the findings from previous studies (Ghebremichael, 2005; Ndabigengesere & Narasiah, 1998) that the use of MO leads generally to an increase in COD levels in the treated water. As for the bacteriological quality, the count in raw water resulted in >100 counts per 100 ml for all three bacteria types at 15 NTU turbidity level, and <1 counts per 100 ml for the equivalent at 50 NTU turbidity level. The amount of faecal streptococci were reduced to 3 after treatment at 15 NTU turbidity level, and the faecal coliforms were increased to 7 after treatment at 50 NTU turbidity level.

4.4. Comparison between coagulants and preparation methods

4.4.1. Optimum dosage and turbidity removal

Figure 9 provides a comparison of turbidity residuals after treatment at optimum dosage rates for all scenarios of raw water turbidity and coagulant reagent used. As can be seen, the efficiency of MO compared to aluminium sulphate was significantly lower in the jar tests. Aluminium sulphate led to outgoing turbidities of 0.5–0.7 NTU regardless of the initial turbidity, whereas MO never produced water with turbidity below 1 NTU. Treatment with aluminium sulphate resulted generally in a more stable effluent quality as is indicated by the relative standard deviation which was never more than 20 %, corresponding to 0.1 NTU.

In contrast, treatment with MO resulted in an effluent quality that varied considerably with the relative standard deviation reaching as high as 50 %. The relative standard deviation at optimum for high initial turbidity levels was however lower for MO than for aluminium sulphate. This could have resulted from the fact that, when using Al for coagulation of water with high initial turbidity, high amounts of reagent are required which may lead to the formation aluminium hydroxide precipitates that increase turbidity levels in the effluent.

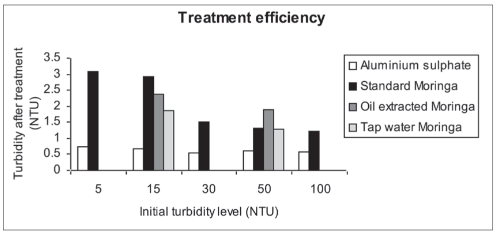

Figure 9. *Comparison of optimum dosage for different coagulants.*

Overall, MO prepared with tap water was more efficient than the other two methods of preparation. The outgoing turbidity was lower, especially at high initial turbidity level, and the dosage needed to reach optimum was significantly lower. Coagulation with MO resulted also in smaller and lighter flocs than with aluminium sulphate. Small and light flocs settle more slowly therefore, they remain longer in the supernatant water. This explains the higher outgoing turbidity levels when MO was used as coagulant. Treatment efficiencies with MO could be improved by prolonging the sedimentation time to about 2 hours. While at laboratory scale these improvements are possible, at large scale operation, increasing duration of sedimentation means that larger investment is needed for construction of larger sedimentation basins. This is generally not feasible. Also, large scale operations flocs that do not settle during sedimentation will continue to subsequent stages of water treatment (filtration), where they may be removed at the expenses of higher costs of operation of filters.

4.4.2. Influence on water quality and characteristics

The effect of adding coagulation reagents on water quality and characteristics is illustrated in Figure 9. As can be seen MO coagulant shows a major advantage compared to aluminium sulphate; it does not affect neither pH and alkalinity nor conductivity and TDS, whereas aluminium sulphate influences all of these. No specific conclusion can be drawn regarding the effect on COD level and bacteriological quality of the water, due to lack of analysis results and large uncertainties in the existing results.

