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RUVIVAL
Publication Series

02

12/2017

Impressum

RUVIVAL Publication Series Volume 2

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December 2017

Identification
http://nbn-resolving.de/urn:nbn:de:gbv:830-88217957
ISSN 2567-8531

Please cite as indicated in each paper.

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From the Editors

Preface by Ruth Schaldach

This is the second volume of the bimonthly published RUVIVAL Publication Series. Each contribution in this publication is connected to further interactive multimedia material, which can be reached under www.ruvival.de.

The RUVIVAL project is dedicated to open access and the sharing of knowledge to face especially environmental challenges in rural areas and to empower people to restore and rebuild them. We collect practices and research conducted from our Institute of Wastewater Management and Water Protection (AWW), but also from all over the world.

Each volume consists of a collection of literature reviews written in collaboration with Master students, PhD students and researchers at the AWW at Hamburg University of Technology. The work is supervised by at least one senior researcher at the Institute, who is specialised in a related subject. The process entails several feedback rounds and a final presentation of the work, where other researchers of the Institute submit their additional comments. This outcome is then published on the RUVIVAL Webpage as a working paper and the broader audience is asked to give some further feedback or ideas. The final version of the literature review is only included in the publication series once all feedback has been incorporated and the paper was once again reviewed by the supervising researchers and the Director of the Institute.

Therefore, we do not just want to open up research to a broader public and make it available for practitioners, we also want to invite our readers to contribute and develop the material. We hope we will reach a broad public and provide a deeper understanding of research fields important for a sustainable rural development and in areas in need of landscape restoration.

Each volume is centred on a specific overarching topic, which is a cornerstone of sustainable rural development. The research approach draws a systematic and interdisciplinary connection between water, soil, nutrition, climate and energy. Measures which enable sustainable use of land resources and improvement of living conditions are reviewed and new ideas developed with consideration of their different social, political and demographic contexts.

Introduction by Ralf Otterpohl

All topics of Volume 2 are related on several levels. All are part of restoration engineering, a subject that is still not very common. The main goal of my team and me is to encourage all stakeholders to know and to combine those wonderful methods in implementation. Single elements that are usually implemented can be efficient by themselves, but have proven to perform miracles if applied in combination. However, the challenge is to choose and apply all elements in a professional way, to adapt them to the given situation and to consider the system's multiple interactions, too. The methods may look simple at first glance, but especially simple and low-cost methods require experience. Few professional failures can be devastating when working with villagers, who often put a lot of their hope, money and labour into implementation, and then running them into famine with ill designed systems. Restoration engineering has the potential to raise productivity of eroded areas hundredfold. Income, excellent nutrition and well-being for family farmers and their children, in my point of view, should be the foundation for self-promoting solutions.

Concerning aquifer recharge, academic tools and practical application should be considered together. With the emphasis on understanding hydrology and the complex interactions of groundwater recharge, local knowledge on the development of groundwater levels should not be forgotten, as it is already a very valuable first assessment. For a broad implementation of these technologies the feasibility of proper modelling, with a high demand for input data, should not be overestimated; it is an endeavour that is applicable in externally funded projects rather than in the vast areas in urgent need of restoration. Action can already be taken with good knowledge of the approaches – a reasonable combination of scientific/engineering and hands-on methods is advisable. The most important aspect in most cases is to increase productivity of agriculture from the beginning. Luckily, this combines nicely with perennial vegetation cover. However, until recharge takes effect, the creation of productive and humus-forming vegetation cover will often require building some reservoirs in addition.

In RUVIVAL we work on the restoration of larger plots, areas and regions. Reservoirs for roof runoff are a topic on its own, but more on a small scale and very limited in areas with distinct rainy seasons. Please do always consider increasing infiltration within the whole community – this can bring the local aquifer up at a fraction of the cost and with volumes that can assure survival over failing rainy seasons. Converting wells in a village into suction wells (for the cleaner part of runoff) in the rainy season can go a long way. Aquifers will not heat up and the water can be of good quality if sanitation and manure are managed properly (used to build humus).

However, in wider regions, rainwater harvesting (RWH) is a different thing. Tools are kilometres of swales, hundreds of check dams, small reservoirs and – often forgotten, but the key to success in the long run – permanent vegetation cover and building humus. This should be done in the whole catchment, starting in the upper reaches, when it comes to check dams. One of the best systems that I know of is the keyline system that was developed by P. A. Yeomans. Even though ploughing is often the reason for erosion, the Yeoman plough is designed to loosen up parts of the eroded area in contour to allow water to soak in quantities that allow the seeded plants to mature and keep the soil loose. Please do understand that the keyline swales or trenches are meant to transport water from the valley/gully to the shoulders with a slight slope to allow water to flow. In steady hills, you will go on contour to capture the runoff and let it seep in. Planting productive and partly perennial trees, crops and tree crops is crucial for the long term success. It cannot be overstated: in cooperation with local authorities, try to work with hundreds of family farms – they can become the best wardens for the vegetation cover and eventual repair of the RWH-systems and create local income for their families.

Inside This Volume

Literature Review on Managed Aquifer Recharge in the Context of Water and Soil Restoration Methods

Berenice Lopez Mendez and Lukas Huhn

'Many farmers know that their children cannot make a living from a depleting aquifer so they continue to maximise irrigated production to enable their children to complete their education and take up city jobs that offer higher returns than farming.'

(Dillon 2016, p. 4)

Please cite as: Lopez Mendez, B & Huhn, L 2017, 'Literature Review on Managed Aquifer Recharge in the Context of Water and Soil Restoration Methods' in R Schaldach & R Otterpohl (eds), RUVIVAL Publication Series, vol. 2, Hamburg, pp. 6-18, <http://nbn-resolving.de/urn:nbn:de:gbv:830-88217957>.

Abstract

Aquifer recharge occurs naturally through infiltration mechanisms. However, due to changes in the vegetation cover and increasing soil erosion, infiltration rates tend to decrease. The recharge of an aquifer can be managed by facilitating natural infiltration processes and/or by the construction of structures that maintain recharge artificially. Several methods are available to enhance the recharge of an aquifer. The implementation of aquifer recharge schemes can massively increase groundwater levels, which are the best possible long-term storage. Recharge can also help to address objectives such as: improvement of source water quality, recovering of yields, creation of barriers to prevent saline intrusion and/or other contaminants, prevention of land subsidence and the reduction of potentially harmful runoff. Alternatives to recover natural infiltration can be the application of ecosystem-based adaptation (EbA) measures or agricultural practices with permanent vegetation cover, such as permaculture. Artificial recharge methods, also called Managed Aquifer Recharge (MAR), can be broadly categorised into in-channel modifications, well, shaft and borehole recharge, induced bank infiltration and rainwater harvesting. The method of recharge depends strongly on the survey of the site. Two key issues have to be considered: the hydrogeological properties of the aquifer and the source of water. Recharge through living topsoil, as in swales, also provides treatment and is by far preferable. In addition, it should not be forgotten that humus rich soil with adequate vegetation cover provides retention and recharge without any technical intervention. However, the techniques described below are often needed to get restoration started at all.

Keywords*: groundwater, aquifer, infiltration, Managed Aquifer Recharge, MAR*

Introduction

The main source of freshwater is groundwater, which accounts for around 99 % (Shiklomanov 1993). Groundwater comprises of all water below the ground surface, found in pores and fractures, in the saturation zone and in direct contact with ground or subsoil (Directive 2000/60/EC). Large volumes of groundwater can be found in aquifers, which provide a safe water buffer by storing groundwater in the subsurface. An assessment made by Döll et al. (2012), indicates that globally, from the total amount of water withdrawn for irrigation, households and manufacturing, groundwater accounts for 42 %, 36 %, and 27 % respectively, which amounts to 35 % of the total water withdrawals. Döll (2009) states that around 70 % of the total withdrawal worldwide is used for irrigation. These figures show how human activities depend on groundwater resources, especially in regard to food security. These figures also denote how agricultural activities put pressure on land and water resources to meet food needs (ed. Conforti 2011).

Aquifer recharge occurs naturally through infiltration mechanisms. Whenever land is modified, this has an influence on the recharge quality and quantity. Some significant changes are, for instance: deforestation, conversion of pasture to arable land, dryland farming, irrigated cropping, afforestation or reforestation or urbanisation (Foster & Cherlet 2014). Sustainable groundwater management must include land-use measures and actions to recover natural infiltration. Infiltration rates can be improved through the restoration of the vegetation cover and usage of surface or subsurface structures, thus reducing runoff and soil erosion.

Additionally, when an aquifer is continuously depleted, irreversible damage, such as saline intrusion, land subsidence, or aquatic ecosystem degradation, can arise (Foster & Cherlet 2014). Increase of an aquifer's storage volume or the restoration of a depleted aquifer can be accomplished by artificial techniques. Artificial recharge uses infrastructure such as infiltration ponds/ditches or injection wells to facilitate soil infiltration (Jakeman et al. 2016).

