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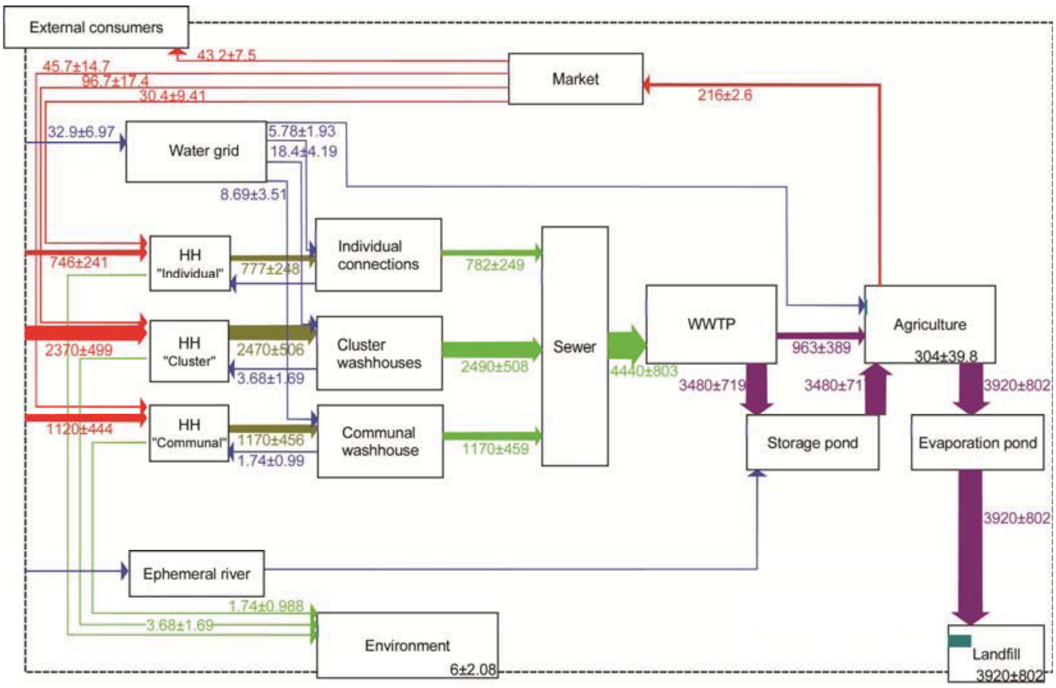
Evaluating alternative water sources and their use for small-holder agriculture from a systemic perspective.
A focus on water reuse and rainwater harvesting in Namibia.



Laura Woltersdorf

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Abstract

Water is scarce in semi-arid and arid regions. Using alternative water sources (i.e. non-conventional water sources), such as municipal reuse water and harvested rain, contributes to using existing water resources more efficiently and productively. The aim of this study is to evaluate the two alternative water sources reuse water and harvested rain for the irrigation of small-holder agriculture from a system perspective. This helps decision and policy makers to have proper information about which system and technology to adopt under local conditions. For this, the evaluation included ecologic, societal, economic, institutional and political as well as technical aspects. For the evaluation, the study area in central-northern Namibia was chosen in the frame of the research and development project CuveWaters. The main methods used include a mathematical material flow analysis, the computation and modelling of crop requirements, a multi-criteria decision analysis using the Analytical Hierarchy Process (AHP) method and a financial cost-benefit analysis. From a systemic perspective, the proposed novel systems were compared to the exciting conventional infrastructure. The results showed that both water reuse and rainwater harvesting systems for the irrigation of small-holder horticulture offer numerous technological, ecologic, economic, societal, institutional and political benefits. Rainwater harvesting based gardens have a positive benefit-cost ratio under favorable conditions. Government programs could fund the infrastructure investment costs, while the micro-entrepreneur can assume a micro-credit to finance operation and maintenance costs. Installing sanitation in informal settlements and reusing municipal water for irrigation reduces the overall water demand of households and agriculture by 39%, compared to improving sanitation facilities in informal settlements without reusing the water for agriculture. Given that water is the limiting factor for crop fertigation, the generated nutrient-rich reuse water is sufficient to annually irrigate about 10 m^2 to 13 m^2 per sanitation user. Compared to crop nutrient requirements, there are too many nutrients in the reuse water. Thus when using nutrient-rich reuse water, no use of fertilizers and a careful salt management is necessary. When comparing this novel system with to the conventional and to two adapted infrastructures, results showed that the novel CuveWaters system is the best option for the given context in a semi-arid developing country. Therefore, the results of this study suggest a further roll-out of the CuveWaters system. The methodology developed and the results of this study demonstrated that taking sanitation users into consideration plays a major role for the planning of an integrated water reuse infrastructure because they are the determinant factor for the amount of available nutrient-rich reuse water. In addition, it could be shown that water reuse and rainwater harvesting systems for the irrigation of small-scale gardens provide a wide range of benefits and can be key to using scarce water resources more efficiently and to contributing to the Sustainable Development Goals.

Zusammenfassung

Einleitung

Wasser ist in semi-ariden und ariden Gebieten eine knappe Ressource. Die Nutzung alternativer Wasserressourcen, wie gesammeltes Regenwasser und wiedergenutztes kommunales Wasser, zur Bewässerung in der kleinbäuerlichen Landwirtschaft, trägt dazu bei, die lokal verfügbaren Wasserressourcen effizienter und produktiver zu nutzen. Das Ziel dieser Studie ist es, die Regenwassersammlung und die Wiedernutzung von nährstoffreichen kommunalen Wasser für die Bewässerung in der kleinbäuerlichen Landwirtschaft aus einer Systemperspektive zu bewerten. Dies trägt dazu bei, dass Entscheidungsträger in Politik und Verwaltung wichtige Informationsgrundlagen und eine Unterstützung bei ihrer Entscheidungsfindung erhalten, insbesondere für der Frage welches System und welche Technologie unter den lokalen Bedingungen am geeignetsten ist. Dazu hat die vorliegende Bewertung ökologische, soziale, ökonomische, institutionelle und politische als auch technische Aspekte integriert berücksichtigt. Als Fallbeispiel für die Bewertung wurde der zentrale Norden Namibias, im Rahmen des CuveWaters Forschungs- und Entwicklungsprojekt, ausgewählt. Als grundlegende Herangehensweise wurde eine Systemperspektive gewählt, mit der das hier vorgeschlagene neuartige Konzept mit der bestehenden, konventionellen Infrastruktur verglichen wird.

Methoden

Folgende Methoden wurden für die Bewertung der Regenwassersammlung angewendet: Mit einer Literaturrecherche wurde der technische, ökonomische, ökologische und soziale Nutzen von Regenwassersammlung zur Bewässerung von Kleingärten zusammengestellt. Dann wurde eine finanzielle Kosten-Nutzen Analyse mit Hilfe der Barwertmethode erstellt. Dafür wurden zwei Optionen zur Bewässerung eines Nutzgartens bewertet: a) Die Sammlung von Regenwasser von einem Hausdach mit Speicherung in einem Ferrozementtank, und b) die Regenwassersammlung und -speicherung in einem wellblechbedachten Teich. Beide Regenwassersammlungsoptionen wurden mit einem Subsistenzgarten und einem am Marktverkauf orientierten Garten kombiniert. Erträge und Preise aus der Pilotphase wurden mit den Literaturwerten verglichen. Ebenso, wurde die Regenwassersammlungs- und Bewässerungsinfrastruktur mit dem Namibia Green Scheme Projekt verglichen, ein Vorhaben mit dem die großflächige und maschinelle Landwirtschaft mit konventionellen Wasserressourcen massiv ausgeweitet werden soll. Zusätzlich wurde ein Finanzierungsmodell entwickelt, dass Mikrokredite mit Staatsprogrammen kombiniert.

Zur Bewertung der Wasserwiederverwendung in der Landwirtschaft wurden folgende Methoden angewendet: Für die Erstellung eines angepassten Anbausszenarios für die Bewässerung mit

wiedergenutztem Wasser wurde zuerst die Anzahl pathogener Keime berechnet, die durch die neuartige Abwasser- und Bewässerungsanlage erreicht werden kann (nach WHO 2006). Danach wurden die Pflanzensorten ausgesucht und der Bewässerungsbedarf mit der FAO Software CROPWAT modelliert sowie der Wasserbedarf zur Salzauswaschung nach FAO berechnet (Pescod 1992). Eine mathematische Materialflussanalyse wurde mit SIMBOX durchgeführt, diese umfasste: Eine Systemanalyse, die Programmierung des mathematischen Modells, das Zusammentragen von geeigneten Daten, die Kalibrierung des Modells mit Felddaten, die Simulation der Wasser, Nährstoff und Salzflüsse zwischen Haushalten, der Abwasserkläranlage, der Landwirtschaft und der Umwelt, die Unsicherheitsanalyse mit Parameterranking, eine Monte Carlo Simulation sowie die Interpretation der Resultate. Für die Quantifizierung der Wasserflüsse wurden drei Fälle berechnet und verglichen: (i) die Situation vor dem Bau der verbesserten Sanitäranlagen und der Wasserwiederverwendung und die Situation beim CuveWaters System, mit (ii) alleiniger Benutzung, oder (iii) geringerer Benutzung der Sanitäranalgen. Für die Quantifizierung der Nährstoff- und Salzflüsse wurde anstatt des Falls mit geringerem Nutzen der Sanitäranlagen, ein Fall quantifiziert, in dem Ergebnisse der Pilotanlage eingegangen sind. Des Weiteren wurde das CuveWaters System mit dem konventionellen System und zwei angepasste System verglichen. Hierzu wurde eine Multi-kriterielle Entscheidungsanalyse mit der AHP Methode angewendet. Dafür wurde eine Hierarchie von Kriterien formuliert, die Kriterien wurden gewichtet, die vier Optionen wurden bewertet und parallel dazu die Bewertung auf Konsistenz überprüft. Dann wurden diese Bewertungen aggregiert und schließlich die Sensitivität der Ergebnisse ausgewertet, indem die Ergebnisse aus den unterschiedlichen Gewichtungen der Nachhaltigkeitsdimensionen analysiert wurden.

Ergebnisse und Diskussion

Die Ergebnisse zeigen, dass sowohl die Regenwassersammlung als auch die Wasserwiedernutzung zur Bewässerung in der kleinbäuerlicher Landwirtschaft eine große Zahl technischer, ökologischer, ökonomischer, sozialer sowohl als institutionellen und politischen Aspekten aufweist. Die Regenwassersammlung zur Bewässerung von Kleingärten hat in Kombination mit dem marktorientiertem Garten, über die Lebensdauer der Anlage hinweg, eine positive Kosten-Nutzen Bilanz: Der Ferrozementtank von 46.943 Namibian Dollar (N$) und der Teich von 64.443 N$ pro Anlage. Dagegen haben mit dem Subsistenzgartenszenario beide Regenwassersammelanlagen eine negative Kosten-Nutzen-Bilanz. Es wurde dabei auch deutlich, dass die Materialkosten der Regenwassersammlungsanlage darin die Hauptkostenkomponente darstellen. Währenddessen sind die Kosten für den Nutzgarten, sowie den Betrieb und die Ersatzteile für die Regenwassersammlungsanlage sehr gering. Die erzielte Erträge und registrierte Preise waren deutlich höher als vorher angenommen. Der durchgeführte Vergleich mit dem Green Scheme Projekt ergab, dass die Schaffung von 11.750 vollzeitequivalenten Jobs in einem Zeitraum von 15 Jahren eine 9,6 bis 14,3-fach höhere Investition pro Job erforderte als bei dem Regenwassersammelteich mit Kleingärten, oder dem Regenwasserferrozementtank mit Kleingärten im gleichen Zeitraum. Jedoch bewässert das Green Scheme eine deutlich größere Fläche und hat eine höhere Produktion pro geschaffenen Job. Die private Finanzierung der Regenwasseranlagen stellt ein Problem für den Großteil der Kleinbauern dar und ist das größte Hindernis für eine Verbreitung der neuartigen Technologie. Daher wird ein Finanzierungsmodell vorgeschlagen, in dem mit Hilfe von staatlichen Programmen die Infrastrukturkosten der Regenwassersammelanlagen finanziert werden. Kosten für Betrieb und Ersatzteile der Anlage können dann mit Mikrokrediten an den Landwirten finanziert werden. Hierfür sollten finanzielle Programme bereitgestellt werden. Des Weiteren muss die Regenwassersammlung für ländliche Kleinstbauern in Namibische Gesetzte und Richtlinien einfließen. Somit hätte die Technologie das Potential, ein wichtiger Bestandteil Namibias Wasserinfrastruktur zu werden. Risiken und Herausforderungen sind der geringe Bildungsgrad und die schwachen Marktstrukturen in der Region. Essentiell ist Bildung und Training um den Mangel an Kenntnissen und Erfahrung im Feldbau in der Region auszugleichen. Zusammenfassend konnte gezeigt werden, dass die Regenwassersammlung für die Bewässerung von Kleingärten eine ganze Reihe vorteilhafter Aspekte aufweist und ein praktikabler und effektiver Weg ist, die ländliche Bevölkerung zu erreichen und sie auf dem Weg aus der Armut zu unterstützen.

Die Ergebnisse der Wiederverwendung von kommunalem Abwasser für die Bewässerung haben gezeigt, dass die Kläranlage und die Wasserwiedernutzungsfläche die von der WHO (2006) geforderte Absenkung der Keimzahl zur uneingeschränkten Bewässerung von Blattgemüse erreichen. Im Vergleich zur Trinkwasserbewässerung ist der Bewässerungswasserbedarf bei der Bewässerung mit wiedergenutztem Wasser etwas höher, wegen des etwas höheren Wasserbedarfs zur Salzauswaschung. Zwar ist mit den neu errichteten Sanitäranlagen der Wasserbedarf der Haushalte erheblich höher, verglichen mit der vorherigen Praktik des öffentlichen Defäkierens und der Nutzung der Grubenlatrinen. Aber bei einer ausschließlichen Nutzung der verbesserten Sanitäreinrichtungen und der Bewässerung mit wiedergenutztem Wasser bestehen immerhin 85 % des Bewässerungswassers aus wiedergenutztem Wasser. Darüber hinaus kann der Austrag von ungeklärtem Abwasser und von Exkreta in die Umwelt auf ein Minimum reduziert werden. Pro Kubikmeter Wasser, der von Haushalten und der Landwirtschaft zusammen verbraucht wird, können 3,4 kg Feldfrüchte produziert werden. Im Vergleich zu der Situation ohne verbesserte Sanitäreinrichtungen und ohne

Wasserwiedernutzung kann der Wasserbedarf von Haushalten und Landwirtschaft zusammen um 10% reduziert werden. Verglichen mit dem Fall, in dem die sanitären Einrichtungen verbessert werden, aber keine Wasserwiederverwendung in der Landwirtschaft stattfindet, verringert sich der den Wasserverbrauch von Haushalten und Landwirtschaft zusammengelegt sogar um 39 %. Mit ausschließlichem Nutzen der Sanitäreinrichtungen und minimalen Wasserverlusten, die immer entstehen, weil nicht das gesamte Abwasser in der Kanalisation gesammelt wird (z.B. Wasser für Kochen oder Garten gießen), sind pro Jahr 27.600 m³ wiederverwendbares Wasser verfügbar. Bei gemischter Nutzung der neuen Sanitäreinrichtungen zusammen mit fortgesetztem öffentlichem Defäkieren und Nutzung der Grubenlatrinen wären jedoch jährlich nur 13.000 m³ verfügbar. Dagegen, würde eine simple Berechnung mit einem festen Wasserverbrauch pro Kopf von beispielsweise 60 l/Person/Tag bei 1.500 Nutzern und der Annahme, dass das gesamte Abwasser in der Kanalisation gesammelt werden kann, eine wesentlich überschätzte jährliche Verfügbarkeit von 32.850 m³ wiederverwendbarem Wasser ergeben. Der Grund hierfür ist, dass die Menge, die zur Wiederverwendung im Bewässerungsfeldbau zur Verfügung steht, maßgeblich von dem Nutzerverhalten in den Sanitäreinrichtungen abhängt. Mit 1.500 Nutzern und ausschließlichem Nutzen der am System angeschlossenen Sanitäreinrichtungen ist das Bewässerungswasser, welches pro Sanitärnutzer produziert werden kann, unter den klimatischen Bedingungen im zentralen-Norden Namibias ausreichend, um 1,5 ha oder 10 m² pro Sanitärnutzer zu bewässern (mit 90% Unsicherheitsbereich 1,1 - 1,8 ha und 7 - 12 m²/cap). Während der Pilotphase hat sich gezeigt, dass der Wasserverbrauch pro Person so hoch war wie für den Fall der idealen Nutzung der Sanitäranlagen angenommen wurde. Jedoch waren deutlich weniger Nährstoffe im Wasser enthalten, da die fortgesetzte öffentliche Defäkation und gewohnheitsmassige Nutzung der Grubenlatrinen die ursprüngliche Einschätzung erheblich übertraf. Es zeigte sich auch, dass die Zahl von 1.500 Nutzern der Sanitäranlagen während der Designphase erheblich zu hoch eingeschätzt worden war und die Modellierung mit Daten aus der Pilotphase auf 588 Nutzer schließen lässt. Die Ergebnisse haben ebenso gezeigt, dass das Verhältnis der Nährstoffe (N, P, K, Ca, Mg) im Abwasser nicht dem Verhältnis entspricht, welches Pflanzen zum Wachstum brauchen. Für eine optimale Düngung enthält das geklärte Wasser zu viel N und nicht genug P und K. Dies könnte sich in anderen Ländern mit abweichender Proteinzufuhr der Bevölkerung anders darstellen, denn es gelangten dann andere N- und P-Mengen ins Abwasser, was die Ergebnisse beeinflussen würde. Ebenso könnte dies mit anderen Feldfrüchten ebenfalls variieren, die einen besonders hohen Bedarf eines bestimmten Nähstoffes haben. Um das Düngungspotential menschlicher Exkremente im Abwasser zu erhöhen, müsste die öffentliche Defäkation und die weitere Nutzung der öffentlichen Grubenlatrinen vermieden werden. Zusätzlich dazu müssten weitere Siedlungen an die Abwasserentsorgung angeschlossen werden um die Auslastung der Kläranlage zu gewährleisten. Da Wasser in der Region knapp ist, wird es, trotz Bewässerung und Düngung mit wiederverwendetem, nährstoffreichem Wasser, auch in Zukunft immer der limitierende Faktor bei der Bewässerung und Düngung bleiben. Beim Vergleich des neuartigen Systems (sanitären Einrichtungen in informellen Siedlungen, erweiterte Abwasserklärung und Wasser- und Nährstoffwiederverwendung) bei CuveWaters, gegenüber dem konventionellen und der zwei angepassten Sanitär- und Abwasserinfrastrukturen, erweist sich das CuveWaters System klar als die nachhaltigste Option. Schaut man sich dabei die einzelnen Dimensionen an, so zeigt sich, dass vor allem in der ökologischen Dimension und in der sozialen Dimension das CuveWaters System die höchsten Prioritäten aufweist. In der ökonomischen Dimension, schneiden alle Optionen vergleichbar ab, jedoch belegt das konventionelle angepasste System knapp den ersten Rang. In der institutionellen und politischen Dimension belegt klar das konventionelle System den ersten Rang. In der technischen Dimension dagegen, belegt das neuartig angepasste System den ersten Platz. Das Ergebnis der gesamten Nachhaltigkeitsbewertung ergibt, bei ausgeglichener Gewichtung der Dimensionen, dass das neuartige CuveWaters System klar die beste Option ist (31 % Priorität), gefolgt von dem neuartigen angepassten System (26% Priorität), während die beiden konventionellen Systeme die letzten Ränge belegen (21% und 22% Priorität). Gewichtet man die Nachhaltigkeitsdimensionen dann unterschiedlich, so führt eine extrem hohe Gewichtung der sozialen und der ökologischen Dimension zu einer noch klareren Präferenz des neuartigen CuveWaters Systems. Bei einer extrem hohen Gewichtung der ökonomischen Dimension ist das konventionell angepasste System knapp die bessere Option. Die Antwort auf die Frage, welches System unter lokalen Bedingungen am besten geeignet ist, hängt also davon ab, welchen Fokus auf die jeweilige Nachhaltigkeitsdimension gelegt wird.

Schlussfolgerungen

Die Ergebnisse dieser Studie belegen deutlich, wie unerlässlich es ist, das Verhalten der Nutzer der sanitären Einrichtungen schon bei der Planung und dann auch während des Betriebes eines integrierten Wasserwiedernutzungssystems zu berücksichtigen und ggf. zu beeinflussen, wenn dieses möglichst effizient sein soll. Außerdem konnte gezeigt werden, dass die Wasserwiedernutzung und die Regenwassersammlung für die Bewässerung kleinbäuerlicher Landwirtschaft eine Vielzahl positiver Aspekte aus einer ganzen Reihe von Lebensbereichen mit sich bringt und der Schlüssel sein könnte, knappe Wasserressourcen effizienter zu nutzen und somit zu den Nachhaltigkeitsentwicklungszielen beizutragen.

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AHP	Analytical Hierarchy Process
Ca	Calcium
Cap	Capita
FAO	Food and Agricultural Organization
IWRM	Integrated Water Resources Management
K	Potassium
Mg	Magnesium
N	Nitrogen
Na	Sodium
N$	Namibian Dollar
P	Phosphor
RBC	Rotating biological contactors
UASB	Upflow anaerobic sludge blanket
UV	Ultraviolet
WHO	World Health Organization
Yr	Year

1 Synopsis

1.1 Introduction

Water for hygiene and agriculture is scarce in semi-arid regions. Many urban and most rural areas in developing countries are characterized by a lack of inadequate infrastructures to provide sanitation, treat wastewater and provide irrigation water. Worldwide around 1.2 billion people live in areas of physical water scarcity and 2.6 billion (194 million alone in cities) are without improved sanitation (UN Water and FAO 2007). At the same time, agriculture accounts already now for around 70% of global freshwater withdrawals; yet, to meet growing future demands, the world needs to produce 70 % more food by 2050 (WWAP 2012). Therefore, the Millennium Development Goals and now the Sustainable Development Goals aim to expand access to sanitation to improve human and environmental well-being, and to decrease poverty, hunger and disease (United Nations 2015, United Nations 2011).

1.1.1 Alternative water sources

Water infrastructure supplying water from conventional water sources such as groundwater and surface water are coming increasingly under pressure. This is particularly the case in areas with limited or scarce water resources, where demand for water by humans is growing and increasing fresh water withdrawals have a growing negative ecological impact. This calls for change in the present conventional water and wastewater system and examining alternative sources of water (Guest et al. 2009). Alternative water sources (or also called non-conventional water sources) include harvested rainwater, reuse water (i.e. former wastewater that has been treated) and desalinated water (Boulware 2013, Qadir et al. 2007). Alternative water sources can be used for non-potable uses (e.g. irrigation, toilet flushing, dust control, fire suppression) and with more advanced treatment for direct or indirect potable reuse (i.e. discharged into a water body before being used in the potable water system) (Qadir et al. 2007, Leflaive 2009). Alternative water systems differ from prevailing ones as they reuse water for a variety of uses and/or they can be based on decentralized infrastructures, producing water where it is consumed. Contexts where alternative ways of supplying water can be viable include rural areas where land is abundant and density is low and urban areas in developing countries where no central infrastructures pre-exist or the existing infrastructure needs to be extended (Leflaive 2009). Potential benefits from an alternative water system are (1) reduced demand for fresh water resources, diversified water sources and enhanced reliability of access to resource; (2) reduced volume of wastewater discharged into the environment; (3) reduced energy to transport water from the point of production to the point of use and reduced greenhouse gas emissions due to energy savings; (4) less infrastructure and reduced costs for the construction of networks; (5) relieving public finance from part of the investment burden, as new players are incited to invest their own money in the (decentralized) infrastructure; and (6) flexibility and adaptation to changes in population and consumption, land use, and technology (Leflaive 2009). Challenges of alternative water systems include for instance their additional costs, in particular when not initially integrated in the plan for service provision and building construction; their risk, associated with the economy of water services at the municipal level, the difficulty of how decentralized water systems will contribute to a sustainable network and, in particular, the combination of decentralized systems with existing, central infrastructures (Leflaive 2009). This study focused on the evaluation of two alternative water sources: reuse water and harvested rain, as they are key to use local water resources in water scarce areas more efficiently.

1.1.1.1 Harvested rainwater

Rainwater can be harvested with a wide range of technologies that collect, store and provide water for humans (Barron 2009). Water can be harvested in rural and urban areas, from natural or artificial surfaces such as roofs, roads, pavements, ground catchments or slopes. The water is then stored in wells, dams, ponds or cisterns (Ishaku et al. 2012; Pachpute et al. 2009). In recent decades rainwater harvesting has experienced rapid expansion in many countries around the world (Barron 2009). Especially in semi-arid regions, governments have promoted rainwater harvesting for the irrigation of agriculture to raise agricultural yields and bridge dry periods. Examples include the Laikipia District in Kenya (Malesu et al. 2006, Hatibu and Mahoo 1999), the Western Pare Lowlands in Tanzania (Senkondo et al. 2004), Rajasthan and Gujarat in north-western India (Agarwal et al. 2001) and the Gansu Province in north-central China (Li et al. 2000, Barron 2009). These regions are characterized by a semi-arid climate with short rainy seasons, high annual potential evaporation, severe seasonal droughts and water shortages and low agricultural productivity. South Africa and the Indian state of Rajasthan have already integrated rainwater harvesting into their national water policy (Mwenge Kahinda et al. 2007, UN-HABITAT and Government of Madhya Pradesh 2007, DWAF 2004). This study focuses on the evaluation of rainwater harvesting from corrugated iron roofs with storage either in ferrocement tanks (30 m^3) or ponds (80 m^3) in a rural area.

1.1.1.2 Reuse water

During the past decades, the attitude towards domestic wastewater has been changing, moving to no longer considering wastewater as a waste but rather as a resource for water, energy and plant fertilizing nutrients (McCarty et al. 2011, Guest et al. 2009). The reuse of treated water in agriculture has been rapidly increasing worldwide, particularly in regions facing physical or economic water stress, growing urban populations and growing demand for irrigation water (Drechsel et al. 2010, Scheierling et al. 2010, Asano 2007, Hamilton et al. 2007). Drivers for water reuse are increased demand for water; reduced availability of water supply, affordability due to falling costs for membrane technologies, practicality of water reuse as a local solution, public policy as for instance stringent standards for wastewater discharge as an incentive to recycle water (Leflaive 2009). Today treated and untreated wastewater is reused in agriculture on an estimated 20 million ha in 50 countries – a tenth of the world's irrigated crops (Jiménez and Asano 2008). Semi-arid higher income countries (e.g. USA (California), Israel and Spain) extensively practice planned reuse of treated water for irrigation, while middle income countries (e.g. Mexico, Chile, Egypt) use not only treated but also untreated wastewater, indicating a transition between unplanned and uncontrolled reuse to planned and controlled reuse. In lower income countries, water supply and sanitation is often inadequate and highly polluted waters from surface-water bodies are reused for irrigation, predominantly unplanned and unintentionally. The resulting agricultural activities are most common in and around cities, as in most cities of Sub-Saharan Africa (Woltersdorf et al. 2015, Drechsel et al. 2010, Scheierling et al. 2010). Especially semi-arid regions with low fertilizer applications and little irrigation, such as in Sub-Saharan Africa, can benefit from a stable supply of nutrient-rich reuse water for irrigation in order to increase yields and local food production (Zaidi 2007). In spite of its potential in developing countries, municipal wastewater is not widely treated and reused in urban agriculture due to a lack of appropriate water infrastructure (Drechsel et al. 2010, Scheierling et al. 2010). In addition, previous studies indicated that the management of existing water reuse schemes can lead to significant challenges such as health risks through the spread of pathogens, soil degradation through salinization, toxic ions, eutrophication or increased mobility of organic contaminants and critical public perceptions toward the reuse of treated water for agricultural irrigation (Chen et al. 2012, Murray and Ray 2010, O'Connor et al. 2008, Hamilton et al. 2007). Keeping the electrical conductivity in soils and irrigation water below tolerable levels for crops is essential for the long-term success for irrigation with reuse water (Biggs and Jiang 2009, O'Connor et al. 2008, Devitt et al. 2007). This study focuses on the evaluation of water reuse designed to be collected from about 1,500 sanitation users in formal and informal settlements of an urban area and is advanced treated in a treatment plant in proximity of the settlements and reused for human food crops. The study focuses on using the reuse water exclusively for the irrigation of small-holder agriculture.

1.1.2 Small-holder agriculture

There is no universal definition of "small" farms as the size is relative and depends on the local context. Criteria often used to define whether a farm is considered small are the size of the farm land, the amount of workers, or the amount of capital invested (HLPE 2013). The most commonly used criterion to define “small” is land (HLPE 2013) and the Food and Agriculture Organization of the United Nations (FAO) adopted a 2 ha threshold as a broad measure of a small farm (IFAD and UNEP 2013); in Africa 80 % of the holdings are below 2 ha, 90 % below 5 ha (HLPE 2013). Also, smallholders provide up to 80 % of the food supply in sub-Saharan Africa (FAO 2012). Smallholder farmers use mainly family labor and retain part of the produce for family consumption. They are characterized by family-focused motives such as favoring the stability of the farm household system and the need to generate high productivity and enough income to fulfill basic needs, and by marginalization in terms of accessibility to markets, resources, information, technology, capital and assets (IFAD and UNEP 2013, HLPE 2013, FAO 2012). The capacity of small-holder agriculture to achieve higher production levels per unit of land compared to larger farms has been widely documented (HLPE 2013). The vast majority of smallholders live in rural areas, although urban and peri-urban smallholdings are an increasingly important source of supply for developing urban areas (IFAD and UNEP 2013). Historical evidence shows that smallholder agriculture, adequately supported by policy and public investments, has the capacity to contribute effectively to food security, food sovereignty, and substantially and significantly to economic growth, the generation of employment, poverty reduction, the emancipation of neglected and marginalized groups, and the reduction of spatial and socio-economic inequalities (HLPE 2013). Within an enabling political and institutional environment, it can contribute to sustainable management of biodiversity and other natural resources while preserving cultural heritage (HLPE 2013). The FAO recognizes agricultural growth involving smallholders to be most effective in reducing extreme poverty and hunger when it increases returns to labor and generates employment for the poor (FAO et al. 2012). However, the productivity of smallholder agriculture and its contribution to the economy, food security, and poverty reduction depend on soil fertility and freshwater delivery among others (IFAD and UNEP 2013). This study analyzes the use of alternative water sources for two extremes of small-holder agriculture: one end is an area of about 50 m² to 220 m² cultivated by one or several small-holders using rainwater harvesting for irrigation. The other end is an area of about 1 to 3 ha cultivated by a group of small-holder farmers using municipal reuse water. Thus, a broad range of small-holder agriculture could be included in the evaluation.

1.1.3 Evaluation of the sustainability of water resource systems

Whether alternative water sources for irrigation are a viable and sustainable option needs to be evaluated. A working group of the American Society of Civil Engineers and the UNESCO has defined sustainability of water resource systems in general as “designed and managed to fully contribute to the objectives of society, now and in the future, while maintaining their ecological, environmental and [engineering] integrity” (ASCE and UNESCO 1998). Their understanding of sustainability implies the provision of efficient services that maintain public health and welfare, are cost-effective, and reduce negative environmental impacts, today and into the future. (ASCE and UNESCO 1998). Sustainable agriculture and rural development has been defined by FAO as: “..the management and conservation of the natural resource base, and the orientation of technological and institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future generations. Such sustainable development in the agricultural [..] sector conserves land, water, plant and animal genetic resources, is environmentally non-degrading, technically appropriate, economically viable and socially acceptable” (FAO 1989). A system perspective implies taking into account all behaviors of a system as a whole in the context of its environment. This includes the interactions and relationships between the system and the environment (Bar-Yam 2011). This study evaluated the two alternative water sources presented above, reuse water and rainwater harvesting, from a system perspective considering ecologic, economic, societal, technical, political and institutional aspects.

1.2 The CuveWaters research project and the study area central-northern Namibia

The research project CuveWaters (2003 – 2015) developed and implemented measures to support the Namibian process towards an Integrated Water Resources Management (IWRM). The aim is to strengthen the potential of the region’s water resources by developing, adapting and implementing novel technologies for water supply and sanitation as pilot plants. IWRM relies on solutions that use various sources, types and qualities of water for different purposes. Depending on its quality, the water is used as drinking water or to irrigate vegetable gardens. CuveWaters implemented pilot plants for rain- and floodwater harvesting, groundwater desalination, and a system consistent of sanitation units connected to a wastewater treatment plant and an agricultural water reuse site (Figure 1) (CuveWaters 2013).

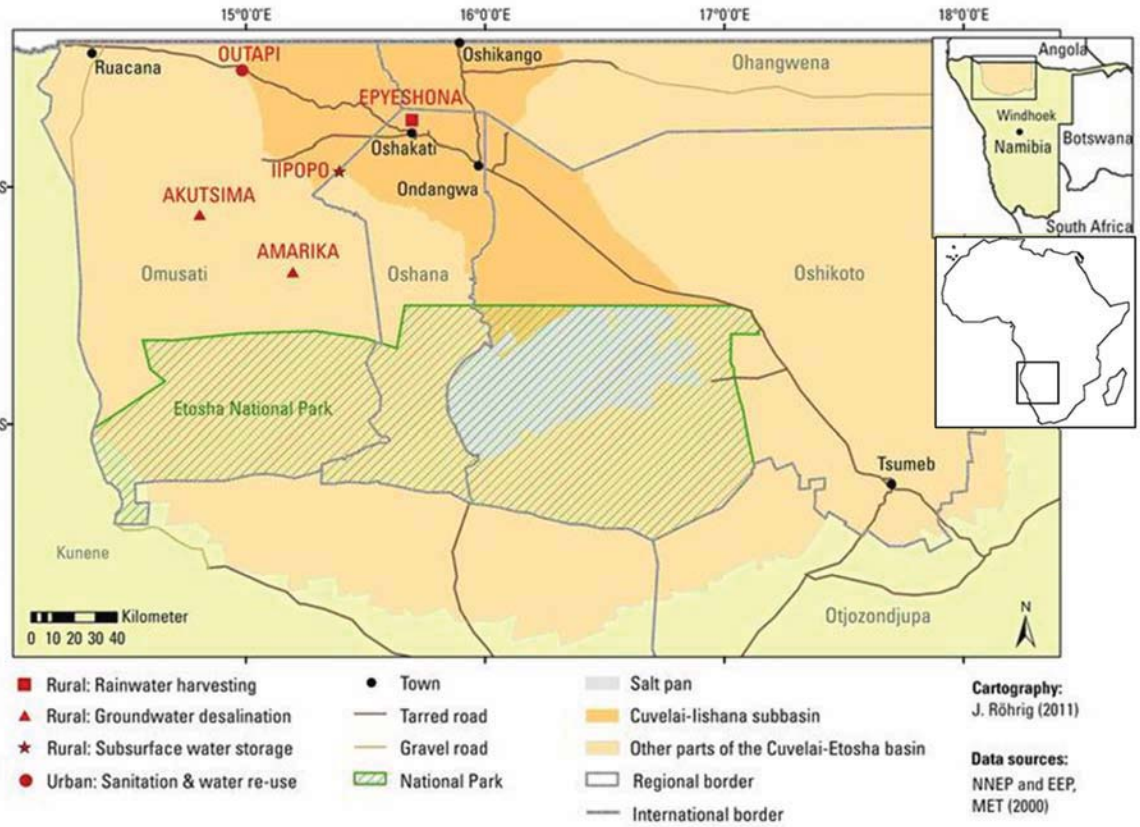

Figure 1: Central-northern Namibia and the Cuvelai-Etosha Basin with CuveWaters project sites (Röhrig 2011)

The case study area central-northern Namibia located in the Cuvelai- Etosha Basin is the most densely populated region in Namibia with around 42% of the Namibian population (Namibian Statistics Agency 2012). The region is semi-arid and water scarce with short rainy seasons, high precipitation variability, alternating droughts and floods, ephemeral river systems, no perennial rivers and mostly brackish or saline (>5 g/l) groundwater (Sturm et al. 2009, Kluge et al. 2008, Heyns 1995). Annual precipitation is highly variable ranging from 262 mm to 666 mm in 2/3 of years, with an average of 464 mm, 96% occurring from November to April (Woltersdorf et al. 2015). Mean monthly temperature ranges from 18°C in June to 28°C in November and December (Ondangwa station, data 2004 to 2007) leading together with high solar radiation and low humidity to high potential evaporation rates of approximately 2600 mm/a (Heyns 1995). Presently, drinking water is abstracted from the Calueque reservoir in Angola from the perennial Kunene river that is shared between Angola and Namibia. The water is transported through an extensive grid of open concrete and earthen canals (150 km) and pipelines (2,000 km) to the settlements in central-norhtern Namibia, making it one of the largest water supply networks in Africa (Heyns 1995).

Growing demand for water has increased pressure and dependency on the water infrastructure (Kluge et al. 2008). The majority of the population is rural (81%), but migration to cities has been increasing and the urban population has doubled from 2001 to 2011 to 19% (Republic of Namibia 2012a). The region has a high demand for agricultural products for food security and import substitution (Government of Namibia 2006). Mean annual per capita income in the region is 9,346 N$ (about 715 Euro), while Namibia wide the mean per capita income of subsistence farmers is lower with 6,533 N$ (about 500 Euro) (Namibia Statistics Agency 2012).

