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Sustainability assessment of potential wastewater treatment techniques in Tupiza, Bolivia

Hållbarhetsanalys av potentiella lösningar för avloppsrening i Tupiza, Bolivia

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Abstract

Sustainability assessment of potential wastewater treatment techniques in Tupiza, Bolivia

Johanna Burström

Aiming for sustainable sanitation systems can provide benefits among a vast range of Sustainable Development Goals. In this study the sustainability of potential options for renovating or upgrading the wastewater treatment plant in Tupiza, a rapidly growing city in the Southern highlands of Bolivia, was evaluated. The local context was characterized by increasing issues of flooding which in recent years has destroyed important wastewater treatment infrastructure and polluted sources of water for several downstream communities. Three system options consisting of different treatment technologies were evaluated against four criteria of sustainability; health, technical, environmental and financial and institutional. A "conventional" option consisting of waste stabilization ponds was compared against two more options with added steps of treatment, such as constructed wetlands, anaerobic reactors and alkaline and ammonia treatment of sludge. Social acceptance and demand of reuse of treated wastewater and sludge in agriculture was evaluated using qualitative research analysis.
Results indicate that the systems with added treatment steps could help improve several areas of sustainability such as risks of disease transmission, space efficiency, treatment capacity and efficiency as well as enable safe reuse of sludge and wastewater in agriculture. Implementation of funding mechanisms covering the entire sanitation service chain as well as flood mitigation measures resulted essential in ensuring the long-term functionality of such improvements.
This project was intended as a pre-study and identified several areas of future research including additional evaluation of nutrient content in effluent, investigation of a possible certification process for recycled byproducts from the wastewater treatment plant, risk assessment of floods of different magnitudes, evaluation of the long-term economic impact of having improved systems and evaluation of local institutional capacity surrounding the sanitation service chain in Tupiza.

Keywords: MCA, wastewater treatment, sustainable sanitation, Bolivia, stabilisation ponds, anaerobic reactors, constructed wetland, alkaline treatment of sludge, ammonia treatment of sludge

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Sammanfattning

Hållbarhetsanalys av potentiella avloppsreningslösningar i Tupiza, Bolivia
Johanna Burström

Hållbara sanitetssystem för med sig många fördelar som kan främja majoriteten av de globala hållbarhetsmålen. I denna studie utreds hållbarheten i potentiella alternativ för renovering eller uppgradering av ett avloppsreningsverk i Tupiza, en snabbt växande stad i södra Bolivias högland. Den lokala kontexten präglades av en tilltagande översvämmningsproblematik som de senaste åren bidragit till förstörelse av central infrastruktur for avloppsvattenrening samt påföljande vattenföroreningar i samhällen nedströms reningsverket. Tre systemalternativ beståendes av olika reningstekniker utreddes utefter fyra hållbarhetskategorier; hälsa, teknologi, miljö samt finansiell/institutionell. Ett konventionellt alternativ som utgjordes av stabiliseringsdammar jämfördes mot två mer avancerade alternativ med ytterligare reningssteg såsom anlagd våtmark, anaerobiska reaktorer samt alkali- och ammoniakbehandling av slam. Social acceptans och efterfrågan för återanvändning av behandlat avloppsvatten och slam inom lantbruket utreddes i en kvalitativ forskningsstudie.

Resultaten tyder på att system med fler reningssteg kan främja flera hållbarhetsområden såsom risk för överföring av sjukdomar, yteffektivitet, reningskapacitet och effektivitet samt möjliggöra säkert återanvändande av slam och avloppsvatten i jordbruket. Implementering av mekanismer för finansiering som täcker hela sanitetskedjan samt åtgärder mor översvämningar visade sig vara centrala för att säkerställa långsiktig funktion av sådana förbättringar.

Det här projektet var menat som en förstudie och identifierade flertalet områden för vidare forskning såsom ytterligare utvärdering av näringsinnehåll i utgående vatten, utredning av möjlig certifieringsprocess för återvunna produkter från avloppsreningsverket, analys av översvämningsrisker av olika magnituder, utvärdering av den indirekta ekonomiska effekten av att ha system med fler reningssteg samt utvärdering av lokal institutionell kapacitet för hela servicekedjan för sanitet i Tupiza.

Nyckelord: MCA, avloppsrening, hållbara VA-lösningar, Bolivia, stabiliseringsdammar, anaerobiska reaktorer, anlagd våtmark, alkalin slambehandling, salmbehandling med ammoniak.

Resumen

Análisis de la sostenibilidad de posibles tratamientos de aguas residuales en Tupiza, Bolivia
Johanna Burström

En este estudio se evaluó la sostenibilidad de opciones potenciales para renovar o mejorar la planta de tratamiento de aguas residuales de Tupiza, una ciudad de rápido crecimiento en las tierras altas del sur de Bolivia. En los últimos años, el contexto local se ha caracterizado por la ocurrencia de lluvias de mayor intensidad. Estas ocasionaron inundaciones que en efecto causaron daños importantes en la infraestructura de la planta de tratamiento de aguas residuales (PTAR). El deterioro de la infraestructura provocó el derrame de aguas residuales al río y la contaminación del agua en las comunidades ubicadas en la cuenca baja.

Trés opciones de sistemas de tecnologías de tratamiento de aguas residuales para la renovación y/o mejoro de la planta de Tupiza fueron evaluadas considerando cuatro criterios de sostenibilidad: Salud, tecnolgía, ambiental y financiera/institucional. Por otra parte la aceptación social y demanda de reúso de aguas residuales y lodos tratados en la agricultura se evaluaron mediante un análisis de investigación cualitativa. La opción convencional que consiste en estanques de estabilización de desechos, se comparó con dos otras alternativas que incluyen pasos adicionales de tratamiento, como son humedales artificiales, reactores anaeróbicos y tratamiento de lodos con urea y cal.

Los resultados indican que los sistemas de pasos adicionales de tratamiento podrían ayudar a mejorar diferentes aspectos de sostenibilidad, como los riesgos de transmisión de enfermedades, la eficiencia espacial, la capacidad y eficiencia de tratamiento y la posibilidad de reutilización segura de lodos y aguas residuales en la agricultura.

La implementación de mecanismos de financiación que cubren toda la cadena de servicios de saneamiento, así como las medidas de mitigacióin de inundaciones se mostraron esenciales para garantizar la funcionalidad a largo plazo de tales mejoras.

La tesis es un estudio preliminar e identificó varias áreas de investigación futuras, la evaluación adicional del contenido de nutrientes en el efluente, la investigación de un posible proceso de certificación de subproductos reciclados de la PTAR, la evaluación de riesgos de inundaciones de diferentes magnitudes, la evaluación del impacto económico a largo plazo de la implementación de sistemas con pasos adicionales de tratamiento y la evaluación de capacidad institucional local a lo largo de la cadena de servicios de sanemiento.

Palabras claves: Análisis multicriterio, tratamiento de aguas residuales, sanemiento sostenible, Bolivia, estanques de estabilización de desechos, reactores anaeróbicos, humedales artificiales, tratamiento de lodo con cal, tratamiento de lodo con urea.

Populärvetenskaplig sammanfattning

Hållbarhetsanalys av potentiella avloppsreningslösningar i Tupiza, Bolivia
Johanna Burström

Förändrad markanvändning och alltmer intensiva regnfall till följd av klimatförändringar har lett till flera och större översvämningar i Tupiza, en snabbt växande stad i södra Bolivias högland. Översvämningarna har bland annat förstört stora delar av stadens avloppsreningsverk vilket öppnat för diskussioner om renovering och uppdatering av infrastrukturen för sanitet. I ett område som präglas av en stark jordbrukskultur och ett klimat som annars drar tankarna till Vilda Västern är frågan om återanvändning av behandlat avloppsvatten och slam högaktuell, samtidigt som anpassning till lokala förutsättningar och speciellt motståndskraft för översvämningar är viktiga faktorer i problemställningen. I ett försök att implementera det som i den vetenskapliga världen kallas för hållbar sanitet har det här projektet utvärderat tre potentiella avloppsreningssystem mot lokala hållbarhetskriterier inom områdena hälsa, teknologi, miljö och ekonomi i en så kallad multikriterieanalys. En kvalitativ studie med fokus på social acceptans och efterfrågan för återanvändning av vatten och slam inom jordbruket har också genomförts.

Förutom att fungerande avloppssystem är en grundförutsättning för att undfly fattigdom, kan hållbara sanitetssystem bidra med en rad positiva effekter för majoriteten av de globala hållbarhetsmålen; bland annat ökade skördar, affärsmöjligheter för små och medium-stora företag, och viktiga strategier för mitigation av klimatförändringarna såsom resursåtervinning och hantering. I ett land som Bolivia, ett av de fattigaste länderna i Sydamerika, där ungefär hälften av befolkningen har tillgång till avloppssystem och endast 22% av insamlat avloppsvatten får någon slags behandling, är implementeringen av hållbara sanitetssystem en viktig utmaning för att uppnå både miljömål och en förbättrad folkhälsa, samtidigt som processer för resursåtervinning och cirkularitet kan förstärkas.

Teknologier som ingick i de tre avloppsreningssystem som utvärderades var bland annat stabiliseringsdammar, två slags anaerobiska reaktorer, anlagd våtmark samt hygiensiering av slam med hjälp av kalk respektive urea. Alla alternativ implementerade eller förstärkte biologiska reningsprocesser och valdes på grund av låga kostnader i drift och teknologi samt krav på underhåll. Multikriterieanalysen visade på att system med fler och mer effektiva reningssteg presterade bättre mot majoriteten av hållbarhetskriterierna, däribland risk för överföring av sjukdomar, yteffektivitet, effekt av översvämmnigar, resurshantering och behandlingseffektivitet. Mer simpla system såsom det nuvarande i Tupiza som endast består av stabiliseringsdammar presterade dock bättre när det kom till direkta kostnader i form utav investering och underhåll. Studien om acceptans och efterfrågan av återanvändning av behandlat vatten och slam visade även på att sådana processer till stor del beror på acceptansen från konsumenterna och kvalitetsgarantier hos produkterna.

För att reducera risker för överföring av sjukdomar samt eutrofierande utsläpp är det viktigt att den nuvarande reningsmetoden av avloppsvatten förbättras, exempelvis med hjälp av ovan nämnda teknologier. Om avloppsreningsverket dessutom ska fungera över en längre tid är det viktigt att se över tillgängliga finansmekanismer för underhåll och drift av verket, samt implementera skydd mot framtida översvämningar. Undersökningen har väckt många intressanta frågor som hur potentialen av återanvändning av slam och avloppsvatten kan bidra till ökad efterfrågan av kontroll och garanti av reningsverkets behandlingseffektivitet. I ett område där många bönder vittnar om förorenade eller opålitliga vattenkällor skulle återanvändning av sådana resurser kunna vara extremt fördelaktig. Studien framhäver också de potentiella samhällskonsekvenserna av att ha ett reningsverk som inte presterar bra enligt vissa hållbarhetskriterier, kan de indirekta kostnaderna på längre sikt i form av sämre folkhälsa och ökad miljöpåverkan och utsläpp vara större än de direkta kostnaderna för investering och underhåll av ett mer avancerat reningsverk?

Frågor som dessa visar på vikten av fortsatt forskning och investering inom sanitetsektorn i Bolivia. Att implementera hållbara sanitetssystem innebär ett brett ståndstagande där flera nyanser av hållbarhet kan diskuteras och prioriteras. I detta fall har det visat sig att mer effektiva system klart gagnar befolkningen i Tupiza, men frågor såsom finansiering, social acceptans, testning och institutionell kapacitet måste lyftas för att system som dessa ska fungera i det långa loppet.

Preface

This master thesis of 30 credits concludes the five year program Master in Sciences of Environmental and Water Engineering at Uppsala University and the Swedish University of Agricultural Sciences (SLU). The work has been conducted in collaboration with the Stockholm Environment Institute (SEI) during the spring semester of 2020. The supervisors were Kim Andersson, senior expert, and Carla Liera, research associate, at SEI Headquarters in Stockholm. Academic supervisor was Jennifer McConville, researcher at the Department for Energy and Technology, SLU, and examinator was Gabriele Messori, lecturer at the Department of Earth Sciences, Uppsala University.

This project, just as the rest of world, has been greatly affected by the Covid-19 pandemic. Naturally I would like to thank Kammarkollegiet for insuring me and making it possible for me to get back to Sweden safely. Even though my stay in South America was halved, a majority of the necessary field work could still be performed, but communication with local stakeholders and collaboration with local organizations was made difficult due to quarantine restrictions. This has obviously had an effects on the quality on parts of the work, but has been compensated for as far as possible with literature review and discussions around any estimations or assumptions that have been made. Some numbers have unfortunately not been possible to control with local stakeholders, which has been clearly mentioned in the report.

I would like to express my greatest gratitude to my supervisors Kim and Carla for their great support througout the entire project process. A big thank you also to Jennifer, my academic supervisor, for providing such generous support and valuable insights to my work, especially when I needed it the most. Thank you also to Melina Balderrama and Cecilia Tapia, representing SEI in Bolivia, for receiving me with such care and always going out of their way to help me, and to the Helvetas Bolivia office for welcoming me to La Paz. A special thanks goes to Renato Montoya, Gustavo Heredia and Ariel Aldunate and the entire Agua Tuya office in Cochabamba for receiving me and providing excellent technical support an local knowledge. Thank you also to Jairo Mosquera for time and effort put into the project. To Saúl Navarro, Juan Carlos Cachambi and everyone else who I've had contact with in Tupiza I would like to extend a big thank you. I would also like to express my gratitude to Frida Rodhe and Guido Meruvia at the Swedish Embassy in La Paz for not only providing me with contacts in Tupiza but also valuable support and input when I was faced with having to leave South America in the middle of a global pandemic.

Contents

Acronyms and abbreviations

CW - Constructed wetland

HRT - Hydraulic retention time

EMPSAAT - Empresa Prestadora de Servicio de Agua Potable y Alcantarillado Tupiza i.e. the municipal company responsible for the collection and treatment of wastewater in Tupiza.

MCA - Multi-criteria assessment

MMAyA - Ministerio de Medio Ambiente y Agua i.e. the Bolivian Ministry of Environment and Water

RAC - Compartmentalized anaerobic reactor (in Spanish: Reactor anaeróbico compartmentalizado)

SIDA - Sweden International Development Agency

SEI - Stockholm Environment Institute

UASB - Upflow anaerobic sludge blanket reactor

WSPs - Waste stabilization ponds

WWTP - Wastewater treatment plant

Glossary

Bolivia WATCH - program initiated by SEI and supported by SIDA in order to promote innovative Water, Sanitation, and Hygiene (WASH) solutions and implementation of Bolivia's National Watershed Plan.

Hygienization - The reduction of pathogenic microorganisms which are harmful to human health in either wastewater or sewage sludge.

O&M costs - Operational and maintenance costs

Pre-treatment of wastewater - Preliminary treatment of wastewater where large solids or objects are removed before they clog or damage other parts of the treatment plant.

Primary treatment of wastewater - The stage where larger particles are settled from the wastewater and the organic load in the wastewater is reduced.

Secondary treatment of wastewater - Degrades the remaining biological material in the wastewater.

Tertiary treatment of wastewater - Final polishing step which degrades pathogenic content in the wastewater.

Sludge - solid particles and organic content generated from wastewater during its treatment process.

1 Introduction

The access to safe water and sanitation is intrinsically connected to the issue of sustainable development worldwide. Today over half of the global population lack access to safe sanitation services and only an estimated 20% of wastewater generated globally receives treatment (WHO/Unicef 2019, UN 2017). An approximated 800 children under the age of five die every day from diseases due to poor sanitation, hygiene or unsafe drinking water (WHO 2019). The same water and sanitation-related diseases can cost some countries up to 5% of their annual GDP, and interventions of basic sanitation in developing countries have proven to give at least five times the return (WHO 2019, Hutton, Haller, and Bartram 2015). In 2010 the access to safe water and sanitation was recognized by the UN General Assembly as a human right and when the Sustainable Development Goals (SDGs) were adopted by the UN in 2015, it was further acknowledged through SDG 6: Clean water and sanitation for all (UN 2010, UN 2016).

The term 'sustainable sanitation' emerged as a result of continued efforts within the global water and sanitation sector, and can be connected to SDG 6.2: aiming for access to adequate and equitable sanitation and SDG 6.3 which focuses on decreasing the amount of untreated wastewater as well as increasing recycling and safe re-use of wastewater globally (UN n.d.). Sanitation and wastewater management is, especially in the development context, generally thought of as a means of public health and environmental protection (Andersson et al. 2016). According to the Sustainable Sanitation Alliance (SuSanA), while the main objective of a sanitation system is to protect human health, sanitation which is sustainable is also economically viable, socially acceptable, technically and institutionally appropriate and protects the environment and natural resources (SuSanA 2017). Sustainable sanitation can contribute in achieving a wide range of SDG targets. Amongst others it can help in relieving a large burden of infectious disease (SDG 3) which in turn can diminish amount of sick days from school or productive work (SDG 4). Systems which prevent the release of nutrients and toxins in the environment can help improving the ecological status and services of freshwater and coastal systems (SDG 14) and systems which implement re-use of nutrients and wastewater contribute to resource efficiency (SDG 12) and food security (SDG 2). The service chains of sanitation and wastewater management can also provide new livelihood opportunities (SDG 1 and 8) (Andersson et al. 2016).

According to the World Bank, an estimated 66% of the population in the Latin American and Caribbean region are connected to a sewage system and only 30-40% of collected wastewater receives some kind of treatment. Given corresponding levels of income and urbanization, this figure seems quite low and efficient investment in wastewater and sanitation infrastructure to achieve public health benefits and environmental objectives is a major challenge (Rodriguez et al. 2020). In Bolivia, one of the poorest countries in the region, numbers are even lower. Here only 48% of the population were connected to a sewage system by 2017 and a mere 22% of collected wastewater received any treatment (WHO/Unicef 2019). Although these circumstances are indeed troublesome, they also present important opportunities of implementing sustainable sanitation systems which emphasize resource recovery and circularity (Rodriguez et al. 2020).

This project studied the sustainability of potential options for renovating or upgrading the watewater treatment plant in Tupiza, a rapidly growing city in the southern highlands of Bolivia. The local context is characterized by a strong agricultural presence and an arid climate which prompts the question of re-use of wastewater products such as water and sludge. As the old plant has reduced in capacity due to failure of maintenance and repeated flood events, organizational capacity and flood resilience are important pieces to the puzzle. Issues such as social acceptance and health risks also need to be adressed in order to implement sustainable wastewater management within the context of Tupiza.

The research took place within the Bolivia WATCH program - a program led by the Stockholm Environment Institute (SEI) and financed by the Swedish International Development Agency (SIDA), and was contextualized as a multi-criteria analysis in an attempt to encapsulate the different dimensions of sustainability associated with wastewater management. To highlight local stakeholders perspective key topics from different interest groups were evaluated. A questionnaire touching upon social acceptance and norms in the agricultural communities also tried to evaluate possibilities of recycling.

1.1 Aim

The aim of this study is to assess different wastewater management and treatment systems with relevance for the city of Tupiza, using multiple sustainability criteria co-developed with relevant local stakeholders and sanitation experts at Stockholm Environment Institute (SEI). By analyzing the key aspects like environment, health, technology, socio-cultural and economy the goal is to capture all dimensions of sustainability related to wastewater management. On a larger scale this project aims at providing information for the Bolivia WATCH program in order to analyze how new potential sanitation options can strengthen the resilience of water and sanitation services and watershed management in the Tupiza watershed, as well as influencing the Bolivian water and sanitation sector.

1.2 Research question

What are the most suitable techniques of wastewater treatment for the city of Tupiza, considering pre-identified issues, such as extreme climate events and long-term functionality, as well as other criteria articulated by different stakeholder groups?

1.3 Scope

The study is limited to the municipality of Tupiza in southern Bolivia, which is characterized by increased flooding problems, a rapidly growing population in the urban areas and a strong agricultural presence in the rural areas. Choices of technology have emphasized low-cost and low maintenance solutions. Analysis will be performed mainly through a multi-critera assessment focusing on health, technology, environment and financial/institutional. Some social aspects will be analyzed using qualitative research methods.

2 Background

The question of sustainable sanitation runs as a common thread throughout this project, for which the local context of Bolivia and Tupiza becomes essential. Other important aspects such as methods of assessing sustainability and suitable treatment technologies are also presented.

2.1 Sustainable sanitation in Bolivia

Since the beginning of the new millennia, Bolivia has experienced massive improvements in poverty rates, with the share of Bolivians living under the national poverty line almost halved (World Bank Data 2019). The development of safe sanitation has followed a similar curve; between the years of 2000 and 2017 the rate of open defecation decreased from 33% to 13,3%, at the same time as treatment rates of sewage increased from 7,6% to 13,5% (WHO/Unicef 2019). However, the fact that majority of waste generated in the sanitation sector remains untreated continues to pose a threat to general public health and especially to communities situated downstream from sources of sanitation waste. One example of this is the Choqueyapu River, which intercepts the administrative capital La Paz. The river receives high amounts of waste generated from nearby sanitation and industrial sectors, which leads to contamination of toxins and heavy metals as well as a high organic loading and prevalence of pathogens that are detrimental to human health. The same water is also used for irrigation of crops grown further downstream and sold in the city, possibly threatening the health of consumers (Lopez Sanchez 2019). Examples like these manifest the importance of wastewater management and the fact that the sector is faced with a multitude of challenges makes it even more crucial, although difficult to solve.

On a governmental level, the Ministry of Environment and Water (Ministerio de Medio-Ambiente y Agua, MMAyA) oversees and promotes the national development of sanitation and watershed management in Bolivia (Helvetas Bolivia 2020). However each municipality is responsible for its own wastewater treatment, something that is usually down prioritized in favor of potable water production and distribution as well as wastewater collection systems (Cossio, J. McConville, et al. 2018). According to a recent publication, a study of 105 Bolivian towns found that 70% of the wastewater that was collected remained untreated, and that only 63% of existing treatment plants were in operation. Problems such as lack of operation and maintenance, inadequate treatment technology, design and construction as well as social issues were common. Generally, the lack of information and low availability of financial resources to cover operational and monitoring costs can present major constraints in the context of wastewater management, especially in smaller towns (idem).

Some non-profit organizations in Bolivia which aim at tackling these issues are Agua Sustentable which works for clean water and safe sanitation, and Agua Tuya which aims specifically at sustainable sanitation and re-use of sanitation waste. There are also other international aid organizations and development agencies which do valuable work that contribute to the development of the sanitation sector in Bolivia. One such example is SIDA which supports the work led by SEI through the Bolivia WATCH program mentioned above. The Swiss development corporation HELVETAS Bolivia also collaborates within the same program. In the case of the wastewater treatment plant in Tupiza, collaboration with both Agua Tuya as well as the municipal wastewater treatment company EMPSAAT and HELVETAS Bolivia has formed parts of the work.