In order to warrant the quality and quantity of the water source, it is essential to use groundwater sustainably. On condition that sustainable water management is established, groundwater can be a safe and permanent source of water for human consumption and economic activities. Sustainable management of groundwater must keep a balance between recharge and abstraction rates with a seasonal and long-term view (Alley, Reilly & Franke 1999). Efficient management of groundwater can also support the reduction and/or avoidance of problems such as high costs of water supply, migration, desertification, loss of agricultural productivity and the subsequent emergence of social and political conflicts.

There are many regions in the world without reliable water supply. Numerous groundwater sources are either not accessible, or abstraction costs are extremely high and some of the accessible sources have been overexploited. Especially in arid and semi-arid regions, where water scarcity is of major concern, the implementation of a sustainable Managed Aquifer Recharge (MAR) scheme can play an important role to restore groundwater balance. This also supports the control of abstraction in an aquifer and the increase of water supply quality.

General Concepts about Groundwater and Aquifer Recharge

The recharge of aquifers forms part of the hydrological cycle. Precipitation (rain or snow) that falls on the land surface can drain into streams, evaporate, or, if the surface soil is porous enough, infiltrate into the ground. First, water seeps into the belt of soil water at the top of the vadose zone, where the roots of plants are located. The fraction of water, which is not drawn by plants, is pulled down by gravity until it reaches the top of the saturation zone, becoming groundwater. The top of the saturation zone is known as the water table (Fetter 2001).

An aquifer is distinguished by its subsurface geological layer formation either of water-bearing permeable rock or unconsolidated material (gravel, sand, or silt), as well as by its thickness and area size. These characteristics, among others, determine the amount of water an aquifer is able to store (Gale & Dillon 2005). Groundwater is moving in and out of the aquifer's geological layers, allowing a significant flow of water in sufficient quantity that can be used as water supply. The process by which water is added from outside of the saturation zone into the aquifer is called groundwater recharge. This movement may occur naturally or artificially (Directive 2000/60/EC 2000; Dillon et al. 2009).

The recharge process of an aquifer can furthermore occur directly or indirectly. Groundwater recharge can be local, occurring from infiltration via surface water bodies, or diffused, by percolation of precipitation through the unsaturated soil zone across the landscape (Döll & Fiedler 2008). The recovered groundwater can be used for irrigation, industrial and domestic supply, or environmental uses. There are different methods and types of structures that can enhance the recharge of an aquifer. In order to have a sustainable recharge scheme, the technique or combination of techniques must be selected in consistency with the conditions of the site: recharge water quality and required quality for the end-use.

Correct site assessment leads to a correct choice of recharge method and a location which enables the highest cost-benefit. Two key issues are commonly discussed by different manuals and articles before establishing a recharge scheme: hydrogeological characteristics and water quality (Dillon et al. 2009; Gale & Dillon 2005; Smith et al. 2016; Tuinhof et al. 2003). An overview of these two key topics is discussed in the following sections. Moreover, further information of surveying methods and groundwater analysis techniques is given by Kinzelbach & Aeschbach (2002) for arid and semi-arid areas, and also by MacDonald, Davies & Dochartaigh (2002) for low permeability areas in Africa.

Hydrogeological Characteristics of the Site

In order to avoid mismanagement and/or incorrect decision making regarding groundwater resources numerous literature sources point out the importance of hydrogeological background concepts (Gale & Dillon 2005; Smith et al. 2016; Tuinhof et al. 2003). A technical understanding of aquifer recharge mechanisms and groundwater concepts such as water table, aquitard, aquiclude, unsaturated zone or vadose zone, alluvial basin, storativity, transmissivity, specific yield, residence time, abstraction, confined, unconfined or semi-confined aquifer is essential. Foster et al. (2003) and Harter (2003) give an overview of relevant hydrogeological concepts related to aquifer recharge. More details can be found in the UNESCO document 'An international guide for hydrogeological investigations' by Kovaleschy, Kruseman & Rushton (2004).

Foster et al. (2003) explain that the geological structure of the aquifer defines characteristics such as storability, transmissivity, flow regimen and residence time. Furthermore, the storage capacity of an aquifer may range from 30 % for highly porous unconsolidated to 10 % for highly consolidated and down to 1 % in case of crystalline rocks (Smith et al. 2016). The characteristics of the catchment area define the infiltration rates. Characteristics of the landscape, such as natural vegetation or erosion, can slow down or increase runoff respectively and subsequently have an impact on the recharge rates. There is a critical link between land use and an aquifer's recharge mechanisms, which is discussed in detail by Foster & Cherlet (2014). Depending on the available hydrogeological data of the recharge site, one may be able to estimate the storage potential, propose a recharge scheme and its cost-benefit.

Water Quality for Recharge

In order to assess the impact of water quality by recharge enhancement, three key issues should be taken into account: natural quality of the underground water, quality of the water source for recharge and anthropogenic activities in the recharge area. Some sources of water for aquifer recharge can be grouped as:

- surface water from perennial or ephemeral river flows or streams, lakes or dams,
- storm runoff water from urban areas like rooftops, agricultural fields, or uncultivated land,
- reclaimed water from treated effluent of industrial or domestic wastewater, or irrigation return flow,
- potable supply water from high-quality treated water like from desalination plants.

When recharging groundwater, the vulnerability of an aquifer depends on two main issues: pollutant characteristics (mobility and persistence) and hydraulic load. It will also depend on aquifer characteristics, such as the type of soil and rock, travel time through the aquifer, ability to adsorb pollutants, and the degree of confinement (Smith et al. 2016). If treated wastewater is used for recharge, it must be noted that even with proper biological treatment the effluents will typically contain a wide range of persistent micro-pollutants, pathogens and micro-plastic. This will restrict recharge to heavily modified systems in an urban context, where groundwater will also undergo advanced treatment before usage. Infiltration with effluents into natural groundwater systems has to be avoided. Direct reuse or through storage ponds for irrigation of industrial crops would be a better option, especially for the uptake of nutrients (Abaidoo et al. 2010; Asano 1998).

Natural Recharge

Modifications in the landscape have reduced the infiltration capacity of natural recharge areas. As explained by Smith et al. (2016), changes in the vegetation cover can impact the amount of water infiltrating into an aquifer. When soil is eroded, the runoff of rainwater increases, which subsequently reduces the rate at which precipitation infiltrates and recharges groundwater aquifers.

Smith et al. (2016) argue that soil characteristics and surface vegetation determine the fraction of precipitation that becomes groundwater. As mentioned by Ansems, Khaka & Villholth (2014), services provided by ecosystems are directly and indirectly dependent on the availability and state of groundwater resources. Integrated management of the ecosystem and groundwater has a positive impact on an aquifer's replenishment. Through the implementation of some Ecosystem-based Adaptation (EbA) measures, the natural recharge of aquifers may be enhanced. As described by Ansems, Khaka & Villholth (2014), such measures include: protection of critical recharge zones, protection of groundwater dependent ecosystems, protection and restoration of riparian zones and floodplains, adaptation of soil and vegetation cover and investment in natural infrastructure.

Furthermore, some concepts of permaculture design also consider the enhancement of natural infiltration. Permaculture design considers factors such as vegetation type, land use, soil structure and organic content, slope and an integrated watershed usage and management. Some of the techniques permaculture design applied in conjunction for infiltration improvement are earthworks, like swales, diversion drains, rain gardens, terracing, keyline system, or dams. Permaculture design also makes use of simulating the soil food web by biodiverse plantings and rotational grazing. A description of these methods is provided by Mollison (1992) or by Francis (2008). Additional resources on permaculture design related to this topic can be found on the website of Geoff Lawton (2017), http://permaculturenews.org/.

Artificial Recharge

The terms artificial and managed are often used interchangeably. Asano (1985) explains that the process of recharge, natural or artificial, is influenced by the same physical laws. Therefore, the term artificial applies to the availability of the water supply for recharge. Gale & Dillon (2005) mention that both terms artificial recharge and managed aquifer recharge describe the intentional storage and treatment of water in aquifers.

There is a wide range of methods with multiple benefits: storage of water, improvement of source water quality, recovery of yields, creation of barriers to prevent saline intrusion or other contaminants, prevention of land subsidence, recycling of stormwater or treated sewage effluent (Dillon 2005). Aquifer recharge methods have been used for decades, however, only recently the implementation of MAR schemes began to increase. Dillon et al. (2010) argue that aquifer recharge has an important role in securing the water supply to sustain cities affected by climate change and increasing population rates, mainly due to the quality of drinking water supplies, which is achieved through aquitard protection, but also due to the aquitard's function as a supply for agricultural irrigation, potable and non-potable uses.

Sprenger et al. (2015) discuss how in Europe MAR methods play an important role in providing drinking water supplies, mainly due to their potential to treat water and attenuate undesired substances. They also describe how factors like hydraulic impact zone, attenuation zone, biotic and abiotic attenuation processes, temperature, oxic and anoxic redox conditions, among others, have an impact on the source water for recharge during subsurface passage. This implies that, according to the characteristics of the aquifer, the water source, and the end-use of the reclaimed water, pre and/or post-treatment should be considered as part of a MAR scheme.