In urban areas in Namibia, around 40% of the population does not have access to improved sanitation. In informal settlements such as in the city of Outapi the situation is even more dramatic and there is an acute need to improve sanitary conditions (Deffner et al. 2012) (Figure 2). Towns in the region, such as Outapi have high population growth and mostly low-density and partly informal settlements (Kluge et al. 2008) and exemplify the typical problems of water supply and low access to sanitation facilities of urban areas in developing countries (see Deffner et al. 2012) with an only partly coverage of sewer and wastewater treatment system, a high rate of people practicing open defecation and insufficient access to functioning public latrines (Deffner et al. 2012). Namibia-wide 8% of the urban households practice urban agriculture (Republic of Namibia 2012 a). Ongoing population growth (up to 0.9% per year, Republic of Namibia 2012 a), further urbanization, increasing withdrawal of Kunene water on the Angolan side, plans for extension of commercial agricultural activities and expected effects of climate change are likely to increase pressure on already scarce water resources in the area (Deffner and Mazambani 2010, Kluge 2008). Therefore the sanitation and wastewater treatment systems of the future need to be adapted to these urban dynamics (CuveWaters 2013) and the Namibian government undertakes considerable efforts to improve the access to water supply and sanitation in accordance with the Millennium Development Goals (Republic of Namibia 2008 c, d).

In rural and remote areas the incidence of poverty is particularly pronounced with 38% of the population being poor (Republic of Namibia 2008 b). Agricultural yields are generally very low, leaving many households vulnerable to food insecurity and inadequate food supplies (Republic of Namibia 2008 c). Unemployment is high (45%) and people mostly depend on subsistence rain-fed crop farming during the rainy season and livestock farming (64%), which is a main source of income for many (43%) households, while income from commercial farming plays a negligible role (0.1%) (Namibia Statistics Agency 2012).

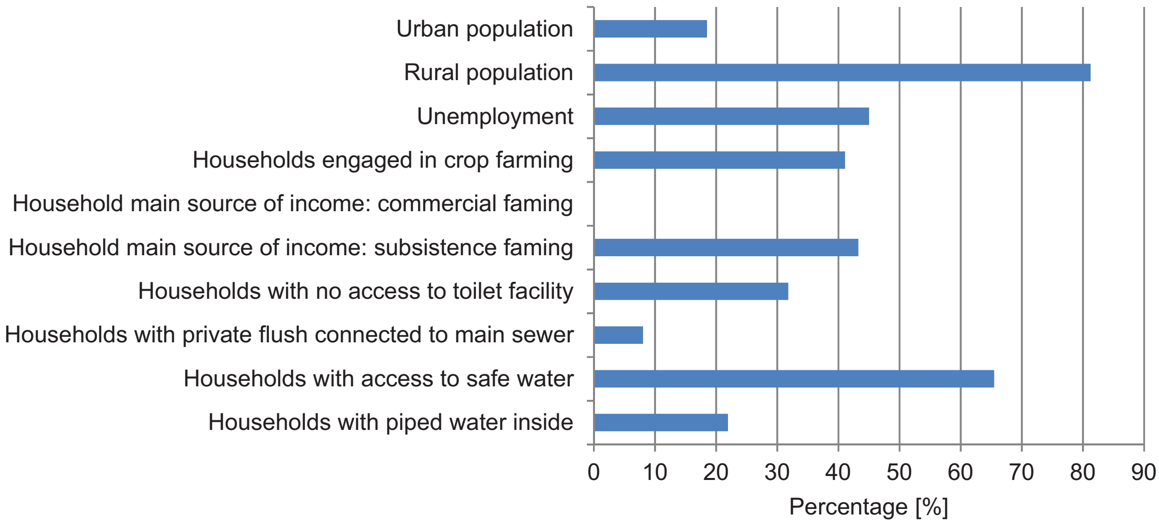

Figure 2: Characteristics of the population in central-northern Namibia at a glance (Republic of Namibia 2008 a, Namibia Statistics Agency 2012)

The Namibian government extensively aims to increase and to invest in commercial, large-scale irrigated crop production including maize and vegetables for import substitution, self-sufficiency, job creation and food security at the national and the household level (MAWF 2008, Republic of Namibia 2008 d, Weidlich 2007). For this, the Namibian government has developed a comprehensive policy framework to promote household food security. However, so far insufficient attention has been given to encourage micro- to small-scale (< 3 ha) local food production (Werner 2011). Current policies and legislation encourage the use of alternative water sources (Republic of Namibia 2008 b). During the 1950s and 1960s several attempts have been made to harvest rain in uncovered pump storage dams in central-northern Namibia. However, owing to poor water quality, caused by evaporation, pollution and salinization, the dams fell into disrepair (Driessen and Jokisch, 2010). Since 1969, in the capital Windhoek domestic wastewater is treated and reused for potable purposes (Du Pisani 2006). Alternative water resources such as harvested rainwater or reuse water for the irrigation of agriculture are not used so far. Alternative water infrastructures could have a broad range of benefits and give essential impetus for the expansion of micro- and small scale irrigated agriculture, the regional economy and poverty reduction. Fertilizers have to be imported, although prices are currently relatively low for commercial farmers. New ways to use the existing and scarce water resources most efficiently and productively have to be found.

1.3 Research goal and questions

The goal of this study was to evaluate the two alternative water sources reuse water and rainwater harvesting providing irrigation water for two ends of small-holder agriculture from a system perspective. For this we considered ecologic, economic, societal, technical, political and institutional aspects. The evaluation is based on a case study in central-northern Namibia.

The goal will be reached by answering the following research questions:

(1) How can rainwater harvesting for the irrigation of small gardens be evaluated in terms of sustainability and especially regarding economic aspects? Are rainwater harvesting based gardens economically advantageous in comparison to conventional large-scale irrigated agriculture?

(2) How much reuse water is available for irrigation when implementing the novel CuveWaters concept? Does the reuse of municipal water for irrigation reduce the overall water demand of households and agriculture?

(3) What quantities of nutrients and salts does municipal reuse water contain? What impact do the users of the sanitation users have on nutrient and salt content of the reuse water? What implications does this have for the area that can be fertilized and for preventing soil salinization? To what extend does the use of sanitation units and wastewater treatment reduce the diffuse discharge of nutrients and salts by inhabitants?

(4) How does a system of improved sanitation connected to advanced wastewater treatment and water reuse for irrigation perform in relation to the local conventional infrastructure?

The research questions 1 to 4 will each be answered in one paper as described below.

1.4 Overview of the papers with methods, results and discussion

The analysis of rainwater harvesting is presented in paper 1 and focuses on the financial part. The analysis of water reuse is presented in paper 2, 3 and 4. Paper 2 and 3 analyze environmental considerations, while paper 4 evaluates technical, economic, environmental, societal, as well as institutional and political aspects of the CuveWaters system in comparison to the local conventional infrastructure. As the research presented in paper 2, 3 and 4 is based on the same pilot facility, but the research was conducted partly simultaneously and partly consecutively, also the data and knowledge available in the course of the time evolved (Table 1). Paper 4 integrated in its ecologic evaluation the results generated in paper 2 and 3. From paper 2, the quantification of water flows was included in the criterion “Resource use efficiency” to calculate the indicator “Share of reused water for irrigation out of total water consumption of irrigation and households”. From paper 3, the results of wastewater discharge to the environment were used for the criterion “Biogeochemical impacts” to calculate the indicator “Wastewater discharged untreated to the environment". As well from paper 3, the quantified amount of available nutrients from sanitation for agriculture was used to calculate the indicator "Costs of irrigation water and fertilizer (farmer perspective)" for the criterion "cost-benefit".

Table 1: Overview of papers and evolution of data during the time of paper preparation

Paper number	Water source	Main topic	Main research	Evolution of data during time of research
1	Rainwater harvesting	Sustainability criteria with focus on economic and financial part	early – end 2012	-
2	Water reuse	Water flows, planning data	second half 2011 – early 2013	-
3	Water reuse	Nutrient and salt flows, planning and monitoring data	second half 2011 – mid 2014	In comparison to paper 2: Availability of more accurate data for the irrigation site: • leaching efficiency of the soil • electrical conductivity of the soil and of irrigation water • agricultural produce and yield New calculation of • irrigation and leaching water demand
4	Water reuse	Sustainability evaluation, integration of results generated in paper 2 and 3	early 2015 – early 2016	• Irrigation and leaching water demand same as in paper 3 • Greater irrigation site

For the mathematical material flow analysis of the water reuse system the following four cases were created and partly renamed in paper 3 (see Table 2).

Table 2: Cases created for the material flow analysis of the water reuse system

Presented in paper number	Case with previous water and sanitation infrastructure	Case with ideal sanitation use, design data during planning	Case with realistic sanitation use, design data during planning	Case with realistic sanitation use, assessment data during pilot phase
2	Case 0	Case 1	Case 2	-
3	$Case_{conv}$	$Case_{ideal}$	-	$Case_{assess}$
Differences	Case 0 and $case_{conv}$ are the same	Case 1 and $case_{ideal}$ are the same	-	-

1.4.1 Paper 1

The first paper assesses an infrastructure consistent of rainwater harvesting tanks and gardens for small-holder agriculture regarding their benefits in technical, economic, environmental and social terms. Then the paper focuses on the economic part with a financial cost-benefit analysis for the pilot rainwater harvesting and gardening facilities in central-northern Namibia. Also a financial comparison to the existing irrigation and drinking water infrastructure in central-northern Namibia was performed. At the end, financial and policy implications for the implementation of rainwater harvesting based gardening are proposed for the Namibian government. The methodology covers five parts: (1) A literature review categorized technological, economic, environmental and social benefits of rainwater harvesting for gardening. (2) Financial benefits for a household or micro-entrepreneur were calculated with a financial cost–benefit analysis using the net present value (NPV) method. Two rainwater harvesting options were analyzed: A roof catchment with ferrocement tank at household level and a roof catchment with pond at community level. For each of the two rainwater harvesting options, two crop scenarios were developed and analyzed: A market garden scenario with only tomatoes, and a subsistence garden scenario with vegetables and fruits for household consumption. (3) Then, yields and prices monitored at the pilot plants in 2011 were presented and compared to those used in the cost–benefit analysis from Price Waterhouse Coopers (2005). (4) The rainwater harvesting and gardening infrastructure was compared to the existing Namibian green scheme project to irrigate large-scale agriculture with conventional water sources, i.e. water abstracted from the Calueque dam and piped through canals to the agricultural sites near the Angolan boarder. This helped to assess the use of an alternative water source for small-holder agriculture against the local situation and current government plans. (5) A proposal to finance the rainwater harvesting and gardening facilities by combining microcredits and government subsidies was presented. The results showed that using harvested rainwater for the irrigation of small-holder horticulture offers numerous technological, environmental, social and economic benefits to local communities. Therefore the technology has the potential to become an important part of Namibia's water infrastructure. Nevertheless, the implementation of small-scale water infrastructure is associated with certain risks and challenges. In rural parts of Namibia, like in most other parts of rural Africa, the low level of education makes it extremely difficult to implement the necessary structures to run gardening ventures that aim to supply markets in the region. Education and training is also essential to counter the lack of knowledge of horticultural production in the region. An additional challenge for planning gardens irrigated with rainwater harvesting is the high rainfall variability in the region. The financial cost–benefit analysis showed that the major cost component of a rainwater harvesting and garden facility are the material costs of the rainwater harvesting facility, while costs for garden material and operation and maintenance costs are relatively low. During the pilot construction phase material costs were much higher than under 'without project' conditions. In addition, government bulk purchase of important raw materials such as wood, steel and cement might drop current monopoly prices considerably. The net present value of both rainwater harvesting facilities is negative when assuming subsistence garden production and integrating the material costs of the rainwater harvesting facility (Table 3). Assuming a market garden production, both facilities have a positive net present value over their lifespan: the ferrocement tank of 46,943 N$ and the pond of 95,711 N$.

Table 3: Results of the cost-benefit analysis of two rainwater harvesting options and gardens, assuming best case costs as with large-scale production, with discount rate of 5% (Woltersdorf et al. 2014)

		Net present value [N$]	
Rainwater harvesting	Garden	Including: material investment costs, labour construction costs, O&M costs	Including: labour construction costs, O&M costs, excluding: material
Ferrocement tank (30 m³) *	subsistence (52 m²) market (84 m²)	- 10,503 + 46,943	+ 6,997 + 64,443
Pond (80 m³) **	subsistence (146 m²) market (229 m²)	- 17,521 + 95,711	+ 25,579 + 138,811

Calculation with lifespan of: * 40 years, ** 20 years

The monitoring of pilot plants after two years of operation showed that revenues were considerably higher than estimated, while water use was higher than modelled. The comparison of rainwater harvesting facilities to the green scheme project in Namibia showed, that in order to create 11,750 full time equivalent jobs over 15 years, the investment per job for the green scheme (914,145

N$/job) is 14.3 to 9.6 times higher compared to the one necessary for rainwater harvesting (with a ferrocement tank: 63,775 N$/job and with storage pond: 95,312 N$/job). However, the Green Scheme with large-scale and mechanized agriculture irrigates with water from the Calueque reservoir a larger area and has a higher vegetable production per created job. Private financing of initial investment costs represents a problem for most micro-entrepreneurs and is the major limiting factor for the up-scaling of rainwater harvesting. In relation to this income level in the Oshana region, tanks and gardens have high investment costs, while the maintenance costs of rainwater harvesting facilities are very low. Therefore, in line with the concept of sustainable cost recovery (OECD 2009), the paper proposes that the government could subsidize rainwater harvesting infrastructure investment costs, while maintenance and operation costs can be financed with a micro-credit to the micro-entrepreneur of the rainwater harvesting and gardening facility. Also Namibian policy needs to be adapted, examples exist form its neighbor country South Africa that has a policy to sustain micro-scale rural vegetable farming with grants and subsidies for water supply infrastructure. Therefore, it could be shown, that the decentralized infrastructure of rainwater harvesting for the irrigation of small-scale gardens provides a wide range of benefits and can be a key in reaching the rural poor and sustain them to overcome poverty.

1.4.2 Paper 2

The second paper analyses the reuse of treated water to irrigate small-holder agriculture, focusing on quantifying the amount of water flows and the water productivity within the system of water supply, sanitation, wastewater treatment and water reuse for agriculture. The methodology involved the four steps: (1) The modelling of the water requirement of the agricultural irrigation site. The crop irrigation requirements were computed with the software CROPWAT 8.0 (FAO 1992, Allen et al. 1998) and the leaching requirement was calculated according to FAO (Pescod 1992). (2) The calculation of the pathogen reduction according to WHO (2006) achieved with the proposed treatment plant, water storage, drip irrigation and an interval between final irrigation and consumption of produce of three days. (3) Design of a crop scheme containing suitable crops for safe unrestricted irrigation with reuse water. (4) A mathematical material flow analysis was performed with SIMBOX, including the analysis of the system, programming of the mathematical model, information on data collection and calibration, the simulation of the water flows including three case calculations, the uncertainty analysis with parameter uncertainty ranking and Monte Carlo simulation and finally the analysis and interpretation of the results. The three cases compared the situation with the previous water supply and sanitation infrastructure, the situation with the CuveWaters system and ideal use of sanitation units, and the situation with the CuveWaters system and mixed use of sanitation units and open defecation. The results showed that the proposed wastewater treatment plant and water reuse site achieves the necessary pathogen reduction of 6 log units for unrestricted irrigation of edible leaf crops (WHO 2006), even in the low range of uncertainty. Irrigating with reuse water, the agricultural irrigation requirement was a little higher compared to drinking water irrigation (Table 4), due to the higher leaching requirement. Household water consumption was considerably higher assuming improved sanitation facilities compared to practicing open defecation and using pit latrines and public water points. In the case of ideal use of sanitation unit and irrigation with reuse water (case 1), the water inflow to the system was the lowest (36,800 m^3/yr) as reusing the used water from households for irrigation of agriculture contributed to lower the total water requirement of the system (-10%) composed of households and agriculture, compared to the previous situation without improved water supply, improved sanitation and water reuse (case 0, 40,700 m^3/yr). As well, 85% of the irrigation water was composed of reuse water and the discharge of untreated water and excreta to the environment is the lowest (6,018 m^3/yr) of all cases. For this reason, water productivity is the highest with 3.4 kg fruits and vegetables produced per m^3 of water used in the system. Improving sanitation with reusing water for irrigation reduces therefore the overall water demand of the system by 39%, compared to improving sanitation without reusing the water for agriculture. In the case of ideal sanitation use, 27,600 m^3 reuse water is available per year, compared to only 13,000 m^3/yr in the case of low sanitation use mixed with open defecation and use of pit latrines (case 2). In comparison to this, conducting a simple calculation with a fixed per capita wastewater inflow, assuming only a water consumption per person of 60 liters/day and 1,500 inhabitants and that wastewater is entirely collected by the sewer, would result in an expected overestimated wastewater flow of 32,850 m^3/year available for water reuse. This is because the amount of household wastewater that is available for reuse in agriculture depends on the behavior of the users of the sanitation facilities. The methodology developed and the results of this study demonstrated that taking sanitation users into consideration plays a major role for the quantification of expected water flows and productivity, as this is the most determinant factor for the amount of available resue water.

Table 4: Summary of mean variable results (Woltersdorf et al. 2015)

	Case 0	Case 1	Case 2
Agricultural production [kg/yr]	124,800		
Agricultural irrigation water requirement [m³/yr]	23,400	27,084	
Household water consumption [m³/yr]	17,340	32,870	25,120
Water inflow to the system [m³/yr]	40,700	36,800	43,700
- From tap water	40,700	34,200	41,100
- From ephemeral river	0	2,600	2,600
Water treated and available for reuse in agriculture [m³/yr]	0%	27,600	13,000
People using sanitation facilities [number]	649	1,501	1,165
Share of irrigation water composed of treated reused water [%]	0%	85%	32%
Untreated water and excreta discharged to the environment	17,769	6,018	12,810
Water productivity of the system [kg/ m³]	3.1	3.4	2.9
Change of water inflow to the system (or of water productivity)	0	-10%	7%
Change of water inflow to the system (or of water productivity) compared to if no reuse takes place [%]	0	-39%	-16%

1.4.3 Paper 3

The third paper analyses water reuse to irrigate small-holder agriculture, focusing on quantifying the nutrient and salt flows as impacted by sanitation user behavior. The methodology involved the quantification of nutrient and salt flows from the households to the wastewater treatment plant, agriculture and the environment. Same as for the water flows this was performed again with mathematical material flow analysis using the software SIMBOX. The model served to quantify how many nutrients and salts are discharged from households to the environment, how many nutrients can be recovered from wastewater for agriculture and which area can be fertilized as well as how many salts are present in the reuse water under different assumptions. First, indicators for nutrient content and salinity were identified and chosen, then the system was defined and the mathematical model was set up, data was collected and calibrated, three cases were designed, the cases were simulated and an uncertainty analysis and parameter uncertainty ranking were performed, and finally the results were analyzed. The nutrient requirement for the crop scenario that has been developed in paper 2 was calculated. In addition, also the leaching requirement for agriculture was calculated for the given salinity of the reuse water and for drinking water based on monitoring results. The results showed, that assuming ideal sanitation use, 1,500 users and the developed crop scheme, the reuse water is sufficient to annually irrigate 1.5 ha (90% probability range 1.1 - 1.8 ha) meaning 10 m² per sanitation user (7 - 12 m² per sanitation user) (Figure 3). Compared to crop water and nutrient requirements, there are too many nutrients in the reuse water.

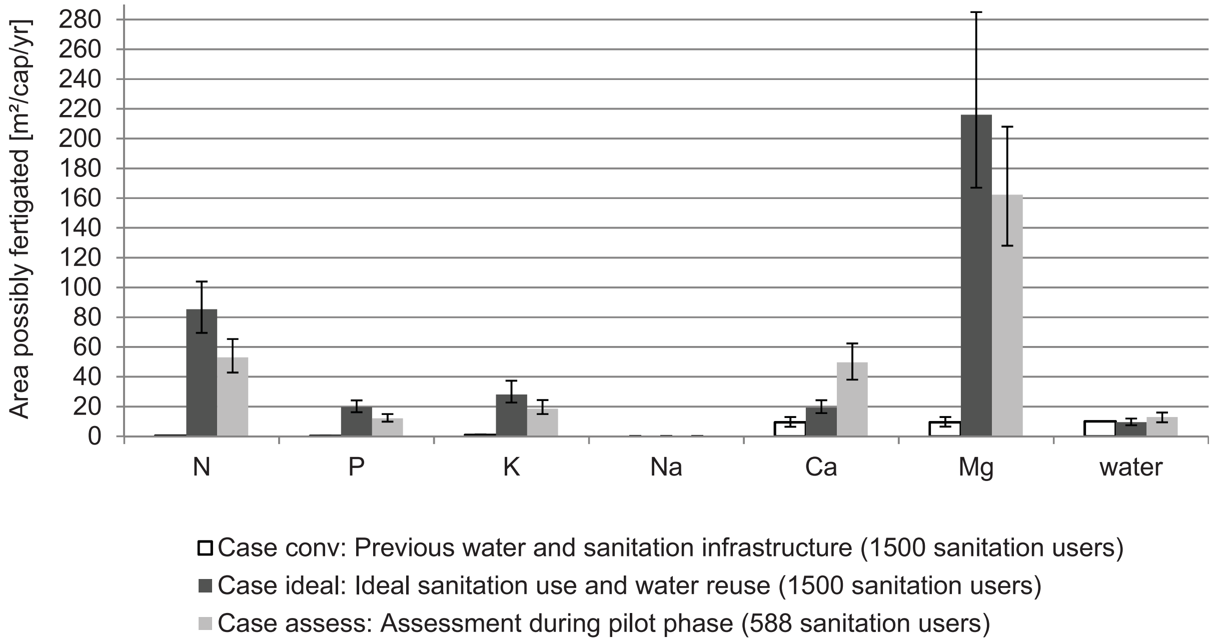

Figure 3: Area that can be fertigated per person and year with grid water ($case_{conv}$) or nutrient-rich reuse water and sludge ($case_{ideal}$, $case_{assess}$) [m^2/cap/yr] (mean value and 90% probability range) (Woltersdorf et al. 2016).

The assessment based on data from the CuveWaters pilot phase showed that water use per person was as high as was expected in the design phase for the case of ideal sanitation use. However fewer nutrients were present in the wastewater, because more open defecation than expected took place even after construction of the CuveWaters infrastructure. As well the assessment showed that the number of 1,500 sanitation users was overestimated in the design phase and model results of this study suggest 588 users. Results also indicated, that the ratio of nutrients (N, P, K, Ca, Mg) in wastewater differs from the ratio of the nutrients required by crops. For optimum crop growth, wastewater contains too much N and not enough P and K. This might be different in other counties with different protein intake of the population or with other crops grown that have other nutrient requirements. To fully exploit the fertigation potential of human excretions and wastewater, open defecation and latrine use needs to be avoided. In addition, additional settlements should be connected to the wastewater treatment plant as its capacity is currently not fully used. Using nutrient-rich reuse water for irrigation makes fertilizer application unnecessary. However, because water is a scarce resource in the area, it is water itself that is likely to remain the factor determining the size of the agricultural area.

1.4.4 Paper 4

The fourth paper compares water reuse to irrigate small-holder agriculture as proposed by the CuveWaters project to the conventional sanitation, wastewater and irrigation infrastructure and to two versions of these systems adapted by this study. The methodology involved first the definition of the goal, scope, spatial and temporal boundary of the evaluation. Second, the options to be compared were explained regarding the amount of sanitation users in formal and informal settlements, the type of water supply, the sanitation infrastructure, the sewer system, the type of wastewater treatment and the agriculture irrigation site. Third, a multi-criteria decision analysis was performed using the Analytical Hierarchy Process (AHP) method, as the evaluation involved multiple different criteria. The AHP Method involved first formulating a hierarchy of criteria, second weighting the criteria, third the evaluation of the four systems and parallel evaluation of the consistency of results, and finally the aggregation and analysis of the results. Fourth, the different weighting of sustainability dimensions in order to test the sensitivity of the results was explained. The results showed that looking at the single dimensions, in the ecologic dimension the CuveWaters system scored highest (54 % priority) followed by the novel adapted system (priority 25%). In the economic dimension, the conventional adapted system scored highest having a priority of 32%, even though all four systems are very close. In societal terms, the evaluation of the four options showed that the novel CuveWaters system and the novel adapted system comprising the same sanitation infrastructure in formal and informal settlements scored by far best (34% priority), the other two having only a priority of 16%. Regarding the institutional and political sustainability, the conventional system scored highest (49 % priority). The CuveWaters system scored lowest, having the highest institutional complexity and requiring the most institutional capacities. The technical sustainability was evaluated to be best for the novel adapted system (31 % priority) followed by the CuveWaters system (26 % priority). Aggregating the five dimensions, the overall sustainability, weighting the dimensions equally, resulted that the CuveWaters system scored highest, having a priority of 31 %, followed by the novel adapted system (26 % priority) and the two conventional options (21 % and 22 % priority). Weighting the ecologic dimension as "extremely important", it contributes 69% and the other four dimensions together 31 % to the overall sustainability, the CuveWaters system is by far the best choice with 45 % priority. Weighting the economic dimension as "extremely important", the conventional adapted system is the best option with 28 % priority, even though all options are very close here, and differences might be questioned due to a range of uncertainty among the priority values.

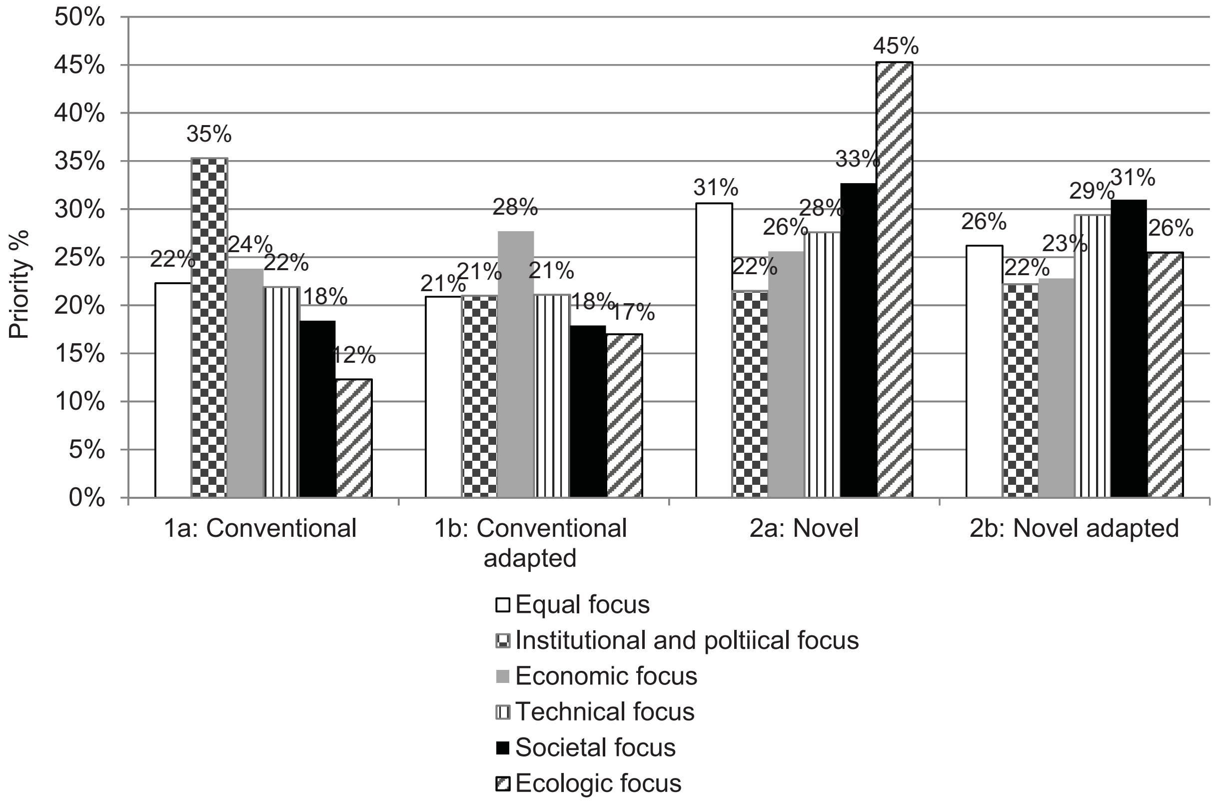

Figure 4: Results of the evaluation of the four options depending on weighting of dimensions

In summary, considering an equal, an ecologic and a societal focus of the dimensions, the CuveWaters system is the most sustainable option compared to the other systems. The options' ranking however depends on the weighting of the dimensions; the other three systems score best in one case each. Therefore, the results of this study suggest a further roll-out of the implemented CuveWaters system.

1.5 Conclusions

The results of the study showed that the two alternative water sources, i.e. harvested rainwater and municipal reuse water, offer a wide range of benefits for the irrigation of small-holder agriculture. Rainwater harvesting is suited to irrigate gardens (ca. 50 – 220 m²) in rural areas and offers numerous societal, economic, environmental and technical benefits. In addition, the activity can be financially viable for micro-entrepreneurs, if specific aspects are considered: Material investment costs for the rainwater harvesting infrastructure should be government funded, while the investment costs for the garden and irrigation infrastructure as well as the operation and maintenance costs for the rainwater harvesting plant can be privately financed, such as with a micro-credit. In addition, horticultural crops combining high water efficiency with a high market price should be planted in order to achieve the necessary revenues. Finally, to facilitate broad implementation and achieve benefits for the regional economy, the adoption of rainwater harvesting in Namibia's water policy framework is required. Reuse water offers a wide range of benefits for small holder agriculture (ca. 1 - 3 ha) in urban areas. In order to collect sufficient municipal wastewater, adequate sanitation facilities need to be implemented that are adapted to the needs in formal and non-formal settlements. Then the wastewater can be advanced treated and reused productively for agriculture, instead of discharging the wastewater untreated to the environment spreading pathogens, salinity and nutrients. Looking at the area that can be fertigated with reuse water, the water is the limiting factor followed by phosphorous. Depending on sanitation user number and behavior, sufficient nutrient-rich reuse water can be generated to irrigate 10 m^2/cap (90% uncertainty range: 7 – 12 m^2/cap) assuming ideal sanitation use and a medium water use per person of 1,500 inhabitants. About 13 m^2/cap (90% uncertainty range: 9 – 16 m^2/cap) can be irrigated assuming mixed sanitation use and a higher water use per person of 588 inhabitants, as monitored during the pilot phase of the CuveWaters infrastructure. If sanitation units are fully used and the drainage pond is lined, the discharge of nutrients and salts to the environment can be almost completely avoided. Enough municipal wastewater can only be collected if sufficient people have access to sanitation units connected to the sewer and if the further use of pit latrines and open defecation is avoided. This poses a significant challenge for planning, since in most urban informal settlements there is no population census and the amount of sanitation users can only be estimated. In addition, the number of inhabitants might considerably fluctuate over time, due to fluctuations in the inhabitants of the settlement itself and due to the sanitation behavior of the inhabitants that partly stick to either using pit latrines or still practicing open defecation, or due to changes of the water and sanitation tariff. Given the conditions in Namibia and the protein intake of the local population, it is likely that too many nutrients are contained in the water related to crop requirements. Also due to the elevated levels of salts originating from human excreta, the risk of soil salinization is higher than with drinking water irrigation. Therefore adequate leaching of the soil is required.

In comparison to the conventional sanitation infrastructure in formal settlements, it is advantageous to implement a sanitation infrastructure in informal settlements that is adapted to the spatial and economic preconditions in the informal settlements and to offer, for instance, shared sanitation facilities. Comparing the proposed adapted sanitation facilities connected to advanced water treatment (UASB, RBC, microsieve, UV-light) for water reuse to the conventional infrastructure including drinking water irrigation and two adapted versions of the systems showed that the CuveWaters system is overall the most sustainable option. Looking at specific sustainability dimensions, the CuveWaters system is clearly most sustainable in environmental and societal terms. However, in the economic, institutional and political as well as in the technical dimension, the other three options score each higher once. Benefits of the CuveWaters system are its better resource efficiency, the lower biogeochemical impacts, the better cost-benefit ratio for the farmer, the positive impact on poverty reduction, its high accordance with national policies, its technical robustness, its superiority regarding accessibility, practicability, acceptance, creation of social capacities, benefits regarding socio-economic and symbolic values and positive health impacts. Challenges are the higher spatial impacts, user affordability, the cost-benefit ratio for the town-council, the lower practicability and higher conflict potential for sanitation users, the higher institutional complexity and a higher need of institutional capacities, its higher effort for construction and maintenance and its lower lifetime. In summary, the results suggest a further roll-out of the CuveWaters system to reuse municipal water for irrigation. Hence, expanding water reuse and rainwater harvesting for agricultural irrigation is a viable way towards a more sustainable use of water sources, using fewer resources, being economically feasible, as well as being institutionally and politically practicable and technically sound. Then, the use of these two alternative water sources is a valuable contribution to reach Namibia's Vision 2030 and the Sustainable Development Goals.

1.6 Recommendations

In water scarce areas, the use of alternative water sources for the irrigation of small-holder agriculture is a viable option to use existing water resources more efficiently. Two options for this are the reuse of municipal water and the use of harvested rainwater. Thus, it has to be considered, that each source of water is suited for a specific context:

- Before the introduction of a new rainwater harvesting and water reuse facility, planners should evaluate different infrastructure options and systems regarding ecologic, economic, societal, institutional and political as well as technical criteria, in order to assess which option is suited best for the local conditions under the given priorities and constraints. For this, a weighting of the different sustainability criteria should be performed in order to rank the options depending on the prioritization of criteria.
- Rainwater harvesting should further be implemented in rural areas for the irrigation of small-scale agriculture of about 50 to 220 m² gardens. To finance the material investment costs of the rainwater harvesting infrastructure, policy makers should design and implement programs and funds adapted to the local context. Programs and local support infrastructure should also be set up to assign micro-credits to small entrepreneurs to finance the garden and irrigation investment costs and the operation and maintenance

costs for both rainwater harvesting and gardens. In addition, local agricultural extension officers should train and advice micro-entrepreneurs in rainwater harvesting and gardening, such as on which crops to plant that combine high water efficiency and a high market price. Also, policy makers should integrate a rainwater harvesting policy framework into the national water policy in order to facilitate a broader implementation.

- When planning and implementing new sanitation, wastewater treatment and irrigation infrastructure in the city, planners and decision-makers should opt for an integrated option with water reuse. Reusing water for irrigation after advanced treatment and collection of the water from adequate sanitation units is the most sustainable option. This is especially the case if ecological and societal benefits have a high priority for the town. However, with a very high priority on the economic side due to financial constraints, water reuse for irrigation obtained after a low-tech treatment in a pond might be the most sustainable option.
- Decision-makers and planners in town councils should further construct sanitation units in informal settlements that are adapted to the spatial and economic preconditions and to the needs in the informal settlements. Even though they are for instance shared by several households and do not offer the benefits of individual sanitation connections in houses, they offer numerous benefits in comparison to the current alternative of open defecation and use of pit latrines.
- The further practice of open defecation and the use of pit latrines should be avoided in order to minimize environmental pollution through the spread of salts and nutrients as well as public health risks through the spread of pathogens. Instead, by closing the loop from sanitation to agriculture through direct water reuse, the water and nutrients should be reused productively for agriculture.
- The town council should concentrate on raising the number of sanitation users in order to collect sufficient water and nutrients for the generation of sufficient nutrient-rich reuse water for irrigation. This could be achieved by continuing to arrange trainings e.g. with Community Health Clubs that have started in the CuveWaters project, where local inhabitants using the sanitation units are trained to use the sanitation units instead of further practicing open defecation or using the former pit latrines. In addition, the town council should ensure that each inhabitant around the cluster washhouses has the necessary access to the sanitation unit, such as having a key.

In summary, the results suggest a further roll-out of water reuse and rainwater harvesting for the irrigation of small-holder agriculture.

1.7 Outlook

- The developed and applied methodology of this study can be used for all areas in developing countries which are characterized by insufficient water supply and wastewater infrastructure with similar starting conditions as those described in central-northern Namibia. Similar starting conditions include for urban areas: informal settlements with public water points, public latrines and a high share of inhabitants practicing open defecation, a low income, high unemployment and low education level of the inhabitants, a semi-arid climate that requires irrigation for agriculture and enough space available to build the wastewater treatment plant and the irrigation area in proximity to the city, such as, for instance on the edge of a city with either a developing area or low population density. The methodology could also be used in semi-arid higher income countries, when adapting the system in the material flow analysis including existing types of sanitation facilities and sanitation user behavior. For the evaluation of an integrated sanitation, a wastewater treatment and water reuse system in comparison to the conventional system, the method used for other areas in developing or developed countries would be the same, however some criteria and indicators would need to be adjusted to the different starting conditions and to the different local context.
- The results of the study could be generalized and broadly transferred to other areas which have conditions similar to those in the model region central-northern Namibia. When comparing the results of this study, also the scale of the water infrastructure should be similar, since for water reuse this includes a similar amount of sanitation users and size of the irrigation area, while for rainwater harvesting this implies a comparable amount of harvested rain and area of the garden. Finally, regarding the necessary amount of irrigation, also the climate including especially precipitation, temperature and UV-radiation should be similar.
- Further studies should test with different case studies, how the method can be easily transferred to other countries and regions with different conditions as those of the presented model region. Also the results obtained in this study could be tested and validated.
- For the evaluation of the water reuse system, future studies should be conducted that also include the view of different local stakeholders into the evaluation process. The same method used for this study would be used and each stakeholder would weigh the criteria and evaluate the options separately. Then, with the evaluation of each participant, the software would compute a result that is more accurate and directly integrate the local perspective. Tests could also reveal if other evaluation methods generate the same results. In addition, further studies could analyze the list of criteria and indicators and rank which ones have the highest impact on the final results of the evaluation. This would result in a list of fewer indicators which

evaluate the water infrastructure, and in addition, this indicator ranking would show which indicators scientists should put the most effort into when collecting the most accurate data. For the ecologic indicators, a parameter ranking was performed indicating which parameters are responsible for the major uncertainty of two ecological indicators. It showed that the number of sanitation users and the share of wastewater that is collected by the sewer (i.e. and not discharged into the environment) have the highest impact on the uncertainty. Therefore, more effort should be put into collecting more certain data on these two parameters.