2.2 Multi criteria approaches to sustainability assessments

The concept of sustainable development was defined in 1987 by the World Commission on Environment and Development (WCED) on behalf of the United Nations (UN) as *"development that meet the need of the present without compromising the ability of future generations to meet their own needs"* (WCED 1987). In 2005 the term was reaffirmed, highlighting economic, social and environmental aspects as crucial pillars of sustainability (UN 2005). This definition of sustainability is also reflected in the term 'sustainable sanitation' which, as previously mentioned, can entail a variety of aspects connected to different areas of society such as economic viability, social acceptance, technical and institutional appropriateness as well as protection of the environment and natural resources (SuSanA n.d.). When evaluating the question of sustainable sanitation, it would therefore be appropriate to take these factors of sustainability into account, otherwise important issues or special requirements might be lost in the decision process.

According to research on municipal wastewater treatment systems in Mexico, a re-ocurring problem seems to be a failure in taking into account certain aspects of the local context, and therefore the systems tend to fail due to problems such as high operation and maintenance costs or lack of local competence (Anda Sánchez 2017). Research made in Greece also suggests that engineers and decision-makers tend to choose only well-established technologies adapted from more developed countries, thus failing to include local requirements and conditions which may look very different (Tsagarakis, Mara, and Angelakis 2001). The same issue generally applies when choosing indicators for sustainability assessments, where existing standard indicators are typically focused on high and upper-middle contries whereas low and lower-middle income countries face entirely different challenges thus requiring a different set of indicators (Cossio, Norrman, et al. 2020).

The selection of treatment techologies and systems requires the involvement of a variety of objectives and criteria related to sustainability in different ways. One methodology that attempts to adress this issue is the multiple criteria assessment (MCA), through which a set of sustainability categories can be identified and evaluated in an effort to approach sustainable sanitation in a more holistic way. Hellström, Jeppsson, and Kärrman (2000) suggested that suitable categories for such an assessment should be covering health and hygiene, social and cultural aspects, environmental aspects, economy and technical considerations. For each category a set of criteria would be identified and from this an indicator intended to measure the criteria would then be defined. Recent research based on small-scale Bolivian WWTPs suggested that suitable indicators within the environmental category could be for example potential recycling, quality of effluent and sludge, and land area. Since each case is unique, it is important that criteria and indicators with most relevance in regards to the local context are prioritized (Cossio, Norrman, et al. 2020). The considered treatment technologies or systems are then evaluated according to the chosen set of criteria (Hellström, Jeppsson, and Kärrman 2000).

Multi-criteria approaches to sustainability assessments provide a flexible framework which takes on a more holistic viewpoint of sustainability and is becoming an increasingly popular methodology for evaluation of sustainable sanitation (Molinos-Senante et al. 2014). However, it is important to point out that an MCA generally does not include all aspects of sustainability, and therefore can not be considered as a tool for measuring total anthropogenic impact. Rather it provides a framework for decision-making and comparison of different technologies over certain factors that are central to the local context (Hellström, Jeppsson, and Kärrman 2000). Within the context of Bolivia WATCH two previous master thesis projects focusing on evaluation of sanitation systems have been carried out with the help of multi-criteria assessments comparing different sanitation models in El Alto and the innovative reuse technologies for dry toilet systems in Montero. Both studies reached similar conclusions indicating that higher sustainability in terms of environmental and health aspects would be reached with improvement and renewal of existing systems or upgrade to more advanced systems, however as the study in Montero pointed out these might also be more expensive and less accessible to low-income families (Smith 2019, Geber 2020).

2.3 Site description

The site description includes a brief introduction to the local context of the Tupiza community as well as the current sanitation service chain and wastewater treatment plant. Some relevant details of the organization and management of the plant are also presented.

2.3.1 The Tupiza community

The city of Tupiza is the capital of a municipality with the same name, which in its turn is the first section of the department Sud Chichas, located in the Potosí region in the south of Bolivia, as can be seen in the maps in Figure 1 below. Population in the municipality was estimated to 49 000 habitants in 2019, whereof 30 000 where estimated to live in the the urban areas (Helvetas Bolivia 2020). In rural communities surrounding the city the main occupation is farming. A large variety of crops are grown, the most common ones are corn, onions and flowers (Berno 2020). In recent years floodings of the area have become increasingly common, something that is believed to result from shorter and more intense rains as well as land use changes upstreams (Helvetas Bolivia 2020). The floodings have had several negative impacts on the community of Tupiza. Amongst other effects they imply added costs for damaged or destroyed infrastructure as well as health risks for the population. During the last big flooding which took place in 2019 the wastewater treatment plant was flooded, consequently destroying freshwater resources for downstream communities. Despite the increased amount of flood events in the area, few measures of flood mitigation exist (Cachambi 2020). As a part of the work within Bolivia WATCH SEI Latin America developed a general flood risk map which can be seen in Figure 2.

Figure 1: To the left is a map of Bolivia, with the location of Tupiza marked by a red pin. To the right is a map of the town of Tupiza where the black square symbolizes the WWTP. Maps collected from Google Maps and edited by Johanna Burström.

2.3.2 Current sanitation service chain

The current sanitation service chain which includes wastewater generation, collection, treatment and disposal and can be overviewed in Figure 3, includes an estimated 7200 households from the urban areas, with a total of 28 800 users (Helvetas Bolivia 2020, Navarro 2020). The wastewater generally consists of mixed household wastewater, i.e. water generated from toilets, showers, washing facilities and kitchens. The wastewater is also commonly mixed with drainage water from small businesses and restaurants (Navarro 2020). The wastewater is transported via a sewage pipe network to the local wastewater treatment plant localized 4,5 kilometers south of the city center (Helvetas Bolivia 2020). The pipe network consists mainly of concrete pipes, and leakage from surface water as well as underground water and cross-connections with the potable water network sometimes leads to dilution of the wastew-

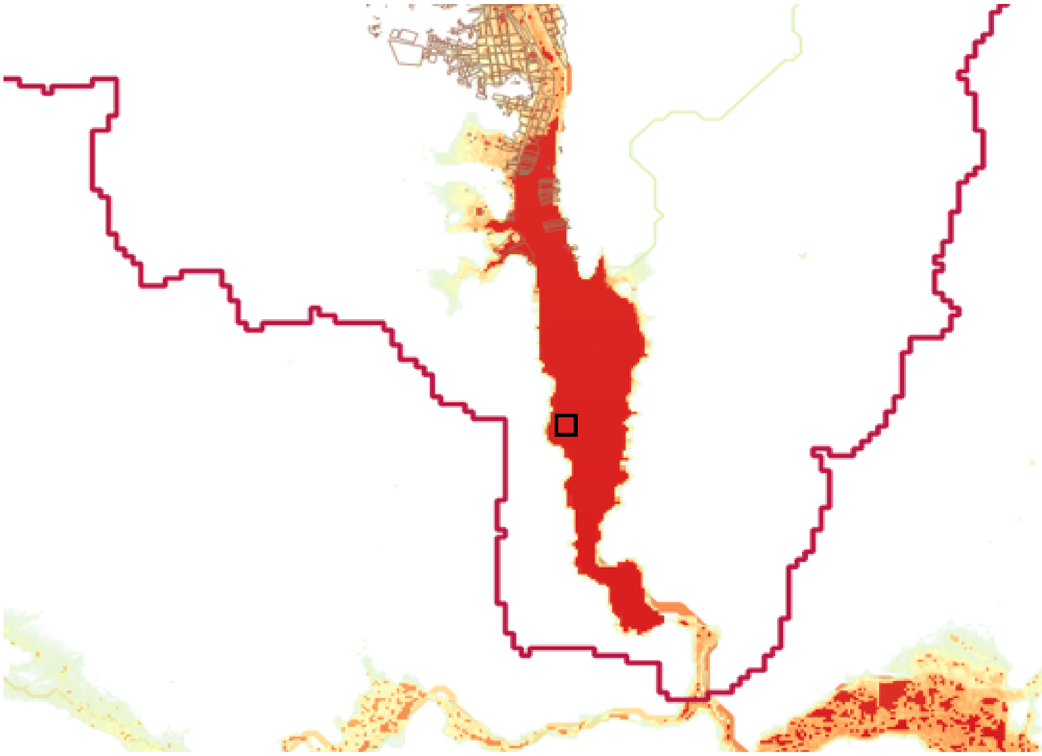


Figure 2: General flood risk map developed by SEI Latin America. The brown lines symbolize the urban areas of Tupiza and the red line is the limits of the Tupiza watershed. The red area symbolizes the area at risk of flooding and the small black box is where the wastewater treatment plant is located which is 4,5 km outside of urban Tupiza. Source: Bolivia WATCH. Edited by Johanna Burström.

ater, especially during the rain season. In dry periods the influent wastewater reaches up to 35 L/s, in comparison with up to 80 L/s in periods of rain (Navarro 2020). In addition to the leakage problems, the plant is located very close to the river which has become more flood prone in recent years due to changes in land use and weather patterns. The two latest floods which took place in the beginning of 2018 and 2019 respectively destroyed some parts of the plant and rendered most of the it useless (Helvetas Bolivia 2020). As a result of this and previous problems of functionality the MMAyA issued a public conventory on the 3rd of March in La Paz for a renovation of the wastewater treatment plant.

For the purposes of this study, the system being studied is limited to the treatment and disposal and/or re-use of water and sludge, as illustrated in Figure 3 below.

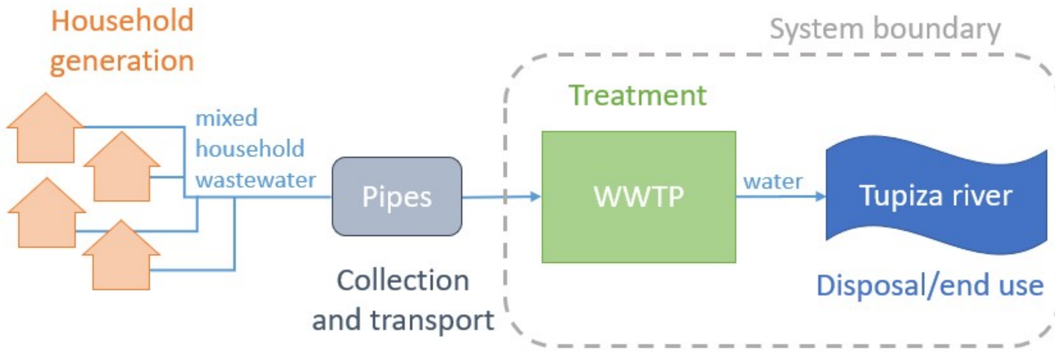


Figure 3: Full sanitation service chain currently in place in Tupiza. Note that the wastewater treatment plant (WWTP) is currently not in full function. Drawn by Johanna Burström.

2.3.3 Current wastewater treatment system

The current design of the wastewater treatment plant (WWTP) includes a Parshall channel which serves to measure influent flow and a pre-treatment which consists of two parallell grids to sort out larger solids and a sedimentation channel to settle larger particles. Further treatment is then achieved through a system of waste stabilization ponds; two parallell facultative ponds and four maturation ponds in series of two, see Figure 4. There are also six small unplanted drying beds for sludge, as well as a bypass channel connected to the sedimentation channel for peak flows. For technical descriptions of waste stabilization ponds and unplanted drying beds for sludge, see sections 2.4.2 and 2.4.6.

Even before the floodings, the plant was operating under some constraints. To begin with there were some issues with the design of the pond system. The maturation ponds were constructed too deep, essentially making them smaller versions of the two bigger facultative ponds (Navarro 2020). This lead to an efluent which would not have met demands of neither pathogen nor nutrient reduction, effectively leading to risks of disease transmission and eutrophication. Already in 2013 there where reports of standards not being met (MMAyA 2013). Another issue was the accumulation of sludge in the two bigger facultative ponds. The plant was installed during the late 1990's, but the ponds were never emptied of sludge which in time lead to cementation of sludge in the bottom of the ponds and consequently a difficult removal (Navarro 2020). This decreased the capacity of the plant to around 85% of incoming wastewater, the remaining 15% of the wastewater was released directly after pre-treatment through the bypass channel to the river, see Figure 4 (Helvetas Bolivia 2016). In the case of an eventual sludge removal, there were six unplanted beds intended for dewatering the sludge. However, according to information from the technician of the municipal wastewater treatment company the beds where too small and lacked an exit for the drained water (Navarro 2020).

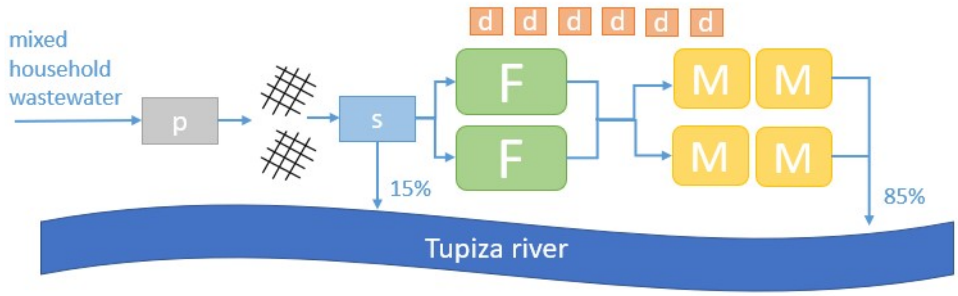


Figure 4: Sketch of current wastewater treatment system. Here p means Parshall channel, s means sedimentation channel, F means facultative pond, M means Maturation pond and d means unplanted drying bed for sludge. The percentages symbolize the share of wastewater disposed at points in the treatment chain. Drawn by Johanna Burström.

After the two floodings of 2018 and 2019 both of the facultative ponds as well as parts of the distribution channels were destroyed. By 2020, one of the facultative ponds was recuperated, restoring the capacity of the plant to an approximated 70% of full capacity (Navarro 2020). It is important to note though that even though 70% of the influent is currently being treated, the degreee of treatment is uncertain and probably not adequate.

2.3.4 Organisation and management of the plant

Maintenance of the plant currently consist of two visits per week from the technician in charge and workers from the local wastewater treatment company, during which the grids, sedimentation channel and distribution channels are cleaned (Navarro 2020).

The plant is owned by the municipal potable water and wastewater treatment company EMPSAAT - Empresa Prestadora de Servicio de Agua Potable y Alcantarillado Tupiza. The company is autonomous, meaning that it works independently from the municipality, with the purpose of providing potable water and sanitation services to the population of the city Tupiza. Although the EMPSAAT is completely autonomous, connections with the municipality exist; the president of the company is the governor of Tupiza (Navarro 2020). On a national level all EPSAS (Bolivian public companies of water and sanitation) companies are regulated by the AAPS (government authority of inspection control of potable water and basic sanitation). From the municipality level there is also the department of environment - Unidad del Medio Ambiente, which tackles everything between testing drinking water in different parts of the municipality to handling complaints from concerned citizens. The department of environment is regulated on a national level by the MMAyA (Helvetas Bolivia 2020).

Currently EMPSAAT is only taking a monthly fee for connection to the potable water network. A percentage of this fee (between 35-40% depending on if the connection is domestic or not) goes to the connection to the sewage network. No fee is taken for the treatment of the wastewater (Helvetas Bolivia 2020). According to numbers from 2016, the annual income of the company did not cover all of the expenses, resulting in a deficit (Helvetas Bolivia 2016). In 2013, EMPSAAT also reported a lack of capacity in organization and management of the plant, as well as adequate competence for the treatment of wastewater (Helvetas Bolivia 2016). This information was further confirmed in talks with the technician in charge of the plant, as well as with the municipal technical manager and responsible person of construction and external finances in the municipality (Navarro 2020; Durán and Herrera 2020).

2.4 Treatment technologies

Treatment technologies for the different system options evaluated in the MCA and described in sections 3.2.1, 3.2.2 and 3.2.3 all include improved pre-treatment and waste stabilization ponds. Other treatment technologies that are present in some options are constructed wetlands as well as two kinds of anaerobic reactors; upflow anaerobic sludge blanket reactor and compartmentalized anaerobic reactor. Possible options for treatment of sludge include dehydration on unplanted drying beds as well as hygienization in the form of alkaline stabilization and ammonia treatment. Treatment technologies currently implemented at the plant are screening coupled with a sedimentation channel and waste stabilization ponds in the form of facultative and maturation ponds, see Figure 4 above.

2.4.1 Screening as pre-treatment

Pre-treatment is the first step of the wastewater treatment process, removing larger solids and constituents such as oil and grease. This added step helps preventing clogging before the other more advanced treatment steps. A common method of pre-treatment is screening, which prevents solids such as plastics or other trash from entering the plant by trapping them in inclined screens. The spacing of the screens usually vary between 15-40 mm and they can be maintained by hand or by mechanized raking. The latter is more common for screens with smaller spacing which also allows for more thorough removal of solids (Tilley et al. 2014). Mechanized screens with smaller spacing between 1 to 6 mm exist as well (Ortega de Miguel et al. 2010). Currently screens with larger spacing that are scraped manually are implemented at the WWTP in Tupiza.

2.4.2 Waste stabilization ponds

Waste stabilization ponds are among the most common waste treatment methods in the world and are especially suitable for rural and peri-urban communities. They typically come in three different forms; sedimentation ponds, facultative ponds and maturation ponds (Tilley et al. 2014). In the case of Tupiza, both facultative and maturation ponds are implemented in the current treatment of wastewater.

A facultative pond is a pond with one aerobic and one anaerobic layer. The upper layer is aerobic and receives oxygen from photosynthesis driven by algae. The lower layer is anaerobic. Settleable organic material is accumulated at the bottom of the pond and digested by anaerobic bacteria, producing CO2 consumed by the algae in the top layer (Tilley et al. 2014). This leads to reductions in settleable solids, BOD and pathogens (Von Sperling 2007). A general illustration of facultative pond can be found in Figure 5.

Facultative ponds can be followed by maturation ponds, which are sometimes referred to as polishing or finishing ponds since they provide the final level of treatment (Tilley et al. 2014). Maturation ponds are more shallow than facultative ponds, ensuring a fully aerobic environment and penetration of sunlight which enables photosynthetic algae to produce oxygen and consume CO2 which lowers the pH (idem). The low pH in combination with solar radiation and high concentration of aerobic bacteria contributes to a high removal of virus and bacteria, providing an efficient hygienization of the water (Von Sperling 2007). A general illustration of maturation pond can be found in Figure 5.

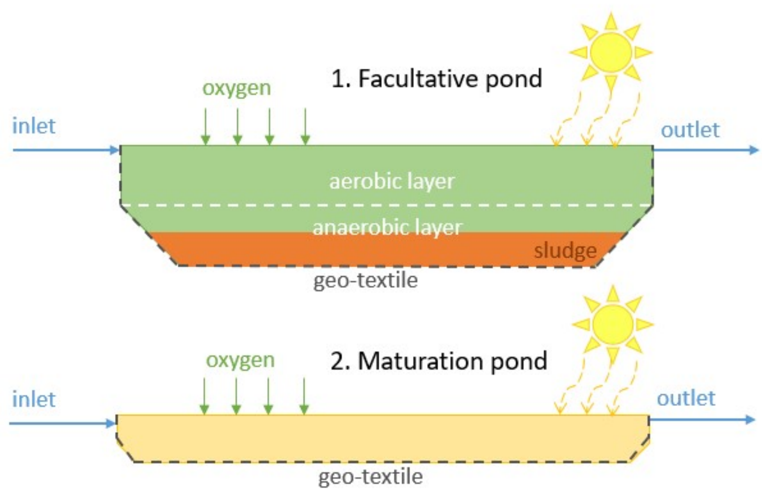


Figure 5: Illustration of facultative and maturation ponds. Drawn by Johanna Burström.

The facultative pond has a depth of 1-2,5 m making it deeper than the maturation pond which should have a depth of 0,5-1,5 m (Tilley et al. 2014). The facultative pond also has a longer hydraulic retention time (HRT) due to the slow process of the photosynthesis and anaerobic digestion (Von Sperling 2007). HRT in the facultative pond can be between 5-30 days, depending on local climate. In contrast, the HRT of maturation ponds depends on the removal efficiency of coliform bacteria, but is generally shorter than that of the facultative ponds. To achieve a higher removal efficiency, maturation ponds are typically designed in series (Tilley et al. 2014; Von Sperling 2007). The design of facultative ponds is mostly dependent on the surface organic loading rate (organic load per unit area), which originates from the need of having a certain amount of exposure to sun in the pond (Von Sperling 2007).

2.4.3 Upflow anaerobic sludge blanket reactor

The upflow anaerobic sludge blanket reactor (UASB) is a form of anaerobic treatment reactor where wastewater is introduced at the bottom of the reactor and flows upward (Tilley et al. 2014). The bottom of the reactor is the so-called bioreactor zone (Figure 6), here microbes flocculate to each other or to small solid particles, forming suspended microbial sludge granules of 1-3 mm in diameter (Vigneswaran, Balasuriya, and Viraraghavan 1986). Because of their weight they can resist being washed out in the upflow of wastewater, creating a sludge blanket which effectively filters the wastewater from smaller solid particles and degrades organic compounds, creating biogas in the form of carbon dioxide and methane (Tilley et al. 2014). In the upper clarifier zone (Figure 6) the separator separates the biogas from the liquid wastewater mix, retaining the anaerobic sludge within the reactor. Above the baffles of the separator a clear zone is created where sludge particles are not able to flocculate. This is where the effluent wastewater is released (Vigneswaran, Balasuriya, and Viraraghavan 1986).

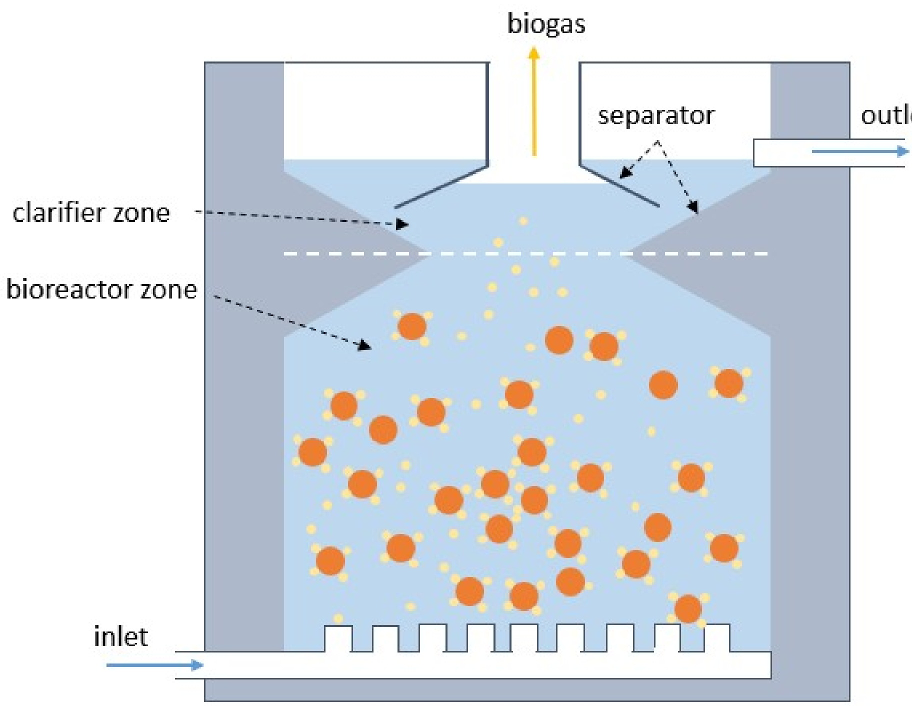


Figure 6: Illustration of a UASB - upflow anaerobic sludge blanket reactor. In the illustration the small yellow circles are biogas bubbles and the larger orange circles are sludge granules. Drawn by Johanna Burström.