In Australia and the USA, the use of MAR methods is well researched and developed. The main purpose in these areas is to create a buffer of water for further usage during dry seasons for non-potable and indirect potable reuse. The implementation of these methods is widespread and developed in guidelines and to a certain degree considered by national or regional frameworks, such as the 'Australian Guidelines for Water Recycling: Managed Aquifer Recharge' and the 'Sustainable Groundwater Management Act' (SGMA) of 2014 from the California Code of Regulations (CCR).

A wide range of methods has been developed to enhance recharge of aquifers, several of them known for hundreds of years. A summary of how different authors categorised these methods is given in Table 1. The terminology introduced in the table is used interchangeably throughout the literature. Based on this, five main groups of MAR methods can be identified. These groups of MAR vary in their design and technology and whether they intercept or infiltrate water. A brief description is given below.

Spreading methods are applied in unconfined aquifers near the ground surface, where a large surface of permeable material is available for the infiltration of water. They are suitable for small and large-scale implementation at a relatively low cost. High loads of sediment in the source water can reduce infiltration

Table 1 Different classifications of MAR methods in the literature

MAR Classification used in this work	**Spreading methods**	**In channel modifications**	**Deep systems**	**Filtration systems**	**Rainfall systems**	
Classification according to Gale & Dillon (2005)	Spreading methods	In-channel modifications	Well, shaft and borehole recharge	Induced bank infiltration	Rainwater harvesting	
Classification according to Escalante et al. (2016)	Surface systems	In channel modifications	Deep systems	Filtration systems	Rainfall	Sustainable urban drainage systems (SUDS)
Classification according to Tuinhof et al. (2002)	Off-channel infiltration ponds	In-channel structures	Pressure injection	Induced bank infiltration	Village level gravity injection	

rates and increase evaporation rates (Gale & Dillon 2005; IGRAC UNESCO-IHE 2007).

In-channel modifications are structures to intercept water across streams, generally built in ephemeral sandy rivers used to enhance groundwater recharge and to control floodwater. Techniques range from small to large scale at relatively low cost without interfering with land use. Low scale structures can be built in cascade at a distributed distance in one stream to increase infiltration rates (IGRAC UNESCO-IHE 2007).

Deep systems are structures used to directly recharge groundwater in aquifers either in shallow or deep depths. Structures used for this purpose are usually wells, boreholes, shafts, or pits. These techniques are very useful for storing significant amounts of water where land is scarce. In case of shallow aquifers, existing extraction structures (wells, pits, trenches) that run dry are regularly used for injection at reasonable costs, but this requires high quality water, to prevent clogging or contamination. Deep structures (borehole) are applied where a thick, low permeable strata overlies the target aquifer, usually to provide storage for drinking water or water for irrigation purposes. These techniques are applied at medium and large scale as drinking water supply for cities and communities, since they require complex design, construction, operation and maintenance (Gale & Dillon 2005; IGRAC UNESCO-IHE 2007).

Filtration systems, commonly galleries or boreholes, are structures located close to perennial surface bodies connected hydraulically to an aquifer. Water is pumped from these structures, lowering the water table and inducing water from the surface water body to enter the aquifer system. Filtration systems are usually used for large-scale drinking water supply because of their pollutant attenuation potential (Gale & Dillon 2005; IGRAC UNESCO-IHE 2007).

Rainfall systems collect and concentrate runoff either to increase infiltration or to recharge directly into an aquifer. They are applied at low scale for domestic and agricultural purposes or at large scale for water harvesting in urban areas (Escalante et al. 2016; Gale & Dillon 2005; IGRAC UNESCO-IHE 2007).

The following MAR techniques are organised according to the previously given classifications:

1. Spreading Methods:
   - Soil Aquifer Treatment (SAT),
   - Incidental recharge from irrigation,
   - Accidental recharges by irrigation return,
   - Infiltration fields (flood and controlled spreading),
   - Controlled flooding,
   - Infiltration/percolation ponds, wetlands and basins,
   - Cross-slope barriers.
2. In-channel Modifications:
   - Check dams,
   - Sand storage dams,
   - Perforated/drilled/leaky dams,
   - Subsurface/underground dams,
   - Reservoir dams,
   - Riverbed scarification.
3. Deep Systems:
   - Well/borehole infiltration,
   - Injection well,
   - Aquifer Storage and Recovery (ASR),

- Aquifer Storage, Transfer and Recovery (ASTR),
- Infiltration galleries (qanats),
- Open infiltration wells,
- Deep wells and well-boreholes,
- Drilled boreholes,
- Sinkholes, collapses.

4. Filtration Systems:
   - Lakebank filtration,
   - Riverbank filtration,
   - Interdune filtration,
   - Underground irrigation.
5. Rainfall systems:
   - Rooftop rainwater harvesting,
   - Rainwater harvesting in unproductive terrains,
   - Reverse drainage, shaft recharge,
   - Sustainable Urban Drainage Systems (SUDS),
   - Dry land intervention (soil and water conservation): keyline system, field bunds, trash lines, grass trips, micro catchments, contour ridges, retention ridges, terraces.

As mentioned before, the method or combination of methods used to recharge an aquifer depends on the local conditions. A global MAR site inventory can be found on the International Groundwater Resources Assessment Centre (IGRAC) website (https://www.un-igrac.org/), which provides general information and case studies from different locations in different climate zones (IGRAC UNESCO-IHE 2015). Case studies of MAR sites in Europe are given in detail by Hannappel et al. (2014). Additional examples are provided by van Steenbergen, Tuinhof & van Beusekom (2009), where descriptions of MAR sites, applied techniques and impacts are compiled.

Common topics discussed by numerous authors (Dillon et al. 2009; ed. Fox 2007; Gale & Dillon 2005; Vanderzalm et al. 2015) in reference to operational issues of MAR systems are: clogging, poor recovery of recharge water, interactions with other groundwater uses, and managing purge water, basin scraping and water treatment byproducts. Special emphasis is put on the clogging of the infiltration medium. This may have an impact on the infiltration rate, the quantity and quality of recovered water and the economic feasibility of the recharge method applied. Clogging occurs as a result of physical, chemical or biological processes. Pre-treatment of the water for recharge can reduce the potential clogging problem. Dillon et al. (2009) give a detailed description of the types of clogging and their causes, as well some methods for management and tools for predicting clogging. Bekele et al. (2015) developed a detailed evaluation and documentation of the clogging processes and water quality impacts that focused on two MAR methods: buried galleries and SAT.

Aquifer Recharge in Arid and Semi-Arid Regions

In arid and semi-arid regions, subsurface storage of water becomes a major alternative over surface storage due to high evaporation rates. Subsurface storage enhances aquifer recharge to overcome dry seasons and droughts. The upper meters of soil in shallow aquifers in combination with low-cost technologies can provide a water buffer (van Steenbergen, Tuinhof & van Beusekom 2009). Generally, shallow aquifers are unconfined and under atmospheric pressure, which results in faster recharge (Smith et al. 2016). In arid and semi-arid regions, groundwater storage may be the only source of freshwater during dry seasons and persistent droughts.

Gale & Dillon (2005) discuss how MAR methods provide a cheap form of safe water supply for towns and small communities. Their research suggests that a local water supply reduces investment in long piping systems and high energy costs for pumping can be avoided. Mutiso (2002) describes some of the water harvesting techniques for recharge applied in Kenya, which may also be applicable in other arid and semi-arid regions. Among them are: trash lines, grass strips micro catchments, contour ridges and bunds, retention ridges, terraces, earth dams, pans and sand dams. Gale & Dillon (2005) provide some examples of the application of MAR schemes in arid and semi-arid regions, among others: floodwater spreading, leaky dams, check dams, injection boreholes, interdune filtration, rainwater harvesting, irrigation channels, bank filtration or injection wells.

MAR methods use the aquifer's potential to receive enhanced recharge for storage and treatment of water. The use of MAR methods as part of a major water management plan not only contributes to meeting the water demand, but also improves the quality of the water supply. If abstraction rates are controlled, the restoration of the groundwater balance can be supported.

Conclusion

The recharge process of an aquifer is part of the hydrological cycle. The geological formation of an aquifer provides subsurface groundwater storage, which can function as a water buffer to bridge human water requirements during dry seasons. In some situations, it is even possible to store enough water to compensate for several failing rainy seasons – a situation that is not at all uncommon. Sustainable water management must comprise a balance between groundwater abstraction rates and aquifer recharge conditions over the years. Aquifer recharge depends on the subsurface geological formation, but also on the surface catchment characteristics, which affect the infiltration rates into the aquifer. Soil erosion can dramatically reduce the infiltration rates.