- Future studies could quantify the amount of nutrients and salts excreted in other countries with different total dietary protein intake and with different share of vegetable protein intake. Also, nutrient requirements and salt tolerances of other crops could be analyzed and categorized. Then, it could be analyzed whether the relationship among nutrients in wastewater fits better to the one required by crops. This could also be analyzed under different climatic conditions and irrigation requirements. However, water is likely to remain the limiting factor for crop growth as related to the irrigation water and the nutrient requirement of crops, the amount of excreted nutrients per person is way too high compared to the water use per person. Scientists could further analyze the impacts of different amounts of users, combined with different amounts of water use per person and amounts of toilet use in relation to different sizes of the agricultural irrigation area.
- It could be quantified and tested how many nutrient and salts are in human excreta in other countries and regions, where people have different diets. Especially a different protein intake will have an impact on how much N and P is present in the wastewater. A different intake of salt and minerals will also have an impact on how much salt is present in excreta. Then, the quantity and the ratio in wastewater could be different. A different crop scenario could have a different quantity and ratio of nutrient uptake. For this, the developed mathematical material flow model of this study could be used for computation.
- For rainwater harvesting and garden facilities, the evaluation of the financial cost-benefit ratio could be further improved by integrating more monitoring data on prices and yields. In addition, also ratios of different tank, catchment and garden sizes should be scientifically analyzed in order to discover the best cost-benefit ratio.

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Oct. 2015 - present	**Institute of Physical Geography, Goethe University Frankfurt, Germany** Research associate: Methods of transdisciplinary knowledge integration
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2 Papers

2.1 Author contributions

The following section describes the contribution of each author to the respective paper.

Paper 1: Woltersdorf, L., Jokisch, A., Kluge, T., 2014. Benefits of rainwater harvesting for gardening and implications for future policy in Namibia. Water Policy 16: 124–143

Contribution of PhD candidate: Laura Woltersdorf generated the results of the cost-benefit analysis, performed the literature research on the benefits of rainwater harvesting based gardening and did the calculation for the comparison to the green scheme project as well as for the financing model and policy implications. She coordinated the preparation of the article and wrote the main text parts, except for the ones mentioned below (Chapter 4.3 and last paragraph of chapter 5.1 by Alexander Jokisch. Chapter 5.2 and 6 in close cooperation with Thomas Kluge).

Contribution of co-authors: Alexander Jokisch provided the data such as costs, prices and dimensions of the pilot rainwater harvesting plants and from monitoring of the plants. He wrote chapter "4.3. First results from monitoring", researched the information about the South African policy 'Financial Assistance to Resource Poor Irrigation Farmers' and wrote the last paragraph of chapter "5.1. Proposed policy implications" on that topic.

Thomas Kluge conceptualized the article, supported with discussions, provided comments and advice and assisted in writing the chapter "5.2. Transferability of results" and the "6. conclusions" chapter.

Paper 2: Woltersdorf, L., Liehr, S., Scheidegger, R., Döll, P., 2015. Small-scale water reuse for urban agriculture in Namibia: Modeling water flows and productivity, Urban Water Journal 5 (12): 414-429. DOI: http://dx.doi.org/10.1080/1573062X.2014.938295

Contribution of PhD candidate: Laura Woltersdorf conceptualized the article, generated the results, prepared the text of the article and coordinated and integrated the author's contributions.

Contribution of co-authors: Ruth Scheidegger provided assistance with the SIMBOX software, controlled the formulated equations of the mathematical material flow analysis, helped with discussions about what to analyze, provided comments to the article and formatted the figures of the mathematical material flow analysis (Figure 2 and Figure 4).

Stefan Liehr informally supervised the PhD thesis and helped with discussions about what to analyze, and provided comments to the article.

Petra Döll supervised the PhD thesis and the preparation of the article, supported with discussions, conceptualization, structuring, provided comments and advice for modification of the article and supported improving the language style of the article.

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Contribution of co-authors: Ruth Scheidegger provided assistance with the SIMBOX software, controlled the formulated equations of the mathematical material flow analysis, helped with discussions about what to analyze, provided comments to the article and formatted the figures of the mathematical material flow analysis (Figure 2 and Figure 4).

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She calculated the results with the online-tool for the AHP calculations, calculated the sensitivity analysis and generated the tables and figures.

Contribution of co-authors: Martin Zimmermann generated the results of the article together with Laura Woltersdorf by jointly determining indicators and indicator values. He supported with discussions and provided comments and input to the article.

Jutta Deffner provided the data for the societal evaluation of the pilot plant from results of the social empirical monitoring. She helped with discussions to develop and evaluate the societal indicators. She also contributed in writing chapter “4.3 societal sustainability”.

Markus Gerlach helped with discussions to develop and evaluate the technical indicators. He also reviewed and added passages to the chapter “3.2.3 Option 2a” and “4.5 Technical sustainability”.

Stefan Liehr set up the evaluation framework consisting of the five sustainability dimensions, the criteria, indicators and indicator values. He supervised the application of the framework, supported with discussions and provided comments to the article.

2.2 Full copies of paper 1 to 4

Paper 1: Woltersdorf et al. 2014 (Water Policy)

Paper 2: Woltersdorf et al. 2015 (Urban Water Journal)

Paper 3: Woltersdorf et al. 2016 (Journal of Environmental Management)

Paper 4: Woltersdorf et al. (submitted to Resources, Conservation and Recycling)

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Benefits of rainwater harvesting for gardening and implications for future policy in Namibia

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Abstract

Rainwater harvesting to irrigate small-scale gardens enhances food self-sufficiency to overcome rural poverty. So far rainwater harvesting is not encouraged by the Namibian National Water Supply and Sanitation Policy nor supported financially by the Namibian government. This study proposes two rainwater harvesting facilities to irrigate gardens; one collects rain from household roofs with tank storage, the second collects rain on a pond roof with pond storage. The aim of this paper is to assess the benefits of rainwater harvesting-based gardening and to propose policy and financing implications for the Namibian government. We investigate the benefits of rainwater harvesting through a literature review, a cost–benefit analysis, monitoring of project pilot plants and a comparison with the existing irrigation and drinking water infrastructure. The results indicate that rainwater harvesting offers numerous benefits in technological, economic, environmental and social terms. The facilities have a positive net present value under favourable circumstances. However, material investment costs pose a financing problem. We recommend that government fund the rainwater harvesting infrastructure and finance privately garden and operation and maintenance costs. Integrating these aspects into a national rainwater harvesting policy would create the conditions to achieve the benefits of an up-scale of rainwater harvesting based gardening in Namibia.

Keywords: Benefits; Central-northern Namibia; Cost–benefit analysis; Financing; Gardening; Rainwater Harvesting; Roof and ground catchments; Water policy; Water supply

1. Introduction

Rainwater harvesting for the irrigation of household gardens buffers the dry season and droughts (van Steenbergen & Tuinhof, 2009). Rainwater harvesting consists of a wide range of technologies that can be divided into *in situ* and *ex situ* techniques to collect and store water (Barron, 2009). *In situ* rainwater harvesting are soil management strategies that enhance rainfall infiltration and reduce surface runoff,

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such as terracing, pitting or conservation tillage practices. The rainwater capture area is within the field where the crop is grown and the soil serves as a capture and storage medium at the same time. *Ex situ* technologies have capture areas external to the point of storage, being a natural soil surface with limited infiltration capacity or an artificial surface with low or no infiltration capacity. Commonly used impermeable surfaces are represented by rooftops, roads, pavements and slopes. Storage systems are often wells, dams, ponds or cisterns (Barron, 2009).

Owing to increasing water scarcity worldwide, in recent decades rainwater harvesting has experienced rapid expansion in many countries around the world (Barron, 2009). Especially in semi-arid regions, governments have promoted rainwater harvesting to raise agricultural yields and bridge dry periods. Examples include the Laikipia District in Kenya (Hatibu & Mahoo, 1999; Malesu *et al*., 2006), the Western Pare Lowlands in Tanzania (Senkondo *et al*., 2004), Rajasthan and Gujarat in north-western India (Agarwal *et al*., 2001) and the Gansu Province in north central China (Li *et al*., 2000; Barron, 2009). These regions are characterised by a semi-arid climate with short rainy seasons, high annual potential evaporation, severe seasonal droughts and water shortages and low agricultural productivity. South Africa and the Indian state of Rajasthan have already integrated rainwater harvesting into their national water policy (DWAF, 2004; Mwenge Kahinda et al. 2007; UN-HABITAT & Government of Madhya Pradesh, 2007). A general precondition to make rainwater harvesting practically and economically feasible is an annual precipitation of at least 300 mm, unless other sources are extremely scarce (Worm & van Hattum, 2006).

Namibia is the driest country in sub-Saharan Africa. In central-northern Namibia annual rainfall ranges from 300–600 mm, 96% falling from November to April (Heyns, 1995; Kluge *et al*., 2008; Sturm *et al*., 2009). The area is characterised by a semi-arid climate with short rainy seasons, high precipitation variability, alternating droughts and floods, ephemeral river systems and brackish or saline groundwater (Heyns, 1995). Presently, most drinking water is abstracted from a reservoir, the Calueque Dam in Angola on the perennial Kunene River that is shared between Angola and Namibia, and transported through an extensive grid of canals and pipelines. Most settlements in the region have access to such supplies in sufficient quantity to serve their drinking water requirements (Heyns, 1995). However, there is no infrastructure to supply irrigation water to rural communities. Many poor households depend on rain-fed subsistence farming during the rainy season to secure their livelihoods (Republic of Namibia, 2006; Republic of Namibia, 2008b). In rural and remote areas the incidence of poverty is particularly pronounced with 38% of the population being poor (Republic of Namibia, 2008a). Agricultural yields are generally very low, leaving many households vulnerable to food insecurity and inadequate food supplies (Republic of Namibia, 2008b; Werner, 2011). A survey conducted by the Food and Agricultural Organization showed that many inhabitants, especially women, wish to extend their garden activities. However, the biggest limiting factor is the lack of sufficient and affordable water for irrigation. Thus most respondents stated that they need help to collect rain (Dima *et al*., 2002). The Namibian Third National Development Plan (NDP3) recognised the low and erratic rainfall and the poor soil quality of the region to be major impediments to a meaningful poverty reduction (Republic of Namibia, 2008b). While the Government of Namibia has responded by developing a comprehensive policy framework to promote household food security, insufficient attention is given to encourage micro- to small-scale local food production (Werner, 2011). Current policies and legislation encourage the use of alternative water sources (Republic of Namibia, 2008a). During the 1950s and 1960s several attempts have been made to harvest rain in uncovered pump storage dams in central-northern Namibia. However, owing to poor water quality, caused by evaporation, pollution and salinisation, the dams fell into disrepair (Driessen & Jokisch, 2010). New investments in more appropriate rainwater harvesting infrastructure could have a broad range of benefits and give essential impetus for the regional economy and poverty reduction. However, in spite of its potential in Namibia, rainwater harvesting has so far not been considered in the current National Water Supply and Sanitation Policy (Republic of Namibia, 2008c) nor in the latest Water Act (Republic of Namibia, 2004).

The aim of this study is to assess the benefits of rainwater harvesting in irrigating small-scale gardens and to propose policy and financing implications for Namibia. In addition, the goal was to draw possible generalisations and broader implications for other regions. The study summarises the benefits identified in previous studies and presents research results of a cost–benefit analysis and first monitoring results for the most promising pilot rainwater harvesting facilities. The amount of investment and number of created jobs related to an up-scaling of rainwater harvesting is modelled and considered in relation to existing Namibian investment in irrigation and drinking water supply. Financing problems are revealed and a financing concept and policy implications are proposed to up-scale the technology in Namibia.

2. Pilot rainwater harvesting facilities in central-northern Namibia

The project CuveWaters[1] introduced three different options for *ex-situ* rainwater harvesting in central-northern Namibia. The pilot plants were built in the villages Epyeshona and Iipopo in the Oshana region and were conceived based on a preliminary literature research (Gould & Nissen-Petersen, 2006), a participatory demand-responsive approach with local communities (Deffner & Mazambani, 2010; Deffner *et al.*, 2012; Zimmermann *et al.*, 2012) and consultations with Namibian ministries and the Namibian Desert Research Foundation. During this process the pilot plants were adjusted to local needs and wishes in terms of size, combinations and materials. The three introduced facilities differ in terms of harvesting surface and storage media; the first consists of a corrugated iron roof (100 m^2) and a tank (30 m^3) either made of ferrocement, bricks or polyethylene. Such tanks can be used for single households and public buildings (schools, clinics, etc.) and are sufficient to irrigate up to 90 m^2 of cultivated garden area. A second pilot facility collects rainwater from a concrete ground catchment (480 m^2) and a greenhouse roof (160 m^2) and stores the water in a covered underground ferrocement tank (120 m^3) and a covered and sealed pond (80 m^3). The stored water irrigates an outside garden (900 m^2) and a greenhouse (160 m^2) jointly used by six households. A third pilot facility collects rainwater from nearby ephemeral rivers, so-called Oshanas, at the height of the rainy season and stores the water in a covered ferrocement underground tank and a pond with a combined storage capacity of 400 m^3. The stored water is sufficient to irrigate a 1,000 m^2 outdoor garden area and a greenhouse of 176 m^2, which are jointly managed by ten households. The Oshanas are difficult to use for permanent irrigation owing to high evaporation rates and therefore quick quality degradation and thus salinisation of the water.

This study assesses the two most promising rainwater harvesting facilities based on a preliminary assessment of the pilot plants (Jokisch *et al.*, 2011). The first is the ferrocement tank with roof catchment at household level as piloted in Epyeshona village (Figure 1). The second is the pond with roof catchment at community level which is an optimal combination of piloted facilities in Epyeshona based on project experience and costs (Figure 2; Table 1). The possible duration of irrigation of gardens

[1] http://www.cuvewaters.net.

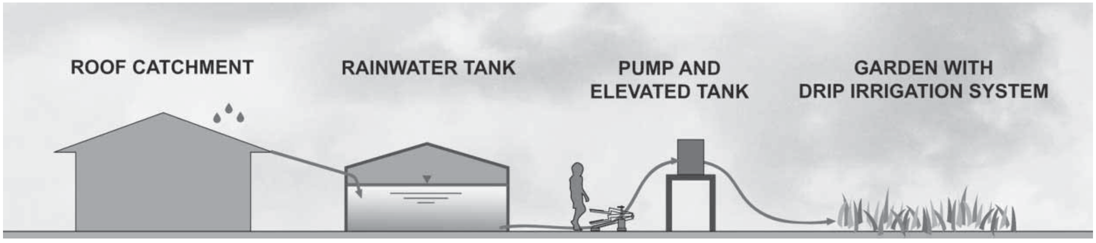

Fig. 1. Rainwater harvesting with roof catchment and ferrocement tank at household level.

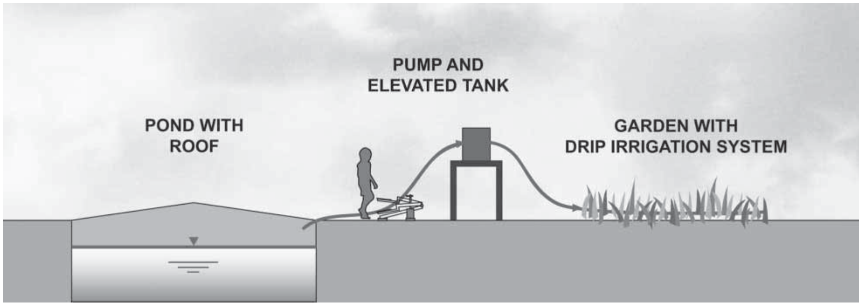

Fig. 2. Rainwater harvesting with roof catchment and pond at community level.

Table 1. Proposed rainwater harvesting options in central-northern Namibia.

Rainwater harvesting option	Tank material	Catchment material	Catchment area (m^2)	Storage volume (m^3)
Tank with roof catchment household level	Ferrocement	Corrugated iron	100	30
Pond with roof catchment community level	Dam liner	Corrugated iron	285	80

with harvested rainwater depends on the irrigation technique, cropping pattern, garden area and the extent of the rainy season. Considering these factors, the stored water is sufficient for the irrigation of one or two additional annual growth seasons. In the project region, rainwater harvesting is meant to enhance the water supply for the productive irrigation of small-scale gardens and not to serve as a substitute for drinking water. However, in remote areas far from the existing pipeline grid harvested rainwater could also be treated and serve as drinking water.

3. Methodology

3.1. Benefits of rainwater harvesting for gardening

The benefits of rainwater harvesting were assessed through a literature review and categorised in technological, economic, environmental and social terms. In this section, non-market benefits were listed in a qualitative manner since placing monetary values on environmental and social non-market costs and benefits is extremely difficult, controversial and not always meaningful (Atkinson & Mourato, 2008).

3.2. Financial cost–benefit analysis

In this section, we assessed the financial benefits of rainwater harvesting-based gardening in monetary terms. We carried out a financial cost–benefit analysis by identifying monetary costs and benefits of rainwater harvesting and gardening for a household or micro-entrepreneur. A cost–benefit analysis involves the identification of costs and benefits occurring over the economic life of a project (Gilpin, 2000; Pearce *et al*., 2006; Ward, 2012). The common method of reducing costs and benefits over the lifespan of a facility to a unique value is the net present value (NPV) method (LAWA, 2005; Pearce *et al*., 2006). Key steps are first to identify the costs and benefits of a project, second to quantify costs and benefits in monetary terms as far as possible and third to discount costs and benefits over the lifetime of the project with a selected discount rate. In purely economic terms, the production of a good is economically justified when the total benefits exceed the total costs (Gilpin, 2000). Benefits correspond to the value of gardening produce at market prices, while costs are equal to expenses. A medium discount rate of 5% was used over an estimated life span of 40 years for the ferrocement tank and 20 years for the pond. These values are based on experiences made by the responsible Kenyan rainwater harvesting consulting company 'One World Consultants' (Kariuki, 2012, personal communication) which has constructed more than 100 rainwater harvesting tanks and ponds in several countries in eastern and southern Africa. The NPV has been calculated as Equation (1) (LAWA, 2005):

$$NPV = -I_0 + \sum_{t=1}^{T} R_t \bullet (1+i)^{-t} \quad (1)$$

where NPV = net present value, I = investment, t = time period from 0 to T, R_t = inflow-outflow in period t, T = time horizon (life span), and i = discount factor. The costs of a rainwater harvesting and gardening facility include material investment costs, labour construction costs and operation and maintenance costs. Material costs include the tank, the pipes and gutters for the roof, the garden fences and the drip irrigation system, Operation and maintenance costs include annual materials costs for spare parts, seeds, fertilizer and pesticides. In a first step, we conducted a cost–benefit analysis including all these costs. In a second step, to show the potential for a more positive cost–benefit ratio, we included only labour, garden material, operation and maintenance costs and excluded the material costs for the rainwater harvesting facility. We calculated with material costs that occurred during the pilot construction phase, operation and maintenance costs were estimated based on local costs and first project experience during the pilot phase. Additionally, we estimated material costs without the conditions of the project.

Financial benefits, the revenue from gardening products at market prices, were modelled based on crop yields, local irrigation requirements, garden area and local market prices. Crop yields were taken as indicated by Price Waterhouse Coopers (2005). Possible garden areas to irrigate with the harvested rainwater were calculated with modelled local irrigation requirements. Specific crop water requirements were calculated with local climate data using the Food and Agricultural Organisation (FAO) software CROPWAT 8.0 (FAO, 1992). A drip irrigation system efficiency of 0.75 was used assuming a conveyance efficiency of 0.85 and an application efficiency of 0.9, calculated according to Brouwer *et al*. (1989) In a preliminary assessment four garden variants considering the amount of annual harvested rainwater were modelled (Woltersdorf *et al*., 2013). The garden size was fitted so that the rainwater harvesting facilities are sufficient for full irrigation with a frequency of 3 out of 4 years, a probability level recommended as appropriate by the FAO (Savva & Frenken, 2002). This study presents a subsistence and a market garden variant. The market scenario contains tomatoes planted in the pilot village Epyeshona, modelled assuming one annual growth cycle with a market price monitored in the market of Epyeshona in 2011. The subsistence garden variant contains vegetables and fruits suitable for household consumption; the surplus can be sold at local markets, planted for two annual growth cycles (Woltersdorf, 2010). Owing to the lack of local market prices, prices were assumed as indicated by Price Waterhouse Coopers (2005) which presents wholesale market prices for imported horticulture products from January to December 2003 to Namibia in N$ per ton. The follow-up study from Price Waterhouse Coopers in 2008 (Price Waterhouse Coopers, 2008) was not used to owing to the unavailability of all data needed. In addition, the CuveWaters Project monitors local prices, which are, however, inconsistent so far owing to the lack of experience of the rainwater harvesting tank owners. In both garden variants yields and revenues are determined to be achieved in 3 out of 4 years, when the garden area can be fully irrigated. In 1 out of 4 years, owing to natural precipitation variability, precipitation is lower and not sufficient to irrigate the garden area fully and therefore yields and revenues will be lower; this is not presented in this study. Further detail regarding garden variants, precipitation probability analysis and calculation of irrigation requirements exceeds the scope of this paper and is provided by Woltersdorf *et al*. (2013).

3.3. Monitoring pilot plants

The rainwater harvesting pilot plants were monitored in terms of maintenance effort and costs, water use and gardening input and output among other criteria. Most data were monitored by tank owners, while some data were also monitored by project team members. This paper presents the first monitoring results from the pilot village Epyeshona of yields of harvested vegetables and local market prices achieved in 2011. Monitored market prices were compared to market prices used in this study for the cost–benefit analysis indicated by Price Waterhouse Coopers (2005).

3.4. Comparison of rainwater harvesting facilities to the Namibian green scheme project

The Namibian government plans to implement an ambitious agricultural project known as the green scheme project (Republic of Namibia, 2008d). In order to put our proposed rainwater harvesting and gardening infrastructure in the light of the local situation, rainwater harvesting and associated garden facilities were compared to the envisaged Namibian green scheme project. The emphasis is to estimate an order of magnitude and to put these different infrastructures in relation to each other rather than calculating accurate absolute numbers. Information about the green scheme was taken from the literature (Weidlich, 2007; Republic of Namibia, 2008d). Over the next 15 years the green scheme plans to create 11,750 full time equivalent jobs. This study calculated how many rainwater harvesting facilities and gardens would need to be constructed to create the same number of 11,750 jobs. Then the green scheme and the rainwater harvesting and garden facilities were compared in terms of required investment and investment per job. For comparability, only investment costs of labour and material were included over a time span of 15 years. Assumptions and estimations are based on the pilot construction phase of the CuveWaters project. The same market and subsistence planting schemes as designed for gardens irrigated with harvested rainwater were transferred to the envisaged area of the green scheme. Owing to the lack of further data about the green scheme, such as operation and maintenance costs, a NPV calculation was not possible.

3.5. Financing of rainwater harvesting facilities

Financing rainwater harvesting and garden infrastructure is the determining criterion for an up-scale of the technology. These costs were related to the household income in central-northern Namibia in order to determine the possibility of financing these infrastructures. We evaluated the possibility of financing rainwater harvesting facilities with microcredits and proposed financing possibilities.

4. Results

4.1. Benefits of rainwater harvesting for gardening

Rainwater harvesting for gardening offers numerous benefits to local communities in technological, environmental, social and economic terms (Table 2). While rainwater harvesting-based gardening broadly effects and stimulated the regional economy, livelihood benefits extend far beyond material gain. Therefore the technology has the potential to become an important part of Namibia's water infrastructure.

During the construction of the pilot tanks, a team of tank technicians, known in the region as the 'Blue Team', have been enabled to build new tanks and operate and maintain existing tanks, plan budgets, calculate costs and procure construction materials. The technicians proved their skills in constructing a privately financed tank in the absence of the CuveWaters staff. Tank users were trained in proper tank operation and maintenance, gardening and irrigation techniques. Trained technicians, tank users and farmers were highly committed owing to community involvement from the very beginning. The pilot rainwater harvesting facility soon became locally known as the 'Epyeshona Green Village' and represents a local success story receiving considerable attention from the media and people from surrounding villages.

Nevertheless the implementation of small-scale water infrastructure is associated with certain risks and challenges. In rural parts of Namibia, like in most other parts of rural Africa, the low level of education makes it extremely difficult to implement the necessary structures to run gardening ventures that aim to supply markets in the region. Training and education is also essential to counter the lack of knowledge of horticultural production in the region. An additional challenge for planning gardens irrigated with rainwater harvesting is the high rainfall variability in the region (UNEP, 2006).

4.2. Financial cost–benefit analysis

4.2.1. Cost. The costs of pilot rainwater harvesting facilities and estimated costs without project conditions are shown in Table 3.

Table 2. Benefits of rainwater harvesting.

Area	Benefits of rainwater harvesting and gardening	Source
Technology	• Maintenance is easy, therefore the technology is also appropriate for remote rural areas • Local water resources are used instead of inter-basin water transfer	Li *et al.* (2000)
Economy	• Broad spill-over effects for the regional economy (e.g. knowledge extension for rainwater harvesting and gardening) • Job creation and income generation in poor rural and peri-urban communities through • Tank and garden construction, maintenance • Local market sale of crops • Education of tank builders, gardeners, etc. improves own (career) prospective for future life • Productive use of rainwater • Higher crop yields • Extended annual planting season of crops through irrigation into the dry season • Possible to plant crops with a longer growth period and higher water requirements (i.e. tomatoes, cabbages) • Additional annual harvest during the dry season achieves higher revenues	Agarwal *et al.* (2001); Senkondo *et al.* (2004); Yuan *et al.* (2003); Rockström *et al.* (2002)
Environment	• Adaptation strategy to climate change and climatic variability • Effective use of heavy rainfall events • Bridge the dry season • Higher crop growth security by bridging rainfall variations and dry periods during the rainy season • Provides additional water supply reducing pressure and demand on surrounding surface water • Contributes to the regeneration of landscapes by increasing biomass for food, fodder, fibre and wood for human consumption	Pandey *et al.* (2003); Barron (2009); Rockström *et al.* (2002); UNEP (2006); Ngigi *et al.* (2007); Jianbing *et al.* (2010); van Steenbergen & Tuinhof (2009); Barron (2009); Li *et al.* (2000); Machiwal *et al.* (2004); Barron (2009)
Social	• Improved food-security and availability particularly during the dry season • Increased household and community self-sufficiency • Improvement of living conditions for vulnerable or marginalised groups through a better diet and the possibility to engage in a productive activity • Time saved for productive activities through availability of water near the house • Improvement of children's education and health conditions due to additional income • Enables communities to adapt to droughts and declining availability of drinking water • Creation of knowledge and capacity building	Wakefield *et al.* (2007); Wills *et al.* (2010); Swanwick (2009); van Averbeke (2007)

Table 3. Costs of rainwater harvesting and gardening facilities in central-northern Namibia.

Type of facility	Material (N$)[a]			Labour construction (N$)[b]	Operation and maintenance per year (N$/yr)
Ferrocement tank (30 m³)	School (under specific project conditions)	13,592	Ferrocement, gutters, pipes	5,500	100
	Household (under specific project conditions)	18,571			
	Without specific project conditions, estimated down (see below)	12,000			
Garden	Market: 1 crop cycle/yr (52 m²)	2,572	Fence, drip irrigation, pedal pump, tools, (shade net)	none	200 (material) 560 (seeds, pesticides, fertilizer)
	Subsistence: 2 crop cycles/yr (84 m²)	3,320			200 (material) 100 (seeds, pesticides)[c]
Pond (80 m³)	Community	48,766	Timber, dam liner, Corrugated iron sheet, gutters, pipes	8,100	155
	Estimated down	35,000			
Garden	Market: 1 crop cycle/yr (229 m²)	6,615	Fence, drip irrigation, pedal pump, tools, (shade net)	none	400 (material) 1,550 (seeds, pesticides, fertilizer)
	Subsistence: 2 crop cycles/yr (148 m²)	4,808			400 (material) 300 (seeds, pesticides,***)

[a]Currency exchange rate: 1 N$ = € 0.07625 (oanda.com, on 17 September 2013).
[b]Labour costs are calculated with Namibian union labour tariffs of 100 N$/day.
[c]Subsistence farmers are assumed to use goat manure as fertilizer.

The major cost component of a rainwater harvesting and garden facility are the material costs of the rainwater harvesting facility. The market garden contains a shade net, while the subsistence garden does not, as it contains fruit trees for shade. Costs for garden material and operation and maintenance costs are relatively low, for example because only pedal pumps are used for pumping the stored water into the irrigation system. It has to be considered that during the pilot construction phase material costs were extraordinary high, as the project was forced to build during a specific and limited timeframe before holidays and during the rainy season. During this period market prices are higher and, because Oshanas were flooded, the sand had to be purchased. Therefore prices are not transferable to 'without project' conditions and costs are expected to decrease down to an estimated 12,000 N$ for the ferrocement tank and 35,000 N$ for the pond if construction takes place at a greater scale without project conditions (i.e. built by locals in the dry season with optimised material use). In addition, government bulk purchase of important raw materials such as wood, steel and cement might drop current monopoly prices considerably.

4.2.2. Benefit. The ferrocement tank achieves annual revenues from gardening of 5,053 N$ (457 €) (337 kg tomatoes) in the market garden variant and 1,143 N$ (103 €) (548 kg of fruit and vegetable) in the subsistence garden variant (Table 4). The pond achieves annual revenues from gardening of

Table 4. Revenues per year of gardening products from rainwater harvesting with different garden variants.

	Crop type	Planting date[a]	Harvesting date[a]	Cultivated area (m^2)	Local yield per area[b] (kg/m^2)	Price[b] (N$/kg)	Gross irrigation requirement[a] (m)	Production (kg)	Revenue (N$)
Ferrocement household tank (30 m^3) with roof catchment (100 m^2)									
Subsistence (worst case)	Water melon	1 Jan	21 Mar	17	5.0	1.07	5.0	86	91
	Cucumber	1 Jul	13 Oct	17	4.0	5.47	10.1	68	372
	Cabbage	1 Jan	14 Jun	17	3.1	0.96	12.9	53	51
	Pepper	1 Dec	30 Mar	17	1.4	6.13	10.8	24	146
	Tomato	15 Apr	2 Sep	17	4.0	2.91	13.8	68	198
	Potato	1 Apr	24 Jul	17	5.2	1.54	8.6	88	136
	Orange[d]	1 Jan	31 Dec	1	23.0	0.92	25.5	161	149
	Sum/year			52			86.7	548	**1,143**
Market (best case)	Tomatoes	1 Jan	4 Jun	84	4.0	15.0[c]	63.9	337	**5,053**
Pond (80 m^3) with roof catchment (200 m^2)									
Subsistence (worst case)	Water melon	1 Jan	21 Mar	48.2	5.0	1.07	14.1	243	259
	Cucumber	1 Jul	13 Oct	48.2	4.0	5.47	28.5	193	1,055
	Cabbage	1 Jan	14 Jun	48.2	3.1	0.96	36.5	151	145
	Pepper	1 Dec	30 Mar	48.2	1.4	6.13	30.6	67	413
	Tomato	15 Apr	2 Sep	48.2	4.0	2.91	39.2	193	562
	Potato	1 Apr	24 Jul	48.2	5.2	1.54	24.4	249	385
	Orange[d]	1 Jan	31 Dec	3	23.0	0.92	1.5	345	318
	Sum/year			146			174.9	1,442	**3,138**
Market (best case)	Tomatoes	1 Jan	4 Jun	229	4.0	15.0[c]	174.1	918	**13,774**

[a]The planting and harvesting date has been determined based on Savva & Frenken (2002) with the growth season coinciding with the rainy season. The gross irrigation requirement has been calculated with Cropwat 8.0 based on local climate data from Ondangwa station; data: Namibian Weather Bureau and crop data for semi-arid regions Savva & Frenken (2002). The area is fitted with probability of tank failure determined to occur in 3 out of 4 years (Woltersdorf *et al.*, 2013).

[b]Data: Price Waterhouse Coopers (2005).

[c]Data: project monitoring of market price in Epyeshona village in 2010.

[d]The orange fruit tree is assumed to occupy 1 m^2 on the ground and 6 m^2 at the treetop.

13,774 N$ (1,247 €) (918 kg tomatoes) in the market garden variant and 3,138 N$ (284 €) (1,442 kg of fruit and vegetable) in the subsistence garden variant.

4.2.3. Cost–benefit. The NPV of both rainwater harvesting facilities is negative when assuming subsistence garden production and integrating the material costs of the rainwater harvesting facility (Table 5). Assuming a market garden production, both facilities have a positive NPV: the ferrocement tank of +46,943 N$ (4,248 €) and the pond of +95,711 N$ (8,662 €). Subsistence garden production can also have a positive NPV when excluding the material costs of the rainwater harvesting facility, while still including labour costs for rainwater harvesting facility construction, operation and maintenance (O&M) costs and garden material costs. In this case, the ferrocement tank has a NPV of +6,997 N$ (633 €) and the pond of +25,578 N$ (2,315 €). Further research results for the CuveWaters project clearly show that in remote villages of central-northern Namibia (e.g. more than 65 km distance from the pipeline scheme) the construction of an adequate number of rainwater harvesting tanks can be considerably cheaper than a connection to the pipeline scheme (Jokisch *et al*., 2011).

4.3. First results from monitoring

Pilot rainwater harvesting tanks and gardens were built in the village of Epyeshona in 2010; a drip irrigation infrastructure was added in 2011. The first harvest in 2010 included butternut, spinach and different varieties of pepper. Gardening products served household consumption and achieved good prices on local markets contributing to household income generation. Since February 2011, the farmers monitor the amount of harvest, income, amount of fertilizers and pesticides applied on the fields. The most popular crop so far is spinach, mainly because it can cope well with the poor soil conditions and grows fast. In 2012, individual household farmers earned up to 900 N$ per month from the sale of spinach. In the greenhouse, tomatoes performed best, as they can be harvested over a long period and generate the highest income. On local markets these tomatoes achieved a mean price of 13 N$/kg compared to 2.91 N$/kg indicated by Price Waterhouse Coopers (2005). In 2012 the farmers focused mainly on spinach and tomatoes based on their experiences in 2011 and stabilised their income from the individual gardens at around 900 N$ per month from the sale of spinach and tomatoes, but in parallel also produced certain other crops for their own consumption thus improving their own diet and health situation. Furthermore the daily water use decreased as a consequence of more experience and knowledge gained in 2011. So far

Table 5. Cost–benefit analysis of two rainwater harvesting options in combination with gardening assuming best case costs (estimated in case of large-scale production), with discount rate of 5%.

		NPV (N$)	
Rainwater harvesting option	Garden variant	Including: material investment costs, labour construction costs, O&M costs	Including: labour construction costs, O&M costs, excluding: material investment cost
Ferrocement tank (30 m^3), lifespan 40 years	Subsistence (52 m^2) Market (84 m^2)	−10,503 +46,943	+6,997 +64,443
Pond (80 m^3), lifespan 20 years	Subsistence (146 m^2) Market (229 m^2)	−17,521 +95,711	+25,579 +138,811

monitoring shows that revenues used in the worst case garden variant are (partly) underestimated, as real income is considerably higher than expected. This is mainly due to higher prices on local markets in central-northern Namibia compared to wholesale prices in the capital Windhoek, used in the Price Waterhouse Coopers (2005) study. Nonetheless, observed water use was higher than calculated and fluctuated considerably over the course of the season, mainly owing to the little experience of the users.

4.4. Comparison of rainwater harvesting facilities to existing water and irrigation infrastructure in Namibia

In 2003 the Namibian government adopted its green scheme policy through the Ministry of Agriculture, Water and Forestry (MAWF). The green scheme's objectives are to increase commercial large-scale irrigated crop production, import substitution, self-sufficiency, food security at national and household level and create jobs (Weidlich, 2007; MAWF, 2008; Republic of Namibia, 2008d). The scheme aims to put an area of approximately 27,000 hectares under irrigation over a period of 15 years (Republic of Namibia, 2008d; Allgemeine Zeitung Namibia, 2011). Irrigated crops include maize, wheat, pearl millet (mahangu) and vegetables mainly along perennial rivers at Namibia's borders (Weidlich, 2007). For project realisation, over the next 15 years the Namibian government aims to invest 3,311 million N$ and 7,430 million N$ are expected to be contributed by the private sector (Weidlich, 2007; Allgemeine Zeitung Namibia, 2007). According to government estimates the green scheme could create 10,000 permanent and 3,500 seasonal jobs. However funding is a permanent constraint and the major reason for slow progress (Weidlich, 2007). In 2007, Namibia had 9,000 ha under irrigation, including 3,000 ha under the green scheme (Weidlich, 2007). Table 6 puts the proposed rainwater harvesting technology in relation to the Namibian green scheme in terms of total investment, created jobs, irrigated area, estimated value of garden produce and investment per job.

We estimated the amount of rainwater harvesting facilities and gardens that can be constructed and cultivated when creating the same number of 11,750 full time equivalent jobs as planned under the

Table 6. Comparison of gardening with rainwater harvesting and the Namibian green scheme (over 15 years' investment), assuming the creation of 11,750 full-time equivalent jobs per technology option.