The UASB provides a high reduction in organic material and is a primary treatment. It also has the capacity of providing a higher quality of effluent than regular septic tanks, coupled with a relatively low sludge production which only requires desludging every 2-3 years. The reactor itself is not complicated to build, although a long start-up time is usually required due to slow development of the sludge granules (Tilley et al. 2014). This is because the process of the anaerobic bacteria is biological, which in turn makes the efficiency dependent on temperature (Chernicharo and Von Sperling 2005). It also requires operation and maintenance by high-skilled personnell as well as a constant supply of energy for pumping (Tilley et al. 2014).

In applications of low-concentration sewage such as municipal wastewater, the design of the UASB is ruled by the HRT, which varies with water temperature as mentioned above. For waters with temperatures between 16-19°C the daily average HRT should be between 10-14 hours with a minimum of 7-9 hours during peak flows, for waters with 20-26°C daily average HRT can be between 6-9 hours with a minimum of 4-6 hours during peak flows (Chernicharo and Von Sperling 2005). In Tupiza average air temperatures vary between 11-20 °C, average water temperatures can then be assumed to be 2 °C lower, that is 9-18 °C (Climate-data.org n.d.).

The UASB is generally applied to industrial wastewaters with higher concentrations organic material, although application to municipal wastewaters exists as well, especially in tropical countries such as Brazil, Colombia and India due to the favourable high temperatures (Vigneswaran, Balasuriya, and Viraraghavan 1986; Chernicharo and Von Sperling 2005).

2.4.4 Compartmentalized anaerobic reactor

The compartmentalized anaerobic reactor (in Spanish Reactor Anaeróbico Compartmentalizado - RAC) is a form of improved anaerobic baffled reactor which is supposed to better withstand clogging and facilitate maintenance, designed by the Bolivian organization Agua Tuya (Aldunate 2020b). The original anaerobic baffled reactor is an enhanced version of the septic tank and consists of a series of compartments which are baffled to force influent wastewater to flow through a series of sludge blankets, see Figure 7. The treatment consists of anaerobic digestion and filtration of smaller particles resulting in a small production of biogas and high reduction of BOD (Tilley et al. 2014). The treatment in the RAC is identical to that of the anaerobic baffled reactor, however the reactor is divided in three compartments as can be seen in Figure 8. The first compartment consists of the reaction zone where the breakdown process is started followed by the digestion zone where most of the upflow sludge blanket process happens and finally comes the clarification zone where water is clarified and separated from the sludge (EcoTrac 2012). In centralized treatment systems these sorts of reactors are generally combined with a primary settler, to settle most of the solid particles and prevent clogging. They are especially suitable where land area is limited since they can be installed underground (Tilley et al. 2014).

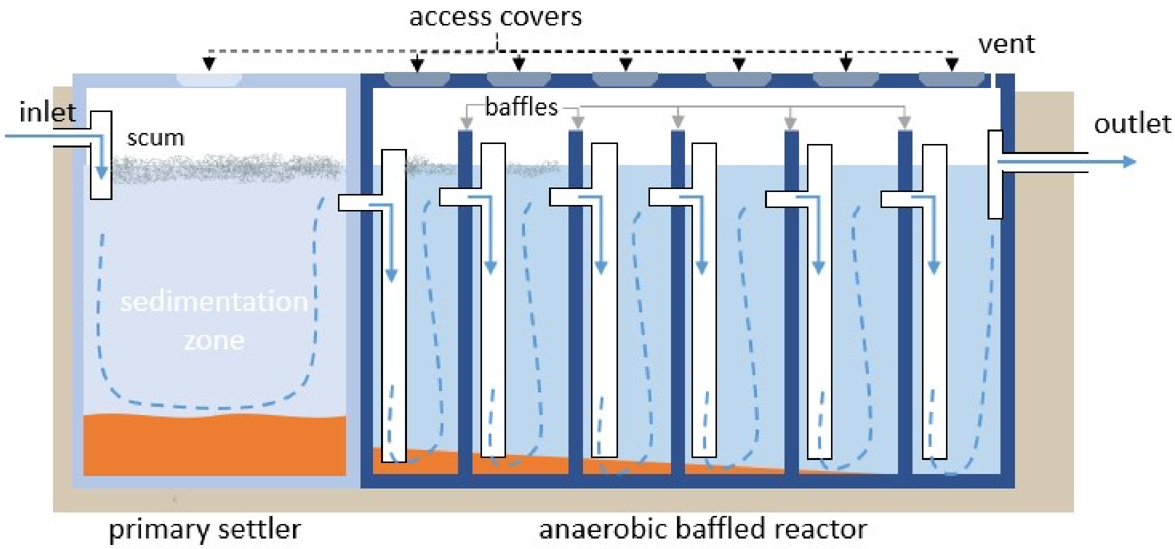


Figure 7: Illustration an anaerobic baffled reactor. The orange part of the bottom of the reactor is sludge. Drawn by Johanna Burström.

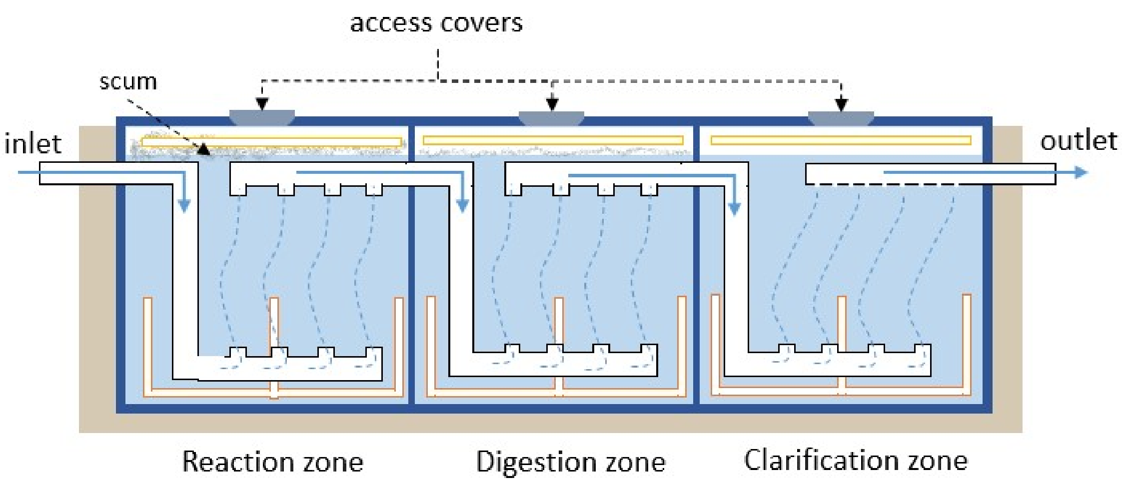


Figure 8: Illustration of a RAC - compartmentalized anaerobic reactor. The yellow pipes in the top of the reactor are for removal of scum and the orange pipes in the bottom are for removal of sludge. Drawn by Johanna Burström.

The RAC has the same treatment efficiency as the anaerobic baffled reactor which can reduce BOD up to 90% but is not very efficient at removing nutrients or pathogens, similarly to the UASB it is a primary treatment which leaves an efluent requiring further treatment (Aldunate 2020b, Tilley et al. 2014). The technology of these reactors is easily adaptable to different climates, even though the efficiency is lower in colder climates. It can also tolerate hydraulic and organic shock loadings (Stuckey 2010). An advantage in comparison to the UASB is that these do not require any electrical energy as it relies on gravital flow, resulting in lower operation and maintenance costs (Tilley et al. 2014). Automatic removal of sludge can be added resulting in some energy dependency. Both reactors have a low sludge production, with the difference of the RAC reactor having scum and sludge removal pipes which enable automatic removal and facilitates maintenance. The RAC has also been implemented by Agua Tuya in different projects throughout Bolivia (Aldunate 2020b).

2.4.5 Horizontal subsurface flow constructed wetland

Constructed wetlands (CW) aim to replicate the processes of natural wetlands, marshes or swamps. There are different kinds of constructed wetlands, in this case the horizontal subsurface flow constructed wetland was investigated. According to the experiences of Agua Tuya, similar results for unplanted and planted contructed wetlands can be achieved, with the benefit of unplanted wetlands requiring less maintenance (Aldunate 2020b). The unplanted constructed wetland consists of a lined basin filled with gravel or sand. Wastewater is led through an inlet underground, flowing horizontally through the basin. A combination of physical, chemical and biological processes then filter solids, degrade and reduce organic and inorganic material, remove nutrients and certain pathogens through the activity of the microorganisms present in the biofilm that forms around the gravel. (Tilley et al. 2014, Aldunate 2020b).

The removal efficiency of the wetland depends on the surface area (length and width), while the maximum possible flow depends on the cross-sectional area (width and depth). Water levels should be kept at 5 to 15 cm cm below surface in order to ensure subsurface flow. A total surface area of 5 to 10m^2 per person equivalent may be required, depending on previous treatment (Tilley et al. 2014). The application of constructed wetlands in developing countries has a huge potential due to the tropical or subtropical climate regions that favour biological activity which is a central for the efficiency of constructed wetlands. In more developed parts of the world constructed wetlands are an established technology for watewater treatment, for example by 2001 in Europe more than 5000 sub-surface constructed wetlands existed for treatment of wastewater (Kivavaisi 2001).

2.4.6 Unplanted drying beds for sludge

Unplanted drying beds are simple permeable beds which help reduce the water content in sludge by letting water drain off or evaporate. The drying beds are lined and equipped with an outlet in the bottom which leads the drained water back to primary or secondary treatment. The beds are usually filled with gravel and have a top layer of sand (Tilley et al. 2014). The sludge is dried after 10-15 days, at which the volume is decreased, but organic content remains the same (Tilley et al. 2014). Depending on the sludge characteristics around 50-80% of the sludge volume is drained as liquid (Rondeltap and Dodane 2014). For re-use, the sludge usually needs to be storaged or further treated in order to reach hygiene standards for use in agriculture, however WHO guidlines estimates that one log-reduction of pathogenic content can be reached by drying the sludge (WHO 2006a).

2.4.7 Alkaline stabilization of sludge

Untreated sewage sludge contains large quantities of pathogenic microorganisms and requires further hygienization in order to minimize health problems and other associated risks when re-using or disposing of the sludge. Among the most resistant pathogens that commonly occur in sludge are Helminth eggs, out of which Ascaris sp. is considered the most resistant one as well as being the most prevalent globally. Concentrations of Helminths also tend to be higher in developing countries, making the question of hygienization of sludge important when it comes to handling risks of infection (Bastos et al. 2013).

One common method of sludge hygienization is alkaline stabilization of the sludge by adding lime, thus raising the pH levels to above 12 and provoking an exoterm reaction which raises the temperature in the material (J.R. McConville et al. 2020). The process is easy to operate and has low capital and operational costs, making it a popular choice in developing contexts (Jimenez 2007). A study from 1995 found that addition of 10% weight of quick lime (85% CaO) and storage of sludge at pH >12 for 3 months was enough to completely inactivate Ascaris eggs which are key indicator organisms for pathogenic content in developing countries (Eriksen, Andreasen, and Ilsoe 1995). However more recent research suggests that a number of sludge characteristics like alkalinity and pH are important to consider in order to establish the most economic lime stabilisation (Rondeltap, Dodane, and Bassan 2014).

By raising the pH the alkaline stabilization has the added benefit of improving nutrient availability in the sludge by converting the ammoniacal nitrogen to ammonia. If used for cultivation the sludge can also improve the soil quality because of the high pH and carbon content. According to local authorities in the rural areas outside of Tupiza soils are generally acid which would make this a suitable method for soil conditioning. Other important considerations include a dry storage space and cover, availability of lime as well as protective clothing when adding the lime to the sludge (Rondeltap, Dodane, and Bassan 2014). The treatment can be significantly improved by covering the sludge during the hygienization process, this retains the ammonia produced and thus increases the level of hygienization as well as preserving valuable nutrient content in the sludge (Jimenez 2007).

2.4.8 Ammonia treatment of sludge

Another method of hygienizing the sludge from pathogenic content is ammonia treatment with urea. This treatment focuses on the hygienizing effect of ammonia, and requires airtight storage in order to preserve ammonia from evaporating. The treatment is highly temperature dependent, with a higher temperature decreasing the required ammonia as well as treatment time. Having a pH value between 9-11 also considerably affects the ammonia equiluibrium, and indirectly increases the hygienization effect (Fidjeland et al. 2015).The method is especially applicable in settings with urine diverting toilets, where urine can be used as source of ammonia instead of commercial fertilizer. Otherwise costs for commercially produced urea will increase operational costs (Rondeltap, Dodane, and Bassan 2014). Swedish research from 2009 showed that adding a 1% or 2% weight of urea to fecal sludge increased the ammonia content threefold and fivefold respectively, and shortened the iactivation time for Ascaris eggs up to four times (Nordin, Nyberg, and Vinnerås 2009).

The ammonia treatment has the added benefit of enriching the sludge with higher nitrogen content. To ensure efficient use of resources, re-use in agriculture should be established if commercial urea is used for the hygienization. This is because current chemical urea production is dependent on non-renewable resources.

3 Method

The methodology for this project consisted mainly of a multi-criteria assessment which analyzed a set of different categories with assigned criteria and indicators, all related to sustainable sanitation. The socio-cultural category which focused on social acceptance and demand was investigated in a separate analysis using qualitative research methodology. A stakeholders mapping was also performed in order to establish local interests and validate chosen criteria.

3.1 Pre-study: Stakeholders perspectives

In order to get an overview of the different stakeholders involved in the system a small stakeholders mapping was performed. This was done according to methodology adapted by SEI from research by Burgers and Ai (2017). Stakeholders were listed and identified according to the methodology on the basis of stakeholder groups as listed in Table 1 and stakeholder roles as listed in Table 2. As a small pre-study, meetings with stakeholders from different groups were carried out in the beginning of the field studies. A total of seven stakeholders were asked to list the three most important elements of the possible buildout or renovation of the wastewater treatment facilities in Tupiza. The answers from the stakeholders were then used to confirm the choice of criteria for the MCA, as well as point out areas of interest that should be added to the analysis. By categorizing stakeholders in groups, the mapping helped ensure that interests from different parts of society were represented in the study, thus ensuring a wide range of perspectives and concerns which could be incorporated in the implementation and analysis of the MCA and the study for social acceptance. Key interests of local stakeholders were mapped and listed in Table 3 below.

It was found that many of the identified key interests confirmed and solidified the chosen criteria of the MCA as well as the social acceptance study. Flood resilience for example was evaluated in the criteria Impact of flood events, adequate technology and affordability was investigated in the criteria for Costs as well as Risk of disease transmission. Social awareness of the WWTP and ability to cultivate organically was investigated in the social acceptance study of acceptance and demand for reuse of subproducts. Treatment efficiency was ensured through the dimensioning of the different systems as performed by Agua Tuya and quality testing was included as maintenance costs in ther O&M costs calculations. Although not listed among key interests, something that was brought up by many stakeholders was the limitation of space provided by the size of the WWTP property. Therefore a criteria about space efficiency was added to the technical category in the MCA.

Table 1: Description of different stakeholders groups.

No.	**Stakeholder group**	**Description**
SH1	Authorities	Local, national, or regional governmental organizations with key decision-making power, or assigned with monitoring and evaluation of management plans of the issue in question.
SH2	Political Representatives	Citizens elected to political office on behalf of their fellow citizens. It is important to involve elected representatives as they are the ones who are most likely influenced by the decisions taken locally.
SH3	Civil Society	Individuals, civil society groups, or NGOs that have been involved in the area and issue in question and/or that may affect, gain , or be affected by the hydro-meteorological event(s) or the NBS.
SH4	Private Sector	Business, entrepreneurs, companies, and corporations that may affect, gain , or be affected by the hydro-meteorological event(s) or the NBS. These may include service-providers, producers, tourist operators, or insurance companies, to name a few.
SH5	Academia	The scientific community with expertise in the area.

Table 2: Description of different stakeholder roles. Note that each stakeholder group can have more than one stakeholder role.

Stakeholder role	**Description**	**Examples**
Decision-makers	Stakeholders in a position to make and execute decisions concerning a society or community. They can be from different (local, national, regional) levels	Representatives of government ministries, state agencies, and departments, staff in national or local administrations, members of parliament, donors.
Implementers	Stakeholders responsible for the execution or implementation of plans and policies.	National authorities, NGOs, regional agencies, civil protection authorities.
Coordinators	Stakeholders that coordinate a variety of actors for the implementation of plans and policies	Umbrella organizations (governmental or not)
Providers of expert knowledge	Stakeholders that provide expert knowledge and information such as research or site-specific data	Think tanks, consultants, universities, insurance companies, energy providers, food-producing companies, local informants from civil society.
Funders	Stakeholders that finance activities in the site. These may refer to governmental agencies but also private and non-governmental financing for instance research or local engagement.	Public agencies, ministries, banks, international organizations, private sector actors.

Table 3: Map of stakeholders relevant to the local context of Tupiza and their key interests.

Position	**Stakeholder group**	**Stakeholder role**	**Key interests**
Technician at EMPSAAT	SH 4	Implementer, provider of expert knowledge	Infiltration of water Varying wastewater quality Flood resilience
Manager in cooperative organization between municipalities	SH 2	Knowledge broker	Flood resilience Adequate technology
Technical manager at municipal level	SH 1	Decision maker	Adequate technology Social acceptance of WWTP Affordability of O&M
Responsible of construciton and external finance at municipal level	SH 1	Decision maker	Adequate technology Social acceptance of WWTP Affordability of O&M
Manager at environmnetal department at municipality	SH 2	Decision maker	Social awareness of WWTP Affordability of O&M Adequate maintenance
Executive at local farmers organizaton	SH 3	Coordinator	Be able to cultivate organically Quality of the effluent
Environmental engineer at HELVETAS Bolivia	SH 5	Provider of expert knowledge	Treatment efficiency Quality testing

3.2 Treatment system options

For the MCA three treatment systems were chosen. The system boundaries were defined from wastewater treatment to discharge or potential re-use, see illustration in Figure 3. All system options where designed based on Bolivian standards for effluent quality, space limitations and pre-existing infrastructure according to the Tupiza local context. Option 0 was chosen as the already existing system if it would be in full function. Option 1 was chosen as an improvement of the conventional system as suggested by Agua Tuya, with added settlers and RAC reactors as well as hygienization of the sludge using alkaline treatment. Option

2 was chosen as a larger renovation of the current system with a UASB reactor and constructed wetlands instead of facultative ponds, urea treatment was used as hygienization of the sludge. All options where equipped with an improved automated pre-treatment.

Together with Agua Tuya all system options were dimensioned according to data of the WWTP in their own Excel spreadsheets. The dimensions of each component can be found in Appendix B. The following sections provide descriptions of the treatment trains and design of the different options.

3.2.1 Option 0 - Pond system

Option 0 was chosen as the conventional system with some minor improvements. In option 0, the original grids were complemented by smaller grids with an automatic removal of solids in order to improve pre-treatment. For primary treatment, water was led to the pre-exisisting two parallell facultative ponds. Water was then further hygienized in secondary treatment consisting of the four maturation ponds before leading effluent water in to the Tupiza river. For this last step the maturation ponds were modified to a depth of 1 m instead of 1.7 m. Treated wastewater could also be led to downstream farms for re-use as irrigation water. Sludge was not treated, just accumulated in the facultative ponds which would need emptying every 10 years, by which the sludge would be transported to sanitary disposal. The emptying could be done via suction from special trucks which would produce wet sludge, or the ponds could be dried out one at a time which would produce a dry sludge that could be emptied through manual labour. A sketch of the system can be seen in Figure 9. For a more detailed description on how facultative and maturation ponds work, see Section 2.4.2 and for dimensions of the system see Appendix B.

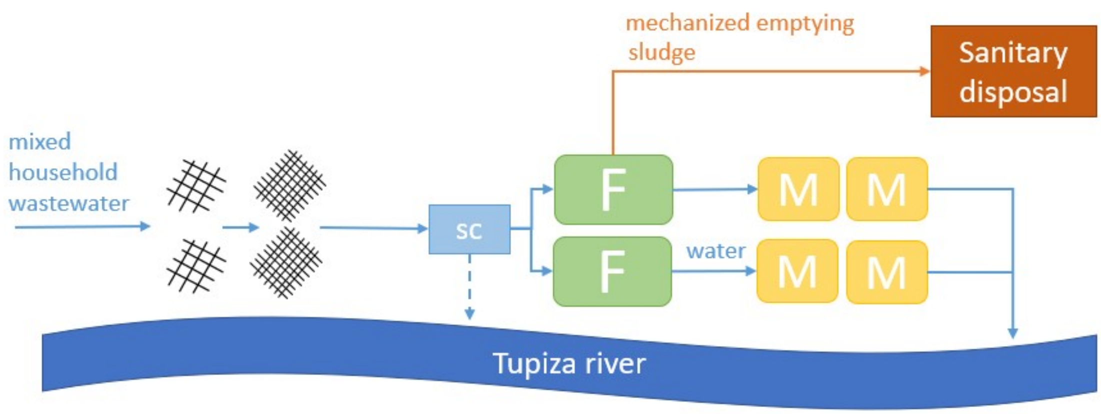


Figure 9: Sketch of alternative 0. Here sc means sedimentation channel, F means facultative pond and M means maturation pond. Drawn by Johanna Burström.

3.2.2 Option 1 - Compartmentalized anaerobic reactor and pond system

Option 1 was chosen as an improvement of the conventional system as suggested by Agua Tuya, using their RAC. This option was focused on improving treatment and space efficiency as well as facilitating aspects of sludge emptying. Since the RAC reactor needs a settler in order to prevent clogging this was also added. Sludge drying beds were dimensioned according to the sludge yields of the settler and the RAC. The facultative and maturation ponds remained in use and were renovated in the same way as in option 0. A hygienization process of alkaline treatment of the sludge was also added in order to set up re-use of the sludge as fertilizer. Treated wastewater could also possibly be led to farms and used as irrigation for crops. A sketch of the system can be seen in Figure 10. For more detailed descriptions of the RAC and the alkaline treatment of sludge, see Sections 2.4.4 and 2.4.7 and for dimensions of the treatment components see Appendix B and C.