There is a wide range of options to enhance the recharge of an aquifer by either natural or artificial methods. The selection of the correct method or their combination will strongly depend on the site characteristics, the sort of water source for recharge and the end-use of the recovered water. In addition, costs and capacity for implementation need to be considered. Natural recharge of an aquifer can be enhanced by the implementation of EbA measures or permaculture techniques. However, by the integrated use of natural recharge techniques combined with artificial techniques, it is possible to protect or recover groundwater resources.

MAR methods can artificially increase the availability of water for the recharge of an aquifer. These methods can be applied either in rural or urban areas. MAR methods have the purpose to improve the quality of groundwater sources, recover recharge yields, prevent saline intrusion or other contaminants from getting into the aquifer, prevent land subsidence, recycle stormwater or treat wastewater, among others. Five main groups of MAR schemes can be identified: spreading methods, in-channel modifications, deep systems, filtration systems and rainfall systems.

Especially in arid and semi-arid regions, the application of MAR methods can have extraordinary benefits for the supply of drinking water and irrigation purposes. Several of these methods can be applied on a small scale at low cost and still have a great potential to store and treat water. This will often require coordinated activities of all villagers and farmers. In vulnerable regions, sustainable water management that applies artificial recharge techniques and methods for the restoration of natural infiltration may warrant the security of the water supply through dry seasons and droughts.

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Literature Review on the Rainwater Harvesting Research Landscape, In-Situ and Domestic Design Examples and Best Practice Projects in China and Brazil

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'Rainwater harvesting system has been regarded as a sound strategy of alternative water sources for increasing water supply capacities.'

(Su et al. 2009, p. 393)

Please cite as: Lasprilla Pina, C & Kassaye, RB 2017, 'Literature Review on the Rainwater Harvesting Research Landscape, In-Situ and Domestic Design Examples and Best Practice Projects in China and Brazil' in R Schaldach & R Otterpohl (eds), RUVIVAL Publication Series, vol. 2, Hamburg, pp. 19-35, <http://nbn-resolving.de/urn:nbn:de:gbv:830-88217957>.

Abstract

Only around one per cent of water is currently easily accessible for human needs. This has encouraged a search for solutions to fight local scarcity. One proposed answer is the collection of rainfall through Rainwater Harvesting (RWH) methods. The process consists of collection, storage and local use of rainwater. RWH systems can be sub-categorised based on the catchment size, runoff transfer distance, source of water, mode of storage, mode of usage and other details. An integral part of human settlements and farming for thousands of years, RWH methods present a number of benefits if suitably applied, namely, diversification with better yields that can increase income, create a number of jobs, reduce poverty, promote sustainable forms of agriculture, mitigate climate change and spread year-round vegetation cover as an erosion precaution. However, the benefits of these systems come with certain challenges: most notably the provision of a high quality and sufficient quantity of water with feasible measures. In this paper, challenges have been divided into technical and quality issues, legislative, economical aspects and lack of awareness. In order to help tackle the above mentioned challenges, as well as to promote and scale-up the usage of RWH systems, best practice examples from the Gansu Province case in China and the north-eastern region of Brazil are presented.

Keywords*: rain-fed agriculture, rainwater catchment, rainfall, rainwater harvesting, water scarcity*

Introduction

Water may seem abundant, but less than one per cent of the world's water is readily accessible for human needs. A 2011 FAO study 'The State of the World's Land and Water Resources for Food and Agriculture: Managing Systems at Risk' raises questions on water availability, as it claims that water demand has been increasing worldwide at a rapid pace, resulting in a gap between support and fulfilment of human needs, and actual supply and access to high quality water, especially in low to medium-income countries. This increase in demand has been caused by demographic changes, socio-economic factors, and changes in agricultural practices, in addition to climatic variation (Fewkes 2012; Lee et al. 2016). Thus, improvements in water use efficiency are required to address water scarcity, and therefore water stress, as well as to avoid possible conflicts that may arise from the given stress. To fight water scarcity, one proposed solution are water harvesting practices, and more specifically Rain Water Harvesting (RWH).

RWH methods represent access to water often through decentralised systems, which translates into direct user management. This empowers households and communities in the decision-making processes and systems' usage (König 2009). The benefits of RWH systems are not limited to the provision of drinking water, but their positive effects have direct and indirect consequences for the social, economic, and environmental spheres of the users' livelihood, communities, and ecosystems. These effects are a result of synergies between human well-being, development and improvement, and ecosystem regeneration and maintenance (Barron 2009; Dile et al. 2013; Falkenmark et al. 2001; Sanches Fernandes, Terêncio & Pacheco 2015; Su et al. 2008; Vohland & Barry 2009).

RWH as an inclusive answer to water scarcity is since millennia an integral part of human settlements and farming: from small dams to runoff systems for agricultural processes, to water reserves for drinking purposes (Mbilinyi et al. 2005). The literature presents examples of RWH techniques that date back as far as over 5000 BC in Iraq (Falkenmark et al. 2001), 3000 BC in the Middle East (Barron 2009), and 2000 BC in the Negev desert in Israel, Africa, and India (Fewkes 2012). Despite their long history, RWH have been displaced in the last century by other technologies that have taken the lead in water management. Some of them excluded indigenous knowledge, while others did not consider social, geological and economic backgrounds of the sites, making them unsuccessful or possible only with a high environmental and/or economic cost. Thus, in the last couple of decades, RWH has regained importance as a holistic approach for sustainable growth (Barron 2009; Lee et al. 2016; WWAP 2016; Zhu 2008). Current best practices can be found worldwide, in Japan, Germany and Australia as leading exponents for urban RWH systems, and China, India and Botswana for rural systems. Nonetheless, RWH systems still face challenges that need to be addressed before scaling-up: water quality control, direct involvement of government and public authorities in form of legislations, financial support, spreading of knowledge and the commitment of final-users. Since the 1970s, the literature on RWH has grown in depth and understanding of the importance of specialising systems for each given economic, social, geological and environmental context. This specialisation has also created specific categories and sub-categories of RWH systems according to the study approach taken by the researcher. This literature review tries to provide a general overview of the benefits and challenges of implementing RWH systems, while illustrating two best practice examples, the Province of Gansu in China and the north-eastern semi-arid region of Brazil, to create a better understanding of RWH methods, while highlighting the importance of water for sustainable development.

Categorisation of RWH Systems

Rainwater harvesting is composed of a wide range of technologies, from high to low-tech ones and from high to low-cost, depending on the area of application and space they cover (Barron 2009). RWH usually consists of three main components: a catchment area, where the rainfall is collected, a storage facility, where the water is stored to be used immediately or later, when water is scarce, and a target system like sanitation facilities or irrigation systems. Generally, RWH systems cater for human consumption and supplementary water-related activities, especially in times of draught (Fewkes 2012).

Categorisation Based on the Catchment Area Size

The richness of RWH technologies and components developed also a variety of classification depending on the focus given by the researchers.

For instance, for agricultural purposes, the 1991 FAO study 'A Manual for the Design and Construction of Water Harvesting Schemes for Plant Production' divides RWH into 3 major categories, classifying them according to the catchment area size and the runoff transfer distance into: internal or micro-catchment rainwater harvesting, external or macro-catchment rainwater harvesting, and flood water harvesting. Other authors include an initial division to these three categories called in-situ rainwater harvesting, or soil and water conservation, as its function is to capture and store rainfall directly in the soil, helping to increase soil infiltration and regeneration (Hatibu & Mahoo 1999; Ibraimo & Munguambe 2007; Mbilinyi et al. 2005; Mzirai & Tumbo 2010). However, Prinz and Malik (2002) exclude the third category of floodwater harvesting in their categorisation of RWH. Internal or micro-catchment rainwater harvesting, are also called within-field catchment systems and refer to systems where rainfall is collected in small catchment areas ranging between 1 to 30 m according to FAO (1991). Oweis, Prinz and Hachum (2001) increased the threshold to up to 1,000 m^2. The runoff from these systems is stored directly in the soil, and there is usually no provision for overflow. They cater directly to trees, bushes, or annual crops. Examples of these systems are contour bunds, contour ridges, and semi-circular bunds, among others (Critchley & Siegert 1991; Dile et al. 2013; Falkenmark et al. 2001; Ibraimo & Munguambe 2007).

External or macro-catchment rainwater harvesting is correspondingly known as a long slope catchment technique. Different to micro-catchment systems, it involves large areas to collect runoff from 30 to 200 m, and is able to overflow excess water. Moreover, the distance to the target systems is much larger (Critchley & Siegert 1991; Falkenmark et al. 2001), which, as Ibraimo and Munguambe (2007) argued, makes this approach much more labour intense. Another major difference is that runoff capture is lower compared to what is collected in micro-catchment systems (Oweis, Prinz & Hachum 2001). Examples of this system are: trapezoidal bunds and contour stone bunds.