	Green scheme	Ferrocement rainwater harvesting tank	Rainwater harvesting pond
Amount of RWH facilities and gardens that can be constructed, creating circa 13,500 jobs over 15 years	–	21,875	22,500
Total investment (million N$)	10,741 million N$	747 million N$ (626 million N$ material costs, 120 million N$ labour costs)	1,119 million. N$ (936 million N$ material costs, 182 million. N$ labour costs)
Irrigated area (ha)	27,000 ha	114 to 184 ha	328 to 515 ha
Estimated value of horticulture produce assuming same crop schemes (million N$/year)	3,150 million N$ to 5,264 million. N$	25 million N$ to 111 million N$	71 million N$ to 310 million N$
Investment per job (N$/job)	914,145 N$/job	63,775 N$/job	95,312 N$/job

green scheme. We estimated that the construction of one ferrocement tank requires a team of one skilled and ten unskilled workers and takes 12 days. Calculating with 250 annual working days it finds that 770 tank builders (70 teams) can construct 21,875 ferrocement rainwater harvesting tanks over a time span of 15 years. A further 10,938 jobs are created in the gardening sector, assuming that workload and income from the gardening with the water from one ferrocement tank is equivalent to one half day job. When creating 11,736 new jobs, 22,500 ponds and gardens can be constructed and cultivated. For this, 486 pond builders (54 teams) with one skilled and eight unskilled workers per team take nine days to construct 1 pond, resulting in 1,500 ponds per year and 22,500 ponds over a period of 15 years. Further 11,250 jobs are created to cultivate gardens, assuming that the workload and income from the gardening with the water from one pond is equivalent to a half day job.

The construction of 21,875 ferrocement rainwater harvesting tanks requires an investment of 747 million N$ resulting in an investment per job of 63,775 N$. The construction of 22,500 rainwater harvesting ponds requires an investment of 1,119 million N$, resulting in an investment per job of 95,312 N$. The income generated with this number of rainwater harvesting tanks and gardens through the sale of horticulture products is 25–111 million N$ per year. These ponds and gardens generate an annual income of 71–310 million N$ (subsistence and market garden variant, respectively). In contrast, the green scheme is expected to require a considerably higher investment of 10,741 Mio N$ creating the same number of jobs but requiring a significantly higher investment per job of 914,145 N$. Assuming the same crop schemes for the green scheme would result in an annually generated income of 3,150–5,264 million N$. However it has to be considered that in reality the green scheme is also producing maize and wheat so that the generated income will be considerably lower than estimated here.

In central-northern Namibia, investment costs for water infrastructure are extraordinary high, owing to the large water supply network (Heyns, 1995). In central-northern Namibia the sales price of grid water is currently around 8.3 N$/m^3, but this price is heavily subsidised. In contrast, we estimate that the full cost recovery price including infrastructure investment costs is between 10 and 15 N$/m^3. In comparison to this, the full cost recovery price of our proposed rainwater harvesting infrastructure (ferrocement rainwater harvesting tank) is 15 N$/m^3. Therefore, the costs per square meter of harvested rainwater are not higher than the cost of grid water.

4.5. Financing of rainwater harvesting facilities

Private financing of initial investment costs represents a problem for most micro-entrepreneurs and is the major limiting factor for the up-scaling of rainwater harvesting. Average annual household income in central-northern Namibia ranges from 26,788 N$ in the Oshikoto region to 45,708 N$ in the Oshana region (Republic of Namibia, 2006). In relation to this income level, tanks and gardens have high investment costs, while the maintenance costs of rainwater harvesting facilities are very low. Therefore, we propose other sources to finance infrastructure material investment costs.

The results of this study indicate that microcredits are not suitable to finance material costs of rainwater harvesting facilities. On the one hand, traditional microcredit loans are usually too small with too short repayment periods (up to 2 years) and are not compatible with the necessary medium- to long-term investment of over 6 years for investment sums of over 12,000 N$. On the other hand repayments for annual interest rates (currently 24–35% p.a. in Namibia) (Chitambo *et al*., 2006) exceed annual garden revenues of the subsistence garden. However, if only garden construction costs have to be financed through a microcredit, the credit can be easily repaid within a reasonable time. For instance, a micro-entrepreneur could assume a microcredit for garden construction of 3,320 N$ (with tank) or 6,615 N$ (with pond) and then repay it within 1 or 2 years with the profits generated from gardening, having subtracted annual maintenance costs for rainwater harvesting and gardening (considering an interest rate of 24%). Annual tank and garden maintenance costs can be easily paid with annual revenues together constituting 21–52% of annual garden revenues in the case of the tank and 15–27% in the case of the pond. Based on these considerations, other sources of finance have to be identified to cover rainwater harvesting facility investment costs. Our suggestion for financing is summarised in Table 7.

5. Discussion

5.1. Proposed policy implications

Owing to the inability of many micro-entrepreneurs and poor households to finance rainwater harvesting and garden infrastructure investment costs privately, other financing solutions have to be found. International institutions such as the Organisation for Economic Co-operation and Development (OECD) and The World Bank are becoming aware of the financing issue and argue that it is unrealistic to base financial planning of water services on full cost recovery of investment costs (OECD, 2009; Banerjee *et al.*, 2010). The OECD therefore adopted a pragmatic policy towards financing investment costs for water services by advocating the concept of sustainable cost recovery.

The concept of sustainable cost recovery entails securing and programming financial means from all sources available to the country in an appropriate combination. This includes tariffs to finance operation and maintenance costs as well as government (taxes) and donor (transfers) support to finance recurrent and investment costs. State support can be justified by the external public benefits from good water services as well as the need to make these services affordable to the poorest households (OECD, 2009). This is also applicable for investments for agricultural water infrastructure.

Many countries wrap their subsidy element into 'soft' loans to utilities or local authorities, which has the advantage of preserving the incentive to make efficient use of the money. While recovering operation and maintenance costs or even investment costs from tariffs is an important economic principle in most circumstances, using tariffs to recover full costs of water services, including investment and

Table 7. Financing a proposal for rainwater harvesting and gardening infrastructure.

Type of cost	Financing	Pay back
Material cost for rainwater harvesting infrastructure	Government-funded (with beneficiary contribution depending on poverty level)	No pay back
Material cost for garden	Micro-entrepreneur with microcredit	Tank: 2 years (market), 22 years (subsistence)[a] Pond: 1 year (market), 2 years (subsistence)[a]
Annual maintenance cost for rainwater harvesting infrastructure and garden	Micro-entrepreneur with revenues from gardening	O&M costs constitute: Tank: 21% (market) to 52% (subsistence) of annual revenues. Pond: 15% (market) to 27% (subsistence) of annual revenues

[a]Time to pay back microcredit considering the available profit after having subtracted operation and maintenance costs from annual revenues.

major rehabilitation, is unusual even in developed countries. In practice, in many countries the governments prefer to subsidise investment costs through taxation (OECD, 2009). Nonetheless, recovering the cost of providing service, at least for operation and maintenance, is a stated objective of water utilities around the world (Banerjee *et al*., 2010). Therefore, government could subsidise rainwater harvesting infrastructure investment costs. Beneficiary contribution of capital costs, for instance of 5–20% depending on beneficiary poverty level, could be considered in order to enhance ownership and sustainability. Then, local tank owners and farmers can finance garden investment costs and maintenance of tanks and gardens by assuming a microcredit and repay it with market sale of gardening products. In doing so, the government could give incentives for value added production, local job creation, improvement and extension of water infrastructure and regional development. Therefore this study recommends state-funded rainwater harvesting material costs.

Besides these financial aspects, current Namibian policy is also an important precondition for the further development of rainwater harvesting-based gardening. The FAO recognises agricultural growth involving smallholders, especially women, to be most effective in reducing extreme poverty and hunger when it increases returns to labour and generates employment for the poor (FAO *et al*., 2012). Historically, smallholders have proved to be key players in meeting food demand. Today, smallholders face considerable challenges, such as limited accessibility to markets, credit, information and resources. Yet, smallholders are capable of meeting these challenges, although they need an appropriate enabling environment in order to do so. Providing improved rural infrastructure such as roads, markets, storage facilities and communication services will reduce transaction costs, enable farmers to reach markets, contribute to a better conservation of products and provide the possibility to add value to products by, for example, processing food. Interventions to ensure land tenure and property rights security will encourage smallholders to invest in land improvements. Provision of education in rural areas is essential if smallholders are to participate in markets (FAO *et al*., 2012). Currently, Namibia has an extensive policy framework to foster food security (Werner, 2011).

With regard to irrigation, however, current policies focus on large-scale commercial production and do not specifically target small-scale food producers at the local level. Therefore, despite the political intention of improving household food security, the majority of poor households in rural areas cultivating less than 20 ha does not directly benefit from current political programmes (Werner, 2011). The proposed rainwater harvesting infrastructure is explicitly not intended to replace the large-scale agriculture plans of the Namibian government. Instead, it is intended to complement it by also addressing small-scale agriculture and local market production. Thus, Namibian and international experts (e.g. Dima *et al*., 2002; Werner, 2011) recommend a review of the current policy framework to provide more focus on micro- to small-scale food production (below 20 ha) and on appropriate technical support and advice in urban, peri-urban and rural areas. This policy review also needs to address institutional mandates and responsibilities in order to provide the appropriate regulation. Promotion of gardening and rainwater harvesting require a concerted campaign at all levels of government and the target population to explain the potential importance and benefits (Werner, 2011). To complement gardening activities, a working infrastructure will be necessary including extension and consulting services for gardening, plant protection and seed nurseries.

An example of financing rainwater harvesting infrastructures with grants is the South African policy 'Financial Assistance to Resource Poor Irrigation Farmers' of the South African Department of Water Affairs and Forestry (DWAF) published in 2004 as part of the National Water Act of 1998. South Africa and Namibia have a similar history of political and economic imbalance between different parts of the population. The South African DWAF aims to promote social and economic development in the country through the use of water in an equitable way. It acknowledges micro-scale vegetable farming, where an estimated 150,000 farmers produce food for millions of people, to be an important sector of rural farming in South Africa. It complements the top-down managed large irrigation schemes that are one of the biggest success stories in agricultural development in the country. The act provides financial assistance for the development of irrigated agriculture by providing resource-poor farmers with grants and subsidies for water supply infrastructure and assistance for water management committees. The grant serves to construct rainwater harvesting storage tanks for resource-poor farmers in rural areas, to serve family food production and other productive uses. The grants provides annually 425,500 €, sufficient to build around 1,000 rainwater harvesting tanks per year (DWAF, 2004). Through this programme, the South African DWAF aims to contribute to the achievement of the UN Millennium Development Goals in South Africa by reducing the number of households suffering from food insecurity (DWAF, 2004). A similar programme can be established in Namibia to reduce poverty especially in its northern regions which are also disadvantaged in terms of economic and agricultural development.

5.2. Transferability of results

Our research and previous studies revealed a broad range of benefits of rainwater harvesting in technical, economic, environmental and social terms. Existing challenges can be handled by training and educating the local population. The results of the cost–benefit analysis in this study showed that rainwater harvesting is a profitable activity with a positive NPV over the lifespan of the infrastructure when planting crops that achieve high local market prices and excluding material costs for the rainwater harvesting facility, while including maintenance and operation costs and garden material. It has to be considered that the result of cost–benefit analyses depends on the choice and quality of data input and often, as in our case, only limited data (e.g. prices and yields of only 1 year from 2003) or data not specific for the model region (e.g. length of growth season for semi-arid regions) are available.

The validity of the results of our cost–benefit calculation has two aspects: the specific data used from the literature are reliable and therefore our specific results are also reliable. However, owing to inter-annual variability of, for example, market prices or agricultural yields, the literature data used from 1 year has limited significance. Therefore, the results of the cost–benefit calculation can be considered as preliminary. In the following years further field data should be collected in order to refine the cost–benefit calculation and obtain a more representative result for central-northern Namibia. In reality, the cost–benefit ratio depends on the actual lifespan of the facilities which we determined according to the extensive experience of a Kenyan rainwater harvesting consultant who constructed more than a hundred rainwater harvesting facilities in Kenya and Uganda in low-tech areas with comparable conditions to central-northern Namibia. In addition, irrigation requirements were modelled which also depend on climatic and crop data input.

First monitoring results showed that local market prices are higher than assumed (according to Price Waterhouse Coopers, 2005) in the worst garden variant and therefore revenues might be underestimated. This indicates that the benefit might be closer to the best case garden variant with a positive cost–benefit ratio. In addition there is a high demand for agricultural products in local markets. Putting rainwater harvesting in the frame of current water and irrigation infrastructure in Namibia, the results of this study indicate that rainwater harvesting-based small-scale gardening has relative low investment costs per created job. Therefore, the invested funds in rainwater harvesting and small-scale gardens are very effective in creating new jobs.

The role of rainwater harvesting for the irrigation of small-scale gardens has not been sufficiently examined in Namibia. However, ground and roof rainwater harvesting is significant for regions with an annual precipitation of at least 300 mm (Gould & Nissen-Petersen, 2006), contrasting rainy and dry seasons and is suitable for rural as well as peri-urban areas. A constraint to an up-scaling in Namibia is the high material cost of steel mesh, cement and wood compared to the poor local income situation. In other African counties comparable rainwater harvesting tanks, that is, 30 m^3 ferrocement tanks, have similar costs to Namibia. In Asia, material costs are 60–80% lower (Li *et al*., 2000; Agarwal *et al*., 2001; Cruddas, 2007; Kariuki, 2012, personal communication). The reasons are the unavailability of cement and clean graded river sand in some parts of Africa and a lack of sufficient water for construction in others. In addition, many parts of Africa have lower and seasonal rainfall and impervious roofs are smaller in number and size. In particular, compared to typical household incomes rainwater harvesting tanks are more expensive in Africa than in Asia. Nevertheless, rainwater collection is becoming more widespread in Africa and in some parts rapid expansion has occurred in recent years, even though progress has been slower than in Southeast Asia (UNEP 2002). In Namibia, government subsidies are necessary to finance the water harvesting infrastructure. The advantage of these technologies is that they are low-tech, they can be constructed by local inhabitants themselves, they better integrate into the natural landscape and into social circumstances and necessary investments are significantly lower than for large-scale irrigation projects. The water buffering capacity of the rainwater harvesting facilities are a good adaptation to the increasing variability of precipitation caused by climate change. Therefore, rainwater harvesting for irrigating gardens has a great future.

6. Conclusion

This study has shown that rainwater harvesting for the irrigation of small-scale gardens and the associated capacity development measures provide a wide range of benefits. Water harvesting and its productive use for horticulture is one key in reaching the poor in peri-urban and rural areas as the decentralised infrastructure provides them with direct access to means of production and allows them to improve their daily meals and their income in order to overcome poverty. In addition, rainwater harvesting is an effective adaptation strategy to climate change and climatic variability. Yet, the potential of rainwater harvesting in combination with gardening has not been developed in Namibia so far. To achieve broader benefits for the regional economy, investments in infrastructure and an adequate policy framework are needed. Owing to the high material costs in Namibia compared to low household incomes, subsidies are necessary to finance the water harvesting infrastructure. We recommend government funding of the rainwater harvesting infrastructure and private finance of garden and maintenance costs. The adoption of rainwater harvesting in Namibia's water policy framework would improve water access for communities in rural areas. Then, rainwater harvesting is a valuable contribution to reach Namibia's Vision 2030 and the Millennium Development Goals.

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RESEARCH ARTICLE

Small-scale water reuse for urban agriculture in Namibia: Modeling water flows and productivity

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Treating and reusing municipal wastewater for urban agriculture raises water productivity. This paper developed a methodology to quantify water flows and productivity of a proposed infrastructure including water supply, sanitation, wastewater treatment and water reuse for agriculture. The methodology consists in calculating the pathogen reduction achieved with wastewater treatment, designing a crop scheme for the irrigation with treated water, modeling irrigation requirements and quantifying water flows with mathematical material flow analysis. This methodology was applied for the current state and with the planned facility in semi-arid Namibia. This infrastructure has the potential to raise water productivity by +10% as household water use increases with improved sanitation. Compared to not reusing the water for agriculture, water productivity can be raised by +39%. This methodology allowed the consideration of the impact of facility user behavior on water flows and found that water productivity increases less than computed with a fixed wastewater inflow.

Keywords: municipal water reuse; urban agriculture; water cycle; material flow analysis; uncertainty; productivity

1. Introduction

Water for drinking, hygiene and agriculture is scarce in semi-arid regions. Worldwide around 1.2 billion people live in areas of physical water scarcity, 1.1 billion lack access to improved water supply and 2.6 billion (194 million alone in cities) are without improved sanitation (UN Water and FAO 2007). Poor water supply and sanitation have a considerable health impact (WWAP 2012). With increasing urbanization, cities require appropriate urban infrastructure to improve water supply and sanitation services that contribute to a sustainable development (Meinzinger 2010). In addition, agriculture accounts already now for around 70% of global freshwater withdrawals and to meet growing future demand, the world needs to produce 70% more food by 2050 (WWAP 2012). In developing countries urban dwellers often partly or completely depend on urban agriculture that contributes to solving several urbanization problems by enhancing the availability of fresh food, providing employment, increasing income and food security, greening cities and recycling wastes (van Veenhuizen 2006, WWAP 2012). Involving 800 million urban residents worldwide in 1996 (Smit *et al.* 1996), in the last couple of decades urban and peri-urban agriculture has been steadily increasing (van Veenhuizen 2006). Therefore, it is essential to provide urban farmers with sufficient means of production while using scarce resources such as water most productively. A holistic approach entails closing the loop between sanitation and agriculture by reusing treated municipal wastewater and recovering nutrients from human excreta for the irrigation and fertilization of food crops that are in turn consumed by humans (Meinzinger 2010, Pasqualino *et al.* 2011).

During the past four decades the reuse of treated water in agriculture has been rapidly increasing worldwide, particularly in regions facing physical or economic water stress, growing urban populations and growing demand for irrigation water (Asano 2007, Hamilton *et al.* 2007, Drechsel *et al.* 2010, Scheierling *et al.* 2010). Especially in regions with low nutrient applications in agriculture such as in Sub-Saharan Africa, the reuse of treated and nutrient rich municipal water for irrigation increases yields and local food production by providing a stable supply of water and nutrients (Zaidi 2007). Today the reuse of treated and untreated wastewater in agriculture is practiced on an estimated 20 million ha in 50 countries – a tenth of the world's irrigated crops (Jiménez and Asano 2008). Semi-arid higher income countries (e.g. USA (California), Israel and Spain) extensively practice planned reuse of treated water for irrigation, while middle income countries (e.g. Mexico, Chile, Egypt) use not only treated but also untreated wastewater, indicating a transition between unplanned and uncontrolled reuse to planned and controlled reuse. In lower income countries, water supply and sanitation is often inadequate and highly polluted waters from surface-water bodies are reused for irrigation, predominantly unplanned

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and unintentionally. The resulting agricultural activities are most common in and around cities, as in most cities of Sub-Saharan Africa (Drechsel *et al.* 2010, Scheierling *et al.* 2010). In spite of its potential, so far the collection and treatment of municipal wastewater and its direct reuse in urban agriculture is not widely practiced in developing countries due to a lack of appropriate water infrastructure (Drechsel *et al.* 2010, Scheierling *et al.* 2010). Previous studies have shown that failure to manage existing water reuse schemes optimally has led to significant problems such as health risks through the spread of pathogens, soil degradation through salinization, toxic ions, eutrophication or increased mobility of organic contaminants and critical public perceptions toward the reuse of treated water for agricultural irrigation (Hamilton *et al.* 2007, O'Connor *et al.* 2008, Murray and Ray 2010, Chen *et al.* 2012). In addition, conducting only a simple calculation with a fixed wastewater inflow including water consumption per person and number of inhabitants without also considering social aspects and user behavior risks to overestimate the expected quantity of water available for water reuse. Planning new water and wastewater infrastructure depends on the choice and quality of data. The low availability of suitable and certain data is a common problem in developing countries.

A systematic assessment of a proposed water supply, sanitation, water treatment and water reuse infrastructure during project planning could help to considerably diminish these challenges. A first step is a quantification of water flows and water productivity from a system perspective. So far several studies on water flows between households and agriculture have been carried out in developing countries usually on a city scale or regional scale (Belevi 2002, Montangero *et al.* 2005, Meinzinger *et al.* 2009, Erni *et al.* 2011). To the authors' knowledge this study is the first to assess the water flows for a small-scale sanitation and water reuse scheme for agriculture. The aim of this study was to develop and apply a methodology to quantify water flows and water productivity of a new water infrastructure including water supply, sanitation, water treatment and water reuse for agriculture. The research is relevant for the future planning and decision making process before the introduction of such a new infrastructure to show to what degree water needs can be reduced and productivity raised in a given area. For this, a combination of modeling methods including mathematical material flow analysis and modeling of crop irrigation requirements was developed. The mathematical material flow analysis accounts for the low availability of direct data and for data uncertainty by including data ranges and probability distributions and by assessing the effects of different assumptions in cases. The proposed infrastructure is designed to offer sanitation facilities for around 1500 inhabitants and to irrigate an agricultural area of 1.5 ha. The study forms the basis for further assessment steps; the quantification of salt and nutrient fluxes which are solved in the water and the potential for nutrient recycling. Finally, a sustainability analysis of the proposed water reuse infrastructure will include economic and social aspects. Nutrient flows, salt flows, economic and social aspects are not within the scope of this paper and will be published elsewhere.

2. Study area

The city of Outapi in central-northern Namibia exemplifies the typical problems of water supply and low access to sanitation facilities of urban areas in low-income countries (see Deffner *et al.* 2012). The Namibian government undertakes considerable efforts to improve the access to water supply and sanitation in accordance with the Millennium Development Goals (Republic of Namibia 2008). However, water resources are scarce and consequently water use conflicts between households and agriculture occur. In order to use scarce water resources most productively, a new sanitation and water reuse infrastructure is proposed to be implemented in the town. Outapi has about 4600 inhabitants, high population growth and mostly low-density and partly informal settlements (Kluge *et al.* 2008). The region is semi-arid and water scarce: Precipitation is highly variable ranging from 262–666 mm/year in 2/3 of years, with an average of 464 mm, 96% occurring from November to April (Woltersdorf *et al.* 2013). Annual potential evaporation is estimated to be 2600 mm (Heyns 1995). Groundwater is mostly brackish or saline, wetlands are seasonal, perennial rivers are absent and frequent droughts alter seasonal floods. Freshwater is provided by a water pipeline originating from the Angolan-Namibian border river Kunene (Heyns 1995). Growing demand for water has increased pressure and dependency on water infrastructure, making the region particularly vulnerable (Kluge *et al.* 2008). Access to drinking water and sanitation in the four project settlements in Outapi (Shack dwellers, Tobias Hainyeko, Onhimbu and Okaikongwe) was investigated during a household inventory survey in June 2012 (Deffner *et al.* 2012). The type of water source predominately used was the communal water taps (95% in Shack dwellers, 91% in Tobias Hainyeko, 87% in Onhimbu, and 96% in Okaikongwe), the remaining used a private tap. Other water sources such as the ephemeral river do not play a significant role ($<2\%$) due to their unreliable and seasonal availability. The minority of the respondents has access to latrines (37% in Shack dwellers, 44% in Tobias Hainyeko, and 4% in Okaikongwe) and most practice open defecation. Only in Onhimbu 90% of the residents use latrines and 10% practice open defecation (Deffner *et al.* 2012). The region has a high demand for agricultural products for food security and import substitution (Government of Namibia 2006). Ongoing population growth, further urbanization, possible effects of an upswing in Angola's economy, plans for commercial agricultural activities in the town's surroundings and expected effects of climate change are likely to increase pressure on already scarce water resources in the area (Deffner and Mazambani 2010).

3. Sanitation and water reuse concept

The innovative infrastructure is proposed by the Cuve-Waters project (see Müller 2012) and provides fresh water, adequate sanitation and resources for agriculture and is planned to consist of four connected parts: sanitation facilities, a vacuum sewer system, a wastewater treatment plant and an irrigation site. Three types of sanitation facilities reflect the different development states of the four settlements in Outapi (Figure 1). In two neighborhoods including an older partially dense part and a new informal suburb (Onhimbu and Okaikongwe) a communal wash-house for a minimum of 250 users offering toilets, showers and sinks for laundry and dish washing will be installed. In a new informal suburb (Tobias Hainyeko) 30 small cluster washhouses will be shared by four households each. In a formalized neighborhood with brick houses (Shack Dwellers), 62 households will be individually connected to water supply and sewage. The wastewater will be collected from these four settlements through a watertight vacuum sewer to prevent the spread of pathogens through flooding in the rainy season. Given the flat topography of the area the vacuum sewer has a lower energy requirement compared to conventional gravitational systems that need to pump the water (Müller 2011). The wastewater will be transported to a wastewater treatment plant with a combined anaerobic (UASB), aerobic, micro sieve and disinfection (UV-light) treatment. Nutrients (78% of nitrogen, 82% of phosphorous and 100% of potassium) are intended to remain in the water. The nutrient rich water will be reused for the irrigation and fertilization of an agricultural area. The wastewater treatment plant will produce biogas by digesting sewage sludge and crop residues from the water reuse site and so partly cover its own electricity and thermal energy demand. Due to space constraints in the city, the Outapi Town Council has assigned an area of 1.5 ha for irrigation next to the treatment plant. The agricultural site will be equipped with a storage pond for treated water and water from the ephemeral river, drip irrigation and an evaporation pond for the drainage water. The steady supply of treated water for irrigation throughout the year means a high reliability for farmers. Revenues from crop sales will help to subsidize drinking water and wastewater tariffs and contribute to the affordability of the operation of the infrastructure for the town and the local users. Community health clubs help to change norms and values regarding hygiene behavior to prevent infections (Müller 2012).

4. Methods and data

4.1 Methods

4.1.1 Crop choice and irrigation requirement for agriculture

A crop scheme for unrestricted irrigation with treated municipal water was designed. The crops were chosen based on health protection and local practices and preferences including local market revenues. Agricultural

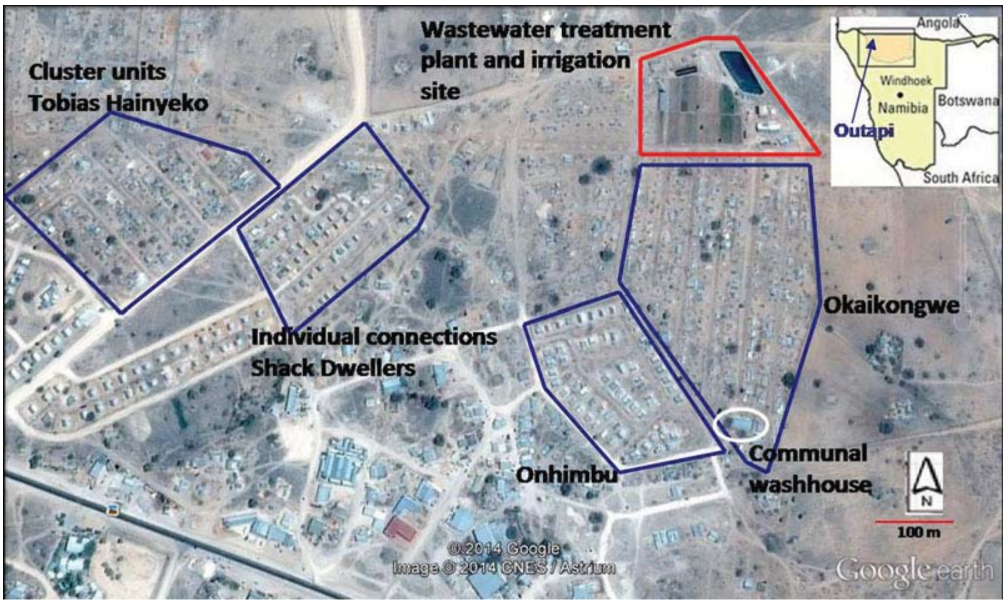

Figure 1. (Color online) Map of the planned sanitation, wastewater treatment and agricultural reuse facility in Outapi. Blue: connected settlements, red: wastewater treatment plant, irrigation fields, storage pond, evaporation pond, white: communal washhouse (satellite image is provided with permission by CNES/Astrium 2013, powered by Google Earth. Map of Namibia: Röhrig 2011, adapted).

yields in Namibia were taken from a study by Price Waterhouse Coopers (2005). Local preferences were determined in close collaboration with local farmers (personal communication Hilengwa 2013). The level of achieved health protection was determined following the approach described in the WHO (2006) health guidelines for the irrigation with treated wastewater. For unrestricted irrigation and full health protection the WHO (2006) requires that the amount of pathogens present in the wastewater is reduced by six log units for leaf crops and seven log units for root crops. The pathogen reduction achieved with the proposed wastewater treatment plant, water storage, drip irrigation and an interval between final irrigation and consumption of produce of three days was calculated indicating a lower and upper range of uncertainty. The wastewater treatment plant includes a microsieve to filter helminth eggs, but unfortunately the WHO (2006) does not provide any data on possible reduction amounts and therefore this could not be included in the calculation. The pathogen die-off on crop surfaces that occurs between last irrigation and consumption depends on climate (temperature, sunlight intensity, humidity), time and crop type. In order to be on the safe side, for all crops a pathogen reduction of two log units was assumed, as indicated for low growing crops irrigated with drip irrigation that grow just above the soil and partially in contact with it. The reason is that it cannot be assured that the harvested part does not contact the soil at some point. With high growing crops, where the harvested part is not in contact with the soil, pathogens can be reduced by further two log units (WHO 2006). In addition, further health protection measures by the consumer further reduce pathogens, including produce peeling, washing and cooking. These are however, not considered here, as the water reuse will produce hygienically safe products. Growth periods and length of crop growth consider local climate conditions and were taken from Savva and Frenken (2002), in accordance with the experience of local farmers (personal communication Hilengwa 2013). Planting dates of crops consider the necessary time for sowing, transplanting, harvest and land preparation for the next crop (Savva and Frenken 2002). Maize provides considerable residues that are needed for the digester of the wastewater treatment plant to produce energy, while the cobs can be sold. Therefore an area of 0.5 ha will be planted with maize.

Crop irrigation requirements were computed with the software CROPWAT 8.0 (FAO 1992, Allen *et al.* 1998). Input parameters included latitude, monthly precipitation, monthly mean minimum and maximum temperature, relative humidity and wind speed. Local climate data from Ondangwa weather station, which is 90 km away from Outapi, were used as provided by the Namibian Weather Bureau. The three latter parameters were calculated with the limited available daily data for temperature from 2003 to 2007, for humidity from 2004 to 2007 and for wind speed from 2006 to 2007. Precipitation and a precipitation probability analysis were calculated with data of the past 30 available years (ranging from 1950 to 2008) (see Woltersdorf *et al.* 2013). Following FAO recommendations (Savva and Frenken 2002), the 75% dependable rainfall was used instead of the mean monthly precipitation for the computation of irrigation requirements. The 75% dependable rainfall is expected to be exceeded in 3 out of 4 years. Crop specific data, e.g. length of growth season of crops, was taken for semi-arid regions from literature (Savva and Frenken 2002) and backed up with experiences from local farmers (Hilengwa 2013). Data on agricultural yields was limited and available from only 1 year in Namibia, from 2003 in Pricewaterhouse Coopers (2007). Due to inter-annual variability of yields and climate, agricultural yields taken from literature data from one year have limited significance but are nonetheless an indicative value. Soil data was used as suggested by CROPWAT 8.0 for light sandy soil. A drip irrigation efficiency of 0.75 was used assuming a conveyance efficiency of 0.85 and an application efficiency of 0.9, calculated according to Brouwer *et al.* (1989). To obtain the gross irrigation water requirement, the calculated net irrigation requirement was divided by the irrigation efficiency. Then the leaching requirement (LR) was calculated, which is the amount of water necessary to remove salts that have accumulated from the irrigation water as a result of evapotranspiration (Pescod 1992). It is expressed as percentage of the gross irrigation requirement (Equation (1)) (Savva and Frenken 2002):

$$LR = \frac{EC_w}{2MaxEC_e} \cdot \frac{1}{L_e} \tag{1}$$

where ECw is the electrical conductivity of the irrigation water (0.9 dS/m) (CuveWaters 2009), MaxECe is the maximum tolerable electrical conductivity of the soil saturation extract for each crop according to Savva and Frenken (2002) and Le is the leaching efficiency (sandy soils 0.3). Irrigation and leaching water add to a raising water table and require adequate sub-surface drainage (Ayers and Westcot 1985). For the model calculations, it was assumed that the amount of leaching water that percolates through the root zone equals the amount of drainage water that is collected by drainage pipes; i.e. there is no loss or accumulation of water in the soil.

4.1.2 *Mathematical material flow analysis*

Water flows within the system were described, quantified and modeled with a mathematical material flow analysis (MMFA) (Baccini and Bader 1996). By modeling the water flows in the system under investigation, an MMFA highlights the linkages between human behavior, technical infrastructure and the impact on the environment. New concepts for linking sanitation with resource recovery for agriculture can be assessed in regard to their sustainability and compared to the current state of water use in the area (Montangero *et al.* 2005, Meinzinger *et al.* 2009). This allows recognizing problems such as low water productivity early. For the calculations, the material flow modeling software SIMBOX was used (Baccini and Bader 1996). A stationary water flow model was developed with the aim to acquire system knowledge by quantifying water flows in, out and within the system in a first approximation, rather than to develop a highly detailed process-based model that would be able to describe all the processes very accurately. The MMFA comprised the following steps (Bader and Scheidegger 2012):

(1) *System analysis*. The temporal and spatial boundaries were defined to identify the processes, balances, flows and interrelationships of the system. The time scale of the system is 1 year, the system boundaries are the four settlements, the wastewater treatment and water reuse site in Outapi. The boxes represent the balance volumes and the arrows indicate the water flows (inputs, outputs and internal flows) of the system at steady-state). The households with a sanitation unit in their house are represented by the box "HH 'individual'" and their individual sanitation units by the box "individual". The households using the cluster units are represented by the box "HH 'cluster'" and the cluster sanitation units by the box "cluster". The households using the community unit are represented by the box "HH 'community'" and the community sanitation unit is represented by the box "community". A MMFA system generally obeys the law of mass conservation. Only key water flows above 1 m^3/y were considered and given in cubic meters per year [m^3/y].

(2) *Mathematical model*. Variables were determined with parameters to describe the current knowledge and the relationships of the input, output and internal water flows as well as processes (stock rate changes) of the system in mathematical terms. The designed MMFA model for the system under consideration is based on 53 system variables and 58 parameters (Figure 2).

(3) *Data collection and calibration*. Input data for the model parameters were derived by primary and secondary sources including publications, modeling software, estimations, balancing and expert opinions. These data were

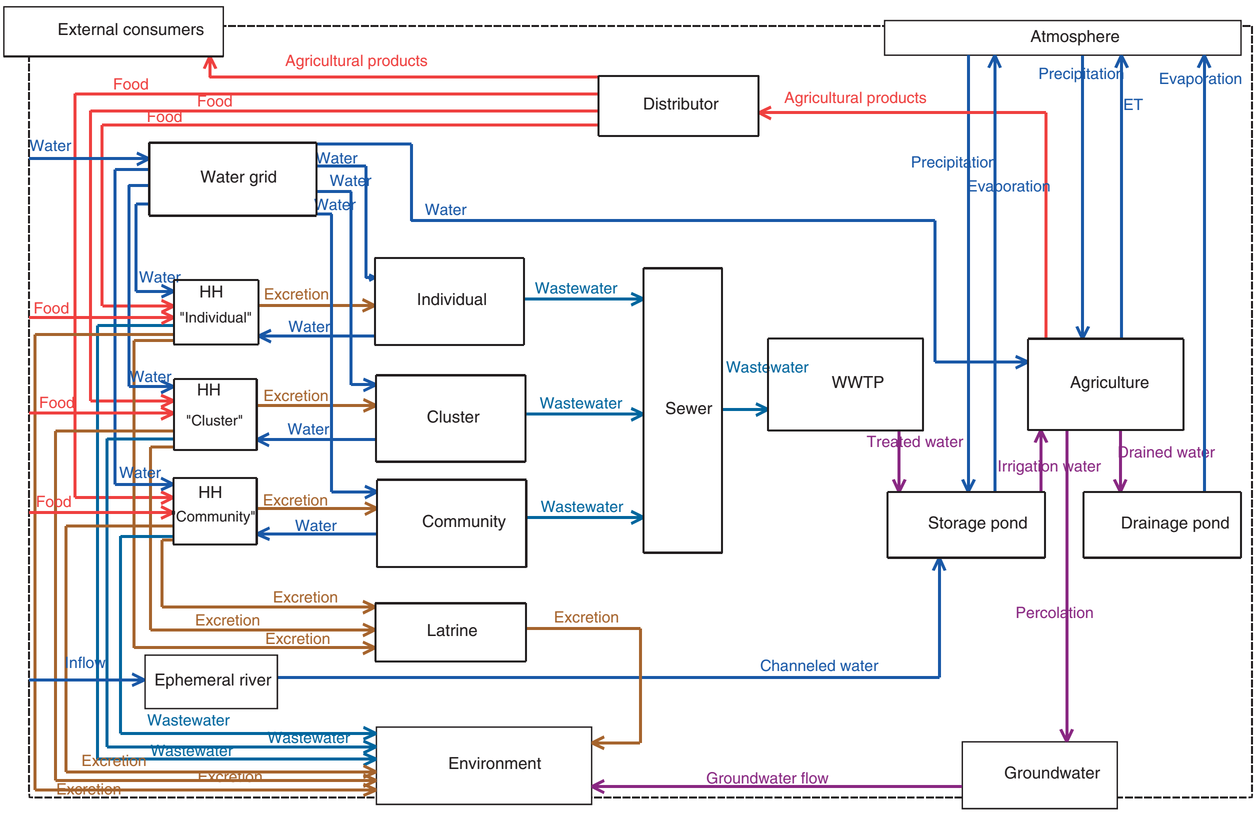

Figure 2. Water flows in the planned sanitation and agricultural reuse system in Outapi, representing the current situation and future development. Red: water in food and beverages, blue: water of good quality, grey-blue: wastewater, brown: water in excreta, purple: treated and irrigation water. HH: households. Future development is reflected by the boxes: individual, cluster and community units, sewer, wastewater treatment plant (wwtp), storage pond and drainage pond.

combined to produce best estimates for the parameters used. It was not yet possible to include primary measurements as the facility is still in the construction phase.