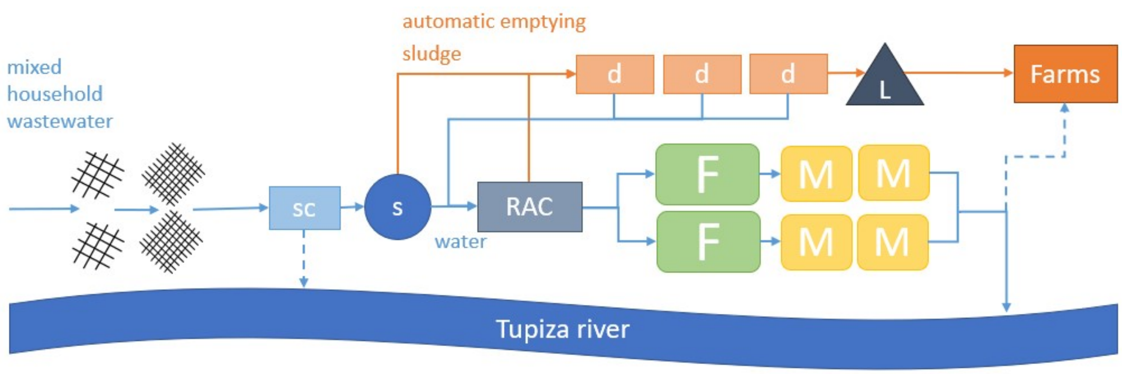


Figure 10: Sketch of alternative 1.Here sc means sedimentation channel, s means settler, RAC means compartmentalized anaerobic reactor, d means unplanted drying bed for sludge, L means lime treatment, F means facultative pond and M means maturation pond. Drawn by Johanna Burström.

3.2.3 Option 2 - Upflow anaerobic sludge blanket reactor and constructed wetland

Option 2 was chosen as a larger renovation project of the plant with a stronger focus on flood resiliency and innovative treatment technologies for the sludge. A UASB was added as primary treatment, and a horizontal subsurface flow constructed wetland was chosen as a more flood resilient option than the facultative ponds. The maturation ponds remained in the system. The hygienization of the sludge was chosen as the more innovative ammonia treatment method with urea. Sludge could therefore be re-used as soil fertilizer and treated wastewater could possibly be lead to farms and used as irrigation for crops. A sketch of the system can be seen in Figure 11. For more detailed descriptions of the UASB, constructed wetland and ammonia treatment of sludge, see Sections 2.4.3, 2.4.5 and 2.4.8 and for dimensions of the treatment components see Appendix B and C.

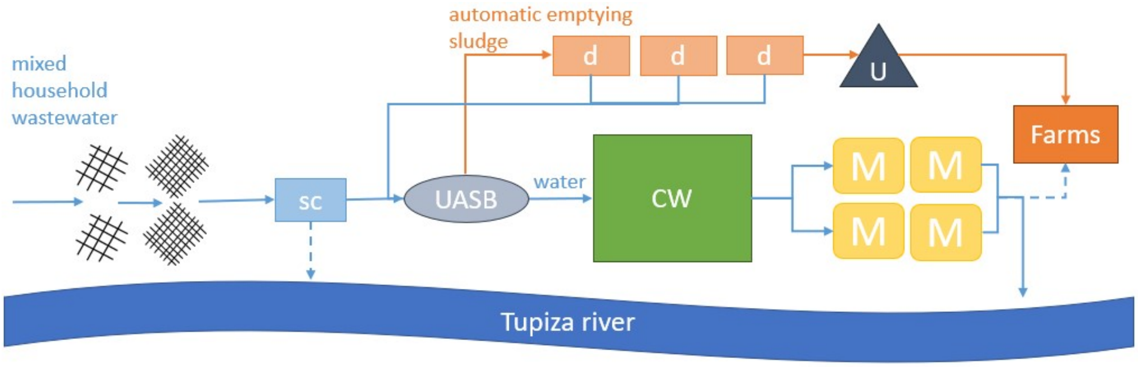


Figure 11: Sketch of alternative 2. Here sc means sedimentation channel, UASB means upflow anaerobic sludge blanket reactor, CW means constructed wetland, M means maturation pond, d means unplanted drying bed for sludge, U means urea treatment. Drawn by Johanna Burström.

3.3 Sustainability assessment using multiple criteria

Five broad categories of sustainability were chosen; health, technical, socio-cultural, environmental and financial/institutional. The socio-cultural category was later taken out of the MCA and treated as a separate evaluation since that category aimed at evaluating the acceptance and demand for sub-products such as treated wastewater and sludge for use in agriculture. Social awareness was listed as a key interest among stakeholders, but since a dominating factor in social acceptance and awareness of a WWTP was assumed to concern issues of location which was pre-determined in this case, and all treatment options were designed based on pre-existing infrastructure which generated quite similar systems it was concluded that an evaluation of general acceptance of different treatment technologies wouldn't generate information which would be valuable in the context of a comparison among the different system options.

Thus the MCA evaluated four categories with a total of five criteria. The categories evaluated were risk of disease transmission, vulnerability to flood events, natural resource management and capital, organization and management costs. After the stakeholders mapping two additional criteria were added; space efficiency and quality of effluent within the categories Technical and Environmental respectively. Both of these were also articulated as pre-requisites for the design of the options. Space efficiency in the terms of designing all options according to the available space and quality of effluent in terms of dimensioning all systems to meet Bolivian regulations of quality of effluent in accordance with Law 1333 which concerns environmental regulations. The categories were assigned 1-3 indicators which would be evaluated either qualitatively or quantitatively. In Table 4 below the MCA matrix is shown with criterias and corresponding indicators.

Category	Criteria	Qualitative or quantitative	Indicator
Health	Risk of disease transmission	Quantitative	Concentration of E.coli in efluent water [CFU/100 ml]
		Quantitative	Amount of added Ascaris eggs to soil from efluent water [eggs/m2]
		Quantitative	Amount of added Ascaris eggs to soil from fecal sludge [eggs/m2]
Technical	Space efficiency	Quantitative	Area required [m2]
	Impact of flood events	Qualitative	Share of system at risk in case of flood [%]
Environmental	Natural resource management	Quantitative	Potential land area fertilized with treated sludge [ha/year]
	Quality of effluent	Quantitative	Level of BOD in effluent [mg/L]
Financial and institutional	Capital and O&M costs	Quantitative	Annual cost [BOB/cap, year]

Table 4: MCA criteria and indicators.

A performance score ranging from very poor performance to very good performance in a scale of five steps was created. The scores were color coded in order to facilitate and accentuate the final MCA matrix.

red - Very poor performance.
orange - Poor performance.
yellow - Neither good nor bad performance.
light green - Good performance.
dark green - Very good performance.

3.3.1 Risk of disease transmission

When evaluating risk of disease transmission the prevalence of two indicator pathogens was investigated. Since Helminth eggs have been pointed out as one of the main health risks connected to re-use of wastewater and sludge in agriculture, Ascaris which is one of the most resistant Helminths was chosen as indicator of the risk of Helminth transmission (Jimenez et al. 2004). In the Bolivian environmental legislation the only indicator pathogen which is regulated when it comes to quality in effluent wastewater is E. coli, for which it was also chosen as an indicator for the risk of disease transmission in the Tupiza case (Helvetas Bolivia 2020).

The WHO (2006a) has established that the re-use of wastewater and sludge in agriculture shouldn't generate a burden of disease of more than 10^{-6} DALY (disability adjusted life year) per person and year. Based on epidemiological studies, a criterion of less than 1 helminth egg L^{-1} for wastewater used for irrigation and 1 helminth egg per gram of total solids ($g^{-1}TS$) in fecal sludge used for fertilizer was recommended. In the case of the fecal sludge, this could be translated to a criterion of less than 500 eggs per square meter of fertilized soil (WHO 2006a, WHO 2006b). Based on these suggestions as well as the requirements for levels of E. coli according to Bolivian law which also follows the recommendations from WHO, the indicator values for the risk of disease transmission criteria were formulated according to Table 5. Levels of E. coli in sludge were not evaluated since the resistant nature of Ascaris eggs and their elimination in the chosen hygienization methods of sludge would guarantee similar or higher elimination of other pathogenic organisms (Fidjeland et al. 2015, Eriksen, Andreasen, and Ilsoe 1995).

Table 5: Threshold levels of pathogenic indicator organisms in treated wastewater and sludge. CFU stands for colony-forming unit and is used as a way of estimating viable bacteria cells in a sample.

Sub-product	**Min. level of E.coli**	**Min. level of viable Ascaris eggs**
Treated wastewater	1000 CFU per 100 ml	< 500 eggs/m^2
Treated sludge	-	< 500 eggs/m^2

Concentration of E. coli in effluent water
influent level of E. coli concentration was $3,09 * 10^7$ CFU per 100 mL according to a test of the incoming wastewater quality from 2013 (Appendix A). Threshold levels of E.coli in effluent water was 10^3 CFU per 100 mL (Table 5). The needed log removal was calculated by taking the logarithm of the ratio of influent E. coli concentration and required effluent E. coli concentration, resulting in a required removal of 4,5 log reductions. Log removals of E. coli for each system option were calculated using Table 6 where log removals for each treatment technology were listed according to publications by WHO (2006b) and Chernicharo and Von Sperling (2005). In the literature nearly all removal values were given at intervals, for which the mean value of that interval was chosen.

Table 6: Removal efficiencies of E.coli for different treatment technologies.

Treatment technology	**Estimated log removal [$\log_{10}$]**	**Source**
Facultative ponds	1	WHO (2006b) Chernicharo and Von Sperling (2005)
Maturation ponds	2	WHO (2006b) Chernicharo and Von Sperling (2005)
Settler	0,5	WHO (2006b)
UASB	1	WHO (2006b) Chernicharo and Von Sperling (2005)
RAC	1	WHO (2006b) Chernicharo and Von Sperling (2005)
Constructed wetland	1,75	WHO (2006b) Hoffman et al. (2011)

The results were transcribed to the MCA performance score as follows:

Very poor performance - E.coli removal is < 1 log removal
Poor performance - E-coli removal is between 1-3 log removals.
Neither good nor bad performance - E.coli removal is between 3-4,5 log removals.
Good performance - E.coli removal is 4,5-5 log removals.
Very good performance - E.coli removal is >5 log removals.

Amount of added Ascaris eggs to soil from effluent water
After literature review of a Bolivian study of intestinal parasites from 2005 and comparison of general values of Ascaris infection rates for developing countries it was approximated that 10% of the population in Tupiza would have a moderate level of infection resulting in 25 000 Ascaris eggs per gram of feces in infected users (Mollinedo and Prieto n.d., Jimenez et al. 2004, WHO 2002). The concentration of eggs in influent wastewater, $C_{Ascaris,ww}$ [eggs/m^3], was then calculated under the assumption that each infected user would produce 250 g of feces per day as determined by Rose et al. (2015), and the daily influent flow, see Equation 1.

$$C_{Ascaris,ww} = share_{infected} * users * m_{f,d} * Q_{in,d} \tag{1}$$

Here was the concentration $m_{f,d}$ was the mass of feces produced [g/user, d], $Q_{in,d}$ was daily influent flow [m^3/d]. The removal efficiencies of each component were investigated thorugh literature review and listed in Table 7 below.

Table 7: Removal efficiencies of Helminth eggs for different treatement technologies.

Treatment technology	**Estimated log removal [$\log_{10}$]**	**Source**
Facultative ponds	1,3	WHO (2006b) Chernicharo and Von Sperling (2005)
Maturation ponds	1,5	WHO (2006b) Chernicharo and Von Sperling (2005)
Settler	1	WHO (2006b)
UASB	0,75	WHO (2006b) Chernicharo and Von Sperling (2005)
RAC	0,75	WHO (2006b) Chernicharo and Von Sperling (2005)
Constructed wetland	2	WHO (2006b) Hoffman et al. (2011)

The total removal efficiency of each system was added up and the effluent concentration of Ascaris eggs was calculated using the estimated influent concentration of Ascaris eggs, $C_{Ascaris,ww}$ and the total removal efficiencies for each system, see Table 9. The average volume of wastewater used for per area of irrigated land (see Eq. 8) was then applied in order to establish amount of Ascaris eggs added to soil. The options were scored according to the MCA performance score as follows:

Very poor performance - Level of Ascaris eggs on soil is >1000 eggs per m^2 .
Poor performance - Level of Ascaris eggs on soil is between 600-1000 eggs per m^2.
Neither good nor bad performance - Level of Ascaris eggs on soil is between 400-600 eggs per m^2.
Good performance - Level of Ascaris eggs on soil is between 50-400 eggs per m^2.
Very good performance - Level of Ascaris eggs on soil is between <50 eggs per m^2.

Amount of added Ascaris eggs to soil from treated sludge

The hygienization steps which included lime and ammonia treatment in option 1 and 2 were dimensioned to meet requirements of pathogenic organisms as listed in Table 5. First an estimation of the concentration of Ascaris eggs in the sludge was made, and then estimations based on nitrogen content in the sludge and recommended nitrogen dosis on soil were used in order to approximate the amount of sludge which should be added per m^2. This generated an estimation for needed log removals of Ascaris eggs which was used to design the different hygienization steps.

In order to calculate the concentration of Ascaris eggs in the dried sludge, $C_{Ascaris,sl}$, the estimated concentration of Ascaris eggs in influent, $C_{Ascaris,ww}$, as calculated in Eq. 1, the total removal efficiencies from the sludge yielding components in each system in Table 7, as well as yielded sludge from the different options, see Appendix B, was used.

$$C_{Ascaris,sl} = \frac{C_{Ascaris,ww} * (1 - 10^{r}) * Q_{in,d}}{y_{sludge}} \tag{2}$$

Here r was the total removal efficiency of Ascaris eggs of the sludge yielding components for each system [log], y_{sludge} was the sludge yielded in each system [kg/d] and $Q_{in,d}$ was the daily volume of treated wastewater [m^3/d].

For the lime treatment in option 1 an assumption was made 100% removal was achieved, this was based on literature review of Eriksen, Andreasen, and Ilsoe (1995).

For the ammonia treatment in option 2 an online app modelling Ascaris inactivation created as part of research by Fidjeland et al. (2015) was used. From the iterations of different concentrations of added urea and log reductions it was concluded that a 4 log reduction of viable Ascaris eggs would be needed, out of which 1 log reduction could be accredited to the drying beds of sludge (WHO 2006a). Recommended dosis of the commercial fertilizer D.A.P. in the Potosí region for cultivation of onion according to FAO (1999), $d_{NH3,DAP}$, was 100 bags per 1 ha, resulting in a dosis of 18 kg of ammoniacal nitrogen per ha. Total solids in sludge after drying beds was assumed to 0,3 kg per L. On the basis of estimated nutrient values in the sludge generated in option 1 and 2 (see Appendix A), final concentration of ammoniacal nitrogen after ammonia treatment (see Results 4.1.4) and the amount of added treated sludge m_{sl} as well as resulting amount of added Ascaris eggs per square meter, E_{soil} was calculated, see Eq. 3, 4, 5 and 6 below.

$$C_{NH3,sl} = \frac{m_{NH3,sl} * TS}{M_{NH3}} \tag{3}$$

Here $m_{NH3,sl}$ is the estimated concentration of ammoniacal nitrogen in the sludge before treatment [g/kg sludge], $C_{NH3,sl}$ is the same concentration converted to [mol/L], TS is the approximated total solids of the sludge [kg/L] and M_{NH3} is the molar mass of nitrogen.

$$C_{NH3,tsl} = 2 * C_{urea} + C_{NH3,sl} \tag{4}$$

Here $C_{NH3,tsl}$ is the molar concentration of ammoniacal nitrogen after ammonia treatment [mol/L], C_{urea} is the added concentration of urea [mol/L].

$$m_{tsl} = \frac{d_{NH3,DAP}}{C_{NH3,tsl}} * TS \tag{5}$$

Here m_{tsl} is the amount of added treated sludge [kg/m^2] and $d_{NH3,DAP}$ is recommended dosis of added ammoniacal nitrogen [mol/m^2].

$$E_{soil} = m_{tsl} * C_{Ascaris,sl} * 10^{-5} \tag{6}$$

The resulting calculated or estimated amounts of added viable Ascaris eggs to soil from treated sludge can be seen in Results 4.1.1 and were transcribed to the MCA performance scores described in the section above.

3.3.2 Space efficiency

In order to evaluate the space efficiency of each system, each option was drawn out on a map of the plant. Satellite images of the plant were taken from Google Maps and paired with drawings of the plant in order to determine the property lines, see Figure 12 below. After that the added steps of treatment for each systems were drawn on top of the resulting image from Figure 12 according to the scale provided by Google. The size of the different steps of treatment such as anaerobic reactors and sludge drying beds were also compared to the existing ponds from the satellite image in order to confirm correct scaling. The size of the improved pre-treatment was unknown, and thus estimated from the visit at the plant during the field studies. All other surface dimensions were taken from the dimensions that were provided by Agua Tuya which can be seen in Appendix B.

Figure 12: Satellite images of the plant from Google Maps and scanned drawings of the plant. In yellow are the property lines. Edited by Johanna Burström.

Each drawn out system option was then rated according to the MCA performance scale accordingly:

Very poor performance - Space requirements not fulfilled.

Poor performance - Space requirements <100 m^2 greater than available space.
Neither good nor bad performance - Space requirements fulfilled but no space for future buildout of the system.
Good performance - Space requirements fulfilled and space left for partial buildout of the system.
Very good performance - Space requirements fulfilled and space left over for full buildout of the system.

The future buildout adressed in the scoring was considered as addition of extra components with the same technology, thus making future buildouts look different for each system. In case of option 0 for example a future buildout would include addition of facultative or maturation ponds whereas for option 1 and 2 it would include additional reactors, settlers or constructed wetland.

3.3.3 Impact of flood events

The impact of flood events for the system options was evaluated using a semi-quantitative risk analysis based on the Quick Scan methodology described in Zevenbergen et al. (2018) which combines the relative importance, as well as exposure and sensitivity of critical infrastructure in order to evaluate the severity of floodings and identifying options for alleviation. The methodology is based on five steps of evaluation, out of which the steps 1-3 were included in the methodology for the MCA, as can be seen in the list below. Each component in the system was graded according to the steps, and then each treatment option was evaluated based on share of potential high risk component in case of flood. The framework was based on three core elements; criticality, c, vulnerability, v, and severity,s. The relationship between these elements when calculating risk of disaster can be seen in Eq. 7 below.

$$s = \frac{v}{c} \tag{7}$$

Criticality of a component related to the severity of the effect in terms of monetary exchange, consequence of component failure in terms of system function and damages to surrounding communities and possible rate of recovery from failure. Vulnerability stood for the exposure and sensitivity to disrutiption, as well as the condition of the component (i.e. susceptibility to flooding, design features or state of repair). Severity symbolized the extent of impact on the components and the entire system in case of a flooding.

1. **Criticality.** This step identifies and analyses critical infrastructure, taking into account the relationship between different networks. The components of the system options were assessed individually and the effects of failure of each component to the full system was evaluated as well as potential consequences to the surrounding communities and cost of replacement or repair. For example if a component would be expensive in terms of invested capital or a long lifespan, or would present a vital function for the rest of the system the component would have a high criticality. Having

a high criticality would be bad in case of failure since that would affect the system more than if the criticality would be low. Each component was ranked on a scale from 1-5 where 5 meant that the component had a low criticality and 1 meant that the component had a high criticality.

2. **Vulnerability.** This step analyses the vulnerability by looking at the exposure and sensitivity of the components, which were both evaluated separately on a scale from 1-5 where 1 would mean that a component had a low exposure or sensitivity to flooding and 5 would mean that the component had a high exposure or sensitivity to flooding.

    - The **exposure** was evaluated by looking at the proximity of each component to the river and source of flood, in this case a flood direction map was created based on local observations from the technical manager, see Figure 13. If a component would be located close to the source of flooding it would rate high. In this case exposure was rated quite high for almost all components since the plant is located so close to the river bed. No data from previous floodings was available for which return periods of floods or probability of certain flood depths was not evaluated.
    - The **sensitivity** was evaluated by assessing the physical aspects of the components. A component would have a low sensitivity and therefore a low rating if when being flooded no permanent damage would be caused, structural integrity could be maintained and normal operation could be resumed rapidly after any operational disruptions. Elements that were evaluated included strength in material, prevalence of electromechanical components and design of the component. Components with an open water surface were considered to have lower structural intergrity and therefore a higher sensitivity rating than for example a closed tank.

3. **Severity.** This step shows the severity of a potential flooding of the system opotions by combining the criticality, exposure and sensitivity scores from step 1 and 2. Here each component received an individual severity score by multiplying the exposure and sensitivity and dividing it by the criticality, as suggested by Eq. 7, resulting in scores ranging from 1-25. A high score of 20-25 would mean that the component had a high impact on the system if flooded, and a low score of 1-4 would mean that if the component was flooded it would barely affect the rest of the system.

Figure 13: Flood direction map. The blue arrows show the direction of the flow that was observed during the last flooding in 2019, and the yellow lines symbolize the property lines. Drawn by Johanna Burström.

Each treatment technology was rated according to steps 1-3 in the list above. The severity scores of each component were divided into five categories which reflected the risk each component posed to the system in case of a flooding. The scores of each treatment technology and treatment system option can be seen in Results 4.1.3.

Very high risk - Rating 20-25.
High risk - Rating 15-19.
Neither high nor low risk - Rating 10-14.
Low risk - Rating 5-9.
Very low risk - Rating 1-4.

When transcribing the performance of each system to MCA, the total share of high or very high risk components as well as the number of very high risk components were evaluated. Round off of the evaluation would represent the worst of the two ratings. The systems were scored as follows:

Very poor performance - The system has an 80% or more share of high risk or very high risk components OR at least two very high risk components.
Poor performance - The system has between 60-79% share of high risk or very high risk components OR at least one very high risk component.
Neither good nor bad performance - The system has between 40-59% share of high risk or very high risk components OR at least one high risk component.
Good performance - The system has between 20-39% share of high risk or very high risk components.
Very good performance - The system has between 0-19% share of high risk or very high risk components.

3.3.4 Natural resource management

Natural resource management was investigated by looking at the potential use of sludge generated in different options. The volume of treated wastewater was also investigated in order to highlight its potential use, but not included in the MCA since it was approximated in the same way for all options.

Potential for reuse of sludge
For the sludge, sludge yields for the different options and calculating how big of an area the sludge would be able to fertilize per year for growth of onion. The FAO (1999) stated that fertilizer use for growth of onions in the Potosí region amounted to 100 kg per ha. The type of fertilizer was however not specified in the report and therefore assumed to be D.A.P., a common commercial fertilizer consisting of 18% ammoniacal nitrogen and 46% phosphorous. The cultivation of onions is especially interesting since it is a commonly grown crop downstream the WWTP in Tupiza. Nutrient values of sludge generated from a UASB reactor in Cochabamba were used as an approximation for phosphorous and nitrogen values in generated sludge in options 1 and 2. Since both of the options had similar processes using anaerobic sludge bankets, an approximation was made that they should have similar nutritional values in the sludge. These values were then re-calculated depending on hygienization method for the sludge, see Appendix A and C. The sludge generated from each system option was transcribed according to the level of applied ammoniacal nitrogen from D.A.P. for cultivation of onions.

The systems were scored based on the annual size of land area which could be fertilized with the sludge. The MCA Performance score was set as follows:

Very poor performance - Generated sludge could fertilize 0 ha.
Poor performance - Generated sludge could fertilize 0,1-0,5 ha.
Neither good nor bad performance - Generated sludge could fertilize 0,51-1 ha.
Good performance - Generated sludge could fertilize 1,1-3 ha.