Floodwater harvesting is also known as water spreading and sometimes spate irrigation. Oweis, Prinz & Hachum (2001) categorise it together with external or macro-catchments systems as they share similar characteristics, such as the provision of overflow and the presence of turbulent runoff; however, their catchment area is far larger, covering several kilometres of distance (Critchley & Siegert 1991). Examples of this system are: permeable rock dams and water spreading bunds.

Oweis, Prinz & Hachum (2001) further divide their target system to include a domestic category. To do this, they present a further sub-categorisation of micro-catchment systems, which includes land catchment surfaces already mentioned in 1991 by the FAO in 'A Manual for the Design and Construction of Water Harvesting Schemes for Plant Production' and add non-land catchment surfaces, including rooftop systems, courtyards and other impermeable structures. They further explain that this type of collection is mainly used for domestic purposes, although if the quality of the water is low, it could be also used in agriculture practices or to support home gardens.

Categorisation Based on the Water Source

The United Nations Environment Programme (UNEP) and Stockholm Environment Institute (SEI) published a study titled 'Rainwater harvesting: a lifeline for human well-being' (Barron 2009), which classified RWH based on the source of water (catchment area) into: in-situ and ex-situ technologies, and manmade/impermeable surfaces (Figure 1). This division is founded on a proposal made by the Stockholm International Water Institute (SIWI).

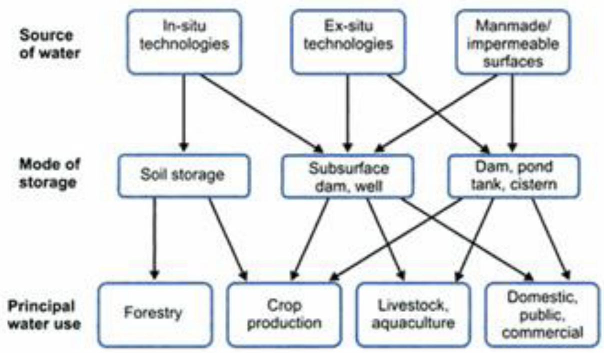

Figure 1 Schematic of RWH Technologies Based on Source of Water, Storage Mode, and Principal Use (Barron 2009)

Other authors (Cortesi, Prasad & Abhiyan 2009; Falkenmark et al. 2001) follow this division, but use only the first two categories, in-situ and ex-situ for their analysis.

In both cases, the main objective of in-situ systems is to reduce runoff water by enhancing soil infiltration (Barron 2009; Helmreich & Horn 2009; Mbilinyi et al. 2005). Water is collected directly where it falls and is stored in the soil (Cortesi, Prasad & Abhiyan 2009). Terracing and living barriers are examples of this collection method.

Ex-situ technologies, differently to in-situ systems, store runoff water externally to where it got captured (Barron 2009; Helmreich & Horn 2009). Examples of these systems are pavement collection, ponds, and/or swales.

Categorisation Based on the Mode of Storage

Once the rainfall is collected, it requires a storage system, thus the UNEP and SEI study (Barron 2009) also provides a subcategory to divide RWH in terms of the mode of storage. These systems can be located externally or underground. Some of the main forms used are: micro-dams, earth dams, farm ponds, sub-surfaces, sand dams or check dams and tanks (Falkenmark et al. 2001). Fewkes (2012) mentions that the storage capacity has a relevant economical and operational connotation for the system. When referring specifically to tanks, the material of construction – plastic, concrete or steel- helps to determine their durability and cost. Falkenmark et al. (2001) also discussed a further subdivision in terms of the time the water remains stored in either of the previous systems.

Finally, the term Domestic Rainwater Harvesting (DRWH) has been used by authors such as Helmreich & Horn (2009), as a category of RWH that collects water for domestic purposes. It is mainly found in studies that analyse rising water demands due to urbanisation in order to develop coping strategies (Mwenge Kahinda, Taigbenu & Boroto 2007). The collection in DRWH can be carried out by different methods: roofs, streets, and ponds, among others.

To summarise, RWH systems can be categorised in different manners. This diversity of categories helps to portray the ability of RWH systems to adapt to different needs, budgets, and spaces to be covered, in addition to providing researchers with a more exact terminology for their analysis. The categories can be determined by catchment size, runoff transfer distance, source of water, systems of storage and usage, among others.

RWH Design Techniques

As described previously, there is a variety of usages and forms of RWH systems, which reflect their dynamic and flexibility (Barron 2009). This section of the paper will help to illustrate two design techniques of RWH systems: keyline systems, which are used for agricultural purposes, and rooftop catchments, as an example for domestic water provision.

The final decision on which design technique should be implemented will depend on the specifics of the area where it will be installed.

Keyline Rainwater Harvesting Systems

Keyline systems are a holistic approach of rainwater harvesting used in agriculture. Their main goal is to increase soil fertility by increasing the total organic matter content within soil. The system was developed in Australia in the 1950s by P. A. Yeomans, and is based on natural topography, contours, and slopes. Figure 2 illustrates how the contours are used to control the water flow by directing it towards the centre of the ridge.

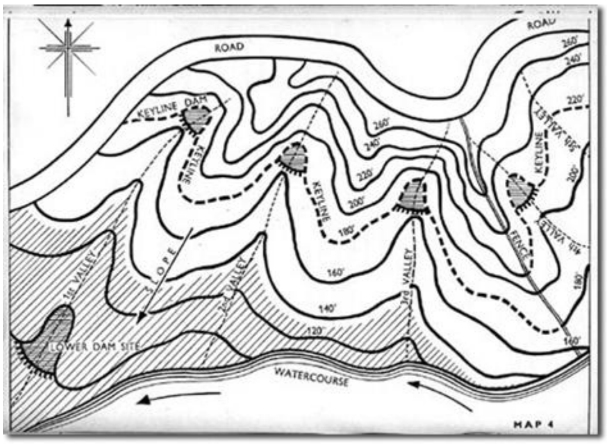

Figure 2 Keyline Systems

Keyline systems have proven to be a complementary tool for agriculture practices; nonetheless, there is still a need for further research to support them. More abundant scientific literature exists on rooftop systems, supporting their usage and a longer tradition as domestic water service providers. However, there are still elements that need to be evaluated, such as the water use for irrigation in green roofs.

One of the most powerful tools that keyline systems offer is the construction of swales or ditches with a small gradient away from gullies, thus bringing overflow runoff in the erosion gullies into the shoulders. Yeomans (1954; 1958; 1971) gives full guidance on where and how swales and small dams should be implemented with the given features of topography. Although the system has received little scientific support (Ferguson 2015; Toensmeier 2016), it is popular with farmers, who regard it for its soil organic matter improvement properties (Toensmeier 2016). Rancho San Ricardo in Mexico, depicted in Figure 3, provides an example of its application.

Figure 3 Application of the Keyline Design Technique in Rancho San Ricardo, Mexico

The main exponents of this implementation are David Holmgren and Bill Mollison, who developed the framework for a new agricultural ecosystem called permaculture, based on the adoption of many concepts of the keyline plan (Ferguson 2015). The reasons behind this adoption are the benefits a keyline system offers, some of which can be seen immediately, while others have a long-term result. These can be enumerated as: reduction of soil erosion, restoration of subsurface hydrological flows and aquifers, abatement of floods and droughts and reduction of sediments carried by rivers, among others (Feineigle 2013).

Rooftops: Domestic Rain Water Harvesting Design Technique

Rooftops are excellent collectors of rainfall for domestic usage. Fewkes (2012) states that out of the different methods currently used, the most common technology for collection are rooftops. To take full advantage of rooftop systems, it is important to pay attention to the selection of construction material, sloping of roofs, maintenance, pollution, and extra water usage. For instance, a study by Helmreich & Horn (2009) says that roofs tied with bamboo gutters are not suitable, due to potential health problems. Their study further expressed that although zinc and copper helped to channel water easier than other systems, it is necessary to pay attention to possible pollution by metallic paint or other coatings, due to the heavy metal concentration. Moreover, in the last couple of years there has been an increased usage of green roofs, as they provide an extensive range of benefits widely known in the literature, namely, sound insulation, urban heat effect reduction, CO_2 reduction, as well as diversification, and maintenance of biodiversity, among others (König 2009). Nonetheless, when it comes to their analysis as RWH systems, it is relevant to count water use for their irrigation, which, as An et al. (2015) pointed out, is a factor that is usually not considered. Moreover, the best roof system will depend on many factors, such as weather and rainfall. However, those with smooth sloping roofs harvest 50 % or more than flat rough roofs (Mun & Han 2012). In addition, Fewkes (2012) recommends those, which are chemically inert, such as slates.

RWH Challenges

RWH systems face several challenges. The most important is the provision of good water quality for the drinking water supply. In addition, there are other challenges that have prevented large scale RWH implementation: technical and quality issues, legislative, economical aspects and the lack of awareness.