(4) *Simulation of the material flows including case calculations*. Three cases were simulated; the current state of water infrastructure with a new agriculture site and two cases with the proposed sanitation and water reuse facility (see Section 4.1.2).

(5) *Uncertainty analysis, parameter uncertainty ranking and Monte Carlo distribution*. Model results are always tied to a certain uncertainty. The uncertainty (standard deviation) and probability density distribution of each parameter was estimated from literature sources, expert opinions and plausible reasoning. Where no uncertainties could be defined for a particular parameter, an standard deviation of 10% was assumed. Depending on the available knowledge of a specific parameter, either a uniform, normal, truncated normal or lognormal probability density distribution was assigned. Then the distribution of the parameters and variables was calculated with a Monte Carlo simulation and the 90% prabability range could be shown. For this a probability density distribution was numerically described for all parameters by a sample size of 10,000. The input parameters were ranked for their impact on the uncertainty of a calculated variable. The parameters were listed making up the bulk uncertainty of model results of two key variables of the system: The first key variable is the water flowing into the system to the water grid, which is an indicator for the overall water requirement of the system. The second key variable is the irrigation water supplied by the grid to agriculture, indicating the amount of fresh water needed by agriculture that cannot be covered with reused water or the ephemeral river.

(6) *Analysis and interpretation of results*. The results of the material flow analysis were analyzed using the water productivity of the system as the main indicator for the efficiency of the water reuse scheme. The water productivity P is defined as the ratio of the mass of agricultural production M to the total water input to the system Q (Equation (2)) (Sadras *et al.* 2011). The total water input to the system equals to the water consumption of the households and of the agricultural area.

$$P = \frac{M}{Q} \tag{2}$$

The percent change in water productivity associated with the implementation of the new sanitation and water reuse infrastructure in comparison to the current state before the new infrastructure is implemented was calculated. As in this study the mass of agricultural production is defined to be the same in all cases, the change in water input to the system is proportional to the change in water productivity.

4.1.3 Cases

Three cases to quantify water flows were designed. Case 0 includes the current situation in the four project settlements with the current water and sanitation infrastructure and a new agriculture site. Case 1 assumes the implementation of the new sanitation and water reuse infrastructure with ideal utilization. Case 2 assumes the implementation of the new sanitation and water reuse infrastructure with a low utilization and acceptance.

Currently, extensive new agricultural areas with food crops to be irrigated with grid water are planned and expanded in the surroundings of the city. For comparability, this study assumed the same agricultural crop scheme for case 0 as designed for the new sanitation and water reuse facility (in Section 4.1.1) with an area of 1.5 ha as assigned by the Outapi Town Council. For the crop scheme, an agricultural production of 154,000 kg/y and an irrigation requirement excluding leaching of 26,640 m^3/y were calculated. Leaching requirements differ, as in case 0 grid water with a lower salt content is used requiring less leaching water (283 m^3/y), while case 1 and 2 use treated water with a higher salt content requiring more leaching water (3980 m^3/y). The agricultural water requirement, including irrigation water and leaching water, is 23,386 m^3/y in case 0 and 27,083 m^3/y in case 1 and 2. Also the agricultural infrastructure differs; case 0 has a drip irrigation system but no other elaborate infrastructure, case 1 and 2 have drip irrigation, a drainage and storage pond and a channel to the ephemeral river. The irrigation requirement was not optimized to the calculated available wastewater, as the area assigned for the water reuse site was determined by the Outapi Town council to be 1.5 ha at first. Parameter input and variations for the three cases are shown in Table 1 and Table 2.

4.2 Data

The 58 parameters used to model water flows of the system are shown with their values for case 1 (Table 1). For the three cases, 19 parameters were varied (Table 2) while the other 39 parameters are the same for all cases.

5. Results and Discussion

5.1 Crop choice and irrigation requirement for agriculture

The proposed wastewater treatment plant and water reuse site reduce pathogens as shown in Table 4.

Considering these calculated reductions (Table 3) the wastewater treatment and water reuse site achieve – even in the worst case – the necessary level of pathogen reduction of six log units, corresponding to a pathogen reduction of 99.9999%, for unrestricted irrigation of edible leaf crops (WHO 2006). In addition, the microsieve considerably reduces the number of helminth eggs, which

Table 1. Parameters used for modeling water flows; values given for case 1.

Parameter	Unit	Mean	STDV	Distrib.	Lower bound.	Upper bound.	Source
H_2O dietary intake	l/p/d	1.5	0.15	tnormal	0.8	4	study assumption
Number of inhabitants designated for:							
Individual units	capita	264	80	tnormal	150	500	project estimation
Cluster units		840	150		350	1300	
Communal washhouse		397	150		250	1600	
Fresh water use per person designated for:							
Individual units	l/p/d	60	6	tnormal	33	120	project estimation, according to Howard and Bartram 2003
Cluster units					34	120	
Communal washhouse					26	120	
Fraction of fresh water becoming raw waste water generated per user of:							
Individual units	decimal	0.9	0.09	tnormal			study assumption
Cluster units		0.8	0.08				
Communal washhouse		0.8	0.08		0	1	
Urine excreted	l/p/d	1.382	0.724	lognormal			Redelinghuys *et al.* 2010, data South Africa
Ratio of inhabitants designated to use individual sanitation units:							
Practicing open defecation	decimal	0	0	uniform			study assumption
Using latrines							
Using directly the water grid							
Ratio of inhabitants designated to use cluster sanitation units:							
Practicing open defecation	decimal	0	0	uniform			study assumption
Using latrines							
Using directly the water grid							
Ratio of inhabitants designated to use the communal washhouse:							
Practicing open defecation	decimal	0	0	uniform			study assumption
Using latrines							
Using directly the water grid							
Storage pond							
volume	m^3	3000	0	uniform			project design
surface	m^2	2000	0	uniform			project design
runoff coefficient	decimal	0.8	0.05	tnormal	0.7	1.0	Gould and Nissen-Petersen 2006
Max. volume from ephemeral river	m^3/y	2600	520	uniform			project estimation
Share of mean precipitation becoming not effective precipitation	decimal	0.13	0.03	tnormal	0.1	0.2	modeled with CROPWAT 8.0, data Namibian Weather Bureau
Part of not effective precipitation and of inefficiency of drip irrigation system that evaporates to the atmosphere	decimal	0.85	0.03	tnormal	0.8	0.9	estimation according to Heyns 1995

(*Continued*)

Table 1 – *continued*

Parameter	Unit	Mean	STDV	Distrib.	Lower bound.	Upper bound.	Source
Size of agriculture area:				uniform			
total	m^2	15,000	0				project design
planted with maize		5000	0				
Irrigation water requirement:							
maize	$m^3/m^2/y$	0.751	0.075	lognormal			modeled with CROPWAT 8.0, data Namibian Weather Bureau, Savva and Frenken 2002
crops, without maize		0.520	0.052				
Leaching water requirement:							
maize	$m^3/m^2/y$	0.124	0.012	lognormal			calculated with formula from Savva and Frenken 2002
crops without maize		0.091	0.009				
Crop cycles per year:							
maize	number	2	0	uniform			study assumption
crops without maize		3	0				
Precipitation	m/y	0.464	0.202	lognormal			Namibian Weather Bureau
Evapotranspiration:							
maize	$m^3/m^2/y$	0.702	0.0702	lognormal			modeled with CROPWAT 8.0, data Namibian Weather Bureau
crops, without maize		0.517	0.0517				
Drip irrigation efficiency	decimal	0.75	0.08	tnormal	0.65	1	Brouwer *et al.* 1989
Yield:							
maize		3.50	0.35				
tomato		4.00	0.40				
pumpkin		3.50	0.35				
watermelon	kg/m^2	5.04	0.50	normal			Price Waterhouse Coopers 2005 and estimations for spinach and sweet melon
pepper		1.40	0.14				
spinach		1.00	0.10				
sweet melon		3.00	0.30				
Evaporation from open water surface	m/y	2.6	0.2	lognormal			Heyns 1995
ECw of irrigation water	dS/m	0.9	0.09	lognormal			estimation according to project laboratory values for wastewater pond in Outapi (2009)
Leaching efficiency of soil	decimal	0.3	0.03	lognormal			study assumption, according to Savva and Frenken 2002
Max ECsoil 0% tolerance:							
maize		10.0	1.00				
tomato		7.4	0.74				
pumpkin		8.6	0.86				
watermelon	dS/m	10.0	1.00	lognormal			Savva and Frenken 2002, estimations for pumpkin, watermelon and sweet melon
pepper		10.0	1.00				
spinach		15.0	1.50				
sweet melon		8.0	0.80				
H_2O contained in produced							
maize cobs	$m^3/m^2/y$	0.00262	0.00026	lognormal			Souci *et al.* 2008, Price Waterhouse Coopers 2005
fruits and vegetable, without maize		0.00272	0.000272				
Ratio of food produced sold to users of the sanitation facilities	decimal	0.8	0.08	tnormal	0	1	study assumption

Table 2. Parameter variations (mean value) for different cases.

Parameter	Unit	Case 0	Case 1	Case 2
Fresh water used per user of:				
Individual units	l/p/d	33		47
Cluster units		34	60	47
Communal washhouse		26		43
Fresh water becoming raw waste water generated per user of:				
Individual units	decimal		0.9	0.9
Cluster units		0	0.8	0.6
Communal washhouse			0.8	0.6
Ratio of individual unit users:				
Practicing open defecation	decimal	0.64		
Using latrines		0.36	0	0.1
Using the water grid		1		
Ratio of cluster unit users:				
Practicing open defecation	decimal	0.56		0.25
Using latrines		0.44	0	0.1
Using the water grid		1		0.3
Ratio of communal washhouse users:				
Practicing open defecation	decimal	0.535		0.25
Using latrines		0.465	0	0.25
Using the water grid		1		0.25
Leaching requirement:				
maize	$m^3/m^2/y$	0.009	0.124	0.124
crops without maize		0.006	0.091	0.091
ECw of irrigation water	dS/m	0.1	0.9	0.9
Ratio of food produced sold to sanitation facility users	decimal	0.8	0.8	0.3

could unfortunately not be quantified. Also, planting high-growing crops and the semi-arid climate in Namibia with high temperatures and high sunlight intensity are expected to cause a high pathogen reduction. Therefore, the actual pathogen reduction is likely to be more on the estimated upper boundary of the values calculated in Table 3. However, in order to be on the safe side, root crops that require a minimum reduction of seven log units were excluded from the crop pattern. The resulting crop pattern for water reuse based on health protection, local habits and preferences and economic considerations that was used for the material flow analysis is shown in Figure 3.

Under local conditions, maize has a mean crop water requirement of 0.751 $m^3/m^2/y$ and a leaching requirement of 0.009 $m^3/m^2/y$ when irrigating with tap water and 0.124 $m^3/m^2/y$ when irrigating with reuse water. The vegetable and fruit area has a mean crop water requirement of 0.520 $m^3/m^2/y$ and a leaching requirement of 0.006 $m^3/m^2/y$ when irrigating with tap water and 0.091 $m^3/m^2/y$ when irrigating with reuse water.

Table 3. Range of pathogen reduction (log units) achieved with components of the proposed wastewater treatment plant and water reuse site (WHO 2006).

	Pathogen reduction (log units)			
	Viruses	Bacteria	Protozoan (oo) cysts	Helminth eggs
Primary sedimentation (*primary treatment*)	0 to 1	0 to 1	0 to 1	0 to 1
UASB anaerobe treatment (*secondary treatment*)	0 to 1	0.5 to 1.5	0 to 1	0.5 to 1
Aerobe treatment	1 to 2	1 to 2	0 to 1	1 to 3
Ultraviolet radiation (*tertiary treatment*)	1 to > 3	2 to > 4	>3	0
Microsieve	0	0	data missing	
Aerated lagoon and settling pond (*water reuse site*)	1 to 2	1 to 2	0 to 1	1 to 3
Three day interval between final irrigation and consumption	1.5 to 6			
Drip irrigation and low growing crops	2			
SUM	6.5 to 12.5	8 to 14	6.5 to 10.5	6 to 11.5

Table 4. Parameters responsible for bulk uncertainty of model results of the two key variables.

Key variable [m^3/y]	Case 0	Case 1	Case 2
Water inflow from outside to the water grid	Number of inhabitants (57%) Irrigation water requirement (26%) Fresh water used per inhabitant (12%)	Irrigation water requirement (40%) Fresh water becoming raw waste water per sanitation unit user (39%) Number of inhabitants (9%)	Number of inhabitants (42%) Irrigation water requirement (34%) Fresh water used per inhabitant (9%)
These parameters are responsible for uncertainty of (% Sum)	95%	87%	85%
Irrigation water from grid to agriculture	Irrigation water requirement (84%) Maize cycles per year (16%)	Number of inhabitants (64%) Irrigation water requirement (11%) Fresh water becoming raw waste water per sanitation unit user (11%) Fresh water used per inhabitant (11%)	Number of inhabitants (43%) Irrigation water requirement (35%) Fresh water used per inhabitant (7%)
These parameters are responsible for uncertainty of (% Sum)	100%	97%	84%

5.2 Mathematical material flow analysis

5.2.1 Case 0: Current water infrastructure with a new agricultural irrigation site

In case 0 household water consumption and sanitation habits were assumed as indicated in the household inventory survey in July 2012 (Deffner *et al.* 2012). Household water consumption was: 33 l/p/d in Shack dwellers, 34 l/p/d in Tobias Hainyeko and 25 l/d/p in Onhimbu and Okaikongwe. As a result, the households consume 17,340 m^3/y. In the absence of other water sources, households and agriculture are solely supplied by the water grid. Simulation results show that the total water inflow to the system through the grid is 40,700 m^3/y (Figure 4). With 23,400 m^3, agriculture consumes the largest part of the water (57%). Currently, there is no wastewater sewer and household wastewater is neither collected, treated nor can be reused in a productive manner. Instead wastewater and excrements are discharged untreated to the environment (17,769 m^3/y) either through open defecation or the pit latrine, thus potentially causing soil, groundwater and surface water pollution as well as diseases, especially during seasonal floods. The agricultural irrigation site was assumed to have only simple equipment and no drainage pond, 2730 m^3/y of water infiltrate into the soil.

5.2.2 Case 1: Ideal use of new sanitation and water reuse facility

For case 1 a water consumption of 60 l/d/p was assumed, which is slightly higher than the value indicated by the WHO (Howard and Bartram 2003) to assure all basic personal needs, food hygiene, laundry and bathing. All potential users use the sanitation facilities; there is no open defecation and no use of the latrine and the communal water point. Irrigation water is supplied with first priority by the wastewater treatment plant, second by the ephemeral river and third by the water grid. Simulation results show that the main water input to the system comes through the water grid (36,800 m^3/y) (Figure 5). The agricultural site is supplied with the maximum possible annual amount of water from the ephemeral river (2600 m^3/y). The household water consumption is 32,870 m^3/y, the irrigation water requirement 27,084 m^3/y. Household water consumption is the highest of the three cases due to the improved availability of water. Still, the water inflow to the system is the lowest of the three cases, due to treatment and reuse of 27,600 m^3/y household wastewater for irrigation. The irrigation water is composed of 85% treated reuse water, also taking into account that the reuse water in the storage pond is reduced by evaporation and increased by precipitation on the surface of the pond. Since all residents use the sanitation facilities, no excreta are released to the environment and pathogens are prevented to spread in the area. A high share of

Field	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	1st	maize			20th		1st	maize			17th	
2		1st	maize			20th		1st	maize			18th
3	1st	pepper		30th	10th	pumpkin		17th	1st	spinach		9th
4	1st	tomato			15th	10th	sweet melon			7th 10th	watermelon	28th

Figure 3. Optimal cropping pattern used for material flow analysis with crop type, planting and harvesting date.

household wastewater, 90% in individual units and 80% in cluster units and the communal washhouse, can be collected and treated. The remaining 6018 m^3/y of untreated domestic water without excreta are not collected by the sewer system and are discharged to the environment. This occurs e.g. when people take the water home in buckets and use it in front of their houses for food, personal hygene or watering the garden. For this reason the water cannot be reused for agricultural irrigation. Due to the lined drainage pond, no polluted leaching water infiltrates to the groundwater.

5.2.3 *Case 2: Low utilization and acceptance of new sanitation and water reuse facility*

In case 2 it was assumed that the users maintain a similar fresh water consumption and partly stick to their former sanitation habits due to long distances between the community sanitation unit and the houses, especially for children or at night. Inhabitants therefore use less the new sanitation facilities and still practice open defection, use the existing latrines and fetch water from the existing water grid to a certain extend. For this, the use of the new sanitation facilities and the amount of daily water consumption per person is assumed to be in between the current state and the case of an ideal utilization of the new infrastructure.

Compared to case 1, less wastewater in the cluster unit and the communal washhouse is collected by the sewer (only 60%) as more users were assumed to stick to their former habits and e.g. take their water home. Due to lower acceptance, the users of the sanitation facilities buy less food produced from the water reuse site and the produce is sold to external consumers. Simulation results (Figure 6) indicate that the water requirement of the system is 43,700 m^3/y, of which 41,100 m^3/y are supplied through

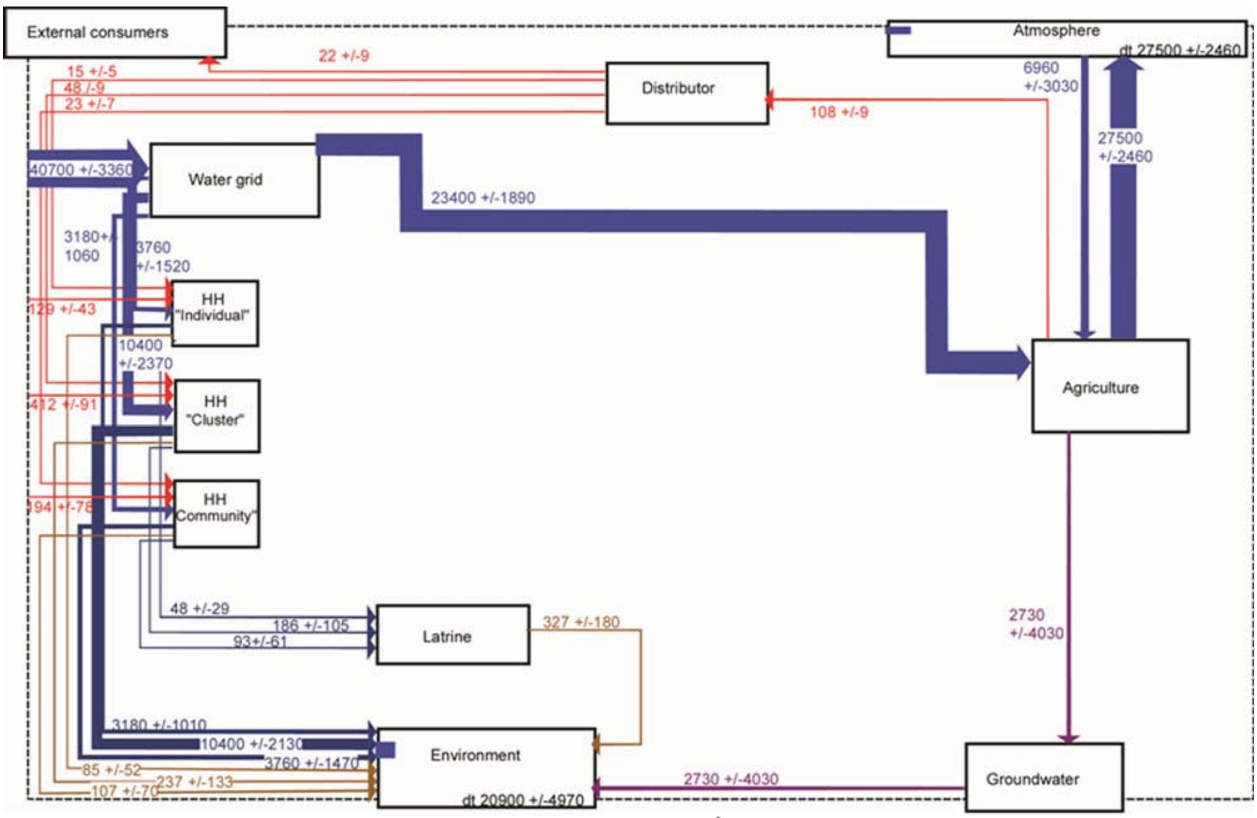

Figure 4. Simulation results for case 0: Current water infrastructure with new agricultural irrigation site (mean value and standard deviation in m^3/y). HH: households, dt: change in time.

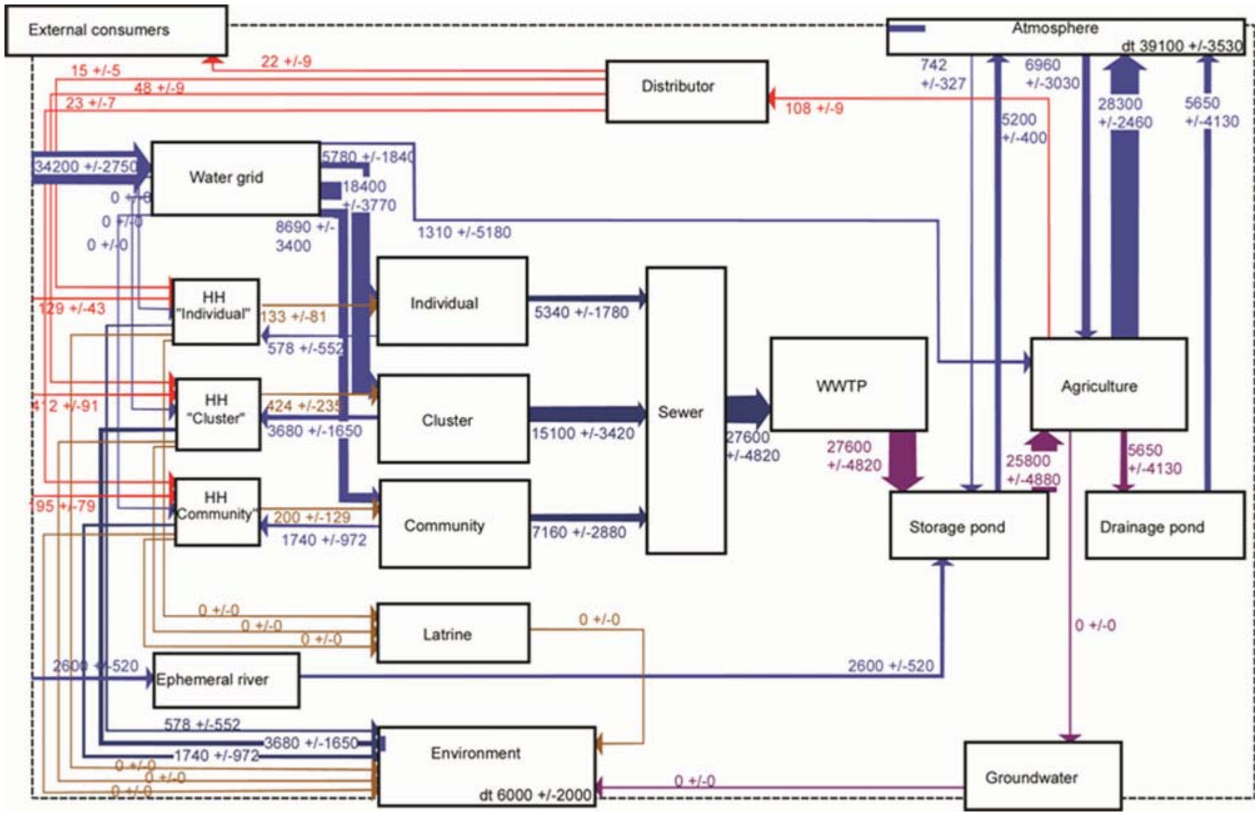

Figure 5. Simulation results for case 1: Ideal use of new sanitation and water reuse facility (mean value and standard deviation in m^3/y). HH: households, dt: change in time.

the water grid and 2600 m^3/y through the ephemeral river. Only 52% (13,000 m^3/y) of household wastewater can be collected, treated and reused productively for irrigation. The irrigation water consists by 32% of reuse water. 12,810 m^3/y of domestic wastewater with excreta are discharged untreated to the environment.

5.2.4 Uncertainty analysis

With a probability of 90% the two key variables of the system are within the following range: the first key variable "water inflow from outside to the water grid" is in case 0 between 36,277 and 46,812 m^3/y, in case 1 between 31,150 and 42,823 m^3/y and in case 2 between 37,007 and 46,518 m^3/y. The second key variable, the "water supplied by the grid to agriculture" is between 20,426 and 26,610 m^3/y in case 0, between 21.0 and 8392 m^3/y in case 1 and between 10,888 and 20,170 m^3/y in case 2.

The parameters responsible for the bulk uncertainty of these model results are ranked in Table 4. It shows that out of the 58 parameters of the system, 12 parameters are alone responsible for over 84% of the uncertainty of the modeled result of the two key variables. The uncertainty of the modeled result of "water inflow from outside to the water grid" in case 0 mainly depends on three parameters: number of inhabitants (57%), the irrigation water requirement and the amount of fresh water used per inhabitant. These three parameters together make up 95% of the uncertainty of the modeled result. For case 1 the most determining parameter for result uncertainty is the amount of irrigation water requirement (40%) and for case 2 the number of inhabitants (42%). The uncertainty of the result of "water from grid to agriculture" is in case 0 mostly determined by the amount of irrigation water (84%) while in case 1 and 3 by the number of inhabitants (64% and 43%).

For both key water flows, the greatest uncertainty is caused by parameters concerning the users and particularly the number of users of the sanitation facilities. This is because the number of users of the sanitation facilities mainly determine the amount of total household water consumption, and consequently the amount of water that can be reused in the system for agriculture, which does not have to be supplied by the grid. In addition, due to difficult data estimation, the parameter values for the number of facility users contain the largest uncertainties with standard deviations of 18% to 38% and the largest ranges between the lower and upper boundary. In comparison, other parameters have a standard deviation of around 10%. Also the amount of irrigation water requirement has a

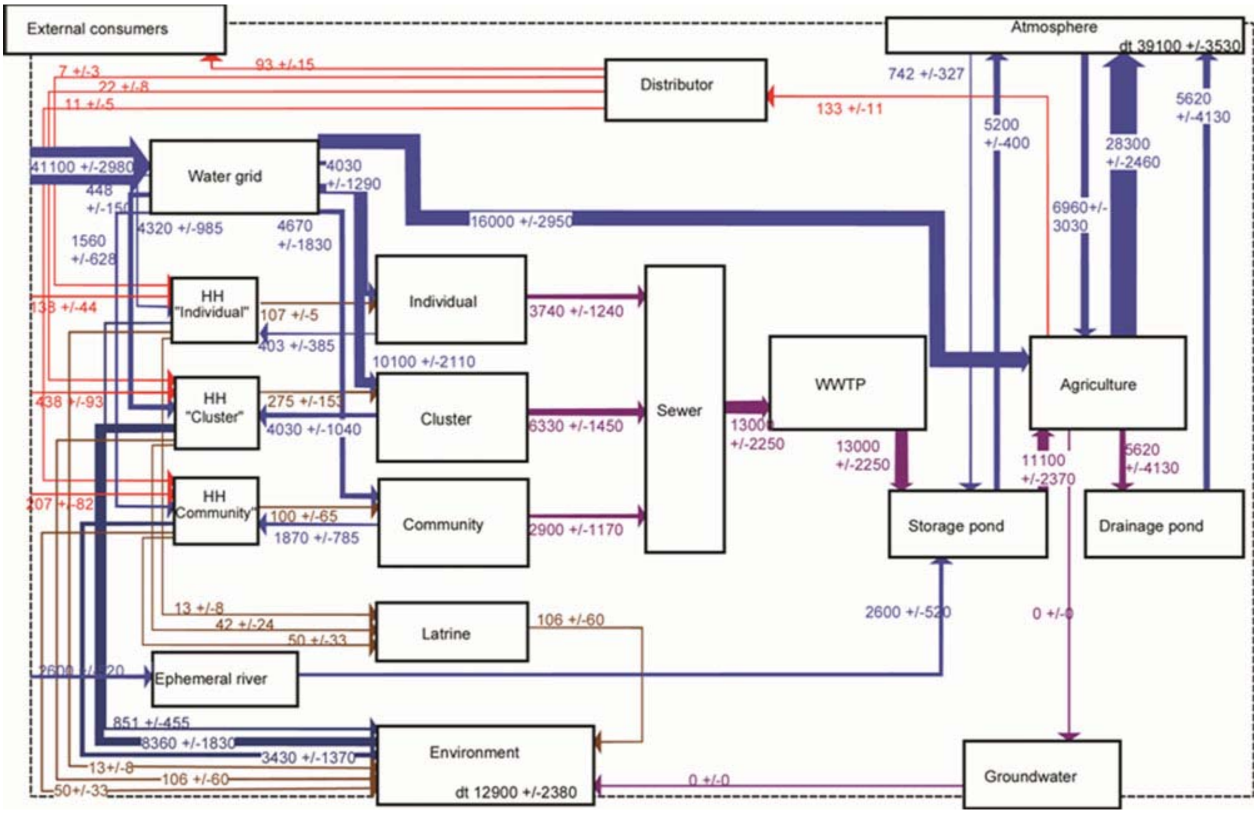

Figure 6. Simulation results for case 2: Low utilization and acceptance of new sanitation and water reuse facility (mean value and standard deviation in m^3/y) HH: households, dt: change in time.

considerable impact on the results of the two key water flows.

In order to reduce these uncertainties it will be important to collect more information on the number of users and their water consumption through detailed and repeated surveys. The uncertainty of the share of wastewater entering the sewer could be reduced by measuring with water meters the difference between drinking water consumption and wastewater entering the sewer. The uncertainty of the amount of crop irrigation water can hardly be reduced due to high inter-annual variability of precipitation. Still it is likely that the user parameters will remain the largest source of uncertainty for the two key variables, as data concerning the users and their behavior is more difficult to assess and has larger uncertainties than measuring technical data does.

5.3 Water productivity

Water flows and water productivity of the system are summarized in Table 5. The change of water inflow to the system is equal to the change in water productivity. This is because water productivity is defined as the ratio of the mass of agricultural production to the total water input to the system, and while the amount of agricultural production is the same in all scenarios, the change in water inflow to the system directly determines the change of water productivity. In case 0, with a lack of sanitation and nearby water supply infrastructure, household water consumption is the lowest (17,340 m^3/y). In case 1, although household water consumption is the highest (32,870 m^3/y), the amount of water supplied by the grid can be reduced (by 6600 m^3/y) to 34,200 m^3/y compared to case 0. The reason is that 27,600 m^3/y (84%) of household wastewater is treated and reused for agriculture constituting 85% of the irrigation water. Therefore, water inflow to the system is reduced and water productivity rises by +10% compared to case 0. In case 2, household water consumption is in between case 0 and case 1, but only 52% are collected by the sewer and treated. Therefore only 32% of the irrigation water can be covered with reuse water and consequently the water inflow to the system is the highest of all cases and most water still needs to be supplied by the grid (+300 m^3/y compared to case 0). Water inflow to the system increases and water productivity decreases by +7% compared to case 0, because more water is supplied to the households and only a low share is reused in agriculture. Without water reuse, households and agriculture together consume 40,700 m^3/y in case 0, 59,954 m^3/y in case 1 and 52,203 m^3/y in case 2. Introducing the new

Table 5. Summary of results with mean variable values.

	Case 0	Case 1	Case 2
Agricultural production [kg/y]		124,800	
Agricultural irrigation water requirement [m^3/y]	23,400	27,084	
Household water consumption [m^3/y]	17,340	32,870	25,120
Water inflow to the system [m^3/y]	40,700	36,800	43,700
- From water grid	40,700	34,200	41,100
- From ephemeral river	0	2600	2600
Water treated and reused for agriculture [m^3/y]	0%	27,600	13,000
People using sanitation facilities [number]	649	1501	1165
Share of irrigation water composed of treated reused water [%]	0%	85%	32%
Untreated water and excreta discharged to the environment [m^3/y]	17,769	6018	12,810
Water productivity of the system [kg/m^3]	3.1	3.4	2.9
Change of water inflow to the system compared to case 0 [%] (the value is equal to the change in water productivity)	0	− 10%	7%
Change of water inflow to the system compared to introducing improved water infrastructure without reusing water for agriculture [%] (the value is equal to the change in water productivity)	0	− 39%	− 16%

water infrastructure and reusing the water for irrigation reduces the water inflow to the system by − 39% (from 59,954 to 36,800 m^3/y) in case 1 and − 16% (from 52,203 to 43,700 m^3/y) in case 2, compared to the assumption that an improved sanitation infrastructure would be introduced without re-using the water.

Model results of this study showed that the expected wastewater available for water reuse is 27,600 m^3/year in case 1 and 13,000 m^3/year in case 2. In comparison to this, conducting a simple calculation with a fixed per capita wastewater inflow, assuming only a water consumption per person of 60 liters/day and 1500 inhabitants in the area where the new water infrastructure is to be introduced, would result in an expected overestimated wastewater flow of 32,850 m^3/year available for water reuse. This is because the amount of household wastewater that is available for reuse in agriculture depends on the behavior of the users of the sanitation facilities. This could be taken into account with the proposed methodology in this paper.

In the coming years, these results and the methodology will need to be validated in the field. Field data needs to be collected through interviews, survey and field measurements over a longer period of time. Then modelling results can be calibrated and refined. A more representative result can be obtained specifically for the model region central-northern Namibia and the city of Outapi. In addition to the parameters integrated in the MMFA also further parameters might affect the quantity of water flows, such as periods of maintenance when the facility has to be closed or leaking water pipes. So far, discussions with local farmers (personal communication Hilengwa 2013) showed that local yields in small farms are likely to be higher than indicated by Price Waterhouse Coopers (2005) and therefore water productivity might be underestimated in this study.

6. Conclusion

Introducing an improved water supply, sanitation, water treatment and water reuse infrastructure increases the water consumption per person. The study showed that for this reason reusing treated household wastewater for agriculture does not automatically reduce overall water consumption by households and agriculture significantly (by −10% to +7%) in comparison to before the introduction of the proposed infrastructure. However, it saves 16% to 39% of water compared to introducing the improved water infrastructure without reusing the water for agriculture.

By using the mathematical material flow analysis the impact of user behavior on water flows within the sanitation and water reuse system could be taken into account. It was found that water productivity increases less than would be computed assuming a fixed wastewater inflow. The methodology is transferable to all urban areas in developing countries characterized by insufficient water supply and wastewater infrastructure with similar starting conditions as described for the model city of this paper in central-northern Namibia. Similar starting conditions include: informal settlements with water points and public latrines, inhabitants practicing open defecation, a similar socio-economic situation with low income and low education level, a semi-arid climate that requires irrigation for agriculture, an urban area with only limited agricultural area available, and the possibility to install the sanitation facilities in proximity of the wastewater treatment plant and the irrigation site. The methodology can also be transferred to semi-arid higher income countries, when adapting the system in the material flow analysis including the existing type of sanitation facilities and sanitation behavior. The results of this study are comparable to other areas with similar conditions to the model region, with a similar scale of the water infrastructure including a comparable amount of sanitation users and size of agricultural area.

The methodology developed and the results of this study demonstrated that taking socio-cultural aspects into consideration plays a major role for the quantification of expected water flows and productivity. The research is relevant for the future planning and decision making process before the introduction of a new water supply, sanitation, water treatment and water reuse infrastructure in order to quantify water flows and water productivity more accurately.

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CORRIGENDUM

Small-scale water reuse for urban agriculture in Namibia: Modeling water flows and productivity

L. Woltersdorf*, S. Liehr, R. Scheidegger and P. Döll

Urban Water Journal

When the above article was first published online, Table 3 was incorrectly amended at the revision stage. The table below is the correct version.

<table>
<tr><th></th><th colspan="4">Pathogen reduction (log units)</th></tr>
<tr><th></th><th>Viruses</th><th>Bacteria</th><th>Protozoan (oo)cysts</th><th>Helminth eggs</th></tr>
<tr><td>Primary sedimentation (primary treatment)</td><td>0 to 1</td><td>0 to 1</td><td>0 to 1</td><td>0 to 1</td></tr>
<tr><td>UASB anaerobe treatment</td><td>0 to 1</td><td>0.5 to 1,5</td><td>0 to 1</td><td>0.5 to 1</td></tr>
<tr><td>Aerobe treatment (secondary treatment)</td><td>1 to 2</td><td>1 to 2</td><td>0 to 1</td><td>1 to 3</td></tr>
<tr><td>Microsieve</td><td>0</td><td>0</td><td colspan="2">data missing</td></tr>
<tr><td>Ultraviolet-radiation (disinfection)</td><td>1 to >3</td><td>2 to >4</td><td>>3</td><td>0</td></tr>
<tr><td>Storage pond (water reuse site)</td><td>1 to 2</td><td>1 to 2</td><td>0 to 1</td><td>1 to 3</td></tr>
<tr><td>Three day interval between final irrigation and consumption</td><td colspan="4">1.5 to 6</td></tr>
<tr><td>Drip irrigation and low growing crops</td><td colspan="4">2</td></tr>
<tr><td>SUM</td><td>6.5 to >17</td><td>8 to >18.5</td><td>6.5 to >15</td><td>6 to 16</td></tr>
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Taylor & Francis apologises for this error.