Very good performance - Generated sludge could fertilize > 3 ha.

Potential for reuse of treated wastewater
The treated wastewater generated from the plant was approximated to be of similar volumes for all options. An annual volume, V_i was calculated by approximating that inflow was equal to water, $Q_{in} = Q_{out}$. This was then compared to according to how big of an area the water would be able to irrigate per year. A mean value w, of cubic meters of water used for irrigation per ha of farmland in Bolivia was calculated using data from Food and Agriculture Organization of the United Nations (FAO) (2015) according to Eq. 8. The mean value was then used for calculating the potential area in ha of farmland which could be irrigated with the treated wastewater from each system option per year, A_{pot}, see Eq. 9.

$$w = \frac{V_{i,tot}}{A_{i,tot}} \tag{8}$$

$$A_{pot} = \frac{V_{ww}}{w} \tag{9}$$

here V_i refers to total volume of water used for irrigation each year in Bolivia [m^3/year], $A_{i,tot}$ to total irrigated area in Bolivia [ha/year] and V_{ww} to volume of treated wastewater generated per year [m^3/year].

3.3.5 Quality of effluent

The quality of effluent was investigated by examining dimensions spreadsheets provided by Agua Tuya. All systems were designed based on regulations for quality of discharge into receiving bodies of water, in Bolivia the threshold level of BOD5 is 80 mg per liter according to the Reglamento en Materia de Contaminación Hídrica - RMCH 1333. The measured influent concentration of BOD5 was 174 mg/L. The system options were graded according to the MCA performance score as follows:

Very poor performance - Effluent BOD5 value exceeds 120 mg/L.
Poor performance - Effluent BOD5 value is between 90-120 mg/L.
Neither good nor bad performance - Effluent BOD5 value is between 70-90 mg/L.
Good performance - Effluent BOD5 value is between 40-70 mg/L.
Very good performance - Effluent BOD5 value is below 40 mg/L.

3.3.6 Capital and O&M costs

For the financial and institutional criteria, capital and O&M (organization and management) costs were chosen as indicator. For each option AguaTuya provided estimations of capital costs, which were compared to capital costs from two system options in the CWIS tool, a costing tool for sanitation systems developed by the World Bank. The CWIS system options that were used both originated from Bolivia and was a UASB and constructed wetland system dimensioned for 10 000 users, and a pond system with facultative and maturation ponds dimensioned for 67 000 users. In both cases the costs were scaled to 28 800 users in order to correspond to the size of the Tupiza plant. When calculating the annual capital cost the annuity method was applied with an interest rate of 5%, since that was the specified discount rate in the CWIS Tool, this was supported by literature review from Simpson (2008). When calculating the annual cost for investment for each component, the Eq. 10 and 11 were used. For each component an annuity factor, A, was calculated based on the loan interest rate, R, and the lifespan of the component in years, n. The annual capital cost, $C_{capital}$ was then calculated by multiplying the investment cost for the component, C_{invest}, with the annuity factor. The annual capital costs for each component were then summed up for each system.

$$A = \frac{R}{1 - (1+R)^{-n}} \tag{10}$$

$$C_{capital} = C_{invest} * A \tag{11}$$

The O&M costs were estimated from the same CWIS system options. The costs of lime and urea in Bolivia were taken from literature review, see Appendix D, and the potential profit from selling the sludge to farmers was approximated according to estimations made by local farmers.

The costs for each system were presented as BOB/capita and year. To transform capital costs into an annual cost, these were divided with the lifespan of each component. Total investment costs for each option was also calculated. An exchange rate of 6,9 BOB per USD was applied (XE 2020). For a summary of the costs for each system, see Results 4.1.6.

The total annual costs for each system were then compared to the minimum salary for Bolivia. According to Geber (2020) an affordable cost of water and sanitation in Bolivia would be 3% of the annual income of a household. 60% of that was estimated to go to sanitation systems, that is 1,8% of the annual income. Literature review of CWIS Costing Tool showed that one third of the total cost for an urban centralized sanitation system could be derived from treatment and two thirds could be derived from the sewage network and connection, so from the 1,8% a total of 0,6% would be specifically for sewage treatment. The minimum salary in Bolivia as of 2019 is 2122 BOB per month, or 3692 USD per year. For threshold cost it was assumed that one minimum salary provided for a household with 4 members, meaning that each household would have one working member. This made the per capita threshold cost one fourth of 0,6% of a minimum salary, which is 0,15%, that is 5,483 USD per capita and year. Thus, the systems were scored according to the MCA performance score as follows:

Very poor performance - Capital and O&M costs exceed 11 USD per year and capita.

Poor performance - Capital and O&M costs are between 6,5-10,9 USD per year and capita.

Neither good nor bad performance - Capital and O&M costs are between 5,0-6,4 USD per

capita and year.
Good performance - Capital and O&M costs are between 3,5-4,9 USD per year and capita.
Very good performance - Capital and O&M costs are between 0-3,4 USD per year and capita.

3.4 Acceptance and demand for re-use of sub-products in agriculture

As previously mentioned the socio-cultural category which focused on the social acceptance and demand for re-use of treated wastewater and sludge among farmers was evaluated separately from the MCA. The reason for this was that the end products from the different system options were quite similar, meaning that the acceptance and demand for these products would look very similar. In order to better depict the different nuances of the socio-cultural category it was therefore decided that it should be evaluated using qualitative research analysis.

The initial plan to evaluate this category was to make a small interview study of about 10 farmers living downstream the WWTP, however external factors made an interview study impossible to complete. Instead the social acceptance and demand was evaluated through a questionnaire filled out either online or via phone calls or face-to-face interviews carried out by leaders from communities surrounding and downstream of the WWTP, coordinated by local Bolivia WATCH coordinator Cecilia Tapia. Because of restrictions in mobility in regards to the Covid-19 outbreak in Bolivia, and limited access to phones and internet among farmers the questionnaires had to be sent via email and printed out for community leaders to interview in their own villages. Photos of answered questionnaires where then sent back and summarized in Excel. In total 29 farmers participated from the villages Entre Ríos, Deseada, Quebrada, Angostura and Bolivar. The questionnaire can be seen translated from Spanish to English in Appendix E.

The questionnaire had three parts. One part focused on background information of the farmers like gender, size of the farms and common crops. The second and third part focused on the social acceptance and demand of re-use of wastewater as irrigation for crops and treated sewage sludge as soil fertilizer. These two parts only had yes/no questions but also gave the opportunity for the farmers to explain why they thought a certain way. Some farmers chose to give more elaborate answers, from which key words or 'codes' were identified and grouped into broader categories which touched upon different subjects and reasonings. The statements can be seen translated in Appendix F.2. From the gathered set of categories four themes were identified from which a theory about the underlying factors of the social acceptance and demand of re-use of treated wastewater and sludge from the WWTP emerged.

Apart from the questionnaire statements from seven farmers from Entre Ríos and Angostura regarding the current water situation in the area were gathered via phone calls by local coordinator Cecilia Tapia. Some of these were chosen and translated an can be seen in F.3. The statements were not part of the survey nor the coding but rather used as a way of depicting the general water situation in the area as well as representing farmers points of view of the river.

4 Results and discussion

In this section the results from the multi-criteria assessment and the qualitative research study on the social acceptance and demand for re-use of byproducts are presented and discussed.

4.1 Performance assessment of sustainability criteria

4.1.1 Risk of disease transmission

Removal of E.coli from wastewater
The resulting E.coli concentrations for each treatment system were summarized and scored according to the MCA Performance score in Table 8.

Table 8: Results of calculated concentrations of E.coli in efluent water and MCA performance score of different options.

Treatment system	Log removals of E.coli [$\log_{10}$]	MCA performance score
Option 0	3	Poor
Option 1	$4,5$	Good
Option 2	$4,75$	Good

Both option 1 and 2 reached the required log removal for E.coli. Option 2 has 0,25 log removals of marginal which might be good in considering future population growth. Option 0 however did not reach the required log removal of E.coli, thus not meeting Bolivian requirements for allowed concentrations of E.coli in effluent wastewaters. Using option 0 might therefore pose a risk for communities downstream of the WWTP which use the water both for irrigation and sometimes for drinking water.

Since the log removals are estimated based on literature review it is possible that an actual implementation of any of the systems would result in different log removals. Factors such as HRT and dimensions might affect the log removals. The results can still function as an indication, for example the probability of option 1 and 2 meeting Bolivian regulations is greater than for option 0.

Waste stabilization ponds are a common treatment method in developing countries, so it is interesting that it doesn't meet the requirements in this case. The estimated log removals are taken from literature, however tests on the effluent in Tupiza from 2013 (Appendix A) confirm that the removal of E.coli in the conventional system is not sufficient. However at that time the facultative ponds were already compromised due to lack of maintenance and sludge removal and the maturation ponds in the existing system were too deep which might have affected the hygienization effect. The measured effluent value indicated only 0,06 log removal. The removal might be improved if the maturation ponds would increase in numbers or size, which would increase the HRT and the hygienization effect.

The removal of E.coli was also calculated by Agua Tuya, however the calculations contained errors which were corrected by the author but not confirmed by Agua Tuya, and therefore not included in the results. Those calculations ended up being more conservative, with removal efficiencies ranging from 1-2 log for all system options. It would be interesting to know the reasoning behind these calculations as values from literature review suggest more generous removal efficiencies, however due to the ongoing Covid-19 pandemic in Bolivia communication was difficult.

Future population growth might mean elevated levels of E.coli and a need for more efficient removal in order to comply to Bolivian regulations. In this case an added chlorination step after the maturation ponds was discussed with Agua Tuya. However since chlorination is known to create toxins when used in BOD rich waters, this should only be done if BOD was at a sufficiently low level. The method would also imply increased O&M costs because of the continuous application of chlorine, Chlorination was not investigated within this project but could be an interesting topic to expand since Tupiza is a rapidly growing city and population size is bound to increase. This would be especially relevant should the water be re-used for irrigation purposes. According to Agua Tuya's calculations population is estimated to be around 38 000 by 2040, compared to the current 30 000 inhabitants.

Amount of added Ascaris eggs to soil from effluent water

The estimated concentration of Ascaris eggs in influent wastewater was calculated to 5952381 eggs per m^3. The resulting estimated amounts of added Ascaris eggs on soil from efluent water and transcription according to MCA performance score can be seen in Table 9.

Table 9: Results of estimated amounts of added Ascaris eggs on soil from efluent water and MCA performance score of different options.

Treatment system	**Log removal [$\log_{10}$]**	**Effluent conc. of Ascaris eggs [eggs/m^3]**	**Amount of added Ascaris eggs to soil [eggs/m^2]**	**MCA performance score**
Option 0	2,8	9435	6100	Very poor
Option 1	4,55	168	108	Good
Option 2	4,25	335	216	Good

Option 1 and 2 perform well here, reaching the threshold level of 500 eggs per m^2. Option 1 has some margin to the threshold level; the option would continue to meet requirements if the prevalence of Ascaris eggs were to be the double. This is not the case for option 2 which could entail a greater risk of infection. Considering that the prevalence of Ascaris eggs is only estimated, such a risk might be possible. Option 0 does not meet the requirements at all. According to Jimenez (2007) waste stabilization ponds are supposed to be efficient in removing Helminth eggs, but only if HRT is around or greater than 20 days. In option 0 the total HRT is 8,5 days.

The reduction of Ascaris eggs in the effluent might be further reduced using a chemical primary treatement called coagulation-flocculation, which is especially recommended for water reused in agriculture (Jimenez 2007). However this is an expensive treatment method and probably not apt for the local context of Tupiza.

It is also worth mentioning that the pathways of infection have not been evaluated in this study. It is possible that farmers using the wastewater would have a greater risk of infection than consumers of the produce, considering that they both eat and might come in contact with the water. Since surface irrigation is common in Tupiza this should be evaluated. It is possible that farmers using the wastewater as irrigation should wear protective clothing or otherwise need training in order to reduce risks of infection.

Amount of added Ascaris eggs to soil from treated sludge

The resulting estimated amounts of added Ascaris eggs on soil from treated sludge and transcription according to MCA performance score can be seen in Table 10. For option 0 which didn't have any frequent sludge removal, but rather removal of bottom sludge from the facultative ponds every 10 years, an assumption was made that amounts of added Ascaris eggs to soil from treated sludge would be over 1000 eggs per m^2. This was based on literature review of inactivation rates in waste stabilization ponds according to Nelson and Darby (2002).

Table 10: Results of estimated amounts of added Ascaris eggs on soil from treated sludge and MCA performance score of different options.

Treatment system	**Amount of added Ascaris eggs to soil from treated sludge [eggs/m2]**	**MCA performance score**
Option 0	$\gg 1000$	Very poor
Option 1	0	Very good
Option 2	72	Very good

Option 1 and 2 perform well in this indicator, this could be expected since they have treatment steps designed specifically to meet the threshold level set in this paper. Both options have plenty of margin should the Ascaris levels be higher than estimated in this paper. Option 0 does not have such a treatment step and consequently implies a much greater risk of infection.

The sludge in option 0 is transported to something named "sanitary disposal" which in this case translates to an unlined and unprotected landfill, thus increasing the chances for human infection. To help mitigate the risk the landfill should at least be protected with fences to prevent direct contact with the sludge. Sludge from the facultative ponds in option

0 is meant to be removed every 10 years resulting in large quantities as well as a high water content. Treatment of the sludge from this option was suggested to both Agua Tuya and to EMPSAAT however such a process seems to be difficult considering the mentioned characteristics and the local context. Such a treatment is possible with for example sludge thickening ponds for dewatering and then drying beds or co-composting of the sludge (Strauss, Larmie, and Heinss 1997). However this would imply increased investment costs as well as use of terrain which is not currently available in Tupiza. Possibly a joint treatment for sludges generated from several towns might be considered, however this would also entail increased strain on institutional capacity and and a type of cooperation between regions which does not exist today. Since option 1 and 2 allow for frequent removal and treatment of sludge, the reuslting volumes are much smaller and treatment can be carried out within the premises of the WWTP.

An important factor for the hygienization efficiency in option 2 is the temperature, since the process of urea treatment is very temperature dependent. Treatment time in this case was calculated using the mean annual temperature of 15,3 °C but treatment time could vary considerably because of Tupiza's temperature range of 9-18 °C. To ensure sufficient hygienization frequent testing is therefore recommended.

4.1.2 Space efficiency

The layout of option 0 according to the dimensions provided by Agua Tuya can be seen in Figure 14, dimensions from AguaTuya can be seen in Appendix B. A future buildout of this system would include addition of facultative or maturation ponds. As can be seen in Figure 15, the area of the property would not allow for such a buildout. According to the MCA performance score this system was scored Neither good nor bad, see Table 11.

The layout of option 1 can be seen in Figure 16. Here a buildout to increase treatment capacity would include additional RAC reactors, settler, sludge drying beds and increased area for hygienization. As can be seen in Figure **??** the area of the property would allow for such a buildout, increasing amount of settlers, reactors, drying beds and hygienizations area by 50%. Therefore, this option scored Very good in the MCA Performance score.

The layout in option 2 can be seen in Figure 18. Here a buildout to increase treatment capacity would include additional UASB reactors, sludge drying beds and hygienization area. The constructed wetland is subsurface horizontal flow only, and could be changed partially to vertical flow in order to increase treatment capacity. From the Figure **??** it is obvious that a full buildout including a 50% increase in the components mentioned above as well as a convertion of t4he constructed wetlands could be possible within the designated area. Therefore this option scored Very good in the MCA performance score.

Figure 14: Layout of option 0. The grey box is the added step of improved pre-treatment. The blue arrows symbolize the route of the wastewater and can be seen more clearly in the enlarged picture to the right.

Figure 15: Layout of a potential buildout for option 0. The brown transparent boxes symbolize the buildout in the form of two added maturation ponds and one added faculattive pond.

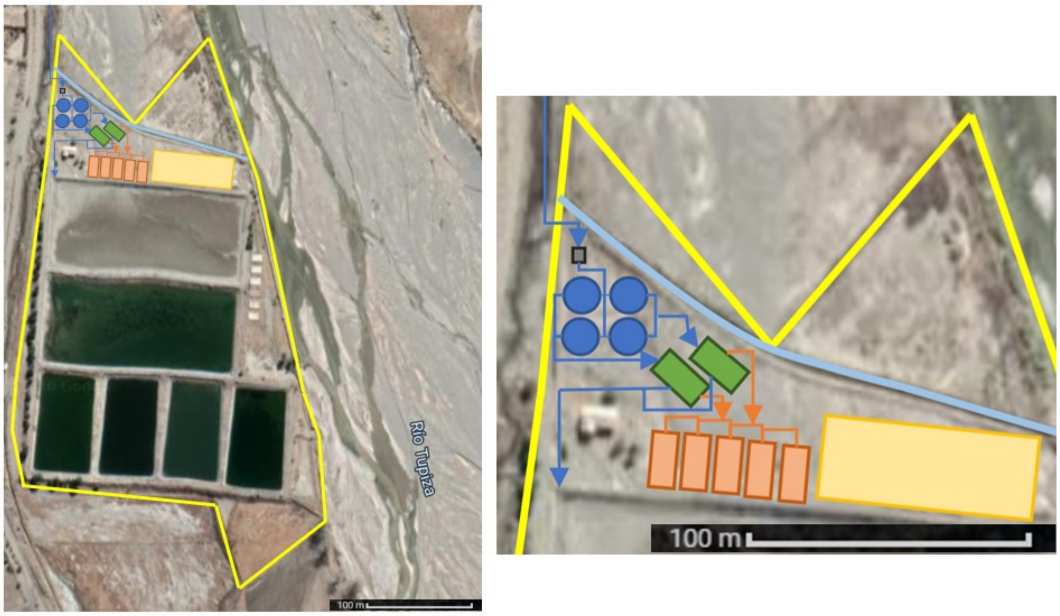


Figure 16: Layout of option 1. The grey box is the improved pre-treatment, the blue circles are the settlers, the green boxes are the RAC reactors and the orange boxes are the sludge drying beds. The yellow box is the designated area for hygienization. The blue and orange arrows show the routes of the wastewater and sludge.

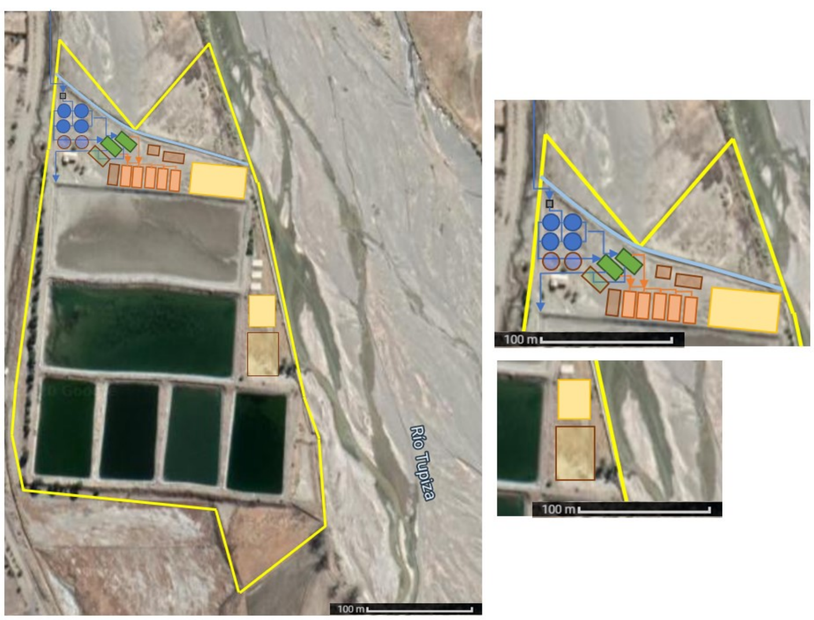


Figure 17: Layout of a potential buildout for option 1. The slightly transparent shapes are added settlers (blue circles), RAC (green box), sludge drying beds (orange boxes) and designated area for hygienization (yellow boxes).

Figure 18: Layout of option 2. The blue circles are the UASBs, the lime green boxes are the constructed wetland and the orange boxes symbolize the sludge drying beds. The yellow box is the designated area for hygienization. The blue and orange arrows show the routes of the wastewater and sludge.

Figure 19: Layout of a potential future buildout for option 2. The slighly transparent shapes are added UASBs (grey circles), sludge drying beds (orange boxes) and designated hygienization area (yellow box). The slightly darker green boxes in the constructed wetland symbolize converted vertical flow wetlands.

The performance scores for space efficiency of each system option can be seen in Tba. 11 below.

Table 11: Performance score of the system options according to space efficiency.

Treatment option	**Option 0**	**Option 1**	**Option 2**
MCA performance score	Neither good nor bad	Very good	Very good

Both option 1 and 2 perform very well here. As can be seen in Figures **??** and **??** there is slightly more space available in option 2 which might be good to consider in case capacity would need to be further extended. Option 0 does not perform well here since waste stabilization ponds are not very space efficient and most of the area that could be used for such treatment is already occupied.

Both option 1 and 2 have added primary treatment steps meaning that it is mostly the area above the facultative ponds or the constructed wetlands which can be used for these components. Sludge however is removed via pipes and treatment steps for this could be moved further down beside the facultative ponds or constructed wetlands. The hygienization area could also be moved outside of the WWTP, provided that proper fencing and lining of the area would be implemented so as to not increse risk of disease transmission. This could be in question if treatment capacity would need to be further incresaed, and land would need to be acquired.

In the risk of disease transmission the added tratment step of chlorination was discussed in order to achieve higher reductions of E.coli. It was mentioned by Agua Tuya that there might be space available for this hygienization step in the lowest part of the treatment area for all options, however it was not investigated in this study. This could be interesting to evaluate, especially if water is to be reused in agriculture.

4.1.3 Impact of flood events

Impact for each option in case of a flood event was evaluated according to the flood risk assessment as described in Section 3.3.3. The evaluation of option 0, seen in Table 12, showed that both the facultative and maturation ponds were very critical to the system as well as being very exposed and having a high sensitivity. Since this option had one component in the risk category High and a total share of 50 % of the system at high or very high risk, it scored as Poor performance in the MCA.

Table 12: Flood impact assessment of Option 0. In this option 50% of the components presented a high or very high risk to the system in case of a flood.

Treatment technology	**Coarse grids**	**Fine grids**	**Fac. ponds**	**Mat. ponds**
Criticality	5	4	1	1
Sensitivity	1	3	5	5
Exposure	5	5	5	4
Severity	1	3,8	25	20
Risk category	Very low	Very low	Very high	High

For option 1 the treatment technologies which presented a high or very high risk to the system were the same; facultative and maturation ponds. However, since option 1 contained far more components than option 0, the total share of treatment technologies with a high risk rating became only 28%, see Table 13. Since the option had one very high risk component but a much smaller total share of high or very high risk components, it score Neither good nor bad performance in the MCA.

Table 13: Flood impact assessment of Option 1. Here RAC is short for compartmentalized anaerobic reactor. In this option 28% of components presented a high or very high risk to the system in case of a flood.