Technical and Quality Issues

Health concerns present the main concern when it comes to implementing RWH systems. Certain case studies attribute low water quality to a lack of monitoring (WWAP 2016), which represented, for instance, high numbers of cases of diarrhoea in a project implemented in Thailand (Salas 2009). Thus, authors with practical experience, as König (2009), have recommended maintaining the collecting surfaces and storing facilities free from pollutants and mosquito breeding – to avoid cases of malaria, dengue and other diseases. Another suggestion came from Fewkes (2012), who argued for storing facilities designed to overflow at least twice a year to facilitate particle removal. Moreover, in order to improve water quality and reduce water pollution levels, a study by Helmreich and Horn (2009) promoted solar and membrane technologies and slow sand filtration systems. These methods allow water disinfection, and microbiological quality improvement. Furthermore, the most important technical challenge is rainfall variability (König 2009; Salas 2009; Sharma 2009). Currently, there are technologies that try to measure and predict rainfall, and thus try to improve the system design, however, this is not an easy task. Sharma (2009 p. 24) goes as far as to name this 'the greatest water challenge'.

Finally, further research on water access to downstream users is needed (Dile et al. 2013; Falkenmark et al. 2001), as it is believed that harvesting water might result in a decreased downstream (Barron 2009). Specifically, a case study carried out in the Saurashtra region, India, showed that although RWH systems have benefits, a rapid unmonitored adoption could potentially affect downstream users (Cortesi, Prasad & Abhiyan 2009). Given the above, increasing infiltration, and thus rising aquifers is preferable over direct storage. At the same time, refilling aquifers will help the whole downstream system to have a balanced water supply. Nonetheless, aquifer recharge is only possible on a certain scale, on community or catchment level, and mostly not very efficient on an individual basis with small patches of land.

Legislative Issues

A UK study shows that there is a negative impact on technology implementation, when there are low or no water quality standards in place, and/or no action undertaken by public health associations (Fewkes 2012). The legislation to back up the development and implementation of RWH systems is lacking in most countries, and, for example, in rural areas of South Africa DRWH is even illegal (Mwenge Kahinda, Taigbenu & Boroto 2007). This absence of legislation has rendered an insignificant transfer of knowledge and best practices among countries. Sharma (2009) argues that one reason for this is the fact that structural and institutional functioning of governments in place do not relate to the actual need of local institutions. Active policy support should be brought together with technical know-how and capacity building, as the UNEP and SEI study (Barron 2009) suggested. Moreover, according to Sanches et al. (2015), the most important challenge for RWH systems to be implemented in a higher number is the lack of inclusion within water policies. Without government intervention, citizens lack awareness of the systems, and thus do not implement them nor force the creation of laws that promote, among others, financial incentives for RWH (Lee et al. 2016). One way to tackle this is to mainstream RWH systems in national policies, and, as suggested by the UNEP and SEI study (Barron 2009), to include rainfall as part of water management plans, as has been done in Germany and Australia, which are current examples of best practices.

Economic Issues

There is a need for financial incentives to increase RWH system usage, i.e. for initial investment subsidies by local governments (König 2009; Fewkes 2012). For instance, a study by the Australian Bureau of Statistics (ABS) established that the main reason for not having installed a rainwater tank lay in the perception of a high cost (Rahman, Keane & Imteaz 2012). Another example is a study carried out by Roebuck (2011), which shows that in order for DRWH to be cost effective in urban areas, there is a need for a type of household allowance. Moreover, another relevant economic aspect is a low water tariff. For instance, in Malaysia, as it was presented by Ern Lee et al. (2016), the installation cost of RWH systems is much higher than local water tariffs, resulting in a negative cost-benefit trade. Thus, authors such as König (2009), recommend providing subsidies to cover the initial step of installation, as was the case in the Gansu Province in China. At a larger scale, specifically for companies, Fewkes (2012) proposed a tax incentive, which enhances the usage of these systems within companies.

Lack of Awareness

Financial incentives should go hand in hand with raising awareness of the systems' potential for the users. As Rahman, Keane & Imteaz (2012) explained, users do not welcome these systems, or lack the motivation to implement them, as they do not see benefits over the long term, or in general there is no involvement (Helmreich & Horn 2009). Another perspective was presented by a case in Malaysia, in which water abundant perception has prevented households from seeing the need to implement these technologies in their homes (Lee et al. 2016). Or as Fewkes (2012) portrayed it, possible users simply lack knowledge and access to information on how the water cycle and water recycling works, and thus do not understand the finite aspect of water availability. Thus, to initiate changes in users' mind-set, it is important to raise awareness of the benefits these systems provide, the finite aspect of water as a natural resource, and the need to create a connection between governments and local authorities, in terms of actions within a community.

In order to overcome these challenges, governments need to work together with local communities to understand their direct needs and to embed local knowledge. The first step towards this is the inclusion of rainfall in legislations, followed by a promotion and increase of awareness of the systems' functioning and utility, as part of school and university curricula. These are essential for the propagation of the systems at a wider scale and for maintaining system standards, resulting in better water quality and no-health risk for users.

RWH Benefits

Best practices can be found in rural and urban areas around the world, as the application of RWH systems provides synergies between human well-being, development and improvement, and ecosystem regeneration and maintenance. These synergies translate into direct and indirect social, economic, and environmental benefits.

In terms of social gains, the UNEP and SEI study carried out by Barron (2009) points out the importance of RWH to provide communities with an opportunity to develop their religious and spiritual rituals. In addition, Sharma (2009) states an improvement in communication between residences and the study by the UNEP (Barron 2009) added the progress of equity and gender balance in these communities. Sharma (2009) describes the economic gains as the increase in the number of jobs available and formation of microfinance and working groups, which influenced poverty reduction (Dile et al. 2013; Falkenmark et al. 2001) and resulted in an increment on farmers' income (Vohland & Barry 2009), benefiting the achievement of the Millennium Development Goals (Barron 2009). Examples come from cases in India and China, where the installation of RWH systems has provided farmers with added value by diversifying their products through the inclusion of vegetables and fruits (Sharma 2009; Sturm et al. 2009; WWDR 2016), or livestock (König 2009). For example, in India, RWH implementation helps farmers to move from small grazing animals – sheep, goats – to large dairy animals – buffaloes, cows – (Sharma 2009), due to a larger vegetation yield, reduction in soil erosion and more water being available for livestock management. Finally, at the ecosystem level, the implementation of RWH systems has helped available species to diversify and vegetation to spread (Sharma 2009; Zhu 2008). Salas (2009) even goes so far as to argue that RWH methods are key allies for climate change adaptation and mitigation. In addition, they help to improve soil conservation, reduce cases and/or intensity of floods, and increase ecosystem biodiversity (König 2009; Sanches Fernandes, Terêncio & Pacheco 2015; Su et al. 2008). In countries such as Germany, Australia and Japan the implementation of DRWH has resulted in a reduction of the so-called urban heat island effect and has promoted a reduction of CO_2 production by cutting back the use of energy (Salas 2009). Furthermore, RWH systems have advanced and increased biodiversity through the implementation of green roofs and green facades and have allowed the recomposition of soil through infiltration systems.

Hence, although the most vital effect of these water efficient technologies has been to enable access to drinking water, they have additional indirect positive effects on: users' livelihood, communities, and ecosystems. The key idea behind these systems is that they are decentralised from the main water supplies, which empowers users and provides them with more autonomy in their decision-making. In addition, local knowledge, skills, materials, and equipment are used, which makes the RWH systems easy to build and maintain (Helmreich & Horn 2009).

Best Practice

RWH technologies have been developed differently, regardless of their collective similarities. Countries with successful cases still observed major challenges, such as system scale-up and understanding the effects on the downstream users (Dile et al. 2013; Falkenmark et al. 2001). Nonetheless, these examples stand as best practices, which, if properly analysed and understood, could be replicated in places with similar environmental, social, and economic conditions. Two best practices are presented: one set in the Province of Gansu in China and another one in the north-eastern region of Brazil.

China: the Revival of a Millenary Technique

Although China has a more than 4,000 years long history in the usage of RWH methods (Falkenmark et al. 2001), it was not until the1980s that a joint strategy between the Provincial Government and the Gansu Research Institute for Water Conservancy (GRIWAC) with the aim to secure economic stability of a whole region, caused a mega-scale reproduction of the systems in the country (Falkenmark et al. 2001; Woltersdorf, 2010; Zheng; Zhu 2008; Zhu et Li 1999). The project was named '121 Project', and it consisted of a simple RWH system: one water collection field subsystem, two storage subsystems and land to plant cash crop, with a water supply and irrigation subsystem (Zhu 1998; Zhu 2008). The region was chosen due to its economic, social and environmental settings: extreme conditions of dryness, water shortage, low agricultural productivity, soil erosion, high poverty level, fragile ecologic environment and low yield-investment ratio (König 2009; Zhao et al. 2009; Zhu 2008). The emphasis was set on water as the backbone of development, as agriculture is the main source of income and the region is totally dependent on natural and irregular rainfall (Zhu 2008). The introduction of the methodology was an easy task, as it was based on an improved tradition of the local people to harvest rainwater for their daily use. Their previous system, however, was mainly based on natural soil, so collection efficiency was very low (Falkenmark et al. 2001; Zhu 2008).