4.5. Filterability of formed suspensions

In large scale operations, the removal of particles from suspensions formed during coagulation-flocculation is

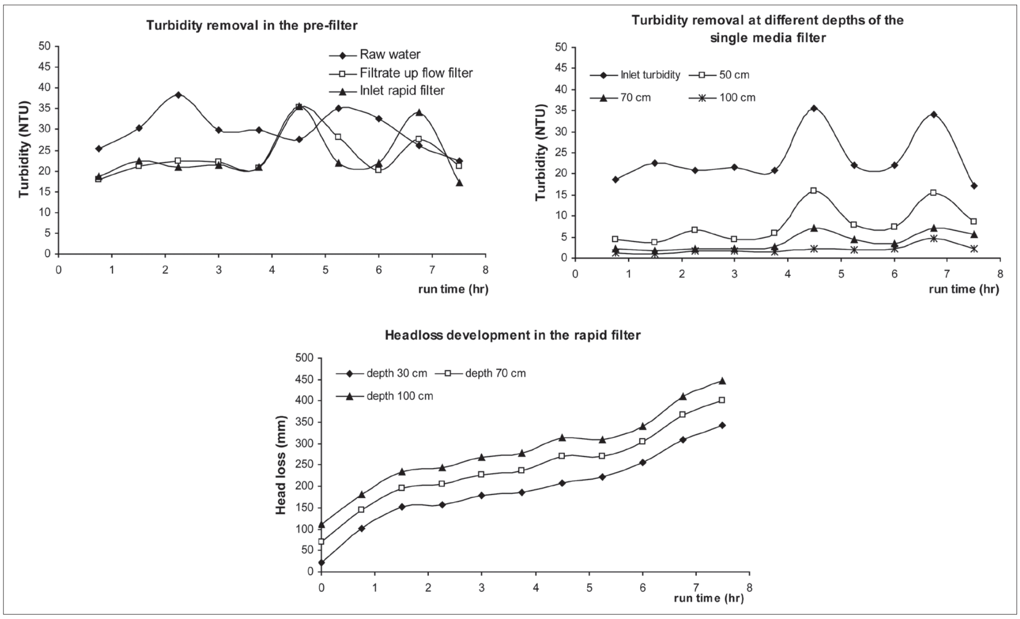

Figure 10. *Time-dependent turbidity residuals in the up-flow filter and single media gravity rapid sand filter and head loss development in the single media filter.*

accomplished by sedimentation followed by filtration in case of conventional treatment or by direct filtration when the sedimentation step is skipped. In order to assess the filterability of suspensions formed during coagulation with *Moringa Oleifera*, filtration experiments were conducted in a pilot plant consisting of an up-flow roughing filter used for hydraulic flocculation and a single media sand filter used for final treatmen. The results are resumed in Figure 10.

Raw water with an average initial turbidity of 30 NTU previously treated with MO extracts was used. Turbidity removal and head loss development were the variables used to evaluate the pilot plant's performance. The results obtained for the pre-filter (Figure 10-top left), indicates that turbidity removal was generally low and in average did not exceed 20 %. The effluent turbidity remained steady during the first 4.0 to 4.5 hours of filtration run but soon after that it started deteriorate and to experience variations. Two major factors might have contributed to this; first the relatively thin aggregates formed when coagulation was performed with MO as noted previously in this study and secondly the fact that the up-flow filter as was filled with a relatively coarse filtering material through which the relatively thin aggregates could flow without being retained.

The performance of the sand filter was much better. Average turbidity removals were in general above 92 % and the filtrate quality remained below 2.0 NTU throughout the entire test. As can be seen from Figure 10 (top-right) most of the particles were retained within the top 50–60 cm of the filter bed. This indicates that particles present in the suspensions transferred from the pre-filter were generally thin and could easily penetrate through the relatively fine filtering material used in the rapid sand filter. This also supports the observation made previously that flocs formed during coagulation with MO are generally thin and light which means they are poorly retained in coarse medium filters (e.g. roughing filters) or sedimentation tanks but are effectively removed in rapid sand filters.

The increase in head loss over filters indicates generally the extent of clogging due to particles being retained in the filter media. As shown in Figure 10, the head loss developed more or less linearly in the rapid sand filter. This indicates a time-dependent reduction of the filter bed porosity as a result of accumulation of particles, and also that a uniform penetration of particles through the depth of the filter bed was observed. It is also seen from Figure 10 that the head losses developed very rapidly during the initial stage of filtration, a fact that was attributed to rapid accumulation of particles in the upper layers of the filter bed.