Treatment technology	**Coarse grids**	**Fine grids**	**Settler**	**RAC**	**Fac. ponds**	**Mat. ponds**	**Drying beds**
Criticality	5	4	3	3	1	1	5
Sensitivity	1	3	2	2	5	5	3
Exposure	5	5	4	5	5	4	5
Severity	1	3,8	3,3	3,3	25	20	3
Risk category	Very low	Very low	Very low	Very low	Very high	High	Very low

Option 2 had six components but only one of them, the maturation pond, presented a high risk to the system, see Table 14. Consequently, total share of high or very high risk components was only 17%. However because one of the options did score as high risk, the overall MCA performance score resulted in Good performance.

Table 14: Flood impact assessment of Option 2. Here UASB is short for upflow anaerobic sludge blanket reactor and CW is short for contructed wetlands. In this option 17% of components presented a high or very high risk to the system in case of a flood.

Treatment technology	**Coarse grids**	**Fine grids**	**UASB**	**CW**	**Mat. ponds**	**Drying beds**
Criticality	5	4	3	3	1	5
Sensitivity	1	3	3	5	5	3
Exposure	5	5	5	5	4	5
Severity	1,3	5	5	12,5	20	3,0
Risk category	Very low	Low	Low	Neither high nor low	High	Very low

The result from the flood impact assessments were summarized and transcribed to the MCA performance scores in Table 15 below.

Table 15: Performance score of the system options according to share of system at high or very high risk in case of a flood event.

Treatment option	**Option 0**	**Option 1**	**Option 2**
Number of components at high risk	1	1	1
Number of components at very high risk	1	1	0
Share of system at high or very high risk	50 %	28%	17%
MCA performance score	Poor	Neither good nor bad	Good

In this criteria only option 2 performed well. Option 1 had a greater share of high or very high risk components, whereof one component posed a very high risk to the system. Considering the local context and previous damages due to flooding it was assumed that having any very high risk component would be detrimental to the system, which is why this option could be considered as having a higher risk of disaster than option 2. Option 0 performes the worst, since it had 50% share of high or very high risk components whereof one was of very high risk. Since this option has fewer components than options 1 and 2 any damage to certain components would have great consequences on the treatment system.

Since all systems have a certain degree of risk connected to flooding, flood mitigation measures would be necessary in order to protect the plant and neighbouring communities. Measures could include elevation of certain electrical components, building higher and stronger mounds or extending permanent flood barriers. A possible re-location of the plant was also discussed with several stakeholders, however it does not seem like a viable option at the moment because of issues with land availability.

Considering the location and the flood risk map in Figure 2 it would be useful to model and map flood risk of different return periods in order to investigate potential flood mitigation measures. According to a case study of WWTPs in China, 35% of WWTPs could experience a significantly higher flood risk by 2035 (Hallegatte, Rentschler, and Rozenberg 2019). Considering that climate change is already affecting risks of flooding in Tupiza, chances are that these risks will amplify over the coming years, making this an even more urgent topic.

Scoring this indicator was difficult as the goal was to assess whether a system with more components would be more vulnerable than a system with fewer components. At the same time, having only one very high risk component could be prove devastating in case of a flood given the local circumstances. Considering past flood events and damages to infrastructure the time of recovery for any sort of serious damage has ranged from 1-2 years which could endanger the health of nearby communities.

4.1.4 Natural resource management

Potential for reuse of sludge

Generated sludge and potential fertilized area for each option can be seen in Table 16. The potential land area which could be fertilized annually by the reused sludge was quite small for all options. If an average farm in Tupiza would have a total area of 0,5 ha, none of the options would have been able to provide fertilizer to more than 1 farm per year. Option 0 did not have any sludge production suitable for reuse and therefore scored Very poor. Option 1 produced larger quantities of sludge but since nutrient content in this sludge was lower it ended up fertilizing a smaller area than the sludge in option 2 which was enriched with ammoniacal nitrogen in the form of urea.

Table 16: Generated sludge and potential fertilized land area for each option.

Treatment system	Option 0	Option 1	Option 2
Generated sludge available for reuse [kg/y]	0	1497,7	507,6
Potential fertilized land area [ha/y]	0	0,21	0,85
MCA Performance score	Very poor	Poor	Neither good nor bad

When evaluating this indicator a size of 0,5 ha for an average farm in Tupiza was assumed. This can be supported by answers in the questionnaire which state that farm sizes range between <0,5 ha up to 2 ha (Appendix F.1). The sectors 5 and 6 which are the geographic areas that cover most of the communities downstream of the WWTP in Tupiza include over 1000 farms each according to Berno (2020). In this context the potential reuse of sludge seems quite small but it could introduce other advantages such as demand for frequent testing as well as hygienization of the sludge which would contribute to less risks of disease transmission. It is also important to note that the use of sludge as fertilizer is calculated based on nutritional content of ammoniacal nitrogen. The sludge also carries other beneficial characteristics such as high organic content which enriches the soil and can improve for example water retention and soil texture. Both of the sludges produced this case also have an elevated pH, this would make them an especially good fit for soils Tupiza which are generally acid.

Centralized treatment systems are generally not as effective in recycling of nutrients compared to semi-centralized or decentralized treatment systems (Wilsenach and Loosdrecht 2003). Dilution of nutrients and organic carbon makes recovery from centralized systems less efficient which could explain the comparatively small amounts of fertilizer produced in the treatment options, despite the system having approximately 28 800 users. The previously mentioned thesis projects in Montero and El Alto found that recycling potential from source separating systems could range from 61-84% weight of nitrogen and 54-68% respectively (Geber 2020, Smith 2019). In comparison the study in El Alto estimated a nitrogen recovery of 9% for the conventional system which consisted of bottom sludge from waste stabilization ponds (Smith 2019). It would have been interesting to investigate the percentage of recycled nutrients from the wastewater treatment, but applicable data for the considered treatment technologies was not found in literature. Continued cooperation with Agua Tuya could help in establishing such data, consequently providing data on mass flow of nutrients in the evaluated treatment technologies as well as further evaluation of the potential gain from recycling nutrients in sludge.

Potential for reuse of treated wastewater

For the evaluation of potential wastewater reuse, the mean value of water used per hectar of irrigated land in Bolivia was calculated to 6 460 m^3 per year, or 646 L per square meter. This was not specific to onions, as such data for Bolivia did not exist. Recommended drip irrigation for growth of onions in the US is around 0,8 L per square meter of farmland (Stewart 2014). The amount of water treated in the plant was calculated to 1 103 760 m^3 per year. According to these values, the treated wastewater would be enough to irrigate around 170 ha of farmland annually when using the Bolivian average. This could be enough to support 340 average sized farms in Tupiza.

Nutrients could also be recycled from water, due to the nature of the biological treatment processes applied in the system options, a significant nutrient content could be assumed. This would increase the value of the water and further motivate reuse of this fraction. The potential nutrient values in effluents from different options was not investigated in this study but could be incorporated in further research.

As mentioned before, onions are acommonly grown crop in Tupiza, especially downstream the WWTP. When looking at crop specific data for onions it is entirely possible that the treated wastewater would suffice for more than 170 ha of farmland. It is important to note here that the data from Stewart (2014) is specifically for drip irrigation which is a much more effective type of irrigation than the surface irrigation generally applied in Tupiza. The amount of water is also specified for one growth period of onions, which could be more than one per year in Tupiza. Water use for growth of onions in Tupiza could therefore be greater, but even if the recommended irrigation for onion would be 10 or 30 times as high (for example 24 L per square meter) it would still be less than the Bolivian average of 646 L per square meter applied in the calculations. This would mean that the water produced could potentially benefit far more land area than 170 ha per year.

4.1.5 Quality of effluent

BOD5 concentrations for each system option as calculated Agua Tuya in the provided dimensions spreadsheets can be seen in 17. Summarized concentrations of BOD, COD, suspended solids and E.coli can be found in Appendix B. Each system option was graded according to the MCA Performance score as follows:

Table 17: Calculated concentrations of BOD in effluent for all treatment options.

Treatment system	**Option 0**	**Option 1**	**Option 2**
BOD concentration [mg/L]	124,21	35,94	27,72
Threshold concentration [mg/L]	80		
MCA Performance score	Very poor	Very good	Very good

As can be seen both option 1 and 2 meet the requirement for discharge concentration of

BOD5. According to the calculations from Agua Tuya constructed wetlands have a removal efficiency of 50% for BOD5 and facultative ponds have a removal efficiency of 30%, while the RAC and the UASB reactor are supposed to be more similar with values of 77% and 84% respectively. This results in option 2 being slightly more efficient. The BOD5 concentration in the influent which the calculations were based on was 174 mg/L, making the total removal efficiency of option 1 and 2 amount to 79% and 84% respectively, as compared to only 29% in option 0 which does not meet the requirements at all.

When calculating the effluent BOD5 concentration influent concentration of BOD5 measured in Tupiza in 2013 was used. Agua Tuya also calculated a theoretical BOD5 value based on future population size in 20 years (around 38 000 inahabitants) which resulted in a much bigger value of 680 mg/L. When applying this to the treatment options resulting effluents amounted to 397,97 mg/L, 89,46 mg/L and 57,31 mg/L for option 0, 1 and 2 respectively. In this case only option 2 met the requirements even if option 1 came very close. Since communicaiton with Agua Tuya was very difficult due to circumstances regarding the Covid-19 pandemic in Bolivia this result was not discussed properly with Agua Tuya and therefore not included in the MCA. However it might be interesting for future research to carry out more tests on influent wastewater quality as well as considering future population sizes which might result in a need for higher treatment efficiency.

4.1.6 Costs

Capital and O&M costs as well as potential profit from recycled products for each system can be seen summarized in Figure 20. All costs are based on pre-existing infrastructure at the WWTP. Due to communication difficulties the O&M costs have not been compared to current costs of running the WWTP in Tupiza. An estimation is that these are much lower than the costs approximated in this study since maintenance is kept at a minimum and no quality testing is currently performed. For the full cost analysis of each option see Appendix D.

Option 0 - the conventional system, is the cheapest option. Out of the three systems option 3 is the most expensive, mostly due to higher O&M costs which are related to the electromechanical costs for the UASB reactor. Investment costs for option 1 and 2 are of similar size however the annual capital cost for option 2 is slightly lower due to longer lifespans of the components, see Table 19. Option 1 however has lower O&M costs but ends up performing within the same range as option 2.

Table 18: Total investment cost for each option.

Treatment system	**Option 0**	**Option 1**	**Option 2**
Total investment cost [USD]	241 361	1 230 277	1 234 647

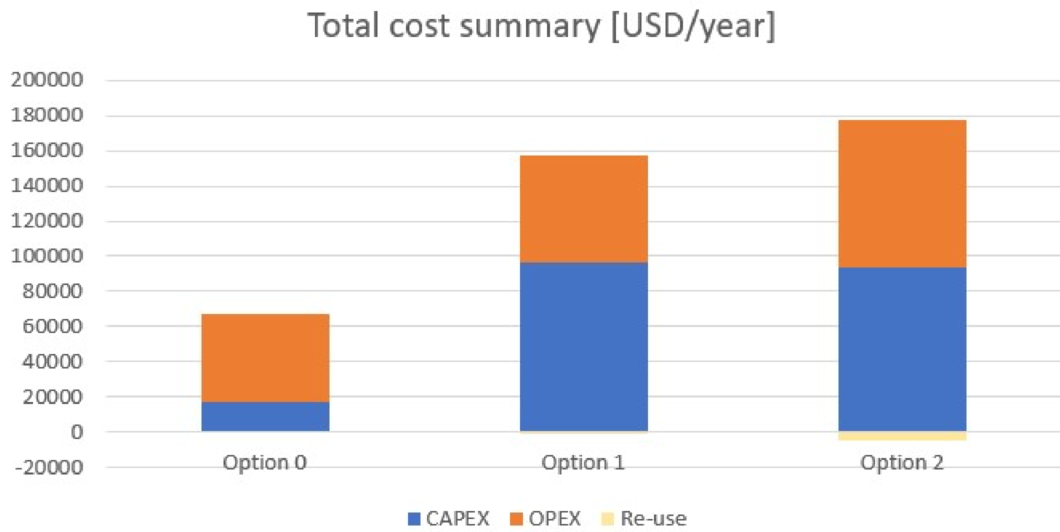


Figure 20: Summary of total annual costs for each system option. Here CAPEX stands for capital costs and OPEX stands for organization and management costs. Re-use is the potential profit from recycled sludge.

The annualized per capita costs were scored according to the MCA Performance score as follows:

Table 19: Cost summary and MCA Performance score of each option.

Treatment system	**Option 0**	**Option 1**	**Option 2**
Capital costs [USD/cap, y]	0,594	3,335	3,235
O&M costs [USD/cap, y]	1,747	2,125	2,915
Total cost [USD/cap, y]	2,341	5,461	6,150
Profit from re-use [USD/cap, y]	0	0,040	0,163
Threshold cost [USD/cap, y]	5,483		
MCA Performance score	Very good	Neither good nor bad	Neither good nor bad

When evaluating the potential profit from reuse it is important to note that the prices for sludge are based on prices for manure which come very cheap in Tupiza. In both option 1 and 2 the sludge contains added benefits of elevated pH levels and it is possible that the economic value would exceed that of the manure, potentially bringing in more profits than calculated here. The extra hygienization of sludge in option 1 and 2 also imply higher O&M costs, however the profit from selling the products would compensate these costs with some margin with the added benefit of decreased risk of infection, see Results 4.1.1 and Appendix D. Adding the profit from re-use to the annual total costs of each system would not change the grading of option 2, for that to happen the value of the sludge would have to increase at least 4 times.

As can be seen in Table 19, not all systems could be considered affordable for a household of 4 people supported by one Bolivian minimum salary. This goes in line with the study in Montero by Geber (2020) where only the richest groups of society could afford most of the non-conventional options.

According to Abeysuriya et al. (2014) all costs of sanitation service provision need to be recovered if services are to be sustained over a long term. In this case two types of revenue were investigated, namely tariffs paid by each household and revenue from sale of by-products. Other types of revenues like government taxes or transfers in the form of contributions by international donors or charitable entities could also form important funding mechanisms in a future buildout or renovation of the plant. The assumed loan interest rate in this case was 5%, and it is possible that a lower interest rate via support from such charitable entities would be possible. For option 2 to reach below the annual threshold cost the loan interest rate would have to be 2,5%.

The estimations are based on the assumption that all households would pay their respective fee for treatment of their wastewater, which might not always be the case in a developing context where communities might be more vulnerable to fluctuations in the national and global economy. Local stakeholders also mentioned that the question of a tariff is a controversial subject in Tupiza, for which social awareness and acceptance of the WWTP would be crucial.

4.1.7 MCA assessment

Table 20: MCA performance matrix.

Category	Criteria	Indicator	MCA performance score		
			Option 0	Option 1	Option 2
Health	Risk of disease transmission	Concentration of E.coli in effluent water			
		Added Ascaris eggs to soil from effluent water			
		Added Ascaris eggs to soil from treated sludge			
Technical	Space efficiency	Area required			
	Impact of flood events	Share of system at risk in case of flood			
Environmental	Natural resource management	Potential land area fertilized with treated sludge			
	Quality of effluent	Level of BOD in effluent			
Financial and institutional	Capital and O&M costs	Annual cost			

Overall both option 1 and 2 perform very well with option 1 only having one performance score rated Poor. This corresponds well with the fact that both of the options have been designed according to local pre-requisites and experiences of the Bolivian context. The two options are also quite similar, as the treatment steps include the same or very similar biological processes.

Option 0 does not perform as well as option 1 and 2, scoring Very poor or Poor in 5 out of 7 indicators. This is despite the option being upgraded into a functioning version of the system which is currently in place. A reason behind this result might be that the system is very basic, which in some developing contexts is a strength as overall costs and the requirement for institutional capacity are very low. However this comes at price of lower performance in other categories such as resource management or risk of disease transmission. When using a system such as option 0, the argument might be that some level of wastewater treatment is better than no treatment at all - meaning that even if the system might perform inadequately in some areas it can still contribute in improving public health or environmental issues. There is also a possibility that a system consisting of only ponds would perform better if having more space available, but this is not the case for Tupiza. Here space requirements as well as overall insitutional capacity shows that an improved system would be both needed as well as feasible, and should therefore also be preferred.

When looking a the capital and O&M costs it is important to note that these have been calculated based on the assumption that existing infrastructure would be used. In case of a complete re-location it is possible that investment costs for option 0 would be somewhat higher due to terrain costs. In case of re-location, new options which have not been evaluated here might provide better space efficiency and thus lower costs for purchase of terrain.

Although the criterias in this MCA have not been weighted some have stood out as especially critical to the Tupiza context. One example of that is the criteria for impact of flood events, a topic which has been brought up by all local stakeholders and decision makers. A parallell could be drawn from here to for example risk of disease transmission, natural resource management or capital and O&M costs since failure of the systems in case of a flood would negatively impact important factors such as pathogen pollution in water, destruction of farming areas, and invested capital or added clean up costs. It is important to note here that flood mitigation measures have not been evaluated, but seem to be quite needed. None of the system options are entirely flood proof and any level of flood impact in the sanitation service chain has already proved to be detrimental to the Tupiza community.

Another important note is that the MCA requires the understanding that trade-offs can be made between different criterias. For example one system which performs poorly within Risk of disease transmission might compensate this by performing better within Space Efficiency or Quality of effluent. The weighting of different criteria according to local conditions and needs would be useful here, but as previously mentioned this was not possible within the frame of this project, Therefore the results should only be seen as general guidance points from which more research will be needed in order to establish the most suitable system.

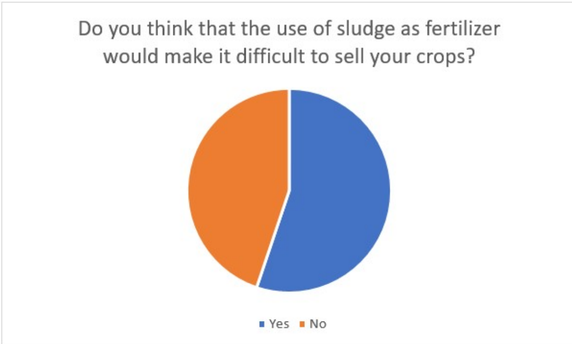
After sharing and discussing the emerging MCA results with local stakeholders and specialists within the area of sanitation and water resources in Latin America, it was concluded that the method of an MCA is indeed succesful in pointing out a variety of areas of interests in order to create a more holistic viewpoint of sustainability within sanitation systems. However the method also requires the understanding that tending to a variety of sustainability criteria will most likely lead to increased economic growth and prosperity for society in the long term. One concern which was raised was that some decision makers might have a tendency to only prioritize the directs costs of the systems. Yet the economic benefits of having systems which perform better according to a larger range of sustainability criteria could benefit the growth and well-being of the community far more in the long run. As mentioned before, sustainable sanitation systems can have several implicit economic effects like improved public health, efficient use and re-use of natural resources, increased crop yields and decreased pollution of water and land. A model for calculating such implicit economic effects, applying a cost-benefit analysis or similar approach, was not created in this case but would be an interesting contrast to the direct costs of the WWTP.

4.2 Social acceptance and demand for reuse of by-products

Opinions from 29 farmers from five communities downstream the WWTP were gathered in the questionnaire about social acceptance and demand for reuse of treated sludge and efluent water. Out of these there were three farmers who had their farmland located upstream from the WWTP and therefore their answers regarding reuse of treated efluent were not accounted for in the summary. Some answers are presented below in Figure 21 and the rest of the answers as well as comments by farmers made in connection to the questions can be seen in Appendix F.1.

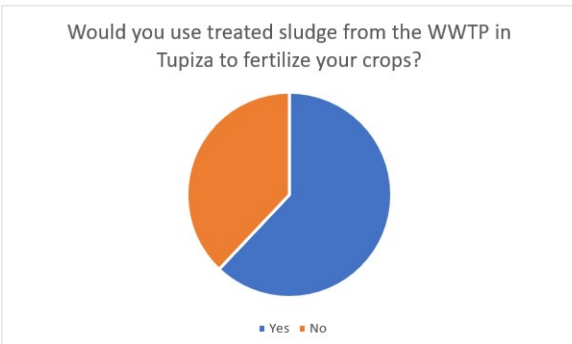
Farmers responding to the questionnaire were aged 21-80 years, with about 50/50 male and female participants. Almost half of the farms owned were less than 0,5 ha big, with some ranging up to 2 ha. People working at the farmers varied between 1-6 and principal crops included corn, onions, potatoes and beans. Other crops grown were flowers, pumpkin, chayote, tomatoes, lettuce and garlic. Majority of the produce was sold in the centre of Tupiza, but some was also sold in the respective villages or to other Bolivian towns. Some farmers didn't sell their produce.

Sources of irrigation water mostly came from the river or channels dug from the river although some farmers also had access to groundwater. Organic compost and manure was mostly used as fertilizer, although a third of the farmers said they used urea. D.A.P. was only used by one farmer. The most popular characteristics when buying fertilizer included organic content, environmental sustainability (environmentally friendly), re-purpose of manure which was produced at the farm and price.



(a) 55% answered Yes and 45% answered No.

(b) 38% answered Yes and 62% answered No.



(c) 62% answered Yes and 38% answered No.

(d) 50% answered Yes and 50% answered No.

Figure 21: Yes/No answers for questions regarding demand and social acceptance of use of efluent water or treated sludge from the WWTP. Answers in Yes are blue and answers in No are orange.

The comments from the farmers were coded and sorted into categories, five main themes were distinguished:

1. Quality of product in terms of for example pathogen levels needs to be continuously measured and communicated.
2. There is interest in using recycled water from the WWTP, if it's treated and especially if there is lack of other water sources.
3. There is interest in using treated sludge as fertilizer, especially if cost is low compared to other fertilizers.
4. Guidance on how to use the sludge and water would help social acceptance of the products among farmers.
5. Social acceptance among buyers and vendors of the crops is essential if sub-products are to be used for agriculture.

From the identified themes it seems that for reuse to be possible there would need to be more knowledge among farmers on how to handle the sludge and wastewater. Producing guidelines might help in ensuring correct handling as well as informing about potential risks and benefits of the byproducts. Certification and continuous testing of the by-products would help to ensure adequate quality and advance the social acceptance among farmers and consumers. Having such a market demand could also hugely benefit the WWTP, as procedures which help guarantee the quality of the products would be necessary for the public acceptance. In addition these sorts of procedures would also strengthen the maintenance and testing practices that are necessary for the long-term function of the plant.

It is evident that acceptance among consumers will steer the potential reuse of both wastewater and sludge. Possibly a public campaign aimed at increasing knowledge and awareness of the benefits of circularity and quality the produce would help.

4.3 General uncertainties

The lack of local data of wastewater quality could be a source of error for the results. Tests from 2013 on the influent and effluent wastewaters in Tupiza was used as a basis for calculations for the treatment systems, however it is possible that greater accuracy could have been achieved had several tests from differents occasions been available. In some instances there have been theoretical values which have been used to discuss and add nuances to the results, however the final performance scores are all based on the afforementioned tests. Similarly there was little to no data regarding past flood events, and any information retrieved relied entirely on word of mouth from local stakeholders. The general flood risk map provided by SEI Latin America helped underpin some of this information but it is still possible that the evaluation of exposure and sensitivity to flood could have been graded differently.