Now, more than 30 years later, the region went from its local government having to dispatch trucks to transport water from far away in order to supply drinking water to more than 1.2 million people meeting their daily water needs through decentralised systems (Zhu & Li 1999). In addition, the project's main purpose still resonates: to enhance the utilisation of rainwater efficiency to promote economic and social prosperity (Zhu 2008). The success of the '121 Project' made it replicable in regions with similar weather conditions – semi-arid, drought prone, and sub-humid – in China (Woltersdorf, 2010). In fact, seventeen provinces in China have adopted rainwater harvesting, providing around 15 million people with drinking water and irrigating around 1.2 million ha of land – by building 5.6 million tanks with a total capacity of 1.8 billion m^3 (König 2009; UNEP 2001).

Brazil: Integrating RWH Systems in the North-East

The semi-arid north-eastern region of Brazil has faced droughts and loss of crops due to insufficient rainfall (Gnadlinger 2007). In this region, annual rainfall can vary from 200 to 1,000 mm (UNEP 2001), being concentrated within a few weeks during a year, and accompanied with a high rate of evaporation – 3,000 mm a year (König 2009). In addition, Brazil has an uneven distribution of freshwater sources. This situation made people of the north-east collect rainfall in hand-dug rock and river bedrock catchments (UNEP 2001) to have some access to water. Nonetheless, this traditional collection lacks efficiency, comparable to the Gansu Province case, but this practice made it easier to introduce improved techniques. One example for this innovation pathway are the rainwater cisterns and subsurface dams introduced in the 1970s by EMBRAPA, the Brazilian Agricultural Research Agency. This pilot project counted on the support of NGOs, grassroot organisations and communities, which resulted in a successful but slow change of the situation in the region. Finally, in 1999 the idea of water management scaled-up, with the creation of 'Articulação Semiárido Brasileiro' (ASA), an association of more than 1,000 grassroot organisations. This changed the lives of over 5 million Brazilians (UNEP 2001) with the establishment of the Program 'P1MC – 1 Million Cisterns' and its complementary program 'P1+2 – One piece of land and two types of water' (Gnadlinger 2007). Both programs receive funding from governmental organisations and the private sector (König 2009). The goal of '1 Million Cisterns' is to supply drinking water to 1 million rural households, which would equal to 5 million people (Gnadlinger 2007). The water is collected in tanks made of pre-cast concrete plates or wire mesh concrete (UNEP

2001), and until August 2012, more than 500,000 cisterns were to be constructed by the project (ABCMAC 2000). Furthermore, its complementary program provides two sources of water, one for human consumption and the other for food production (Gnadlinger 2007).

The health improvements these two projects brought to the region, made people in the north-east see the benefits of RWH systems. These were mainly reached by enabling access to better drinking water quality, which also saved time for women, as they no longer had to cover long distances to fetch water for their households. Locals have accepted RWH systems and have come to an understanding for the need to manage water (König 2009). Consequently, the utilisation of RWH systems and maintenance are now an integral part of educational programs in this region and their usage is spreading in Brazil, especially within urban areas (UNEP 2001).

The key elements for the projects' success can summed up:

- Recognition of water as a key element for development by both government and local people,
- Direct involvement of government through financial support in form of subsidies,
- Decentralisation of solutions and systems,
- Direct participation of technical exchange by farmers/locals – i.e. inclusion of previous knowledge and compatibility with local lifestyle,
- Diversification of farmers' income-sources.

These two best practices show the importance of joint efforts between governments, communities and other stakeholders in order to implement legislations and policies, but also to ensure a sustainable implementation by embedding the maintenance of RWH in local communities.

Conclusion and Literature Gap

Rainfall as a water supply source and RWH methods are an integral part of human settlements and farming since thousands of years. This long tradition has been continuously present in rural areas, while it has just started to regain importance in urban areas. There are ample collection, storage and application methods to choose from and the local context should be considered to find the fitting system. These systems help then to overcome changes in water demand and challenges in water scarcity and variability of rainfall, while providing social, economic, and environmental benefits to users and ecosystems, in the form of income growth and product diversification, sustainable forms of agriculture, climate change mitigation and adaptation.

Current examples of best practices, namely Australia, Germany, and Japan for urban areas, and China, India, and Brazil, among others for rural ones showed, that the involvement stakeholders in local communities helped to implement RWH systems. Specifically, the Gansu Province case in China is an example of the recognition of water as a key element for development and was considered as the first step for adoption and spreading RWH technologies. Educational programs were considered to be crucial for understanding the water cycle and system usage. Further inclusion in the curricula of schools and universities is necessary for making RWH a standard approach in all land use designs – from domestic over on-site to catchment-wide systems. Subsequently, technical exchange and capacity building are needed to promote legislative changes. Thus, to fully gain the benefits of RWH systems, society still needs to overcome challenges on quality and technical aspects, legislation, lack of awareness among possible users, and presence of economical support. To overcome them, the main element claimed by most of the studies was to have rainfall embedded within local water policies, strategies and plans, and to create parallel to it an initial cost-sharing strategy among users and governments.

There is still a need for research, specifically in terms of downstream user effects, understanding and enumerating the differences of each system according to their context and to be able to properly transfer and scale them up. RWH are methods of adaptation to changes that are taking place right now and techniques that enhance ecosystems services. As scarcity of water continues to grow, so does the need to look for more sustainable methods working hand in hand with resource loops.

Picture Credits

Figure 1 (p. 22) Schematic of RWH Technologies Based on Source of Water, Storage Mode, and Principal Use
Source: Barron (2009, p. 12) this image may be reproduced in whole or in part and in any form for educational or non-profit purposes, without special permission from the copyright holder(s) provided acknowledgement of the source is made.

Figure 2 (p. 24) Keyline Systems
'Keyline.jpg' <https://commons.wikimedia.org/wiki/File:Keyline.jpg> by Rodquiros is licensed under CC BY-SA <https://creativecommons.org/licenses/by-sa/4.0/deed.en>.

Figure 3 (p. 24) Application of the Keyline Design Technique in Rancho San Ricardo, Mexico
'Rancho San Ricardo.jpg' <https://commons.wikimedia.org/wiki/File:Rancho_San_Ricardo.JPG> by Pablo Ruiz Lavalle is licensed under CC BY-SA <https://creativecommons.org/licenses/by-sa/4.0/deed.en>.

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A Review of Land-Based Rainwater Harvesting Systems for Micro and Macro-Catchments

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'Saving our planet, lifting people out of poverty, advancing economic growth ... these are one and the same fight. We must connect the dots between climate change, water scarcity, energy shortages, global health, food security and women's empowerment. Solutions to one problem must be solutions for all.'

Ban Ki-moon at the 66th UN General Assembly (2011)

Please cite as: Mehl, V, Oloruntoba, A, Gonzalez Alvarez, A, Möller, J, Ho, SY, Al Baff, A, Kassaye, RB 2017, 'A Review of Land-Based Rainwater Harvesting Systems for Micro and Macro-Catchments ' in R Schaldach & R Otterpohl (eds), RUVIVAL Publication Series, vol. 2, Hamburg, pp. 36-49, <http://nbn-resolving.de/urn:nbn:de:gbv:830-88217957>.

Abstract

In arid and semi-arid regions of the world, water is the limiting factor for food production; especially in areas where rain-fed agriculture dominates. Rainwater harvesting systems have the potential to provide a sustainable source of water, while helping to achieve food security and combat soil erosion and flood hazards, simultaneously, if designed correctly. Therefore, land-based rainwater harvesting systems are able to increase crop yields significantly. A variety of techniques for micro and macro-catchment rainwater harvesting schemes are reviewed, with emphasis on design factors which will ensure a functional system. However, in spite of the potential to increase agricultural productivity with the help of micro and macro-catchment rainwater harvesting, and thus food availability, the implementation of these techniques is not as widely distributed amongst farmers as it could be.

Keywords*: rainwater harvesting, food production, micro-catchments, macro-catchments*

Introduction

The importance of water to overall economic development, and life in general, cannot be overstated. Globally, trends like climate change, population growth, consumption habits, as well as land use are increasing the pressure on our dwindling water resources. Severe water scarcity is a problem which currently affects more than 40 % of the global population, and is projected to see a year-on-year increase (United Nations 2015). As a result, groundwater and surface water bodies become increasingly depleted and polluted. However, most conventional irrigation methods rely on these sources and perpetuate the vicious cycle. Furthermore, currently much of the global food supply is produced in rain-fed agriculture, which is very vulnerable to climate variations, especially in arid and semi-arid regions (Mekdaschi Studer & Liniger 2013). One way to enhance usage of available rainfall and make these regions more resilient is via the use of rainwater harvesting.