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Research article

Municipal water reuse for urban agriculture in Namibia: Modeling nutrient and salt flows as impacted by sanitation user behavior

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ABSTRACT

Adequate sanitation, wastewater treatment and irrigation infrastructure often lacks in urban areas of developing countries. While treated, nutrient-rich reuse water is a precious resource for crop production in dry regions, excessive salinity might harm the crops. The aim of this study was to quantify, from a system perspective, the nutrient and salt flows a new infrastructure connecting water supply, sanitation, wastewater treatment and nutrient-rich water reuse for the irrigation of agriculture, from a system perspective. For this, we developed and applied a quantitative assessment method to understand the benefits and to support the management of the new water infrastructure in an urban area in semi-arid Namibia. The nutrient and salt flows, as affected by sanitation user behavior, were quantified by mathematical material flow analysis that accounts for the low availability of suitable and certain data in developing countries, by including data ranges and by assessing the effects of different assumptions in cases. Also the nutrient and leaching requirements of a crop scheme were calculated. We found that, with ideal sanitation use, 100% of nutrients and salts are reclaimed and the slightly saline reuse water is sufficient to fertigate 10 m^2/cap/yr (90% uncertainty interval 7–12 m^2/cap/yr). However, only 50% of the P contained in human excreta could be finally used for crop nutrition. During the pilot phase fewer sanitation users than expected used slightly more water per capita, used the toilets less frequently and practiced open defecation more frequently. Therefore, it was only possible to reclaim about 85% of nutrients from human excreta, the reuse water was non-saline and contained less nutrient so that the P was the limiting factor for crop fertigation. To reclaim all nutrients from human excreta and fertigate a larger agricultural area, sanitation user behavior needs to be improved. The results and the methodology of this study can be generalized and used worldwide in other semi-arid regions requiring irrigation for agriculture as well as urban areas in developing countries with inadequate sanitation infrastructure.

1. Introduction

In developing countries urban agriculture provides fresh food, employment and income as well as greens cities and recycles wastes (van Veenhuizen, 2006). In 1996, urban agriculture involved 800 million urban residents worldwide (Smit et al., 1996) and this number has steadily increased over the last twenty years (van Veenhuizen, 2006). Like all farmers, urban farmers need sufficient fertilizer and, especially in dry areas of the globe, they need water that allows irrigation without producing soil salinization. Fertilizers contain nitrogen, phosphorus, potassium, magnesium or calcium (Barker and Pilbeam, 2007). Between 1950 and 2000, global use of synthetic fertilizers increased by 600% (IFA, 2006). However, production of synthetic nitrogen fertilizer is particularly energy intensive, and phosphorous and potassium have to be derived from finite and non-renewable resources of phosphate rock and potash. Applications of nitrogen and phosphorous in excess of what can be taken up by crops cause environmental pollution (UNEP, 2011). While world reserves appear adequate for the foreseeable future, fertilizer costs will probably rise as the most easily extracted materials are consumed (Fixen and Johnston, 2012). Already today, high costs and low accessibility prevent many farmers in Sub-Saharan Africa from acquiring fertilizer (UNEP, 2011). However, only small amounts of nutrients are recovered from waste and

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recycled even though this would reduce environmental pressures and increase long-term resource supply. Soil salinization, the accumulation of salts from irrigation water, affects approximately 10% of the world's irrigated lands (WWAP, 2012). Excess salinity within the plant root zone reduces plant transpiration and growth because it increases the energy that must be expended to acquire water from the soil and to make the biochemical adjustments necessary to survive under stress. This effect is primarily related to total electrolyte concentration and is largely independent of its specific composition (Rhoades et al., 1992). Major ions making up salinity are sodium, calcium, magnesium, potassium, chloride and nitrate (Tanji and Kielen, 2002).

An advantage of urban agriculture is that sufficient municipal wastewater can be collected and treated to produce nutrient-rich irrigation water (Woltersdorf et al., 2015). Currently, treated or untreated water is used for an estimated 10% of the irrigated crops (Jiménez and Asano, 2008). Treated wastewater is extensively used for irrigation in semi-arid high-income countries such as USA (California), Israel and Spain. Nutrients are either (partly) removed or retained, depending on the treatment technology and the amount of nutrients desired in the irrigation water. For the desalinization of treated wastewater, most often membrane filtration with reverse osmosis is used. However, this process requires a lot of energy and also removes all nutrients. Processes for desalinization without removing nutrients are increasingly being researched (Norton-Brandão et al., 2013). The salinity and nutrient levels that can be accepted in reuse water for irrigation depend on soil type, climate, crops and irrigation and drainage techniques. Middle income countries such as Mexico, Chile, and Egypt use both treated and untreated wastewater, indicating that they are in transition between unplanned and uncontrolled reuse to planned and controlled reuse (Scheierling et al., 2010). In low income countries, such as in Sub-Saharan Africa, highly polluted water from surface-water bodies is reused for irrigation, predominantly unintentionally. In these countries, and in spite of its potential, municipal wastewater has not yet been widely collected, treated and reused for fertigation of crops (combined application of nutrients and water) due to a lack of appropriate water and sanitation infrastructure (Scheierling et al., 2010). Nevertheless, pilot projects exist such as in Burkina Faso, where treated water has been used on a very small scale (6 m^3/d water, 15 m^2 garden) for fertigation (Akponikpè et al., 2011).

Previous studies have shown that failure to carefully manage existing water reuse schemes adversely affect soils, groundwater and crops. Accumulation of salinity is frequently the single most important criterion determining the suitability of reuse water for agricultural irrigation (Bedbabis et al., 2014; Biggs and Jiang, 2009). Thus keeping the electrical conductivity below levels tolerable for crops is essential for long-term successful irrigation with wastewater (O'Connor et al., 2008; Devitt et al., 2007). Nutrients in reuse water exceeding crop requirements can pollute soil water, soil and air and reduce yield, crop maturation, and the disease resistance of plants (Tanji and Kielen, 2002; Pablo et al., 2013). The challenge is to find ways of reusing treated nutrient-rich water efficiently for agricultural irrigation while minimizing the risk of soil salinization and over fertilization. Therefore during the design and implementation phase a systematic assessment is necessary.

The aim of this study was to quantify from a system perspective the nutrient and salt flows of an innovative infrastructure connecting water supply, sanitation, wastewater treatment and nutrient-rich water reuse for the irrigation in urban agriculture (Henceforth, Water-Sanitation-Treatment-Irrigation (WSTI) infrastructure). For this, we used a case study in northern Namibia for which we have already quantified water flows and crop productivity (Woltersdorf et al., 2015), while we focus on the nutrients and salts here.

2. Sanitation and water reuse concept

During the CuveWaters project (CuveWaters, 2013), the innovative WSTI infrastructure was implemented in the outskirts of Outapi in central-northern Namibia. The low-density, partly informal settlements have poor water supply and poor sanitation typical of urban areas in low income countries (Deffner et al., 2012). The region is semi-arid and water scarce (Woltersdorf et al., 2015). Water is supplied by a pipeline from the Kunene river on the Angolan-Namibian border. Currently, the town plans to establish extensive new agricultural areas with irrigation of piped water and with use of mineral fertilizer. Population growth, further urbanization, the expected effects of climate change are likely to increase the pressure on water resources (Deffner and Mazambani, 2010). The town council and the CuveWaters project estimated the four project settlements to have about 1500 inhabitants (Müller et al., 2013). Few of the residents have access to latrines and most defecate in the open (Deffner et al., 2012). In the four project settlements, three types of water supply and sanitation units were constructed: In an older partially dense suburb (Onhimbu) and a new informal suburb (Okaikongwe) a communal washhouse contains toilets, showers and sinks for laundry and dish washing. In a new informal suburb (Tobias Hainyeko) thirty small cluster washhouses are each shared by four households. In a formalized suburb with brick houses (Shack Dwellers), households were individually connected to water supply and sewage. Even though water supply and sanitation tariffs are in general affordable for the local inhabitants, the tariffs are expected to affect user behavior. Inhabitants can still use the previously existing fee-based water points and free latrines, which may lower the amount of wastewater that can be collected and treated. Even with ideal sanitation use, not all wastewater can be collected by the sewer, as a certain share is used for e.g. watering the garden, cooking or cleaning the house.

The wastewater is treated nearby with combined anaerobic (UASB), aerobic (RBC), micro strainer and disinfection (UV-light). The treatment removes 22% of the nitrogen, 18% of the phosphorus and none of the potassium (Müller et al., 2013). Salts are not removed because of high investment and energy costs as well as the intention to produce nutrient-rich reuse water. After treatment the hygienically safe and nutrient-rich water is reused for fertigation of 1.5 ha growing human food crops. To minimize evaporation and, consequently, soil salinization, the fertigation is by drip irrigation. The leaching water is collected with sub-surface drainage in an evaporation pond to prevent the salty water to rise and cause root zone salinization. The constructed evaporation pond is unlined, however in our modeling and analysis, we assume a lined pond that prevents groundwater contamination with nutrients, salts and other agro-pollutants. The agricultural site is equipped with a storage pond for treated water. In addition to the infrastructure already in place, we also consider the possibility of pumping water (up to 2600 m^3/yr) from a nearby ephemeral river in the rainy season and store it together with the reuse water in a storage pond. The soil of the root zone of the irrigation site (down to 30 cm) is a medium textured sandy loam with a medium infiltration capacity, very little organic matter, low nutrient content, a pH of 5.5–7.0 and medium salinity (EC 1.04 dS/m) (Reichenbach, 2013).

3. Methods

3.1. Mathematical material flow analysis (MMFA)

The MMFA comprised the following steps (see Bader and Scheidegger, 2012):

(1) *Choice of indicators for nutrient content and salinity*

The most important plant nutrients are nitrogen (N), phosphorous (P) and potassium (K) (Barker and Pilbeam, 2007). This study quantified the mass of total N, P, and K as indicators and dids not consider speciation or transformation processes. In feces, wastewater and soils, nutrients can be present in various compounds (Jönsson et al., 2004a,b). In urine they are excreted in water-soluble form. Over 90% of N and P in urine is in the form of urea ($H_2N{-}CO{-}NH_2$), ammonium (NH_4^+) or phosphate (PO_4^{3-}), while all of the K occurs as the cation K^+ (Lentner, 1981). Feces contain both water-soluble nutrients and nutrients combined in particles not soluble in water. P is mostly found as calcium phosphate. By microbiological degradation, the organic N and P content dissolves and becomes available to plants. Urea is degraded within hours to NH_4^+ by microbial urease, normally present in urban piping systems. NH_4^+, if applied to arable soils, is transformed by aerobic microbes to nitrite (NO_2^-) and then to nitrate (NO_3^-), normally within a few days. The transformation takes longer in soils with very low microbial activity (or lack of oxygen). Under reducing conditions, dissolved nitrate can be denitrified to the gases nitrous oxide (N_2O) or molecular nitrogen. NO_3^- is transported with the soil water, while NH_4^+ can also be adsorbed to clay particles. P has lower mobility and may exist in the particulate phase as mineral PO_4^{3-} with Fe^{3+}, Ca^{2+} or Al^{3+} counter ions or as organic P bound in plant matter rather than as PO_4^{3-} ions in solution. K^+ is highly soluble in water and also in soils. Plants take up N mainly as NO_3^-, but also as NH_4^+ and urea, P as PO_4^{3-}, K as K^+ (Ongley, 1996; Jönsson et al., 2004a,b).

As indicators for the salinity of water and soils, we chose sodium (Na^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}) (after Blume et al., 2010). The anions were not quantified since they are present as counter ions to Na^+, Ca^{2+} and Mg^{2+} and are more difficult to quantify due to their composition. Na^+ is much more soluble than Ca^{2+} while Mg^{2+} ranges from highly soluble to sparingly soluble (Tanji and Kielen, 2002). Ca^{2+} and Mg^{2+} are also essential crop nutrients, while NO^{3-}, K^+ and PO_4^{3-} are also responsible for soil and water salinity (Blume et al., 2010). We use henceforth the terms N, P, K, Na, Ca, and Mg to designate the total quantities of these elements. In addition, in order to compare the salinity of the irrigation water to crop tolerances, we also measured the electrical conductivity of the irrigation water which is largely independent of the specific composition of solutes (Rhoades et al., 1992).

(2) *System representation and mathematical model*

Flows were modeled with MMFA using the software SIMBOX (Bader and Scheidegger, 2012). The nutrients and salts are dissolved in water and thus correlated with the water flows that were presented in Woltersdorf et al. (2015). We defined the temporal and spatial boundaries, the flows, processes, balances and interrelationships within and of the system. The system spatially comprised the four settlements and the WSTI infrastructure in Outapi. The nutrient and salt flows (represented by arrows in Fig. 1) among compartments (boxes in Fig. 1) of the system were averaged over 1 year at steady-state. Only flows and boxes with flows above 1 kg/yr were indicated with a maximum of three significant digits. For each flow a variable was formulated and mathematically expressed as system equation. There are 50 flows for each of the six substances and 49 water flows, adding up to 349 variables. These variables are characterized by 50 parameters that describe our system knowledge. For instance, the variable N_{ex} "N excreted from individual household connections to the environment per year" is characterized by the three parameters (a) number of inhabitants designated to use individual household connections, (b) amount of N excreted daily in urine and feces and (c) ratio of inhabitants defecating in the open to those designated as using individual household connections. The equation was therefore $N_{ex} = a * b * 365 \text{ days} * c$. Open defecation was determined as "Excretion from households to the environment" (Fig. 1). The content of the pit latrines was assumed to flow eventually to the environment. Precipitation is not shown in Fig. 1, as it only has an impact on the water balance, not on nutrient and salt flows.

Detergents for laundry, personal hygiene or cleaning are negligible inputs in the settlements and were not considered. N is not emitted to the atmosphere during the treatment process. Irrigation water is supplied with first priority from the wastewater treatment plant, secondly from the ephemeral river and thirdly from the water grid. The size of the agricultural area was not optimum for the quantity of nutrients and reuse water available, because the local authority assigned a limited area of 1.5 ha for urban agriculture. The amounts of substances contained in the upper 100 cm of the soil i.e. from the surface to the drainage pipes, were included in the MMFA as material stock in the box "agriculture".

(3) *Data collection and calibration*

Input data for the parameters were drawn from primary and secondary sources including publications, modeling software, estimations, balancing, expert opinion, plausible reasoning and local soil and water analyses. We combined these data to produce best estimates for the parameters used. The model was calibrated by integrating empirical data and measurements as explained in Section 4.

(4) *Designing three cases*

We designed three cases simulating the situation (Table 1): The conventional situation without WSTI and with a new crop irrigation site ($case_{conv}$), with WSTI and the best available data during the planning stage assuming exclusive use of new sanitation units ($case_{ideal}$), and the pilot phase of the WSTI with available data after 10 months of operation ($case_{assess}$). For comparability, all cases comprise the same agricultural crop scheme, production and irrigation requirement. They have different leaching requirements, as this depends on the concentration of ions dissolved in the water. Inhabitants of the three settlements have the option to use the new sanitation units or the preexisting latrines and the public water points connected to the water grid. Residents not at home during the day and those using sanitation units in other parts of the town connected to the old wastewater system were assumed in the model to use the latrines. Data for the cases are described in Section 4.

(5) *Simulation, uncertainty analysis and parameter uncertainty ranking*

For each parameter, the type of probability density distribution was set together with its value for the mean, standard deviation, minimum and maximum. Depending on the available knowledge of a specific parameter, we assigned either a uniform, normal, truncated normal or lognormal probability density distribution. If no value could be identified for the standard deviation, we assumed a

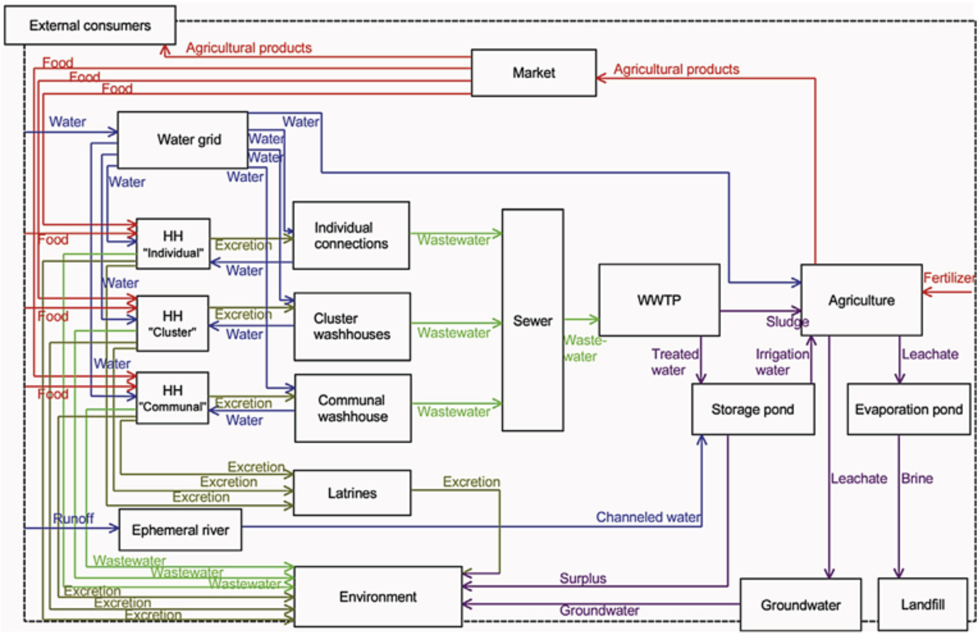

Fig. 1. System with nutrient and salt flows, including the situation with and without the WSTI infrastructure. The WSTI infrastructure is represented by the boxes "individual washhouses", "cluster washhouses" and "communal washhouses", sewer, wwtp (wastewater treatment plant), storage pond and evaporation pond. Flows are represented by arrows in different colors. Red: nutrients and salts in food and beverages, blue: nutrients and salts in piped and ephemeral river water, light green: nutrients and salts in wastewater, olive green: nutrients and salts in excreta, purple: nutrients and salts in treated and irrigation water. HH refers to the households that use the three types of water supply and sanitation units. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Differences between the cases simulated.

	$Case_{conv}$	$Case_{ideal}$	$Case_{assess}$
Situation	Conventional situation, before WSTI implementation	Planning with WSTI and ideal sanitation use	Assessment after 10 months of WSTI operation
Data	Baseline study	Design data	Assessment after 10 month of operation
Water supply	Communal water points, some private taps	Same as $case_{conv}$, in addition: Household connections (SD), cluster washhouses (TH), communal washhouse (OO)	Same as $case_{ideal}$: Less individual households were connected to water supply
Sanitation	Some public latrines, open defecation	Same as $case_{conv}$, in addition: Household connections (SD), cluster washhouses (TH), communal washhouse (OO). Most (82%) wastewater is collected and treated	Same as $case_{ideal}$: Less individual households were connected to the sewer than planned
Wastewater treatment	No	Advanced	Advanced
Agriculture	1.5 ha, irrigation with grid water, commercial fertilizer	1.5 ha, irrigation with reuse water (100%), nutrients are solved in the reuse water	1.5 ha, irrigation with reuse water (66%) and grid water, nutrients are solved in the reuse water

Settlements: SD: Shack Dwellers, TH: Tobias Hainyeko, OO: Onhimbu and Okaikongwe.

coefficient of variation of 10%. For all parameters, the probability density distribution was numerically described by a sample size of 10,000, and the probability distribution of the variables was calculated by Monte Carlo simulation. The parameter uncertainty ranking sorted the parameters with respect to their impact on the uncertainty of the variable calculated.

(6) *Analysis of results*

The output of the MMFA was analyzed for a) the amount of nutrients and salts discharged from inhabitants to the environment, b) the amount of nutrients and salts in irrigation water compared to crop requirements, c) the potential area that can be fertigated with the reclaimed nutrient-rich wastewater, and d) the reuse efficiency of each substance. In our study the reuse efficiency of a substance ($Reuse_{eff}$) is defined as (Eq. (1)):

$$Reuse_{eff} = \frac{CR_{reuse}}{S_{available}} \quad (1)$$

where CR_{reuse} is the crop requirement met from reuse water (as substance output) and $S_{available}$ is the substance available from human excreta and wastewater (as substance input). The reuse efficiency of each substance largely depends on the size of the agricultural area and the different requirement for each substance by crops. Ideally, 100% of the substances in excreta and wastewater would be reused by crops. A ratio of <100% means that substances in excreta and wastewater exceed the amount reused by crops and substances are left unused. The water reuse efficiency was defined as gross irrigation requirement including leaching related to reuse water available in the storage pond.

3.2. Leaching requirement for agriculture

The leaching requirement (LR) is the amount of water necessary to remove salts that have accumulated from the irrigation water as a result of evapotranspiration (Pescod, 1992). The LR was calculated for different irrigation water salinities and shows how the leaching requirement would vary depending on the electrical conductivity (EC) of the irrigation water. LR [mm] was calculated for localized irrigation according to Eq. (2) (Savva and Frenken, 2002):

$$LR = \frac{ET_C}{\left[1 - \left(\frac{EC_w}{2MaxEC_e} \cdot \frac{1}{L_e}\right)\right]} - ET_C \qquad (2)$$

where ET_c is the crop evapotranspiration [mm] computed with CROPWAT 8.0 (Woltersdorf et al., 2015), EC_w is the electrical conductivity [dS/m] of the irrigation water, $MaxEC_e$ is the maximum tolerable electrical conductivity of the soil saturation extract [dS/m] for each crop (from Savva and Frenken, 2002) and L_e is the leaching efficiency [decimal]. Given a medium infiltration capacity of the soil (Reichenbach, 2013), a medium leaching efficiency (0.5) for sandy loam was chosen. For the model calculations, we assumed that there is no accumulation of substances in the soil because leaching is adequate. We also assumed that for the case without WSTI, the fertilizer application necessary exactly equals crop requirements and we did not consider inefficiencies in crop uptake of nutrients.

4. Data

The data used for the modeling is presented below.

4.1. Human excretion of the six substances in Namibia

The amount of the six substances in excreta roughly equals intake of adults (NHMRC, 2006). Therefore, due to lack of more specific information, we assumed that the amounts in food intake and excreta are equal. The amounts of the six substances in dietary intake and human excretion for Namibia are given in Table 2. We applied standard equations to calculate N, P and K excretion from dietary protein intake (Jönsson et al., 2004a,b). The estimates produced in our study depend strongly on the type of database used.

4.2. Nutrient and leaching requirement of agriculture

We used an existing crop scheme for unrestricted irrigation with treated and nutrient-rich municipal water (Woltersdorf et al., 2015). The crops were chosen based on health protection, local practices, preferences and market revenues, salt tolerance and nutrient requirements. Given a soil salinity of 1 dS/m (Reichenbach, 2013) only moderately salt-sensitive crops should be cultivated according to FAO (Ayers and Westcot, 1985) to achieve full yield potential. Salt sensitive crops were therefore excluded from the crop scheme. Given the very low nutrient content of the soil, the nutrient requirement of crops was assumed to be at the upper end of the range provided by FAO (Doorenbos, 1979) (see Supplement, Table S1). The crops chosen have relatively similar nutrient requirements except for maize which requires higher quantities of N and P than the other crops (Doorenbos, 1979) and which can therefore profit most from the nutrient-rich irrigation water. Therefore, 0.5 ha of the available 1.5 ha was planted with maize.

4.3. Empirical data of soil, water and sanitation users

Before construction of the WSTI infrastructure, one sample of grid water and one sample of sewage water was analyzed (Müller, 2009) from an existing oxidation pond in Outapi that received urban wastewater. These data were used to characterize grid water in cases 0 and 1, and the EC of reuse water in $case_{ideal}$. Also one sample of the close-by ephemeral river water was analyzed (CuveWaters, 2011). The households in the settlements were surveyed in 2012 in order to determine their sanitation habits (Deffner et al., 2012). The soil at the agriculture site was analyzed before irrigation with reuse water (Reichenbach, 2013).

The WSTI infrastructure started its operation step-wise in May 2013. After 10 month of WSTI infrastructure operation, water samples were taken from the WSTI in March and April 2014. Water samples were taken at the inlet of the wastewater treatment plant, of the treated water, the storage pond, the washhouse, as well as selected cluster washhouses and individual household connections. For model calibration only the data from samples of the treated water were used (Table 3), as the data of the other sample points did not exactly match due to the delays caused by water transport within the WSTI. Müller (2014) analyzed the EC of the water samples during this period (Table 3) and recorded the water flows during March 2014. We then calculated the annual inflow to the wastewater treatment plant (15,955 m^3/yr), the water use in the communal washhouse (7846 m^3/yr) and in the cluster washhouses (6776 m^3/yr). The difference was attributed to the individual household connections (1333 m^3/yr). Deffner and Kramm (2014) surveyed washhouse and cluster washhouses users regarding their sanitation and water use habits and the frequency with which they used the washhouse and the cluster washhouses.

4.4. Cases

The three cases differ in the use of sanitation units and number of users as shown by parameter variations in Table 4. Differences in EC of the irrigation water is shown in Table 5. All other parameter inputs are the same for all cases.

In $case_{assess}$, the parameters shown in Table 4 were calibrated as follows: (1) The wastewater inflow to the wastewater treatment plant (15,955 m^3/yr) which is equal to the amount of treated water was newly estimated (see Section 4.3). (2) The concentration of substances measured in the treated water (Table 3) was multiplied by the amount of treated water to give the annual loads of substances in treated water. However, the relation between nutrients measured did not exactly match the one expected from

Table 2
Daily per-capita human excretion of the substances N, P, K, Na, Ca and Mg in Namibia assumed in this study.

Substance	Quantity in human excreta [g/p/d]	Source
N	7.9	Dietary protein intake: FAO 2014 data Namibia 2011; Substance excreted from protein intake: Jönsson et al., 2004a,b
P	1.1	
K	2.4	Urine measurements: Charlton et al., 2005, data South Africa, black; Share in urine: Schmidt et al., 2011
Na	3.3	
Ca	0.2	
Mg	1.7	

Table 3
Water sample analysis (our samples were analyzed by Namwater Ltd., water was sampled and EC measured by Müller (2014))

Point of sample	Date	n	Type	Mean quantitiy of substances [mg/l] and analyses methods/standards						n	Type	mean EC [μS/cm], analysis method/ standard
				N_{tot}	P_{tot}	K^+	Na^+	Ca^{2+}	Mg^{2+}			
Treated water	Sat 29-03-2014, Mon 31-03-2014	2	9h00-17h00 mean, 8h00- 18h00 mean	33 Photo-meter, ISO 11905-01	6.7 Photo- meter, 4500E	16	39	35	17	2	0h00-23h59 mean, 18h00-23h59 mean	446 Multi 1970i, EC electrode: TetraCon 325, WTW
						Inductively coupled plasma, 3120B (APHA et al., 1992)						

Table 4
Case differences indicated by different parameter values. In $case_{assess}$ parameters have been adjusted during model calibration. The mean parameter value is shown. Parameters for each type of sanitation unit are indicated, the weighted average for all sanitation units is printed in bold.

Parameter	Unit	$Case_{conv}$	$Case_{ideal}$	$Case_{assess}$	Source
Number of sanitation users (total)	capita	**1501**	**1501**	**588**	$Case_{conv}$, $Case_{ideal}$: Project estimation
Household connections		264	264	68	$Case_{assess}$: Own estimation based on Deffner and Kramm 2014
Cluster washhouse		840	840	260	
Communal washhouse		397	397	260	
Fresh water use (weighted mean)	l/p/d	**32**	**60**	**97**	$Case_{conv}$: Own estimation based on CuveWaters, 2008.
Household connections		33	60	70	$Case_{ideal}$: Project estimation based on CuveWaters, 2008 and WHO (Howard and Bartram, 2003).
Cluster washhouse		34	60	100	
Communal washhouse		26	60	100	$Case_{assess}$: Own estimation based on Deffner and Kramm 2014
Share of wastewater collected by sewer (weighted mean)	decimal	**0.00**	**0.80**	**0.90**	$Case_{conv}$, $Case_{ideal}$: Own estimation based on discussion with Deffner. $Case_{assess}$: Own estimation based on Deffner and Kramm 2014
Household connections		0.00	0.90	0.90	
Cluster washhouse		0.00	0.80	0.90	
Communal washhouse		0.00	0.80	0.90	
Ratio of users practicing open defecation (weighted mean)	decimal	**0.57**	**0.00**	**0.18**	$Case_{conv}$: Deffner et al., 2012. $Case_{ideal}$: Own estimation based on discussion with Deffner.
Household connections		0.64	0.00	0.00	$Case_{assess}$: Own estimation based on Deffner and Kramm 2014
Cluster washhouse		0.56	0.00	0.10	
Communal washhouse		0.54	0.00	0.30	
Ratio of users using the existing latrines (weighted mean)	decimal	**0.43**	**0.00**	**0.20**	
Household connections		0.36	0.00	0.20	
Cluster washhouse		0.44	0.00	0.20	
Communal washhouse		0.47	0.00	0.20	
Ratio of users using the existing water grid (weighted mean)	decimal	**1.00**	**0.00**	**0.14**	
Household connections		1.00	0.00	0.10	
Cluster washhouse		1.00	0.00	0.20	
Communal washhouse		1.00	0.00	0.10	

Table 5
Leaching requirement (LR) and leaching fraction (LF) depending on the type of irrigation water used with different salinity level.

	$Case_{conv}$	$Case_{ideal}$	$Case_{assess}$
Type of water used for irrigation	grid water	reuse water	reuse and grid water
EC [dS/m]	0.075 (Müller, 2009)	0.902 (Müller, 2009)	0.446 (Müller, 2014)
Classification and suitability according to FAO (Rhoades et al., 1992)	non saline, drinking and irrigation	slightly saline, irrigation	non saline, drinking and irrigation
LR [m^3/y/ha]	114	1504	707
LF [% of gross irrigation requirement]	1%	12%	5%

calculations. In particular the water samples contained more Na and Ca and much less N in relation to each other. Therefore the parameters were calibrated with the measured concentration of K and P in treated water, the two substances in the middle. The ratio among the substances contained in excreta indicated by literature in Table 2 was left unchanged. The other substances were then adjusted using these per capita excretion values. (3) The parameter values concerning the number of sanitation users, water use per capita, fresh water use, use of latrines and the existing water grid and open defecation were calibrated to match a) the newly estimated annual loads of substances in treated water, b) the results of the survey (Deffner and Kramm, 2014) of the number of users of the cluster washhouses and the washhouse, their water use per capita and the frequency they use the toilets, showers and washing sinks of the sanitation units, and c) the information provided by the Outapi Town Council that 17 households were individually connected to the wastewater treatment plant. (4) This resulted in 588 sanitation users, a weighted average for water use per capita of 97 l/cap/d, a slightly higher share of wastewater collected by the sewer (0.9), and more users practicing open defecation (0.18), using the latrines (0.2) and the existing water grid (0.14).

5. Results and discussion

5.1. Leaching for agriculture

The leaching requirement and fraction (Table 5) are lowest when irrigating with non-saline grid water ($case_{conv}$), about 1% of gross irrigation requirement. The reuse water assuming ideal sanitation use is slightly saline and requires about 13-times more water for leaching (12% of gross irrigation requirement). In $case_{assess}$, with fewer people using toilets and using them less frequently, the reuse water is non-saline and requires only half the leaching water required in $case_{ideal}$. Calculating the irrigation requirement of the crop pattern for 1.5 ha (after Woltersdorf et al., 2015), the net irrigation requirement without leaching is 19,589 m^3/yr for all cases. Adding the different leaching requirements (Table 5) and dividing by an irrigation efficiency of 0.9, the gross irrigation requirement is 21,956 m^3/yr in $case_{conv}$, 24,273 m^3/yr in $case_{ideal}$, and 22,944 m^3/yr in $case_{assess}$.

Previous studies (Ben-Hur, 2004; Ayers and Westcot, 1985) even suggest that an annual rainfall of about 500 mm might be sufficient to leach excess salts in the soil below the root zone during the rainy season, in particular when the rainy season is concentrated in 3–4 months as it is in central-northern Namibia. The sodium adsorption ratio (SAR) indicating potential problems with infiltration or specific ion toxicity was calculated according to FAO (Ayers and Westcot, 1985) to be slight to moderate (2.7) in $case_{ideal}$ and low (1.5) in $case_{assess}$. Therefore, no problems with soil salinization, infiltration or ion toxicity are expected.

5.2. MMFA: quantification of nutrient and salt flows

Results are first presented and discussed for the single cases. Then the system flows are compared and, finally, the two most important flows of the system are analyzed.

5.2.1. $Case_{conv}$

Without WSTI, the inhabitants take their water from the water grid via communal water points and some private taps. Of the inhabitants 57% practiced open defecation and the rest use the public latrines (Table 4). As indicated by the main flow of substances (Fig. 2a), as there is no sewer, all wastewater and excreta flow untreated to the environment and so cannot be used for agriculture. Household discharge via open defecation, public latrines and wastewater to the environment is 4430 kg N (2.95 kg N/cap) with a 90% probability interval of 3390-5950 kg (2.44–3.51 kg N/cap) (Fig. 3). For irrigation, piped water (Fig. 4) contains sufficient quantities of Ca and Mg to satisfy crop requirements, insufficient amounts of K and no N or P. Therefore, the remainder needed by crops (assuming that crop uptake is equal to crop requirement) is supplied as fertilizer (498 kg N, 349 kg P, 444 kg K).

5.2.2. $Case_{ideal}$

The potential of WSTI is indicated by $case_{ideal}$ assuming that all users use the sanitation units ideally; there is no open defecation and no use of the latrine and the communal water point (Table 4). Thus (Fig. 2b) all excreta and a large proportion of the wastewater (90% in individual household connections, 80% in cluster washhouses units and the communal washhouse) could be collected and treated. For this reason, little greywater containing practically no substances are discharged from the households to the environment (Fig. 3). In consequence, the load of substances in the irrigation water (Fig. 4) is the highest of all cases: For instance, a mean of 3480 kg N (90% probability interval 2470–4440 kg N) is applied to agriculture. All nutrient loads far exceed crop requirements. In addition, 2010 kg Na originating from human excreta is applied to agriculture with the reuse water. This is 15 times more than the 138 kg reaching agriculture from irrigation with piped water ($case_{conv}$). Consequently, the nutrients and salts not taken up by the crops are collected in the lined evaporation pond. From there they would have, eventually, to be deposited in landfill. Major accumulation of nutrients and salts in the soil is not predicted due to the medium texture of the sandy loam and adequate leaching that washes out excess salts and nutrients. In contrast to $case_{conv}$, in $case_{ideal}$ all nutrient requirements could be provided in irrigation water, no fertilizer is required and practically no wastewater discharged untreated to the environment.

5.2.3. $Case_{assess}$

After 10 months of WSTI operation, during 2 days of sampling, we found that the treated water contained far lower amounts of nutrients and salts than had been expected in the planning phase with ideal sanitation use. Instead of 66 households in the Shack Dwellers settlement, only 17 were connected in April 2014, the households in Tobias Hainyeko settlement are considerably smaller than previously assumed and only 270 and 260 residents used the cluster and the communal washhouse in March 2014 (Deffner and Kramm, 2014). In addition, many inhabitants are often not at home as they work far away (Deffner and Kramm, 2014). On this basis, the number of users estimate was 588 (Section 4.4). As 588 users excrete far less than 1501 users as expected in the planning phase (Table 4), nutrient and salt flows are smaller in total than expected (Fig. 2). We estimated that 0% of individual connection users, 10% of cluster washhouse users and 30% of communal washhouse users practiced open defecation (Table 4). Toilet use was considerably lower than ideal, users using the toilets in all sanitation units on only 62% of the occasions possible. For this reason, a fairly large amount of substances are discharged from households to the environment, and less excreta is collected by the sewer (Fig. 3). This outcome seems due, particularly, to the current tariff structures. Therefore, despite there being only 588 users, discharge to the environment is very much greater than it would have been with ideal sanitation use (Fig. 3). Consequently, the irrigation water consists of 70% reuse water rather than 100% had sanitation use been ideal. Nevertheless, in the communal washhouse and the cluster washhouses, water use per person (100 l/p/d) is considerably higher than estimated in $case_{ideal}$ because sanitation users predominantly use the washhouse to shower and to wash laundry, while urination predominantly still takes place in the open. In the cluster washhouses the hand wash basin is free of charge. For agriculture, additional piped water (8690 m^3) needs to be supplied. Irrigation water (Fig. 4) contains lower quantities of nutrients than with ideal sanitation use. N, Ca, and Mg were just sufficient to meet crop requirements. Additional 188 kg P and 85 kg K need to be supplied as artificial fertilizers.

During the planning phase, we also modeled a more realistic case with mixed sanitation use. This case included a lower water use per person and a greater proportion of open defecation and latrine use than $case_{ideal}$. Compared to $case_{assess}$, in the realistic case water use per person was slightly lower, but toilet use was slightly higher (64% compared to 62% of times). Under these conditions the results indicated slightly more reuse water and more nutrients and salts to be available.