A general lack of data concerning treatment efficiencies and different removals in the system led to several assumptions based on literature review. The cooperation with Agua Tuya has helped in confirming some of these assupmtions, but because of the ongoing Covid-19 pandemic in Bolivia the communication with the organization became difficult especially in the end of the project when most of these discussion were held. Some data input in the errors were found in the dimensioning of the systems. These were corrected by the author but not confirmed by Agua Tuya, for which it is important to note that any real implementation made for the Tupiza WWTP should be based on fully confirmed dimensions.

Another factor which might have contributed in scewing the results is the scoring of the different indicators in the MCA. In most cases the scores were based on some sort of regulations or threshold levels found in literature or based on the local context in Tupiza. The threshold levels or ranges incorporating these were generally assigned the MCA Performance score Good, however the scales of some indicators might be more narrow than for others which could result in less or more variation among options in the final MCA matrix. A way to achieve apropriate ranges or scales for the different indicators, would be to engage or recieving feedback from topic experts covering the different sustainability dimensions.

For any future use of the MCA which was produced in this study it is important to note that no sensitivity analysis was performed, thus the robustness of the assessment can not be confirmed.

For the social acceptance study there could also be several sources of misinformation or error. The study was coordinated by the local Bolivia WATCH coordinator in Tupiza, who at the time was located in La Paz. Most communication with leaders from the villages was held via phone and since some farmers lacked phones the study relied on these leaders carrying out the questionnaire in their respective villages. Some questionnaires and statements were gathered via phone calls by the local coordinator. No recordings were made, for which it is possible that some information was missed when transcribing the answers to a digital format. Statements and comments made by farmers were translated by the author for which it is possible that some interpretational errors might exist.

5 Recommendations

5.1 Recommendations for further research within the Tupiza context

Considering the result of the MCA which points to the fact that more improved systems tend to perform better against a larger range of sustainability criteria, it would be interesting to investigate the long-term economic effects of having such improved systems in comparison to the most basic systems, this could be done through for example a cost-benefit analysis. Such indirect economic outcomes might be difficult to evaluate considering that issues such as public health, environmental pollution or more efficient use of natural resources rely on a multitude of factors which are not solely dependent on sanitation systems. However measuring the impact of sustainable sanitation systems would provide an essential argument for the importance of investment in improved sanitation systems in Bolivia.

Regarding the quality of effluent it is important to note that only BOD and E.coli were evaluated in this study. Parameters such as nitrogen or phosphorous content would be very valuable to investigate. Nutrient content is generally not as prioritized as pathogenic or biological content in wastewater effluents, however it is an important factor in mitigating environmental impact in the form of eutrophication. The nutrient levels would also be interesting from a reuse perspective, as this would further motivate why the water should be used for irrigation rather than released in the Tupiza river. Potential benefits from this could also include a reliable source of irrigation for 340 families or more, making this an area of research which is highly motivated in the Tupiza case. Nutrient values in sludge and effluent water are also of importance both from an economic and circular perspective in terms of potential cost recovery for the WWTP, increased agricultural production and less consumption of mineral fertilizers. It would be interesting to investigate nutrient removal efficiencies in the different treatment technologies and further establish the economic value for treated sludge. An amplified reuse of byproducts from the plant would also imply requirements of higher institutional capacity as well as increased organization and management procedures. The question of local competence and expertise in hygienization and testing would also need to be evaluated, since any implemented reuse would have to be safe in order to benefit the community. From the questionnaire it seems like the demand for recycled products would also largely depend on social acceptance from buyers of the produce. Here it would be interesting to evaluate a possible certification process or a public campaign on re-use of treated sludge and watewater. Such a campaign might also be beneficial for the entires anitation service chain as it could help raise public awareness and show the overall utility of the WWTP. Notwithstanding, safe reuse of either treated wastewater or sludge would be beneficial to the local communities, and the model for Tupiza could help advocate questions of reuse from centralized WWTPs throughout Bolivia.

Another issue which is especially alarming for the Tupiza case are the problems of flooding. Within this particular study the probability of different flood events has not been evaluated, and within the Bolivia WATCH program much of the flood specific work thus far has consisted of general risk maps such as the one displayed in Fig. 2. As problems of floodings are evident in the area measures of mitigation need to be taken in order to protect important infrastructure as well as the general public. For the WWTP it would be interesting to evaluate flood scenarios of different magnitudes and establish the probability of the plant being flooded as well as options of flood mitigation or a possible re-location. Considering that lifespans of different components range from 10-30 years, any serious flood event with a return period of less than that would pose a significant risk to investment made in the plant. Moreover, protecting the plant from flooding would also safeguard farmers, as statements from the questionnaire show that significant damage in the form of pollution of water and devastation of farmland has already been imposed on the agricultural communities.

From discussion with local stakeholders it is also evident that there is a lack of institutional capacity for the sanitation system in Tupiza. Some stakeholders expressed a desire for 'adequate technology' (see Table 3) which in light of the malfunctioning system that is currently in place is a convincing demand. However social and institutional dimensions such as more frequent and extensive maintenance and supervision, tariffs especially for wastewater treatment, competence and budget for testing and quality assurance as well as discussion about common goals among decision makers for the sanitation service chain, would all be important puzzle pieces to a functioning treatment plant and should be investigated more.

5.2 Short-term recommendations for local stakeholders and decisionmakers

In order to mitigate risks of infection and issues of water quality it is essential that the wastewater treatment plant complies with regulations for quality of effluent as well as accommodates other factors which are important to the local context of Tupiza. From the evaluations made in this study it is evident that the current treatment system in Tupiza is not a sustainable option according to several sustainability criteria such as space efficiency, impact of flood events, natural resource management and quality of effluent. This study has largely focused on potential reuse from the wastewater treatment plant, for which higher standards of hygienization would be necessary in order to protect farmers and consumers of produce. However even without implementation of reuse the conventional option entails significant health risks for inhabitants of Tupiza and should therefore be re-considered. In this study more advanced treatment technologies such as anaerobic reactors, contructed wetlands and hygienization of sludge have been shown to substantially improve several aspects of sustainability and should be considered for an improvement of the current treatment plant.

The more advanced treatment technologies would vastly improve the sanitation situation in Tupiza, however it is important to note that any improvements also need to be supported by financial means. More efficient treatment generally comes at a higher price which becomes evident when looking at the MCA analysis. It is crucial to the long-term function of the plant that financial mechanisms are put into place in order to cover costs of investment and O&M.

It is clear that financing mechanisms need to be put in place for the sanitation service chain to improve in Tupiza, however any investments would be threatened by the prevalence of floods in the area, for which flood mitigation measures are of great importance. From the MCA it is evident that all systems entail a certain level of risk, and no matter which treatment system is put in place the unfortunate location of the plant means that planning and funding for flood mitigation measures is essential. This would increase the security of the plant as well as securie the treatment processes and protect the health of nearby communities.

5.3 Long-term recommendations for local stakeholders and decisionmakers

Results from the MCA analysis and questionnaire indicate that a more elaborate treatment system such as option 1 or 2 would benefit several dimensions of sustainability in Tupiza. Opting for a more advanced system such as option 1 or 2 would increase and ensure treatment efficiency as population and connections to the sanitation service chain increase. Expansion of the treatment plant will have to be considered at some point, which could be handled in several ways. In option 1 and 2 there is some space to increase treatment capacity. Another strategy would be to build new and smaller treatment plants in another part of Tupiza. In order to uphold sanitation services for the town's inhabitants in the future this is an important factor to consider.

While hygienization of sludge in this case has primarily been brought up as a mean of implementing reuse of sludge, this treatment step should also be highly considered even if reuse is not applied, especially considering that the current landfill is unlined and unprotected. Eliminating risks of disease transmission improves issues of public health. Implementing processes of reuse might not be essential to the sanitation service plant, but from an agricultural and natural resource perspective the potential gain is not to be ignored. Reuse from the WWTP in Tupiza has the potential of securing the irrigation water for more than 340 farming households. This becomes an especially important factor in light of climatic change in the region which might contribute to potential water shortages. Having reuse of wastewater and sludge could also help strengthen maintenance and quality testing procedures at the plant, since one of the conclusions from the qualitative research study was that this would be crucial in order to gain public acceptance of the products. Furthermore, the agricultural community is quite large in the Tupiza region, and if reuse from the central WWTP is implemented chances are that the reuse from other semi-centralized or small-scale systems could also increase. Safe reuse of byproducts from urban Tupiza would also entail the development of local competence which could be used to spread information and knowledge throughout the region, thus helping to spread advocacy for sustainable sanitation in Bolivia.

6 Conclusions

This project has evaluated three possible system options for wastewater treatment in a small Bolivian town through the implementation of an MCA using different sustainability criteria. Further it has also evaluated the social acceptance for re-use of treated sludge and wastewater for agricultural purposes through a qualitative research study. It is important to note that although this specific methodology captures several dimensions of sustainability it serves merely as a comparison among a few chosen treatment systems over a limited amount of topics within the vast topic that is sustainable sanitation. There might exist criteria which have not been identified in this study where other options might perform better. Furthermore, this study has not weighted or prioritized any of the criteria. Perhaps some local stakeholders will think that for example the capital and O&M costs are more important than natural resource management, while others may prioritize risks of disease transmission or impact of flood events, potentially giving the analysis a different result. This project serves as a pre-study in order to highlight important topics within the sanitation service in Tupiza as well as inform about possible choices. It is up to local stakeholders and decision makers involved to make informed choices and priorities which benefit the community of Tupiza.

The recommendations for local stakeholders and decision makers in Tupiza aim at mitigating risks of infection, issues of water quality, potential impacts of flooding as well as ensuring long-term function. The recommenadtions include the following:

- In order to reduce risk of disease transmissions as well as mitigating risks of eutrophying emissions it is vital that the current treatment method be improved. Treatment steps such as anaerobic reactors, constructed wetlands and hygienization of sludge have been evaluated in this study and have shown to substantially improve several areas related to sustainability. Such improvements could be combined with exisiting infrastructure which would help reduce investment costs. Issues such as space efficiency and treatment capacity could also be improved with the afforementioned treatment processes which provide higher treatment efficiencies with less space requirements.

- Implementation of flood mitigation measures will be crucial in ensuring function of any chosen treatment system, and should be highly prioritized given the current situation of frequent floodings and negative consequences for nearby communities.

- For the long-term function of the WWTP in Tupiza financial means which cover the entire sanitation service chain including the wastewater treatment facilities are needed. Such funding mechanisms could include tariffs, revenues from sale of by-products, governement taxes or transfers in the form of contributions or aid from international donors or charitable entities.

- Reuse of byproducts and especially treated wastewater from the wWWTP in Tupiza could help support 340 farming families or more, as well as strengthen procedures for hygienization, maintenance and quality testing, therefore such reuse should be highly considered for a future renovation of the plant.

As a result of this study several areas of further research have also been identified:

- Evaluation of the long-term economic impact, e.g. a cost-benefit analysis, of having improved systems which perform well within a larger range of sustainability criteria as opposed to implementing systems with minimized direct costs.

- Further evaluation of quality of effluent would help ensure mitigation of environmental impacts such as eutrophication, as well as underpin the value of direct reuse of treated wastewater.Investigation of nutrient removals to sludge for different sludge yielding treatment technologies would help further establish the potential economic and environmental benefits of reusing sludge.

- A possible certification process or public campaign regarding reuse of by-products could help increase social acceptance and demand as well raise public awareness around the utility of the WWTP. For such a campaign or certification process it would be interesting to investigate what information should be communicated and how it could be verified.

- Flood scenarios of different magnitudes should be evaluated in order to establish the risk of flood. Flood mitigation measures should also be investigated.

- The general institutional capacity and competence surrounding the sanitation service chain in Tupiza should be evaluated in order to ensure long-term functionality and maintenance of the plant.

Adding the dimension of sustainability to the case of sanitation in Tupiza brings forth a wide set of issues and questions which need to be adressed. As mentioned before this project was intended as a pre-study and has identified several areas of research as well as recommendations in order to improve the current sanitation situation. Furthermore it has shown that improvement of the conventional pond system would greatly benefit the community of Tupiza. However support mechanisms such as funding, public awareness, testing and institutional capacity are vital for the long-term function of these improvements and should be established to ensure progress of any implemented improvements.

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A Appendix - Sludge and wastewater characteristics

Table 21: Water analysis test from 15/11/2013 on influent wastewater in the Tupiza WWTP. Testing performed by RIMH Laboratorio de Aguas, Suelos, Alimentos y Análisis Ambiental.

Parameter	**Unit**	**Value**
Temperature	°C	23
pH	-	7,2
Total SS	mg/L	284,70
Dissolved SS	mg/L	857,27
Total solids	mg/L	1881,82
BOD5	mg/L	174
COD5	mg/L	282,8
Total coliforms	NMP/100 mL	3,09E+07
Fecal coliforms	NMP/100mL	1,04E+07

Table 22: Water analysis test from 15/11/2013 on effluent wastewater in the Tupiza WWTP. Testing performed by RIMH Laboratorio de Aguas, Suelos, Alimentos y Análisis Ambiental.

Parameter	**Unit**	**Value**
Temperature	°C	23,10
pH	-	7,60
Total SS	mg/L	103,00
Dissolved SS	mg/L	888,44
Total solids	mg/L	2114,99
BOD5	mg/L	150,00
COD5	mg/L	208,11
Total coliforms	NMP/100 mL	2,89E+07
Fecal coliforms	NMP/100mL	9,11E+06

Table 23: Nutritional content of dried sludge generated from a UASB reactor in Cochabamba, Bolivia. Testing performed by Agua Tuya.

Type of content	**Unit**	**Nutritional value**
Total nitrogen	mg N/kg	4111
Ammoniacal nitrogen	mg N_{NH3}/kg	2287
Phosphorous	mg P/kg	2359

B Appendix - Design of system options

B.1 Dimensions

Dimensions - Option 0						
Component	**#**	**Shape**	**Dimensions [m]**	**Capacity [m3]**	**HRT**	**Source:**
Fine grids	1	Cuboid	h = 3 w = 0,5	none	none	Aldunate (2020a)
Facultative ponds	2	Cuboid	h = 187 w = 77,5 d = 1,8	26805	5 d	Helvetas Bolivia (2016)
Maturation ponds	4	Cuboid	h = 107,2 w = 44,7 d = 1	4791	3,5 d	Helvetas Bolivia (2016)

Dimensions - Option 1						
Component	**#**	**Shape**	**Dimensions [m]**	**Capacity [m3]**	**HRT**	**Source**
Fine grids	1	Cuboid	h = 3 w = 0,5		none	Aldunate (2020a)
Settler	4	Cone and cylinder	d = 6,33 h_{cone} = 1,6 h_{cyl} = 2,5	94,6	3 h	Agua Tuya (2020)
RAC	2	Cuboid	h = 21 w = 9 d = 7,5	1408	10 h	Agua Tuya (2020)
Facultative ponds	2	Cuboid	h = 187 w = 77,5 d = 1,8	26805	5 d	Helvetas Bolivia (2016)
Maturation ponds	4	Cuboid	h = 107,2 w = 44,7 d = 1	4791	3,5 d	Helvetas Bolivia (2016)
Drying beds	5	Cuboid	h = 20 w = 10 d = 0,4	80	68 d	Agua Tuya (2020)
Hygienization area	1	Rectangular	h = 75 w = 17	1247,4	90 d	Calculated from Eriksen et al. (1995)

Dimensions - Option 2						
Component	**#**	**Shape**	**Dimensions [m]**	**Capacity [m3]**	**HRT**	**Source**
Fine grids	1	Cuboid	h = 3 w = 0,5	none	none	Agua Tuya (2020)
UASB	4	Cone and cylinder	d=12,5	704	10 h	Agua Tuya (2020)
CW	8	Cuboid	h = 16 w = 38 d = 0,8	1748	41 h	Calculated from Agua Tuya (2020)
Maturation ponds	4	Cuboid	h = 107,2 w = 44,7 d = 1	4791	3,5 d	Helvetas Bolivia (2020)
Drying beds	5	Cuboid	h = 15 w = 10 d = 0,4	266	60 d	Agua Tuya (2020)
Hygienization area	1	Rectangular	h = 75 w = 8	606,48	135 d	Calculated from Fidjeland et al. (2015)

B.2 Quality of effluent and sludge yield

Effluent concentrations of BOD, COD, suspended solids and E.coli for the different treatment systems as well as sludge yields for option 1 and 2 as dimensioned by Agua Tuya. Calculations are partially based on theoretical values of BOD, COD and suspended solids, based on size of population as well as tests of influent wastewater quality from 2013, see Appendix A. Note here that the estimated level of E.coli was not used in the criteria for Risk of disease transmission. This was because the calculations from Agua Tuya seemed quite conservative and were contradicted by literature from WHO (2006b) and Von Sperling (2007). Because of external factors communication and cooperation with Agua Tuya was made very difficult and the numbers could not be discussed properly. For a future design of any of these options any numbers would need to be controlled thoroughly.

Table 24: Estimated quality of effluent as calculated by Agua Tuya. Note here that the effluent concentration of E.coli was not used in this study.

Estimated quality of effluent - Option 0		
Parameter	**Unit**	**Value**
BOD	g/m3	124,21
COD	g/m3	213,07
Suspended solids	mg/L	22,09
E.coli	NMP/100 mL	3,50E+6

Table 25: Estimated quality of effluent as calculated by Agua Tuya. Note here that the effluent concentration of E.coli was not used in this study.

Estimated quality of effluent and sludge yield - Option 1		
Parameter	**Unit**	**Value**
BOD	g/m3	107,44
COD	g/m3	209,15
Suspended solids	mg/L	11,41
E.coli	NMP/100 mL	5,01E+6
Sludge yield (wet)	kg SS/d	3214,52
Sludge concentration (wet)	%	25
Specific sludge weight	kg SST/m^3	1020
Sludge yield (dry)	m^3/d	12,61

Table 26: Estimated quality of effluent as calculated by Agua Tuya. Note here that the effluent concentration of E.coli was not used in this study.

Estimated quality of effluent and sludge yield - Option 2		
Parameter	**Unit**	**Value**
BOD	g/m3	57,31
COD	g/m3	111,04
Suspended solids	mg/L	79,34
E.coli	NMP/100 mL	1,67E+6
Sludge yield (wet)	kg SS/d	1129,09
Sludge concentration (wet)	%	25
Specific sludge weight	kg SST/m^3	1020
Sludge yield (dry)	m^3/d	4,43

C Appendix - Calculations for treatment of sludge

1 log reduction of Ascaris eggs was assumed to be reached via dehydration of the sludge. Nutritional values in the sludge was assumed to be the same as in the sludge test from a UASB reactor in Cochabamba, see Appendix A.

Alkaline treatment with lime

For treatment using quick lime, a 10% w/w was added to dried sludge and stored under cover for 90 days. 85% of the quick lime was estimated to consist of CaO. The pH was approximated to 12. Nutrirional values were assumed to be lower than the dried sludge as the lime treatment meant a 10% increase in volume. Concetration of ammoniacal nitrogen was therefore caluclated to $[N_{NH3}] = 2{,}53$ g per kg TS. According to recommended addition of ammoniacal nitrogen for growth of onions, this resulted in an average addition of 0,7 kg per m^2 of farmland.

The resulting Ascaris concentration in the treated sludge was approximated to zero as the treatment of lime would render full inactivation of viable Ascaris eggs. (Eriksen, Andreasen, and Ilsoe 1995).

Ammonia treatment with urea

For the treatment with urea it was assumed that pH would rise to 9,2 with an addition of 300mM of urea to the dried sludge which would achieve a 3 log reduction within after 116 days. Temperature was assumed to be 15,3 °C as that is the annual average temperature in Tupiza. Total concentration of ammoniacal nitrogen was calculated to $[N_{NH3}] = 2{,}72$ g per kg TS which would entail 0,06 kg of sludge per m^2 of farmland. The total log removal of Ascaris would amount to 4 log reductions, making the total addition of sludge to soil 0,06 kg per m^2 and added Ascaris eggs 49 eggs per ^{2}.

D Appendix - Cost analysis of system options

Table 27: Analysis of operation and management costs for option 0.

O&M Costs - Option 0				
Item	**Cost per period [USD]**	**Periods per year**	**Annual cost [USD/cap, y]**	**Source**
Technical staff (supervision)	469,01	12	0,19	(WB WGP n.d.)
Technical staff (monitoring)	1440,0	12	0,6	(WB WGP n.d.)
Operator	987,44	12	0,41	
Regular electromechanical maintenance	208,00	3	0,022	(WB WGP n.d.)
Reporting	492,88	4	0,068	(WB WGP n.d.)
Tools	617,13	2	0,043	(WB WGP n.d.)
Cleaning materials	164,56	4	0,023	(WB WGP n.d.)
Energy	579,31	12	0,24	(WB WGP n.d.)
Water quality monitoring	1024,13	4	0,14	(WB WGP n.d.)
Total			1,75	

Table 28: Analysis of capital costs for option 0.

Capital costs - Option 0					
Item	**Investment cost [USD]**	**Life-span [y]**	**Annuity factor**	**Annual cost [USD /cap, y]**	**Source**
Coarse grids and bypass channel	43865	30	0,065	0,099	Aldunate (2020a)
Fine grids	47453	20	0,080	0,13	Aldunate (2020a)
Sedimentation channel	28786	30	0,065	0,065	Aldunate (2020a)
Restauration facultative ponds	37476	20	0,080	0,10	Aldunate (2020a)
Restauration maturation ponds	75683	30	0,065	0,17	Aldunate (2020a)
Electric installations	8098	20	0,089	0,022	Aldunate (2020a)
Total				0,594	

Table 29: Analysis of operation and management costs for option 1.

O&M Costs - Option 1				
Item	**Cost per period [USD]**	**Periods per year**	**Annual cost [USD/cap, y]**	**Source**
Technical staff (supervision)	469,01	12	0,195	(WB WGP n.d.)
Technical staff (monitoring)	1440,00	12	0,6	(WB WGP n.d.)
Operator	987,44	12	0,411	(WB WGP n.d.)
Regular electromechanical maintenance	208,00	3	0,022	(WB WGP n.d.)
Sludge removal	2468,56	4	0,343	(WB WGP n.d.)
Reporting	492,88	4	0,068	(WB WGP n.d.)
Tools	617,13	2	0,043	(WB WGP n.d.)
Cleaning materials	164,56	4	0,023	(WB WGP n.d.)
Energy	579,31	12	0,241	(WB WGP n.d.)
Water quality monitoring	1024,13	4	0,142	(WB WGP n.d.)
Lime	17,77	1	0,00062	(Geber 2020)
Sludge quality monitoring	1024,13	4	0,036	(WB WGP n.d.)
Sold sludge as fertilizer	-7948,51	1	-0,040	Estimated based on references from local farmers.
Total			2,725	

Table 30: Analysis of capital costs for option 1.