The pressure drop in the pre-filter was in all cases of a few centimetres and in general negligible. This resulted from the fact that the pre-filter did not contribute for the retention of aggregates formed during coagulation-flocculation.

Similar tests performed with aluminium sulphate as the main coagulant and with raw water turbidity in the range 4.0 to 22NTU produced better results. Overall, filtrate turbidities ranging from 0.4–0.8NTU could be attained at the end of the treatment train. The increase of head loss pressure in both units was significant and generally higher than that observed when using MO. The results also indicated that aggregates formed during coagulation were effectively retained at the pre-filter and rapid sand filter. This is an expected pattern since coagulation with aluminium sulphate generally results in large and dense aggregates which are easily retained even within coarse filter media such as that used in the pre-filter.

4.6. Applicability at large scale operation

The optimum dosage of MO, using tap water, was found between 17 mg/l and 67 mg/l for both low (15 NTU) and medium (50 NTU) initial turbidities. Assuming daily water production of about 5 000 m^3/d which is enough for an average of 50 000 people at an average of 100l/person/day, an average dosage of about 40 g MO seeds/m^3, an average daily supply of about 0.2 tons of MO seeds is required if alum sulphate is replaced with MO. This corresponds to a plantation of about 60 ha if an average of 3kg seed kernels/tree is assumed with a tree spacing of about 3 m (WELL, 1999).

The area required for production of MO seeds is not entirely unrealistic particularly for small to medium size water supplies located in rural areas. Moreover, a hypothetical change from aluminium sulphate to MO may bring about significant reductions in transportation costs of imported chemicals. Yet, additional investments will be required concerning facilities for storage, grinding and mixing of the seeds.

The preparation of the extract should be carried out on-site to minimize transport costs and also because the extract must not be stored for too long before use. Since the extracts can be stored for one day without losing coagulation properties, batch processes designed for the demand of one full production day are probably more suitable than continuous process.

5. Conclusions

1 MO shows good coagulating properties, and has many advantages compared to aluminium sulphate; it does not affect the pH, alkalinity or conductivity of the water and it can be produced locally at low cost. The optimum dosage of MO, using tap water preparation method, was found to be between 17 mg/l and 67 mg/l for both low (15 NTU) and medium (50 NTU) turbidity levels.

2 The extraction of MO should be performed using tap water as this is the cheapest, most practical and most efficient method. MO does not show the same efficiency in turbidity removal as aluminium sulphate, particularly for low turbid waters. In this case, turbidity removal can be increased by increased sedimentation time at the expenses however of large investment and operational costs.

3 MO combined to direct filtration is less effective for turbidity removal than aluminium sulphate with direct filtration. Yet, the treated water turbidity when MO was used was within acceptable limits for drinking water production (less than 2 NTU) and the increase in head losses over the filters was not higher for MO than for aluminium sulphate. This suggests that MO could be a very good substitute for aluminium sulphate when using this technique.

4 MO is a method that can be considered as a good, sustainable and cheap solution for smaller waterworks, if the supply of MO seeds can be guaranteed. Tap water extracted MO and treatment with flocculation followed by direct filtration processes should be considered in the event of expansion or construction of small scale waterworks. Complementary tests should however be carried out in order to determine the impact of raw water pH on treatment efficiency.

5 Overall, the amount of seeds required for production of MO extract is quite large. On the other hand, the knowledge about actual production of MO seeds in Mozambique is limited which means the potential for large scale use of MO in drinking water production still needs further research. Aspects concerning pH dependence, COD increase and optimum direct filtration treatment design should also be further examined before the method is implemented at large scale basis. However, once plantations are established and the supply of seeds secured, MO provides a good, cheap and sustainable alternative to aluminium sulphate which should be considered as a coagulant in smaller waterworks.

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