5.2.4. MMFA diagrams of the three cases

The MMFA diagrams (example for N; Fig. 2) demonstrate how substance flows differ between the three cases. Nutrient inflows to the system originate mostly from the food consumed in households (>89% N, >59% P, >68% K), the remainder originates from fertilizers applied in agriculture and grid water supply for households and irrigation, while irrigation with water from the ephemeral river

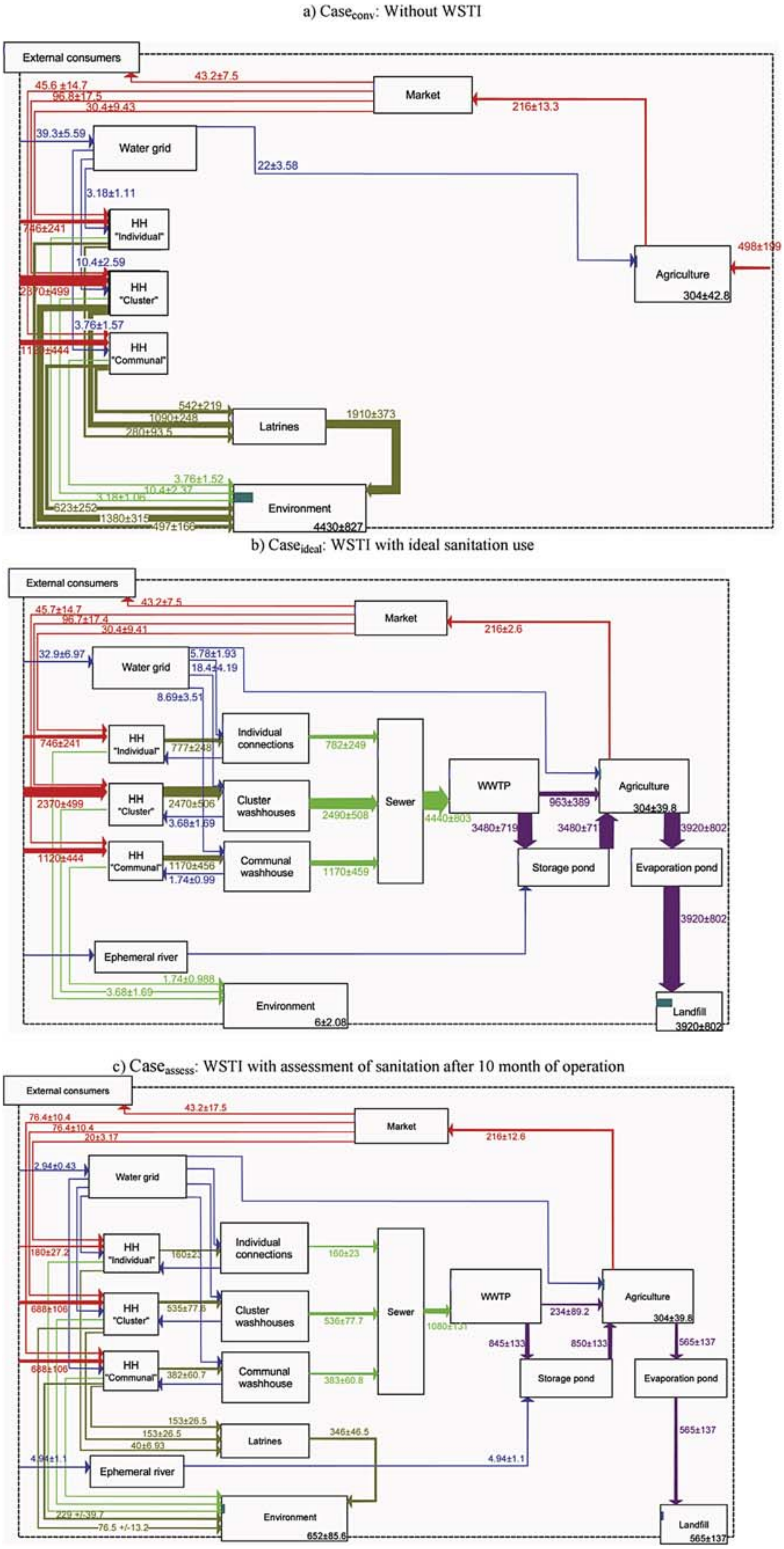

Fig. 2. Simulation results of nitrogen (N_{tot}) flows for a) case$_{conv}$ b) case$_{ideal}$ and c) case$_{assess}$ (mean value and standard deviation) [kg/yr].

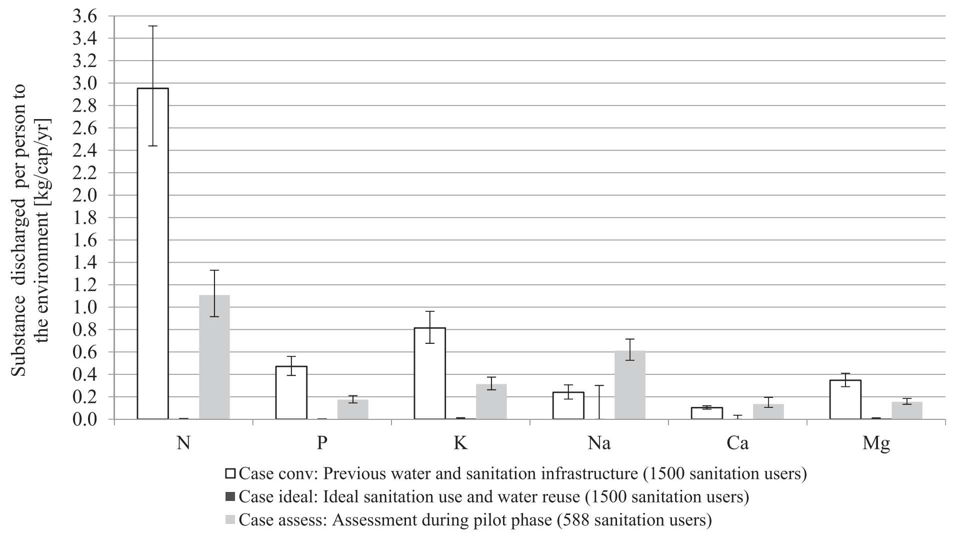

Fig. 3. Substances discharged per person (through open defecation, public latrines, wastewater) to the environment (mean value and 90% probability range) [kg/cap/yr].

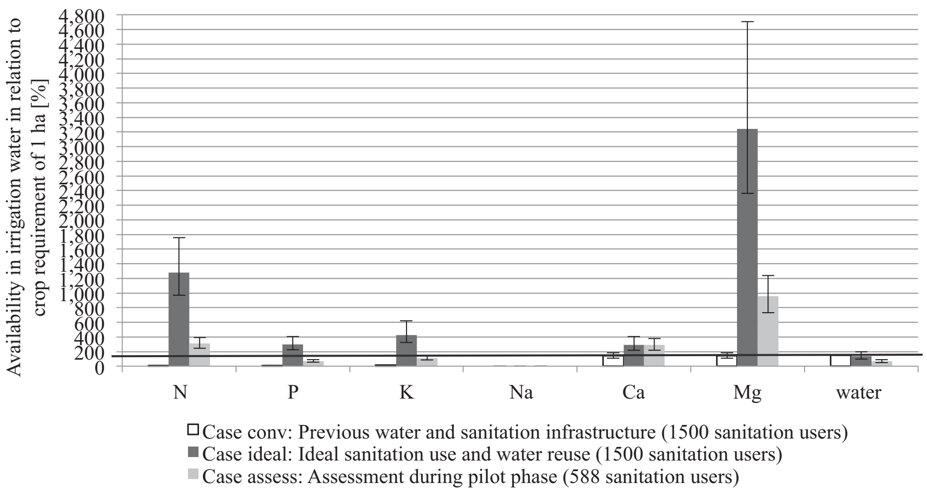

Fig. 4. Availability of substances in irrigation water. Contained in reuse water flowing from the wastewater treatment plant to the pond ($case_{ideal}$, $case_{assess}$) or in grid water ($case_{conv}$) (mean value and 90% probability range) in relation to crop requirement of 1 ha per year [%]. Black line: Crop requirement of 1.5 ha (equals 150% of crop requirement of 1 ha).

plays a minor role. Salts also originate mostly from food (>77% Na, >7% Ca, >76% Mg) but also from grid and irrigation water supply from the water grid (>65% Ca, >6% Mg), the remainder coming from irrigation water taken from the ephemeral river. The nutrients and salts contained in 110,000 kg agricultural produce of the water reuse site contain: 216 kg N, 33 kg P, 289 kg K, 11 kg Na, 21 kg Ca and 17 kg Mg. This is the amount of recycled nutrients in the sanitation-agriculture loop. The MMFA diagrams show that without WSTI (Fig. 2a) most substances excreted from households end up in the environment, while with WSTI (Fig. 2b and c) the flow to the environment is smaller and most substances can be collected in landfill. Furthermore, without WSTI, nutrients to agriculture are supplied in fertilizers. With WSTI, however, they are supplied in irrigation water. Therefore, with WSTI the amount of substances in the system is reduced by the amount of fertilizers supplied to agriculture without WSTI. Crop residues containing nutrients are left on the agricultural area to improve the soil.

5.2.5. Analysis of the two most important flows

The two most important flows are: 1) The discharge of inhabitants to the environment (Fig. 3) and 2) the irrigation water either supplied from the wastewater treatment plant to the storage pond or from grid water, related to crop requirements (Fig. 4). The discharge flow (via open defecation, the latrine and released wastewater) shows the potential of wastewater reclamation and treatment to reduce environmental pollution through eutrophication and salinization. The irrigation flow is important because it shows the amount of nutrients available from human excreta that can be used for crop nutrition and the amount of salts that might harm crops and thus need to be managed carefully. Precipitation and evaporation in and from the storage pond have been considered.

5.3. Parameters causing uncertainty in the results

Five parameters cause over 90% of the uncertainty of the result of the two most important flows presented previously in Section 5.2.5. The uncertainty of the flow "substances discharged per person through open defecation, public latrines and wastewater to the environment" presented in Fig. 3 depends, in $case_{ideal}$, for all substances by 90% on 3 parameters.

- The share of wastewater collected by the sewer (67% of uncertainty). This parameter causes the highest uncertainty because, with ideal sanitation use where only some wastewater (no excreta) is discharged to the environment, it most determines the amount of substances that is discharged to the environment (see Fig. 3).
- Number of sanitation users (>20% of uncertainty)
- Substance in tap water (8% of uncertainty)

For the flow “availability of substances in irrigation water” over 90% of the uncertainty of the result is caused by 3 parameters (% of uncertainty given for $case_{ideal}$):

- The number of sanitation users (N, P, K: 22%, Na: 26%, Ca: 0.3%, Mg: 31%). This parameter causes the highest uncertainty because N, P and K contained in irrigation water originate from human excreta and the amount of substances available from human excreta mainly depends on the amount of sanitation users.
- The amount of substance not removed during wastewater treatment (N, P: 22%, K: 26%, Na: 30%, Ca: 23%, Mg: 46%)
- The amount of excreted substance in urine and feaces (N, P, K: 44–48%) and in urine (Na: 5%, Ca: 35%, Mg: 5%)

Better information about these five parameters would reduce the uncertainty of the two flows. The amount of substances in grid water can be easily analyzed. Also the percentage of the substances not removed during the wastewater treatment can be easily determined after longer operation by measuring the difference between substances inflow and outflow of the plant. The amount of substances in human excreta could be determined more precisely by urine analyses of local inhabitants. However, the two most relevant parameters are likely to remain the highest source of uncertainty: the share of grid water that is collected by the sewer and the number of inhabitants using the sanitation units. These parameters are difficult to determine more precisely, due to the high fluctuation of the inhabitants and the absence of a counter measuring the difference between grid water supply and wastewater collected.

5.4. Fertigated area and substance reuse efficiency

With ideal sanitation use, 1500 users and the developed crop scheme, the reuse water would be sufficient to annually irrigate 1.5 ha (90% probability range 1.1–1.8 ha) meaning 10 m^2/cap (7–12 m^2/cap) (Fig. 5). Adding sufficient grid water, nutrients could be reused more fully. P is then the limiting factor and sufficient to fertigate 20 m^2/cap (16–24 m^2/cap). Adding also sufficient P, K and Ca, the area could be optimized for available N to fertigate 85 m^2/cap (70–104 m^2/cap). The assessment during the pilot phase with 588 users, showed that there was insufficient P and water for fertigating 1.5 ha: P was sufficient for fertigating 12 m^2/cap (10–15 m^2/cap), the water for fertigating 13 m^2/cap (9–16 m^2/cap). However, because water is a scarce resource in the area, it is water itself that is likely to remain the factor determining the size of the agricultural area.

With ideal sanitation use, all the excreta from 1500 inhabitants are collected by the sewer. Looking at the chain from inhabitants to crop uptake, only 12% N, 50% P, 35% K, 0% Na, 46% Ca and 5% Mg present in excreta and wastewater are finally taken up by crops (Fig. 6). The first reason is the unequal availability of reuse water and nutrients in relation to crop requirements: The reuse water contains too many nutrients. This means, that the water use per person is too low compared to the excreta of each person that contain high nutrient amounts, related to crop water and nutrient requirements. The second reason is that the ratios of the substances in human excreta are not the same as those of nutrients required by crops. Therefore, not all substances can be taken up by crops and they largely remain unused. Consequently, the substance reuse efficiency is fairly low for all substances even with ideal sanitation use. Our assessment during the WSTI pilot phase showed that in addition considerable amounts of nutrients were lost through open defecation, public latrines and wastewater release to the environment. The amounts of P and K are lower, while the amount of N is larger in excreta than in crop requirements. Therefore N reuse efficiency is particularly low (12% in $case_{ideal}$, 30% in $case_{assess}$). The reuse efficiency of water is the highest with 71% (90% uncertainty range: 61%–80%), as the area irrigated has been adjusted for water. However, even the water reuse efficiency is not 100%, because 19% of the treated water evaporates from the storage pond even though a small amount is added by precipitation.

5.5. Limitations, outlook and applicability

The relationship among nutrients (N, P, K, Ca, Mg) in wastewater differs from that among nutrients required by crops. Thus, the reuse water contains too much N and not enough P and K for optimum crop growth. The amount of N, P and K in excreta depends on the

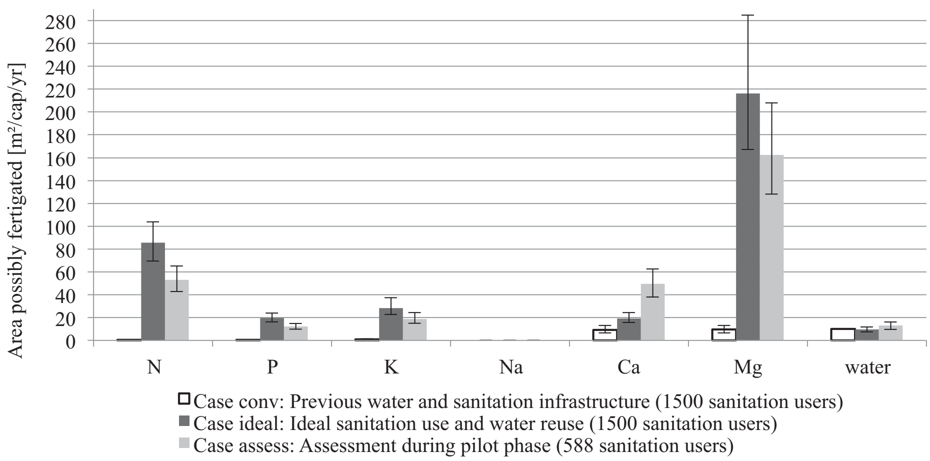

Fig. 5. Area that can be fertigated per person and year with grid water ($case_{conv}$) or nutrient-rich reuse water and sludge ($case_{ideal}$, $case_{assess}$) [m^2/cap/yr] (mean value and 90% probability range).

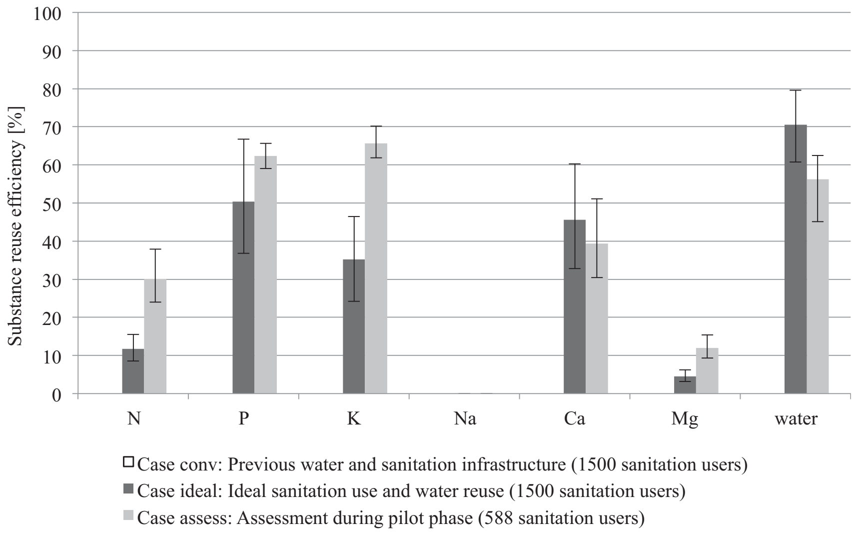

Fig. 6. Substance reuse efficiency defined as substances originating from reuse water taken up by crops on 1.5 ha in relation to substances in human excreta and wastewater from sanitation users (mean value and 90% probability range).

amount of food protein, while P and K also depend on the amount of food vegetable protein. Namibians have a particularly low intake of vegetable proteins (total protein: 61 g/cap/d, including vegetable protein: 37 g/cap/d) compared to other countries with similar total protein intake such as Nigeria or Kenya but a much higher share of vegetable protein (vegetable protein: 52 and 47 g/cap/d) (FAO, 2014; data for 2011). In Namibia, therefore, the amount of P and K in excreta is particularly low compared to the amount of N. In other countries with a higher vegetable protein intake, thus more P and K are expected to be in the reuse water. In addition, also other crops may have different irrigation and nutrient requirements. Tomatoes, for example, have particularly high K requirements and beans particularly low N requirements. Citrus trees have particularly low P requirements relative to their high requirement for irrigation (Doorenbos, J., 1979). However, the crop scheme we used was chosen on other criteria. In particular, maize was chosen because it provides the optimum market potential, best meets local preferences and is free of the risks to health of people eating crops growing below the surface. It was therefore not possible to select crops on their optimal nutrient ratio requirements.

Instead of evaporating water from the leachate in the evaporation pond and depositing the resulting brine in landfill, the leachate itself could be reused for irrigation. However, the second highest component of leachate, after N, is Na. It would therefore only be possible to apply the leaching water to very salt tolerant crops such as fodder grasses with very careful salt management. As well, after several years of fertigation with reuse water, the levels of accumulation of substances in the soil and the degree of leaching necessary should be added to the model. Where the evaporation pond is unlined (as currently in the pilot area) the leachate might well percolate into the groundwater. It would then pollute the environment with salts and excess nutrients because it contains 3920 kg N, 354 kg P, 897 kg K, 2010 kg Na, 154 kg Ca and 967 kg Mg, assuming ideal sanitation use.

Where WSTI is not implemented, field measurements should be made to investigate how much fertilizer applications need to be increased relative to the crop requirement then existing in order to account for nutrient losses. Furthermore, we used water quality analyses over only 2 days. A wider range of monitoring data from the WSTI needs to be used in order to validate and improve calibration of the model results. New calibrations should also be made after WSTI has been operating for more time. This is because the number of sanitation users indicated in $case_{assess}$ is expected to increase with length of WSTI operation towards the number expected in $case_{ideal}$. New calibration of the model with new measurements would produce additional results. It would also be useful to investigate the pharmaceuticals and heavy metals in the reuse water. Heavy metals are not expected to pose problems in municipal wastewater. In contrast, pharmaceuticals, especially those used against HIV, may well be present in central-northern Namibia. It is therefore relevant to investigate closely what amounts wastewater contains, the degree to which they are decomposed during wastewater treatment and in the soil, and their uptake by crops and impact on humans that eat the vegetables. The risk should however be put in relation to the current difficult socio-economic situation of the inhabitants in central-northern Namibia.

Our quantitative assessment method is applicable to all urban areas in developing countries with similar starting conditions such as in Outapi where our study took place. These conditions include insufficient sanitation and wastewater treatment infrastructure, informal settlements with public latrines, inhabitants practicing open defecation, high unemployment, low income and little education, a semi-arid climate that necessitates irrigation for agriculture, and the possibility of installing a water reuse site next to the wastewater treatment plant. The methodology can also be transferred to semi-arid high income countries if adapted to the existing type of sanitation units and user behavior. The results of this study can be compared to results obtained in other areas with similar conditions to those in our study region with similar numbers of sanitation users and size of agricultural area.

6. Conclusions

1. The quantitative assessment method we developed is suitable for supporting the design and operation of WSTI infrastructure because quantification of water, nutrient and salt flows allows assessing the fulfillment of crop requirements regarding water and nutrients as well as environmental pollution through salinity and nutrients. As nutrient and salt flows depend greatly on the WSTI infrastructure being used by residents, the mathematical material flow analysis applied can also be used, in

combination with water quality measurements, to monitor the actual number of users of WSTI infrastructure.

2. According to the quantitative assessment of the design phase of the WSTI infrastructure in Namibia, water is the limiting factor for crop fertigation if ideal sanitation use is assumed, closely followed by P. Without additional grid water, P and especially N, K, Ca and Mg cannot be fully used. P is the substance that is used most fully. Of the amount of P in human excreta, we estimated that 50% is reused by crops, while the remainder is lost through wastewater treatment or not taken up by crops due to the small size of the field available for irrigated by reuse water. The reuse water is sufficient to fertigate a crop area of 1.5 ha (90% uncertainty range 1.1–1.8 ha) or 10 m^2/cap (7–12 m^2/cap) per year. With additional grid water, P is sufficient to fertigate 10 m^2/cap (16–24 m^2/cap).
3. The ratio of nutrients (N, P, K, Ca, Mg) in wastewater differs from that of the nutrients required by crops. For optimum crop growth, wastewater contains too much N and not enough P and K. This might be different in other counties and with other crops grown.
4. The assessment based on data from the WSTI pilot phase showed that water use per person was as high as was expected in the design phase for the case of ideal sanitation use. However fewer nutrients were present in the wastewater, because more open defecation than expected took place even after construction of the WSTI infrastructure. Consequently, P became the limiting factor and insufficient P and water were available for fertigating 1.5 ha. P was sufficient to fertigate only 0.6 ha or 12 m^2/cap (10–15 m^2/cap), the water was sufficient to fertigate 13 m^2/cap (0–16 m^2/cap). In addition, the assessment showed that the number of 1500 sanitation users was overestimated in the design phase and the estimate was revised to 588 users.
5. The WSTI infrastructure prevents diffuse discharge of nutrients and salts to the environment almost completely if the sanitation units provided are used by the residents and the evaporation pond is lined.
6. The reuse water containing salts from human excreta is classified as slightly saline with ideal sanitation use and non-saline after assessment during the pilot phase. With ideal sanitation use and irrigation with reuse water, the leaching requirement is 13-times higher compared to grid water irrigation (21% compared to 1% of crop water requirements).
7. To reduce uncertainties in the amount of nutrients and salts in the reuse water and the amount discharged to the environment, better information is necessary on the share of wastewater that is collected by the sewer (i.e. not discharged to the environment) and of the correct number of inhabitants using the sanitation units.
8. To fully exploit the fertigation potential of human excretions and waste water, open defecation and latrine use needs to be avoided. In addition, additional settlements should be connected to the waste water treatment plant as its capacity is currently not fully used.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2015.12.025.

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Benefits of an integrated water and nutrient reuse system for urban areas in semi-arid developing countries

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Abstract

Urban areas of developing countries face the challenge to implement adequate urban water infrastructures while managing resources in a sustainable manner. The objective of this study was to identify the benefits and challenges of a novel resource recovery system that integrates sanitation infrastructure, wastewater treatment and reuse of nutrient-rich water for the irrigation of human food crops, in relation to the local conventional system and to two adapted systems. A town in Namibia exemplifying the typical problems of urban areas in developing countries served as a case study. The four options were compared with ecologic, economic, societal, institutional and political as well as technical criteria using the Analytic Hierarchy Process (AHP), a tool for multi-decision criteria analysis for dealing with complex decision-making. This methodology helps decision-makers and engineers to have proper information on which options to implement for increasing the livability in cities towards a more sustainable future. Results indicate that the novel system has numerous benefits especially in the societal and environmental dimensions and scores highest when weighting all dimensions equally as well as with a particular focus on environmental and societal criteria. Hence, we suggest that the novel resource recovery system is a viable way for urban areas of developing countries towards a more sustainable urban sanitation, wastewater and irrigation infrastructure, using fewer resources, being economically feasible, institutionally and politically practical and technically sound. However, in light of its challenges, the answer to the question which resource recovery system is the best option for the local context is, that it also depends on the particular focus in the relative context.

1 Introduction

Adequate sanitation and wastewater treatment is often lacking in urban areas of many developing countries (WWAP 2012). Also the provision of sufficient water and fertilizers for urban agriculture is a major issue in semi-arid developing countries. In the past decades there has been a paradigm shift of the present conventional urban water and wastewater infrastructure (Guest 2009). Thus, the attitude towards domestic wastewater has been changing, towards regarding sanitation and wastewater treatment systems as resource recovery systems for water and nutrients (Guest 2009, Adewumi 2010, McCarty 2011). Among the numerous emerging water reuse concepts, the challenge is to select the system that is best suited to the specific local context. This is important for policy-makers, engineers and the general public in order to have proper information about the benefits and challenges of different options for water and nutrient recovery systems. To find the best suited system, decision-support systems are helpful tools especially indicated to support complex multi-criteria decision making (Power et al 2002).

Evaluating and comparing alternative options of resource recovery systems using sustainability criteria and indictors is a common method (ASCE 1998, Morrison et al. 2001, Balkema et al. 2002, Palme et al. 2005, Cinelli et al 2014). While multi-criteria decision systems such as the AHP method have been previously used to evaluate wastewater management technologies (e.g. Molinos-Senante et al. 2014, 2015, Aydiner et al 2015), to the knowledge of the authors, this approach has not yet been applied to resource recovery systems in a developing country setting. In addition, to be as context specific as possible, a wide range of criteria need to be integrated into the evaluation. However, integrating a wide range of sustainability dimensions (ecologic, economic, societal, institutional and political, technical) into the evaluation of resource recovery systems is rather unusual (Garcia and Pargament 2015, Molinos-Senante et al 2014, Balkema et al. 2002).

Previous studies have shown that for wastewater treatment in developing countries, wastewater stabilization ponds are usually the best option, as they are simple, low cost, efficient and robust (Mara 2003, von Sperling and Chernicharo 2005). However, if badly managed, they become overloaded spilling over during heavy rain storms and floods, might release odors, have high land requirements, might also be a breeding ground for mosquitos and therefore a serious health problem and energy cannot be recovered as methane is emitted to the atmosphere and the treated water might have a poor quality (Mara 2003). Therefore, it can be questioned whether wastewater stabilization ponds can be the best option to be integrated in resource recovery systems for reusing water and nutrients for the irrigation of urban agriculture.

A novel water and nutrient reuse system has been implemented in the northern part of Outapi by the CuveWaters research project (CuveWaters 2013). The reuse system connects water supply, improved sanitation, advanced wastewater treatment and nutrient-rich water to the reused for the irrigation of urban agriculture. The novel concept has not been technically implemented before, including its small-scale (1400 inhabitants, 3 ha crop area) and the direct reuse of treated nutrient-rich water for human crop production in an urban-area in a developing country. The objective of this study is to identify benefits and challenges of this novel nutrient and water reuse system in relation to the conventional system in the area and to two adapted systems proposed by this study.

2 Study area

The town of Outapi in central-northern Namibia served as our case study. Outapi exemplifies the typical problems of urban areas in semi-arid developing countries: Inadequate water supply for hygiene and agriculture, low access to sanitation facilities, inadequate wastewater treatment, nutrient poor soils, population growth (according to the former CEO of Outapi, the population is currently doubling in number roughly every 3 years (in 2014 ca. 13,200)), further urbanization (see Deffner et al. 2012), and a mix of low-density informal suburbs (with shacks) and low-density formal suburbs (with brick houses). Central-northern Namibia is a semi-arid and water scarce region. Mean precipitation is 464 mm/y occurring from November to April. In the absence of perennial water resources, water is supplied by an open canal and pipelines originating from the Angolan-Namibian border river Kunene (Heyns 1995). Currently, extensive new agricultural areas with food crops are planned and expanded in the surroundings of the city, using tap water for irrigation and mineral fertilizer. The region has a high demand for agricultural products to increase food security and import substitution (Government of Namibia 2006). Four settlements in the north of the town (Fig. 1) including informal suburbs with shacks and an open market (Onhimbu, Okaikongwe, Tobias Hainyeko) and a formalized suburb with brick houses (Shack Dwellers) were estimated to have about 1,400 inhabitants in September 2015. The previously existing water and sanitation infrastructure comprises the water pipeline scheme with communal water taps, some private taps and some public-pit latrines (Kramm and Deffner, in prep.). The minority of the inhabitants had access to latrines (37% in Shack Dwellers, 44% in Tobias Hainyeko, 4% in Okaikongwe, 90% in Onhimbu) and most practiced open defecation (Kramm and Deffner, in prep.). In the southern part of the town, a conventional gravitational sewer system transports the wastewater from connected formalized buildings outside of the city to a series of large wastewater stabilization ponds. The water is evaporated and not used anymore. These ponds are not well managed and regularly spill over during the frequent floods in the area constituting a health risk for the local population.

3 Methodology

The methodology consists of four steps: (1) establishing the goal, scope and boundaries of the evaluation, (2) designing the options to be evaluated, (3) setting up the evaluation team, (4) selecting an appropriate method for multi-criteria decision making, (5) assessing the uncertainty of results with sensitivity analyses and (6) identify benefits and challenges.

3.1 Goal, scope, spatial and temporal boundary of the evaluation

The goal of the evaluation is to identify benefits and challenges of different nutrient and water reuse systems. The scope of the evaluation includes the five pillars of sustainability, adding to the triple bottom line (WCED 1987) of economic, environmental and social pillars, also a technical as well as an institutional and political dimension, due to the complexity associated with a resource recovery system. The spatial and temporal boundaries are the same for all systems: The spatial boundary is given by the four settlements in Outapi with an estimated 1,400 inhabitants (Fig. 1). The temporal boundary is the situation in September 2015.

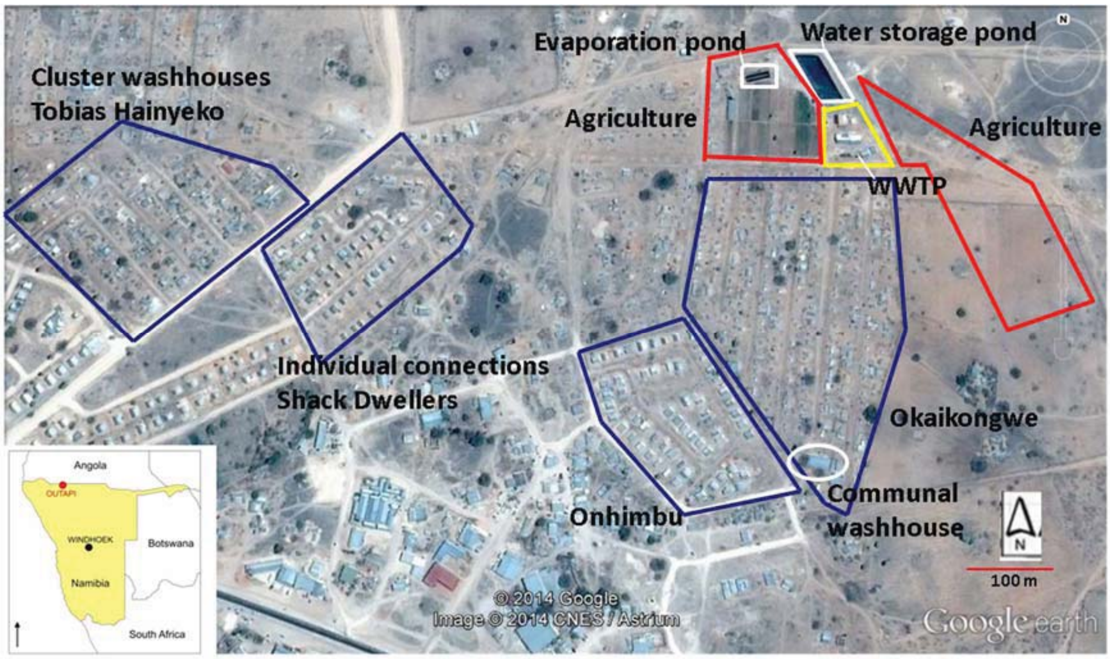


Fig. 1: Map of the four settlements in Outapi (blue), agriculture site (red), as located for all options. WWTP: Wastewater treatment plant (yellow). The water storage pond for reuse water only existing in options 1b, 2a and 2b. The communal washhouse only in option 2a and 2b. (Satellite image is provided with permission by CNES/ Astrium 2013, powered by Google Earth, small map source: Natural Earth) (Adapted from Woltersdorf et al. 2016)

3.2 Design of options for evaluation

Four systems were evaluated: the conventional (1a), the conventional adapted (1b), the novel (2a) and the novel adapted (2b) (Tab. 1). The novel system has been piloted in Outapi and is evaluated on the basis of monitoring data of the pilot plant and expertise gained from its start in April 2013 to September 2015. The conventional system is evaluated on the basis of the existing sanitation and water infrastructure in the four settlements before the introduction of the novel system and in other parts of Outapi and central-northern Namibia. The two adapted systems were designed by this study as optimizations of the conventional and the novel system by changing specific components (Tab. 1 and 2). The adapted systems 1b and 2b are evaluated based on assumptions of this study and the experience of local current practices. To ensure the comparability of the evaluation of the four systems, an ideal management of the stabilization ponds was assumed with the necessary amount of financial resources and labor. This has an impact on costs as well as on the institutional capacities and institutional complexity.

Tab. 1: Options designed for evaluation

<table>
<tr><th colspan="2" rowspan="2">Option</th><th colspan="2">Sanitation</th><th colspan="2">Wastewater treatment</th><th rowspan="2">Agriculture</th></tr>
<tr><th>Formal settlements</th><th>Informal settlements</th><th>Formal settlements</th><th>Informal settlements</th></tr>
<tr><td>1a</td><td>Conventional</td><td rowspan="2">Individual household connection</td><td rowspan="2">Open defecation, pit latrines</td><td>Ponds</td><td rowspan="2">None</td><td>Tap water, chemical fertilizer</td></tr>
<tr><td>1b</td><td>Conventional adapted</td><td>Adapted ponds</td><td>Reuse water, tap water</td></tr>
<tr><td>2a</td><td>Novel</td><td rowspan="2">Individual household connection</td><td rowspan="2">Cluster washhouses, Community washhouse</td><td colspan="2">Advanced</td><td rowspan="2">Reuse Water</td></tr>
<tr><td>2b</td><td>Novel adapted</td><td>Adapted ponds</td><td>Adapted ponds</td></tr>
</table>

Formal settlements (Shack Dwellers), Informal settlements (Tobias Hainyeko, Onhimbu and Okaikongwe)

All systems were designed to be suited in the identical position regarding settlements, wastewater treatment and the agricultural site (Fig. 1). In all systems, the agricultural area is assumed to have the same: crop scheme producing food for human consumption, size (3 ha), yield (18.5 t/ha/year), irrigation requirement (16,181m³/ha/year), equipment (drip irrigation, high tanks, sub-surface drainage) and operator of the farm who employs several workers and sells the produced fruits and vegetables directly on site.

The four systems differ in terms of type of water supply connection (i.e. public water points, washhouses), sanitation and wastewater treatment infrastructure and type of irrigation water (Tab. 1). The agricultural area can be irrigation with tap water, with reuse water or with both, depending on the availability of reuse water in the system under consideration. The wastewater that can be collected by the sewer and treated in both conventional options is 16 m³/day originating only from the formal settlement. In both novel options 52 m³/day can be collected, originating from both formal and informal settlements. For water reuse, this study designed the wastewater stabilization ponds in options 1b and 2b to reach, together with drip irrigation, according to literature values (Sperling and Lemos Chernicharo 2005), the necessary pathogen reduction of 6 log units required by the WHO guideline (2006). The sludge is not applied in agriculture as it is not hygienically safe, e.g. might contain sedimented viruses. Compared to option 1a, in option 1b and 2b, the facultative and the maturation pond have been redimensioned (height and length/breadth ratio) and the hydraulic detention time has been increased (Tab. 2) in order to reduce more E.coli and fecal coliform bacteria. Therefore, it can be expected, that in all options reusing nutrients and water, the fruits and vegetables are safe for consumption.

Tab. 2: Wastewater treatment components in the evaluated systems

		1a: Conventional	1b: Conventional adapted	2a: Novel	2b: Novel adapted
Series of connected ponds	1: Anaerobic pond	t=3, H=3, L/B=2	t=10, H=2.5, L/B=3.0	/	same as 1b
	2: Facultative pond	t=15, H=2, L/B=2	t=20, H=1.5, L/B=3	/	same as 1b
	3: Maturation pond	t=30, H=1, L/B=2.2	t=40, H=1, L/B=3	/	same as 1b
	4: Evaporation pond for wastewater	t=120, H= 1, L/B= 1.6	/	/	/
	5: Storage pond for irrigation water	/	t=10, H=2, L/B=3	t=54, H=2, L/B=2.6	same as 1b
Wastewater treatment plant		/	/	UASB, RBC, micro strainer, UV-radiation	/

t= hydraulic detention time (days), H= height (m), L/B= length/breadth ratio

3.2.1 Option 1a: Conventional system

The conventional system comprises the infrastructure that currently exists in the southern part of Outapi and in most other towns of central-northern Namibia, and is now assumed to be implemented also in the study area, in the northern-part of the city. Brick houses in the formal settlement (200 inhabitants) are individually connected (or are planned to be connected in the future, which is assumed to be realized in this study) to water supply and sewage. Their wastewater is transported via gravitational sewer to a series of wastewater stabilization ponds (anaerobic-facultative-maturation ponds) (Tab. 2) where the water is treated and evaporates. Informal settlements with shacks of corrugated iron sheets cannot be connected individually to water supply and sewage; here a few water points supply water and some public latrines provide sanitation, while most (50%) inhabitants practice open defection. As no nutrient and water reuse takes place, agriculture is irrigated with tap water, chemical fertilizers are used and no storage pond for reuse water is necessary. Fertilizer prices are currently low although steadily increasing, while tap water is rather expensive for commercial farmers.