Capital costs - Option 1					
Item	**Investment cost [USD]**	**Life-span [y]**	**Annuity factor**	**Annual cost [USD /cap, y]**	**Source**
Coarse grids and bypass channel	43869,1	30	0,065	0,099	Aldunate (2020a)
Fine grids	47452,5	20	0,080	0,13	Aldunate (2020a)
Sedimentation channel	28786,1	30	0,065	0,065	Aldunate (2020a)
Pumping station	72294,1	20	0,080	0,20	Aldunate (2020a)
Settler	101131	20	0,080	0,28	Aldunate (2020a)
RAC	760170	20	0,080	2,12	Aldunate (2020a)
Sludge drying beds	26695	30	0,065	0,060	Aldunate (2020a)
Restauration facultative ponds	44348,9	20	0,080	0,12	Aldunate (2020a)
Restauration maturation ponds	75683	30	0,065	0,17	Aldunate (2020a)
Hydraulic and electric installations	29847,7	20	0,080	0,083	Aldunate (2020a)
Total				3,33	

Table 31: Analysis of operation and management costs of option 2.

O&M Costs - Option 2				
Item	**Cost per period [USD]**	**Periods per year**	**Annual cost [USD/cap, y]**	**Source**
Technical staff (supervision)	469,01	12	0,195	(WB WGP n.d.)
Technical staff (monitoring)	2880,00	12	1,200	(WB WGP n.d.)
Operator	987,44	12	0,411	(WB WGP n.d.)
Regular electromechanical maintenance	1008,00	3	0,105	(WB WGP n.d.)
Sludge removal	2468,56	4	0,343	(WB WGP n.d.)
Reporting	492,88	4	0,068	(WB WGP n.d.)
Tools	617,13	2	0,043	(WB WGP n.d.)
Cleaning materials	164,56	4	0,023	(WB WGP n.d.)
Energy	579,31	12	0,241	(WB WGP n.d.)
Water quality monitoring	1024,00	4	0,142	(WB WGP n.d.)
Urea	13,84	1	0,0005	(YPFB 2020)
Sludge quality monitoring	1024,00	4	0,141	(WB WGP n.d.)
Sold sludge as fertilizer	-4683,98	1	-0,165	Estimated based on references from local farmers.
Total			2,915	

Table 32: Analysis of capital costs for option 2.

Capital costs - Option 2					
Item	**Investment cost [USD]**	**Life-span [y]**	**Annuity factor**	**Annual cost [USD /cap, y]**	**Source**
Coarse grids and bypass channel	43869,025	30	0,065	0,099	Aldunate (2020a)
Fine grids	47452,41	20	0,080	0,132	Aldunate (2020a)
Sedimentation channel	28786,125	30	0,065	0,065	Aldunate (2020a)
Pumping station	72294,12175	20	0,080	0,204	Aldunate (2020a)
UASB	696841,0664	20	0,080	1,941	Aldunate (2020a)
CW	213179,016	30	0,065	0,481	Aldunate (2020a)
Sludge drying beds	26695,0104	30	0,065	0,061	Aldunate (2020a)
Restauration maturation ponds	75683,0429	30	0,065	0,171	Aldunate (2020a)
Hydraulic and electric installations	29847,65405	20	0,080	0,0832	Aldunate (2020a)
Total				3,235	

E Appendix - Translated questionnaire

Introduction
To whomever it may correspond.

This questionnaire is part of a master thesis project of environmental and water engineering, carried out by the Swedish student Johanna Burström within the program Bolivia WATCH initiated by the Stockholm Environment Institute (SEI). The thesis evaluates potential watewater treatment technologies for the wastewater treatment plant in Tupiza. Parts of the project focuses on the re-use of treated water and sludge generated at the plant for use in agriculture, for which this questionnaire will examine acceptance and demand of said products. The answers generated from this questionnaire will help highlight circular technologies and incorporate the view of the farmers in the project of Bolivia WATCH. The questionnaire will be anonymous. Thank you for your cooperation.
Best regards,
Johanna Burström and Zoraida Cecilia Tapia Benitez.

Questionnaire
Disclaimer: Part 1 refers to questions 1-9, part 2 refers to questions 10-14 and part 3 refers to questions 15-18.

1. Gender
   - ☐ Female
   - ☐ Male
2. Community role
   - ☐ Community official
   - ☐ Community member
3. Age (years)
   - ☐ 11-20
   - ☐ 21-30
   - ☐ 31-40
   - ☐ 41-50
   - ☐ 51-60
   - ☐ 61-70
   - ☐ 71-80
4. Community

- ☐ Bolivar
- ☐ Entre Ríos
- ☐ Tocloca
- ☐ Angostura
- ☐ Deseada
- ☐ Palquisa
- ☐ Chuquiago
- ☐ Suipacha
- ☐ Other:

5. What is the size of your farm?
   - ☐ Less than 0,5 ha
   - ☐ 0,5-1 ha
   - ☐ 1-2 ha
   - ☐ 2-3 ha
   - ☐ More than 3 ha
6. How many people besides yourself work at the farm?
   - ☐ Only me
   - ☐ 1-2 people other than me
   - ☐ 3-5 peopåle other than me
   - ☐ 6-10 people other than me
   - ☐ More than 11 people other than me
7. What are your most commonly grown crops?
   - ☐ Onion
   - ☐ Garlic
   - ☐ Lettuce
   - ☐ Corn
   - ☐ Beans
   - ☐ Potatoes
   - ☐ Tomatoes
   - ☐ Chayote
   - ☐ Pumpkin

- ☐ Flowers
- ☐ Other:

8. Which of your crops do you sell?

   - ☐ I don't sell any of my crops.
   - ☐ Onion
   - ☐ Garlic
   - ☐ Lettuce
   - ☐ Corn
   - ☐ Beans
   - ☐ Potatoes
   - ☐ Tomatoes
   - ☐ Chayote
   - ☐ Pumpkin
   - ☐ Flowers
   - ☐ Other:

9. If you sell your crops, where do you sell them?

   - ☐ Within the community where we live.
   - ☐ In the centre of Tupiza.
   - ☐ To other towns of Bolivia.
   - ☐ The crops are exported.

10. Where does the water that you use to irrigate your crops come frome?

    - ☐ River
    - ☐ Channel
    - ☐ Rain
    - ☐ Stream
    - ☐ Groundwater source

11. Would you consider using treated wastewater from the WWTP in Tupiza to irrigate your crops?

    - ☐ Yes, for the following reasons:
    - ☐ No, for the following reasons:

12. Is there in anything in particular that makes you doubt using water which comes from the WWTP for irrigation of your crops?
    - ☐ No.
    - ☐ Yes, these are my doubts:
13. Would you be inclined to pay for the water if you would be able to use it in times when the water from the river is too muddy to use?
    - ☐ Yes.
    - ☐ No.
    - ☐ Comments:
14. Do you think that the use of wastewater as irrigation water would make it more difficult to sell your crops?
    - ☐ Yes, because of the following reasons:
    - ☐ No, because of the following reasons:
15. What typ of fertilizer do you use at the farm?
    - ☐ I don't use any fertilizer.
    - ☐ Organic compost
    - ☐ Manure
    - ☐ Chemical fertilizer with urea
    - ☐ Chemical fertilizer with NPK (nitrogen, phosphorous, potassium)
    - ☐ Other:
16. What characteristics do you value when buying fertilizer?
    - ☐ Organic content
    - ☐ NPK content
    - ☐ Environmentally friendly
    - ☐ Price
    - ☐ Solid consistency
    - ☐ Liquid consistency
    - ☐ Solubility
    - ☐ I re-use manure produced at my own farm.
17. Would you use treated sludge from the WWTP in Tupiza to fertilize your crops?

- ☐ Yes, because of the following reasons:
- ☐ No, because of the following reasons:

18. Do you think that the use of sludge as fertilizer would make it difficult to sell your crops?

    - ☐ Yes, for the following reasons:
    - ☐ No, for the following reasons:

F Appendix - Responses to questionnaire

F.1 Gathered data

Table 33: Responses in part 1.

Question	**Options**	**Response**
Gender	Female	45 %
	Male	55%
Age	21-30 years	14%
	31-40 years	10%
	41-50 years	38%
	51-60 years	0%
	61-70 years	24%
	71-80 yeras	7%
Community	Entre Ríos	3%
	Angostura	28%
	Deseada	3%
	Quebrada	31%
	Bolivar	10%
Area of farm	<0,5 ha	45%
	0,5-1 ha	21%
	1-2 ha	34%
People working at farm	1 person	17%
	2-3 people	34%
	4-6 people	41%
	7-11 people	0%
	>12 people	0%

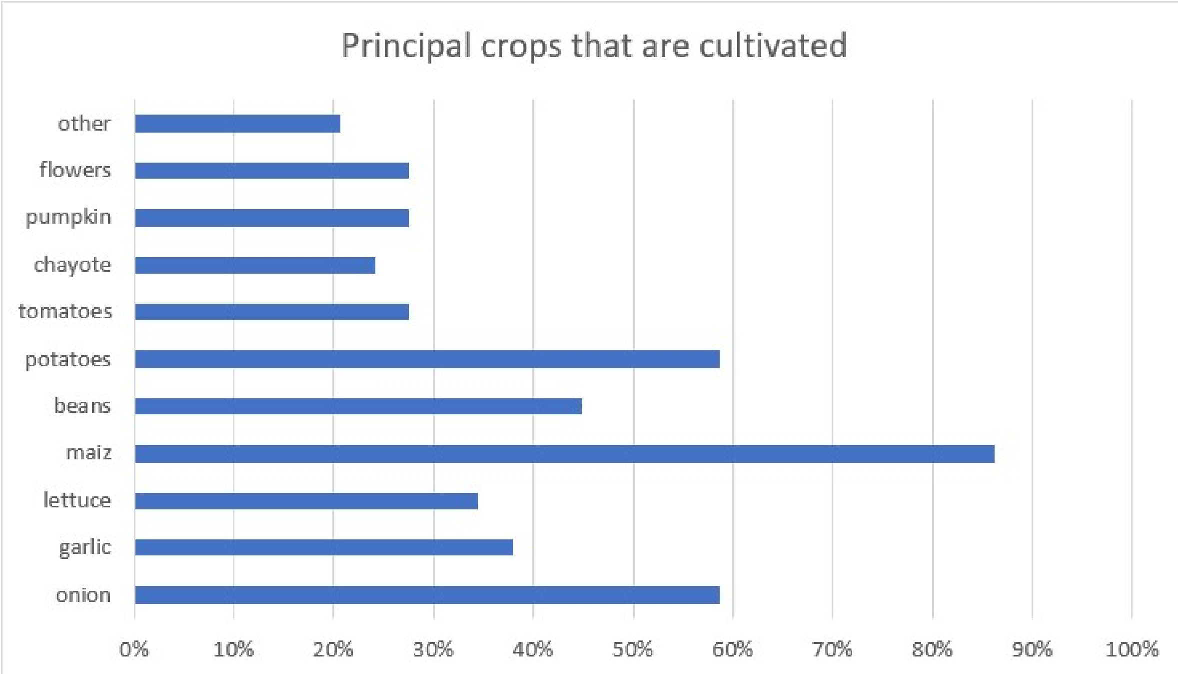

Figure 22: Caption

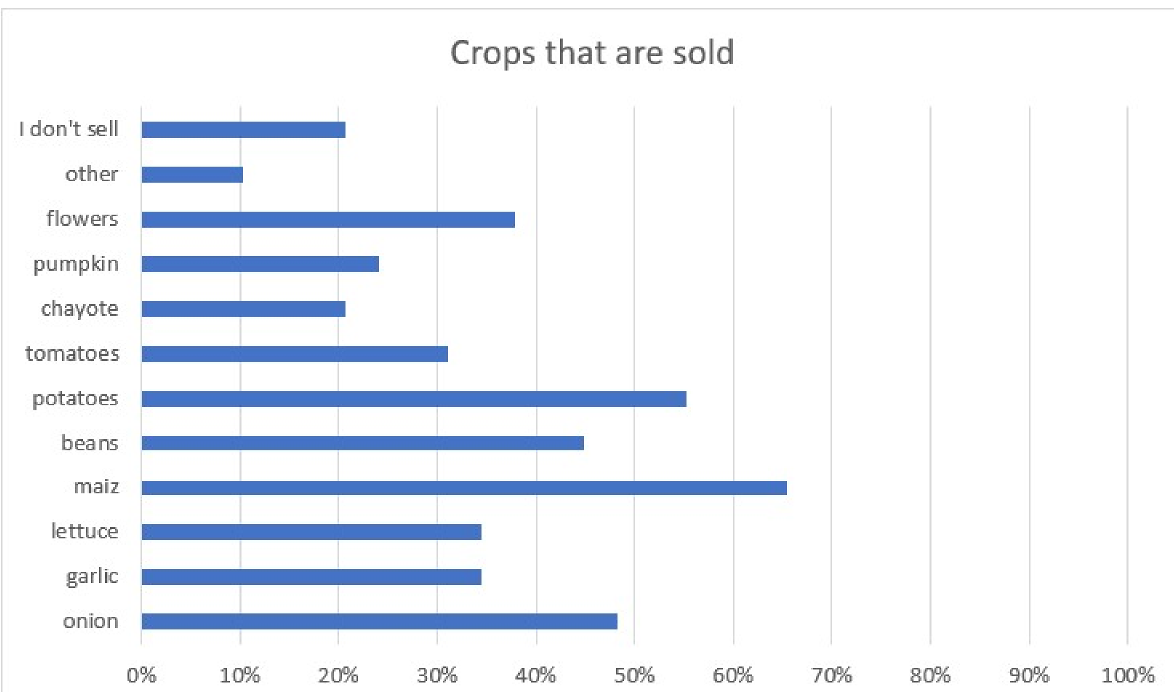

Figure 23: Caption

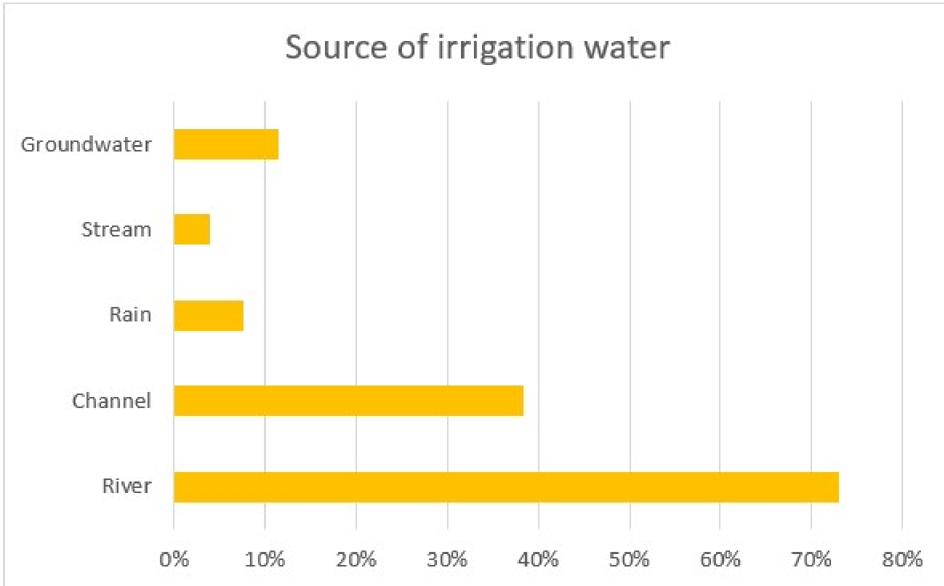

Figure 24: Irrigation source

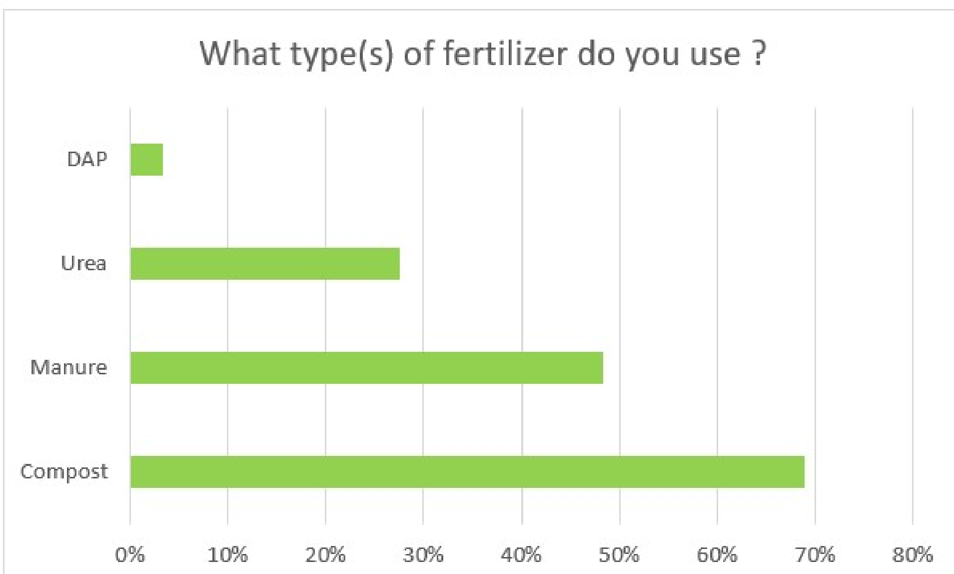

Figure 25: Use of fertilizer

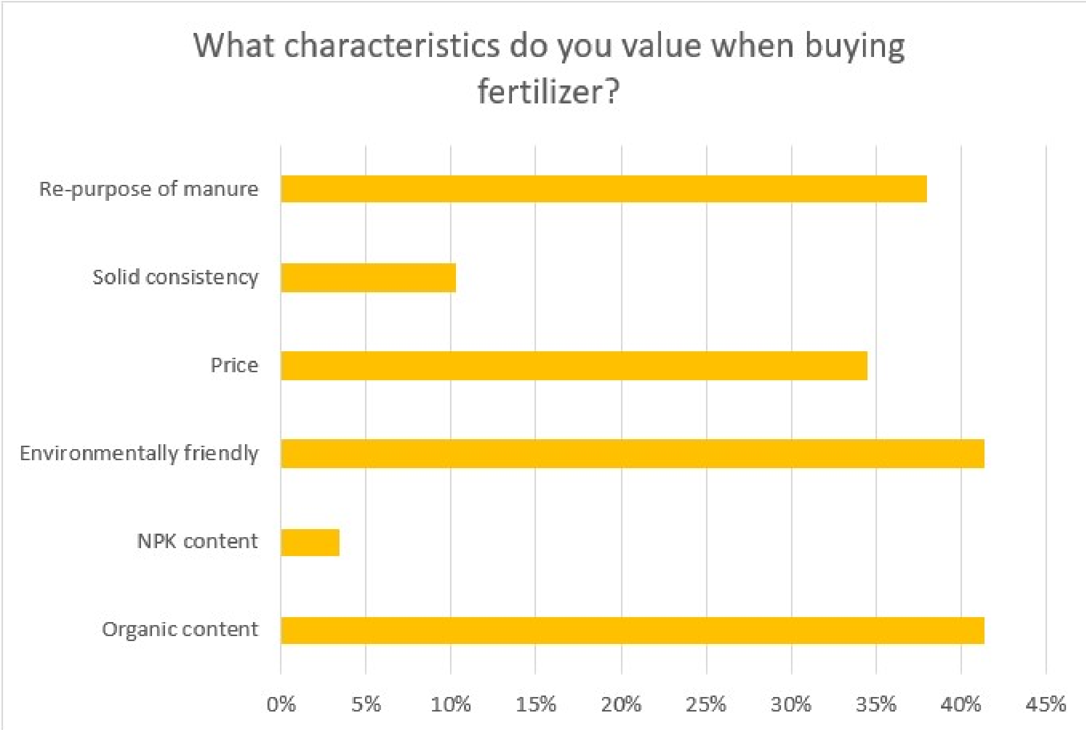

Figure 26: Caption

F.2 Summary of comments from questionnaire

The water from the WWTP would be treated so I would use it.

I would use the water if it was treated/quality of water was guaranteed.

It's better to use water from the river but if no other option exists I would use the recycled wastewater.

We have no need for recycled wastewater.

No because I don't know the quality of the water.

I don't have any doubts about using the treated wastewater as irrigation.

The treated wastewater might harm the crops.

The treated wastewater needs to meet regulations in terms of E. coli.

The treated wastewater needs to be hygienic.

The treated wastewater needs to have a neutral pH.

The acceptance from the consumer is important when it comes to re-use of treated wastewater.

I wouldn't pay for the water since my land isn't suited for harvest.

I wouldn't be inclined to pay for the water.

I wouldn't be inclined to pay for the water since we have enough water for free from other sources.

If it was necessary I would pay for the water.

If the water is treated there shouldn't be a problem with selling the crops.

People would doubt the hygiene of crops irrigated with wastewater.

People already doubt the quality of our crops because of contamination in the river.

People would doubt the quality of the crops irrigated with wastewater.

The guarantee of the quality of the treated wastewater would help sell the crops.

When the river was contaminated because of the floodings the crops were more difficult to sell because they were irrigated with that water.

The treated sludge is good for the soil. If the cost was low I would use the treated sludge.

The treated sludge is organic which is good.

I would not use the treated sludge because I lack technical knowledge of it.

The treated sludge isn't hygienic. I wouldn't be sure if the treated sludge would be safe to use.

I would use the treated sludge if the cost was low.

The treated sludge would be good for the crops.

I prefer using manure or compost because we generate that on our own – lower cost.

We're not used to using treated sludge as fertilizer.

Crops fertilized with sludge wouldn't be socially acceptable to buy.
The idea of the general public governs the sale of the crops.

In order to sell crops fertilized by sludge consumers and vendors would need to be educated about the quality of the product.

In Bolivia there are cases where crops irrigated with wastewater are sold on a daily basis.

If the sludge is free from pathogens the crops could be sold easily.

F.3 Summary of statements in connection to questionnaire

Seven farmers gave statements concerning the general water situation in their area. These were gathered via phone calls by Cecila Tapia who was the local coordinator for Bolivia WATCH in Tupiza. A selection of statements were translated by Johanna Burström and can be seen below.

"Our products for example, are 2-3 years without water, we don't have water, currentluy we don't have anything to irrigate with, we have not harvested our lands. And this is where majority of vegetables cosumed in Tupiza, Uyuni and Atocha are grown."

"About the water quality which we have right now from Tupiza, since 2013 we've been very affected, there aren't any farms which grow crops.."

"I'm from Entre Ríos and I grow vegetables, we irrigate with water from the Tupiza river, right now the water is really bad, contaminated. I cultivate carrpots and onions. The onion is very badly affected by the water [...] The water is not apt for irrigation, please I would ask that water quality would improve, it's very bad. I was drinking that water 2 years ago y it made me very sick."

"We suffer greatly beacuse of the waters from Tupiza, it is contaminating, we grow vegetables, corn, and the animal are also affected, they can't drink the water or they will get sick. We also drink that water but it's dirty, we can't wash our clothes or anything. The water is dirty."