3.2.2 Option 1b: Conventional adapted system

The conventional adapted system is the conventional system 1a, adapted for nutrient and water reuse in agriculture. For this, the conventional wastewater treatment ponds are redesigned and their hydraulic detention time is increased to achieve the necessary pathogen reduction required for reuse water for the irrigation of food crops (according to WHO 2006 and Lemos Chernicharo 2005) (Tab. 2). The wastewater stabilization ponds directly supply the nutrient-rich irrigation water for the agricultural irrigation site.

3.2.3 Option 2a: Novel system

The novel system includes as sanitation infrastructure: (i) conventional individual household connections (200 inhabitants) to water and sewage in the formal settlement, (ii), two types of sanitation infrastructure offering toilets, showers, sinks for laundry and dish washing in the informal settlements (1,200 inhabitants); one communal washhouse for inhabitants and visitors of the near-by open market and 30 cluster washhouses to be shared each by 4 surrounding households. Two factors may lower the potential amount of wastewater that can be collected and reused: First, the novel sanitation infrastructure comes at a cost, even though the sanitation and water tariffs are affordable for local inhabitants. Second, all inhabitants of formal and informal settlements can still use the existing water points, free latrines and practice open defecation according to their habits before the implementation of the novel system. The wastewater from both formal and informal settlements (1,400 inhabitants) is treated and hygienised in a nearby wastewater treatment plant (treatment steps in Tab. 2). Nutrients are intentionally not removed and mostly remain in the water (78% N, 82% P, 100% K). The treated nutrient-rich reuse water is directly pumped to a storage pond on the agricultural irrigation site and used for fertigation. The Outapi town council manages the sanitation and the wastewater treatment infrastructure and sells the fertigation water to a farmer. The revenues help to subsidize drinking water and sanitation tariffs and contribute to the affordability of the sanitation infrastructures for local inhabitants.

3.2.4 Option 2b: Novel adapted system

The novel adapted system is the novel system 2a, adapted to contain the simple, low-tech wastewater treatment components of the conventional adapted system 1b. For this, the series of wastewater stabilization ponds have been redimensioned to treat water from all (1400) inhabitants of the formal and informal settlements (Tab. 2).

3.3 Setting up the team to conduct the evaluation

The broader evaluation team was constituted by members of the research project; i.e. scientists from different disciplinary backgrounds (engineers, economists, sociologists, natural scientists) and the industry partner. Here iterative discussions on criteria and valuation of criteria (see section 3.4, step 2-5) took place. The members of the research project CuveWaters contributed with experience gained throughout the project duration and the numerous exchanges with and intensive involvement of local stakeholders (the municipality, ministries, farmers and sanitation users) during project design, implementation and operation (2006-2015). Among the broader evaluation team, five members (who are also the authors of this study) were closely involved in the evaluation regarding their specific discipline and field of expertise, while two members coordinated and were mainly in charge of the evaluation process. The authors of this study aspired to conduct an evaluation with a clear and transparent structured procedure and transparent results. However, at this point it was not possible to organize transdisciplinary stakeholder processes to integrate stakeholder knowledge in a direct participatory manner to determine criteria and evaluate them jointly. Such direct participation would clearly add to the quality and validity of the evaluation and we suggest it to be the next step. This study can be regarded as the first step and future studies may use the described methodology (with AHP method and user-friendly software).

3.4 Multi-criteria decision analysis with Analytical Hierarchy Process (AHP) method

Multi-criteria decision analysis (MCDA) methods are commonly used to deal with complex decision-making. They are used to systematically evaluate an option and determine the most suited one based on multiple criteria (Kiker et al. 2005). During the past thirty years, a multitude of MCDA methods have emerged, including for instance the multi-attribute utility methods (MAUT), the Analytical Hierarchy Process (AHP), outranking and value-added analysis (Chen 2006, Figueira et al. 2005). For this study, we selected to use the AHP method (Saaty 1980) as it is a widely accepted formal decision-making method (Bushan and Rai 2004). Its strength is that it can integrate both qualitative and quantitative criteria. It reduces complex decision-making to a series of pair-wise comparisons and then synthesizes results, calculates the consistency of the evaluation and allows to perform a sensitivity analysis (Saaty and Vargas 2012). AHP is a trade-off based method (Chen 2006) and results in a ranking of the evaluated options. To perform AHP calculations, we used the online application AHP-OS home (Version 2014-05-18 by Klaus D. Goepel/ Business Performance Management BPMSG, bpmsg.com). AHP comprises the following steps (Saaty and Vargas 2012):

*(1) Defining criteria: We selected m*ain-criteria and sub-criteria based on the iterative discussions among the research group members. The societal criteria were defined based on

the close contact with sanitation users during community health clubs and regular questionnaire organized by the research project. The institutional and political criteria were developed based on close collaboration with and the input of members of the Outapi Town Council (OTC). The economic criteria were selected from standard economic criteria (Balkema et al. 2002) and in close contact with the farmer and the municipality. Technical and ecological criteria were selected from existing standard criteria catalogues (Balkema et al. 2002, DWA 2014).

(2) Formulating the hierarchy: A hierarchy of goal, main-criteria, sub-criteria and option was set up to structure the decision problem (Fig. 2). The sub-criteria were each described by a strategic guiding question, a target and an indicator. The definition of a criteria and indicators are shown in Tab 4-8.

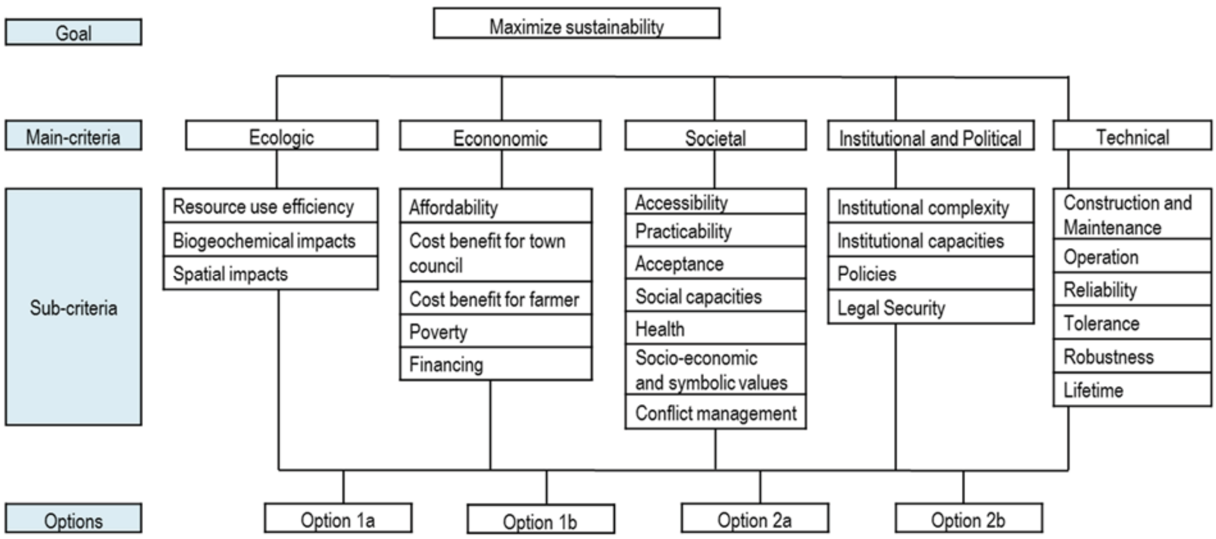


Fig. 2: Hierarchy of goal, main-criteria, sub-criteria and options

(3) Weighting *criteria:* For weighting the criteria, a scale (1-9) was used (Tab. 3). First, we assumed the main criteria to be all equally important, assigning each a weight of 1. Then, we tested the sensitivity (uncertainty of results) of each main-criterion by weighting one main-criterion as “extremely important” (maximum possible weight of 9) leaving all other main-criteria equally important (weight of 1). Thus, the sensitivity analysis shows the maximum possible range of results due to a different weight of the sensitivity dimensions. The sub-criteria were always assumed to be equally important as we perceived it as extremely difficult to assign a specific weight.

(4) Data collection: Data was collected from project documents, modelling, interviews with local experts, questionnaires of sanitation users, plausible reasoning, expert experience and calculations.

Tab. 3: Graduation scale used for weighting of criteria and evaluation of options (Flores 1988)

Scale	Relative importance of criterion or priority of option	Explanation
1	Equal	Both factors contribute equally to the main-criterion or priority of option
3	Moderate	The base factor (row) is slightly more important than the second factor (column)
5	Strong	The base factor (row) is strongly preferred over the second factor (column)
7	Very strong	Definite preference for the base factor (row)
9	Extreme	The base factor is preferred at the highest possible level
Reciprocals		Reflect the dominance of the second factor (column) compared to the base factor (row)

(5) Evaluation of options: The authors of this study evaluated all options with a pair-wise comparison of each option in relation to each sub-criterion (see supplement S1). The scale of the evaluation was the same as for weighting the criteria (Tab. 3). Two criteria had to be fulfilled to qualify an option for evaluation: (i) The treated water was required to achieve the necessary pathogen reduction (6 log units) for unrestricted irrigation (WHO 2006) and (ii) the technology was required to be locally available and basically functional. For instance, the evaluation of the sub-criterion "health" is based on a questionnaire (Kramm and Deffner, in prep.) of the sanitation users before the implementation of the novel sanitation system (used to evaluate the conventional system) and two years after its implementation (the difference between the two was used to evaluate the novel system).

(6) Evaluation of consistency: During the pair-wise evaluation of the options, the software simultaneously checked the consistency of the evaluation. AHP allows for inconsistency, however if the consistency index exceeded 10% (Saaty 1980) the evaluation was re-examined.

(7) Calculation of results: The software multiplied the rating of each option (from step (5) by the weight of each sub-criterion (from step (3) to obtain a local rating of each sub-criterion. The local ratings of each sub-criterion were then multiplied by the weights of the main-criteria (from step (3) and aggregated to obtain a global rating of each option.

(8) Analysis of results: The ranking of each option was analyzed and the strengths and benefits of each option concerning the main-criteria and the sub-criteria were identified.

4 Results and discussion of the sustainability evaluation

At first, the results of the evaluation of each of the five main-criteria (sustainability dimensions) are presented separately. Then, the overall result of the evaluation is shown, aggregating the main-criteria together with the sensitivity analysis.

4.1 Ecologic sustainability

In terms of ecologic sustainability, the novel system scored significantly highest (54% priority) followed by the novel adapted system (25% priority) (Tab. 4). Ecologic benefits of the novel system are the good resource use efficiency with a high share of reuse water for irrigation (novel: 27%, novel adapted: 16%, conventional adapted: 6%) due to the high number of connected sanitation users and its evaporation prevention in the treatment plant. In terms of biogeochemical impact, the two novel systems (2a and 2b) discharge less wastewater untreated to the environment (6 m³ compared to 18 m³ of 1a and 1b) as all inhabitants have improved sanitation with sewer connections. The novel system has also the least spatial impact with only about 1,300 m² area occupied by sanitation and wastewater treatment, while wastewater stabilization ponds (1a, 1b, 2b) occupy a relatively large area.

Tab. 4: Evaluation of ecologic criteria

			Option							
Criterion	Indicator	Unit	1a: Conventional		1b: Conventional adapted		2a: Novel		2b: Novel adapted	
			Value	Rank	Value	Rank	Value	Rank	Value	Rank
Resource use efficiency	Share of reused water for irrigation out of total water consumption of irrigation and households	%	0%	4	6%	3	27%	1	16%	2
Biogeochemical impacts (soil, water cycle, flora, fauna etc.)	Wastewater discharged untreated to the environment	m³/y	35	3	35	3	6	1	6	1
Spatial impacts	Area occupied by the irrigation site, wastewater treatment facility, sanitation site	m²	3,236	3	1,668	2	1,284	1	4,465	4
Ecologic dimension			6%	4	15%	3	54%	1	25%	2

4.2 Economic sustainability

In terms of economic sustainability, the conventional adapted system scores highest (32% priority) all other options being very close (21-25% priority). The conventional adapted system has the best affordability for sanitation users, having the lowest costs for water supply and sanitation per person (weighted mean: 406 N$/cap/y): In informal settlements pit latrines and open defecation are completely free of charge, while with fetching water from communal water points costs of about 100 N$/cap/y. In all options, the individual household connections in formal settlements have the highest costs (2.250 N$/cap/y), partly due to higher water consumption. In contrast, the sanitation infrastructure of the novel systems (2a, 2b) in informal settlements comes at a cost (users of cluster washhouses 342 N$/cap/y, users of communal washhouse 171 N$/cap/y). The weighted average of costs per inhabitant of each sanitation infrastructure is shown in Tab. 5.

Tab. 5: Evaluation of economic criteria

Criterion	Indicator	Unit	Option: 1a: Conventional Value	R	1b: Conventional adapted Value	R	2a: Novel Value	R	2b: Novel adapted Value	R
Affordability	Annual cost for water supply and sanitation per person	N$/y	406	1	406	1	500	3	500	3
Financial benefit-cost	O&M revenues - costs (Town council perspective)	N$/m³/y	0	2	3	1	-25	4	-1	3
	Costs of irrigation water and fertilizer (farmer perspective)	N$/y	465,227	4	455,890	3	437,246	1	437,246	1
Poverty	Number of formerly unemployed workers employed now in washhouse, wwtp, farm (full time equivalent)	People	1	4	2	3	8	1	7	2
Financing	Investment costs	N$	Low	1	Low	1	High	4	Medium	3
Economic dimension			25%	2	32%	1	23%	3	21%	4

R: Rank

**The value of the investment costs of the novel system could not be presented, however the evaluation and the rank in comparison to the other two options is shown. The investment costs of the novel system apply for the implementation of the pilot plant. The investment costs for the replication of the system (without pilot character and a higher number of users) are expected to be cheaper with regard to per capita costs. Expenses may also vary depending on local conditions.

Also, the conventional adapted system has the least O&M revenues-cost ratio for the town council with 3 N$/m³/y meaning a net profit per year, while for the two novel systems annual costs for sanitation and water treatment exceed the revenues from sanitation and irrigation water tariffs. A further reason, is that the wastewater stabilization ponds (option 1a, 1b, 2b) have no energy requirements except for a diesel pump in exceptional cases, while the novel wastewater treatment plant (option 2a) requires electricity (6 kWh/m³). The two conventional systems have also lower investment costs compared to the two novel systems, due to the costs for the washhouses that do not exist in the conventional options and mainly due to the difference of the low-tech wastewater stabilization pond to the high-tech wastewater treatment plant: The novel wastewater treatment plant (option 2a) costs about 9 times as much as the wastewater stabilization pond in option 2b, both designed for the same amount of sanitation users. However, the novel and the novel adapted systems have the lowest costs for irrigation water and fertilizer for the farmer as nutrient-rich reuse water (8.25 N$/m³) is cheaper than drinking water (9.45 N$/m³) and less fertilizer needs to be purchased (2,700 N$/y), compared to the conventional adapted system with less nutrient-rich water available for reuse (due to less collected wastewater and more evaporation) and the conventional system irrigating only with tap water (fertilizer costs: 3,200 N$/y and 6,500 N$/y respectively). The novel system has also the best impact on reducing poverty, having the highest amount of employees: 8 workers (full time equivalent) for the community washhouse, wastewater treatment plant and the farm. Although poverty reduction has both economic and social notions, we chose to emphasize the economic implications here in terms of employed workers that were formerly unemployed. Societal aspects of poverty, e.g. health, have been considered in the corresponding dimension.

4.3 Societal sustainability

Societal criteria include material, objectively verifiable as well as subjective and symbolic aspects of the use of the sanitation infrastructure, while the other option's components (wastewater treatment, agriculture) were not considered here. Three of seven criteria are based on qualitative assessments, four on quantitative deductions based on empirical data collected (Kramm and Deffner, in prep.). The novel sanitation infrastructure, which is exactly the same in option 2a and 2b, has the most societal benefits (in 5 out of 7 criteria) and occupies the first rank (34% priority). The conventional sanitation option, which is exactly the same in option 1a and 1b, scores considerably lower (16% priority) (Tab. 6). The novel sanitation infrastructure has the best "accessibility", as with the washhouses also inhabitants in informal settlements have access to sanitation. Furthermore, it has the best "acceptance", having the benefits of comfort, privacy and security. It also scores highest in terms of "social capacities" indicating if users possess the necessary skills to maintain sanitation infrastructure in a proper manner. Here, the novel infrastructure was introduced accompanied by a special "community health club" program, training sanitation users in formal and informal settlements on hygiene, with 23% of the sanitation users taking part. In comparison, with conventional sanitation we would assume that only users in formal settlements (9%) would take part. The criterion "health" is based on diarrhea cases among the population. An ex-ante survey provided data on the occurrence of diarrhea among the population before the implementation of the novel system (45%) compared to the ex-post survey were the occurrence was considerably reduced (13%) (Deffner and Kramm, in prep.). "Socio-economic and symbolic values" is based on the ex-post survey where users were asked to subjectively assess what has changes in their environment concerning sanitation and hygiene.

Conventional sanitation has its benefits regarding "practicability" and "conflict management": Low-tech latrines and open defecation are more practicable having less technical requirements for users, as almost nothing limits the use, while novel sanitation with its sewer has some limitations e.g. what can be used for anal cleansing. Also the conflict potential is lower, as in informal settlements no sanitation infrastructure is shared with other users when practicing open defecation, while in the novel sanitation option sharing washhouses offers some conflict potential.

Tab. 6: Evaluation of societal criteria (only sanitation infrastructure)

			Option			
Criterion	Indicator	Unit	1a: Conventional and 1b: Conventional adapted		2a: Novel and 2b: Novel adapted	
			Value	R	Value	R
Accessibility	Amount of people connected to sanitation units and wastewater treatment	Inhabitants	198	3	1,400	1
Practicability	Technical practicability of water and sanitation infrastructure	High, medium, low	High	1	Low-medium	3
Acceptance	Degree of privacy (shame), security (violence, exposure to weather) and ease of use (comfort)	High, medium, low	Low	3	Medium	1
Social capacities	Share of sanitation users that have taken part in health and hygiene training out of target population	%	9%	3	23%	1
Health	Share of people in target population having diarrhea	%	45%	3	13%	1
Socio-economic and symbolic values	Proudness/symbolic value of sanitation units	High, medium, low	Low	3	Medium	1
Conflict management	Does the sanitation practice/ use of sanitation infrastructure create conflicts?	No, yes and manageable, yes and difficult to solve	Formal: no, informal: yes and manageable	1	Formal: no, informal: yes and manageable (community washhouse), difficult to solve (cluster washhouses)	3
Societal dimension			16%	3	34%	1

R= Rank, Formal: Formal settlements (Shack Dwellers), informal: Informal settlements (Tobias Hainyeko, Onhimbu and Okaikongwe)

4.4 Institutional and political sustainability

Regarding the institutional and political sustainability dimension, the results show (Tab. 7) that the conventional option clearly scored highest (44% priority) followed by the adapted conventional system (21% priority) and the novel system (20% priority) have a similar score. The conventional option scored highest in almost all criteria having the least institutional complexity and requiring the lowest institutional capacities and the lowest effort to achieve legal security. Both novel system scored highest only regarding the criterion "policies" being in accordance with the national water and sanitation strategy in terms of promoting improved sanitation and reusing water.

Tab. 7: Evaluation of institutional and political criteria

Criterion	Indicator	Unit	Option: 1a: Conventional Value	R	1b: Conventional adapted Value	R	2a: Novel Value	R	2b: Novel adapted Value	R
Institutional complexity	Number of areas of responsibility in the town council for sanitation, wastewater treatment and the farmer	Number	3	1	3	1	8	4	7	3
Institutional capacities	Access to capacities to manage the sanitation, wwtp, farm in the town council and in the farm	Easy, medium, difficult	Easy	1	Medium	2	Difficult	4	Medium	2
Policies	Accordance to the existing national water and sanitation strategy	High, medium, low	Low	4	Medium	3	High	1	High	1
Legal security	Effort to achieve legal security for the town council (e.g. legal contracts)	High, medium, low	Low	3	Medium	2	Medium	2	Medium	2
Institutional and political dimension			44%	1	21%	2	16%	4	20%	3

R: Rank, wwtp: Wastewater treatment plant

4.5 Technical sustainability

The technical evaluation comprises the sanitation and wastewater treatment infrastructure, while the agricultural irrigation site is technically the same for all options and was not evaluated here. The novel adapted system scored highest (31% priority), followed by the novel system (26% priority). The novel adapted system scored best in all six technical criteria, while it was the second best system only in the criterion “robustness”, having a medium susceptibility to natural hazards. The criteria operation (described by adequately trained workers), reliability (downtime days per year) and lifespan are evaluated the same for all options. Since the novel wastewater treatment is technically more sophisticated, the investments allowed for high quality products, fully automatic operation, intensive operator training and after-sales service. In the criterion “construction and maintenance” all options score the same having a high availability of technical supply for sanitation infrastructure, except for the high-tech wastewater treatment plant in the novel option that has a low availability and therefore occupies the last rank. In terms of robustness and susceptibility to natural hazards, the novel wastewater treatment plant scores best, being not susceptible to floods, while in the other options the ponds (1a, 1b, 2b) might overspill and latrines (1a, 1b) might be flooded as well.

Tab. 8: Evaluation of technical criteria

			Option							
Criterion	Indicator	Unit	1a: Conventional		1b: Conventional adapted		2a: Novel		2b: Novel adapted	
			Value	R	Value	R	Value	R	Value	R
Construction and maintenance	Degree of local availability of technical supply (for sanitation, wwtp, sewer, farm)	High, medium, low	Sanitation: high wwtp, sewer: medium	1	Sanitation: high wwtp, sewer: medium	1	Sanitation: high wwtp: low sewer: medium	4	Sanitation: high wwtp, sewer: medium	1
Operation	Are workers adequately trained and instructed to guarantee operational safety at work?	Yes, no	Yes	1	Yes	1	Yes	1	Yes	1
Reliability	Downtime days per year of wastewater treatment	days/y	0	1	0	1	0	1	0	1
Tolerance	Susceptibility of wwtp, sanitation facilities, farm to maloperation and vandalism	High, medium, low	Low	2	Low	3	Medium	4	Low	1
Robustness	Susceptibility of wwtp, sanitation facilities, farm to natural hazards	High, medium, low	High	3	High	3	Low	1	Medium	2
Lifetime	Lifespan	years	High	1	High	1	High	1	High	1
Technical dimension			22%	3	21%	4	26%	2	31%	1

R: Rank, wwtp: wastewater treatment plant

4.6 Overall sustainability and testing of sensitivity

The overall sustainability, integrating the five sustainability dimensions with different weighting of the dimensions (Fig. 3) shows that (i) the options' ranking depends on the weighting of the dimensions and (ii) in 3 out of 6 cases the novel system (2a) scores best (with equal, ecologic and social focus). The other three systems score best in one case each.

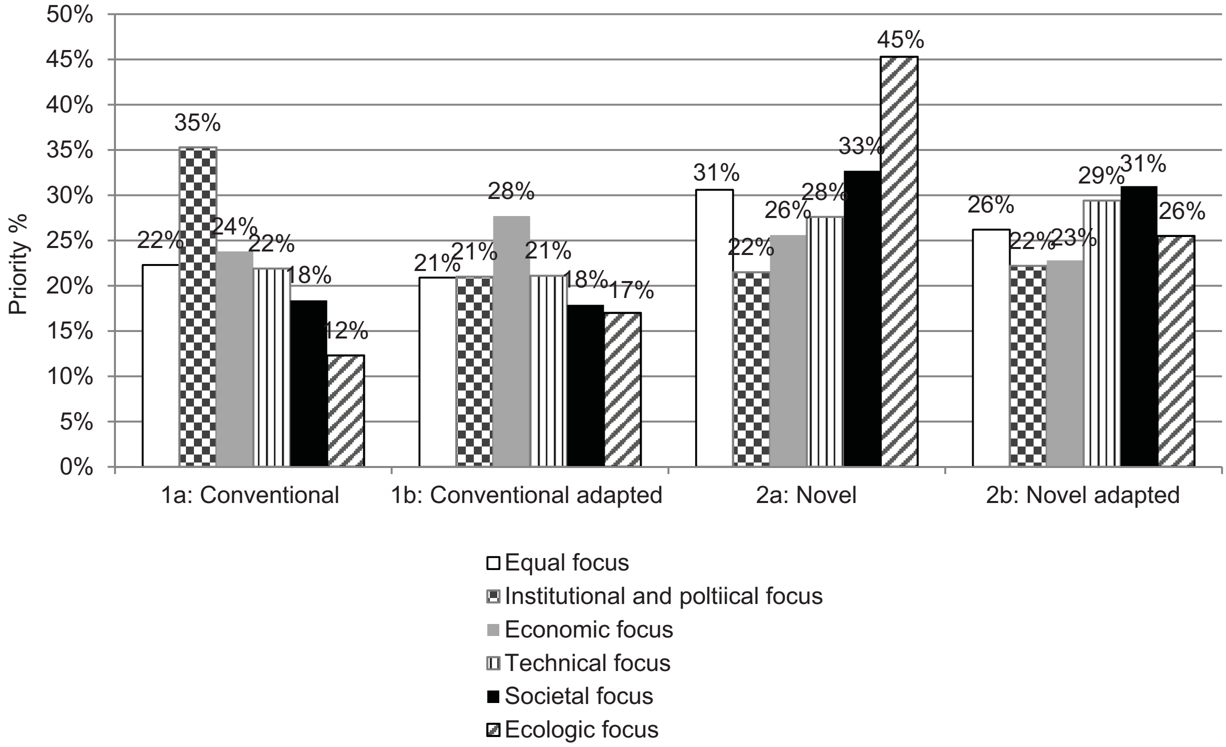
With equal focus, all dimensions are equally important and weighted with 1, so that all dimensions have an equal weight of 20%. Because each dimension does not have the same amount of criteria, the contribution of each criterion (i.e. the weight of each of this dimension's criteria) to the overall evaluation differs as follows: ecologic 6.7%, economic 4%, societal 2.9%, institutional and political 5% as well as technical 2.9%. With a focus on a certain dimension, the dimension was rated as "extremely important", obtaining a weigh of 9, contributing with 69% to overall sustainability, while all other dimensions obtained an equal weight of 1, each contributing 7.7% to the overall sustainability result.

(1) Equal focus: In this balanced evaluation case, the novel system scores clearly best (31% priority), followed by the novel adapted system (26% priority).

(2) Ecologic focus: The novel system has clearly the highest rank (45% priority) followed with a large distance by the novel adapted system (26% priority).

(3) Economic focus: The conventional adapted system ranks first (28% priority) followed by the novel system (26% priority).
(4) Societal focus: The novel system scores best (33% priority), closely followed by the novel adapted system (31% priority), while both conventional systems score considerably worse.
(5) Institutional and political focus: The conventional system scores highest (35% priority) all other systems being very close.
(6) Technical focus: The novel adapted system scores highest (29% priority), immediately followed by the novel system (28% priority), while both conventional systems are considerably behind.

Fig. 3: Overall sustainability



Overall, the novel system achieves the highest rank, considering an equal focus of sustainability dimensions and even more so with a societal and ecological focus. In all these three cases, the novel adapted system occupies the second rank. However, with an extreme economic focus, the conventional adapted system has the most benefits, even more so considering its highest rank in the sub-criteria investment costs, annual revenues/costs for the town council, and affordability for sanitation users. These criteria are often the most important and determining ones for the implementation of such a system in a developing country context. However, the two conventional systems have the least ecologic and societal benefits, inhabitants in informal settlements are not connected to sanitation and sewage and no resources at all (1a) or less resources (1b) can be recovered and reused. Moreover, also technical requirements and most importantly technical operation and maintenance play an important role, where the novel adapted system is the most advantageous system. The novel system has the following benefits and challenges compared to the other systems (Tab. 9).

Tab. 9: Benefits and challenges of the novel system

Dimension	Benefits	Challenges
Ecologic	Resource-use efficiency Biogeochemical impacts Spatial impact	
Economic	Costs of irrigation water and fertilizer for farmer Poverty reduction	Affordability O&M revenues-costs for town council Financing
Societal	Accessibility of sanitation units Acceptance of sanitation units Social capacities of sanitation units Health Socio-economic and symbolic values	Practicability of sanitation units Conflict potential
Institutional and political	Policies Legal security	Institutional complexity Institutional capacity
Technical	Operation Reliability Robustness Lifespan	Construction and maintenance Technical tolerance

It should also be kept in mind, that the priority values have an uncertainty range. Looking at the evaluation of single dimensions and of overall sustainability, options are often so close, that considering a range of uncertainty, the differences among options might be questioned: This is the case in the economic dimension and in overall sustainability with an economic focus. Nonetheless, differences are often also significant that a most sustainable option can be clearly identified: This is the case in the ecologic and the societal dimension, and in overall sustainability evaluation with an ecologic, societal as well as institutional and political focus.

In summary, the results of this study show that the novel system offers the most benefits for the local developing country context. However, in light of its challenges, the answer to the question which resource recovery system is the best option for the local context is, that it also depends on the particular focus in the relative context.

4.7 Discussion of the methodology and the study design

In methodological terms, the Analytical Hierarchy Process (AHP) offers a good compromise between modelling and usability. Beforehand, considerable efforts have to be made to set up the list of assessment criteria in order to avoid dependencies or complementarities among indicators. By discussing the set of criteria with experts, a sound foundation for the evaluation could be laid. AHP provides a clear guidance how to carry out the pairwise comparisons by defining a corresponding evaluation scale. This is not the case with other MCDA methods, especially the weighted sum model (also known as utility analysis). However, one drawback of the method is the dependency on a software tool. Due to the number of criteria, the calculation of utility values cannot be done manually with reasonable efforts. The algorithm, therefore, might remain a black box for outsiders. Hence, AHP is not as transparent as some other MCDA methods, which is of particular interest when involving stakeholders in the evaluation phase.

In order to improve the evaluation in the future, also empirical data from the conventional wastewater stabilization ponds and from other water reuse pilot projects should be integrated. The quantification of the pathogen reduction achieved with wastewater treatment presented in this study should be complemented with an investigation on the maximum tolerable disease burden (DALY) with a quantitative microbial risk analysis (QMRA) according to WHO (2006). Particularly, it should be investigated whether the wastewater stabilization ponds and the water reuse site reach the required pathogen removal efficiency by the WHO (2006) that was calculated to be achieved according to literature values. Additionally, the wastewater treatment plant of the novel system was intended to be extended by a biogas module. However, this could not be implemented satisfactorily during the pilot phase. The sewage sludge from wastewater can be digested together with crop residues from the water reuse site and other agricultural areas to produce biogas and completely cover heat demand and partly cover electricity demand (about 50%) of the treatment plant. This could also be tested in other pilot resource recovery systems in order to recover energy from the wastewater and should be included in further evaluations of resource recovery systems.

5 Conclusion

To understand the benefits of a novel resource recovery system, we compared it to the conventional system and to two adapted versions of the systems. Surprisingly, our results showed that the novel system, including sanitation infrastructure in informal settlements (a community washhouse and cluster washhouses), a wastewater treatment plant for the recovery of water and crop nutrients and a nutrient-rich water reuse site for the irrigation of food crops, offers the most benefits for the developing country context. The hypothesis that the novel adapted system would score best since it combines the benefits of the novel sanitation infrastructure with easy to manage low-tech wastewater stabilization ponds for resource recovery could not be verified.

The evaluation showed that its sanitation infrastructure, which is the same as in the novel option, does not overtake the novel option. Secondly, the wastewater stabilization ponds of the novel adapted system have to be large enough (as opposed to the conventional adapted option connecting only formal settlements) so that it scores worse in ecologic terms and not good enough in economic, institutional and political as well as technical terms to offer more benefits than the novel system. In summary, the results of this study show that the novel system offers the most benefits for a semi-arid developing country context. Hence, we suggest the novel system is a viable resource recovery system towards a more sustainable urban sanitation, wastewater and irrigation infrastructure, using fewer resources, being economically feasible, institutionally and politically practical and technically sound. However, in the light of its challenges, local conditions, such as financial resources and human capacities, have to be thoroughly examined first in order to answer the question which resource recovery system is the best option for a specific case.

These results are relevant for decision-makers, engineers and the general public in order to have proper information on which options to implement for increasing livability in cities towards a more sustainable future. The results of this study are transferrable to other countries and regions with similar conditions of those described for the project region. These conditions comprise low-density urban areas in developing countries with informal settlements with insufficient sanitation and wastewater treatment infrastructure, public latrines and inhabitants practicing open defecation, a similar socio-economic situation with low income and little education, a semi-arid climate that necessitates irrigation for agriculture and an urban area with sufficient area available to install wastewater treatment facilities and agriculture irrigation sites in close proximity (e.g. periphery of a city). The methodology can, furthermore, be applied to countries and regions with conditions that differ from the ones described in this study. Especially, the comprehensive set of assessment criteria might be used as a starting point for comparable evaluations. However, the criteria list might need to be adapted and further developed together with relevant stakeholders of the local context. Hence, from our results, we suggest the novel system is a viable resource recovery system towards a more sustainable urban sanitation, wastewater and irrigation infrastructure, using fewer resources, being economically feasible, institutionally and politically practical and technically sound. These results are relevant for decision-makers, engineers and the general public in order to have proper information on which options to implement for increasing livability in cities towards a more sustainable future. The results of this study are transferrable to other countries and regions with similar conditions of those described for the project region. These conditions comprise low-density urban areas in developing countries with informal settlements with insufficient sanitation and wastewater treatment infrastructure, public latrines and inhabitants practicing open defecation, a similar socio-economic situation with low income and little education, a semi-arid climate that necessitates irrigation for agriculture and an urban area

(e.g. periphery of a city) with sufficient area available to install wastewater treatment facilities and agriculture irrigation sites in close proximity. The methodology can, furthermore, be applied to countries and regions with conditions that differ from the ones described in this study. Especially, the comprehensive set of assessment criteria might be used as a starting point for comparable evaluations. However, the criteria list might need to be adapted and further developed together with relevant actors of the respective local context.

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Supplement

S1: Values assigned in the pair-wise comparison of each option for each sub-criterion (Scale: see Tab. 3)

Ecological

Resource use efficiency

Option	1a	1b	2a	2b
1a		1/3	1/9	1/7
1b			1/7	1/3
2a				3

Biogeochemical impacts

Option	1a	1b	2a	2b
1a		1	1/9	1/9
1b			1/9	1/9
2a				1

Spatial impacts

Option	1a	1b	2a	2b
1a		1/5	1/7	3
1b			1/3	7
2a				9

Economic

Affordability

Option	1a	1b	2a	2b
1a		1	5	5
1b			5	5
2a				1

O&M costs - revenues (for town council)

Option	1a	1b	2a	2b
1a		1/3	7	3
1b			9	3
2a				1/7

Costs for irrigation water and fertilizers

Option	1a	1b	2a	2b
1a		1/3	1/5	1/5
1b			1/3	1/3
2a				1

Poverty

Option	1a	1b	2a	2b
1a		1/3	1/9	1/7
1b			1/7	1/5
2a				3

Financing

Option	1a	1b	2a	2b
1a		1	9	5
1b			9	5
2a				1/5

Social

Accessibility

Option	1a	1b	2a	2b
1a		1	1/9	1/9
1b			1/9	1/9
2a				1

Practicability

Option	1a	1b	2a	2b
1a		1	9	9
1b			9	9
2a				1

Acceptance

Institutional and political

Institutional complexity

Option	1a	1b	2a	2b
1a		1	9	7
1b			9	7
2a				1/3

Institutional capacities

Option	1a	1b	2a	2b
1a		5	9	5
1b			5	1
2a				1/5

Policies

Option	1a	1b	2a	2b
1a		1/5	1/9	1/9
1b			1/5	1/5
2a				1

Legal Security

Option	1a	1b	2a	2b
1a		5	5	5
1b			1	1
2a				1

Technical

Construction and maintenance

Option	1a	1b	2a	2b
1a		1	3	1
1b			3	1
2a				1/3

Operation

Option	1a	1b	2a	2b
1a		1	1	1
1b			1	1
2a				1

Reliability

Option	1a	1b	2a	2b
1a		1	1	1
1b			1	1
2a				1

Tolerance

Option	1a	1b	2a	2b
1a		1	5	1/3
1b			5	1/7
2a				1/7

Robustness

Option	1a	1b	2a	2b
1a		1	1/9	1/5
1b			1/9	1/5
2a				5

Lifetime

Option	1a	1b	1c	1c
1a		1	1	1
1b			1	1
2a				1

Option	1a	1b	2a	2b
1a		1	1/9	1/9
1b			1/9	1/9
2a				1
Social capacities				
Option	1a	1b	2a	2b
1a		1	1/7	1/7
1b			1/7	1/7
2a				1
Health				
Option	1a	1b	2a	2b
1a		1	1/9	1/9
1b			1/9	1/9
2a				1
Socio-economic and symbolic values				
Option	1a	1b	2a	2b
1a		1	1/5	1/5
1b			1/5	1/5
2a				1
Conflict management				
Option	1a	1b	2a	2b
1a		1	3	3
1b			3	3
2a				1