Rainwater harvesting refers to the deliberate collection of water from a catchment area, such as rooftops or land surfaces, and subsequent storage using physical structures, such as reservoirs or within the soil profile – it is a practice which dates back thousands of years, especially in arid and semi-arid regions, and has undergone a long period of refinement (Helmreich & Horn 2010; Mati et al. 2006; Sazakli, Alexopoulos & Leotsinidis 2007). A rainwater harvesting system typically consists of a catchment area, a reservoir for storage and a water delivery system.

There are many different classifications of rainwater harvesting systems. This paper will classify these systems into roof-based and land-based rainwater harvesting methods. Rain-water harvesting for domestic use includes roof, street or courtyard rainwater harvesting systems (Hajani & Rahman 2014). Land-based systems, which can be further sub-divided into micro and macro-catchment rainwater harvesting systems, are usually used for irrigation of crops (Assefa et al. 2016) and groundwater recharge (Mekdaschi Studer & Liniger 2013). Rainwater harvesting, besides providing a source of water, can also be used for stormwater management in areas with a high and unpredictable rainfall rate, for reducing flooding (Guo & Mao 2012). Additionally, it can be applied as an erosion control mechanism (Mekdaschi Studer & Liniger 2013).

The aim of this literature review is to review techniques using rainwater harvesting as a method of enhancing crop yields in rain-fed agriculture while reducing soil degradation and inducing groundwater recharge in water scarce regions.

It is organised as follows: the first chapter introduces techniques of micro-catchment rainwater harvesting and discusses, which design parameters must be considered in the planning process. The second chapter reviews rainwater harvesting in macro-catchments and presents its main characteristics. Furthermore, delineation from other water harvesting practices is discussed before the benefits and drawbacks of macro-catchment rainwater harvesting are listed. Subsequently, a summary of selected techniques for macro-catchments is provided.

Rainwater Harvesting from Micro-Catchments

Micro-catchment rainwater harvesting is a method used to increase the water availability for crops in rain-fed agriculture. Applications are effective in dry sub-humid, semi-arid and arid regions, and can effectively increase biomass production significantly in comparison to systems using no rainwater harvesting in the same region (Oweis & Hachum 2006).

Micro-catchment rainwater harvesting is a method of collecting surface runoff from a catchment area and channelling it to a cropped basin where a single tree, bush or row crops could be planted. The purpose of this is to store water in the root zone of the plants to provide enough water for consumption throughout the growing period (Boers & Ben-Asher 1982). The delivery of water from the catchment area to the cropped basin occurs over relatively short distances of less than 100 m, across mild land slopes (Ali et al. 2010), therefore usually on the land of one farm. Micro-catchment rainwater harvesting is especially suitable for semi-arid and arid regions (100 - 700 mm/year average annual rainfall) with highly variable rainfall during seasons (Anschütz et al. 2003; Mekdaschi Studer & Liniger 2013).

Numerous advantages of micro-catchment rainwater harvesting have been observed and documented, especially during the past decades. An increase in biomass production and the reduced risk of crop failures due to an increased efficiency of rainwater use allows small scale farmers to better cope with given conditions in the face of climate change (Malesu, Odour & Odhiambo 2007; Panday, Gupta & Anderson 2003). High runoff efficiency due to a short travel distance of water from the catchment area to the cropped basin (less than 100 m), reduces infiltration losses (Gowing et al. 1999). Furthermore, soil erosion and flood hazards are mitigated, while simultaneously nutrient-rich sediment is trapped in cropping basins (Mekdaschi Studer & Liniger 2013). Through deep percolation during rainy seasons, micro-catchments help to restore the regional water balance when they are applied over an extensive area (Boers, Zondervan & Ben-Asher 1986). Utilisation of micro-catchment rainwater harvesting for the provision of cattle water reduces the reliance on wells, which preserves the groundwater for use during the dry periods. The strategic placement of micro-catchments at proper distances from one another helps to distribute the human and animal population across the land, particularly in arid zones, instead of concentrating the population around wells (Boers, Zondervan & Ben-Asher 1986). Finally, cost efficiency and simplicity of micro-catchment installations and the use of local materials increase the receptivity and participation of the local population (Boers, Zondervan & Ben-Asher 1986; Helmreich & Horn 2010).

However, some disadvantages also need to be considered while planning a micro-catchment system. Potentially arable land remains uncropped, as catchment area. Therefore, when assessing the overall value of the system for a certain area, this opportunity cost must be considered (Gowing, Mahoo, Mzirai, & Hatibu 1999). Additional labour is required to keep the catchment area free of vegetation (Mekdaschi Studer & Liniger 2013). Systems can be damaged in exceptionally heavy rainstorms and in falsely implemented systems soil erosion may occur (Mekdaschi Studer & Liniger 2013).

In a nutshell, micro-catchment rainwater harvesting provides social, economic and environmental benefits. However, the disadvantages ought to be taken into account in the planning phase.

Design Factors concerning Micro-Catchment Rainwater Harvesting

The effectiveness of a micro-catchment depends on several environmental, socio-economic and strategic factors, which should be considered in the design. These include the size of the micro-catchment, average annual rainfall, crop requirements, catchment area to cropped basin ratio (also called CA/CB ratio), length/width ratio of catchment area and cropped basin, characteristics of the catchment and the application area.

Sizes of the micro-catchment in the range of 0.5 m^2 to 1,000 m^2 have been cited for trees, shrubs and row crops. As the size of the micro-catchment decreases, the percentage of runoff increases due to reduced losses as a result of infiltration (Boers & Ben-Asher 1982).

Annual average rainfall ranges from 100 mm to 650 mm in experimental micro-catchments, though a minimum annual rainfall of around 250 mm was recommended by Boers, Zondervan & Ben-Asher (1986). As rainfall varies from year-to-year, Anschütz et al. (2003) propose a design of micro-catchment systems per 'design rainfall', which should be slightly less than the average annual rainfall, although underestimating the rainfall by too much may cause water logging.

The micro-catchment design also depends on the crops/trees that are to be planted and the amount of water they need during the growing season (Anschütz et al. 2003). Furthermore, square, rectangular or circular micro-catchments are more appropriate for trees, while longitudinal micro-catchments that align with the contour lines allow for mechanisation, and are more desirable for field crops (Bruins, Evenari & Nessler 1986).

The recommended CA/CB ratios range from 1:1 to 10:1 (Anschütz et al. 2003; Boers & Ben-Asher 1982; Mekdaschi Studer & Liniger 2013; Schuetze 2013), depending on the climate, soil conditions and crop water requirement. However, care should be taken not to overestimate the CA/CB ratio, which could otherwise result in deep percolation losses, a need for higher structures (e.g. berms or stone barriers) to retain the runoff, and extended water ponding in the cropped basin. For this reason, Anschütz et al. (2003, p.26) developed a formula for determining the appropriate CA/CB ratio (for cropland):

$$\frac{CA}{CB} = \frac{Crop\ water\ requirements - Design\ rainfall}{Runoff\ factor\ x\ Design\ rainfall\ x\ Efficiency\ factor},$$

where the runoff factor is the percentage of rainfall generating surface runoff, the design rainfall is the rainfall quantity that the water harvesting system is designed to and the efficiency factor is the part of collected water that can be used by the plants (usually between 0.5 and 0.75). The optimum CA/CB ratio is influenced by the rainfall attributes, topography, and water-spreading ability of the soil. Catchment areas whose length/width ratio is too high could face challenges in earth-work and erosion. In addition, a cropped basin which is too long may not be entirely wetted (Boers & Ben-Asher 1982).

The catchment area must be capable of generating runoff from rainfall. According to Boers, Zondervan & Ben-Asher (1986), loess soils[1] are suitable for this function, while gravel or coarse sand are not (Bruins, Evenari & Nessler 1986). Boers, Zondervan & Ben-Asher (1986) argue that surface treatment such as smoothing and rock clearing can improve runoff generation, however Oweis & Hachum (2006) show that a compacted surface shows no significant difference in runoff, than a natural surface. Nonetheless, most authors (Anschütz et al. 2003; Boers & Ben-Asher 1982; Malesu, Odour & Odhiambo 2007) recommend the clearing of vegetation in the catchment area, as plants increase the infiltration capacity of the soil. Additionally, elevation differences are necessary in the landscape in order to allow the runoff flow and collect in the cropped basin.

The soil in the cultivated area should have a high infiltration and storage capacity, e.g. a deep loamy soil, for a high water availability for the crops (Helmreich & Horn 2010). To improve the infiltration and moisture retention capacity of the soil in the cropped basin, cover crops and/or mulching should be implemented (Anschütz et al. 2003).

While planning, it is essential to design the micro-catchment system according to the above named factors, otherwise the efficiency may be low or waterlogging and increased soil erosion may occur. Furthermore, Bruins, Evenari & Nessler (1986) highlighted the importance of tailoring the design and construction of the micro-catchment to best match the landscape contours on site.

Selected Techniques

In this sub-section, five of the most documented techniques of micro-catchment rainwater harvesting will be described. These are: strip catchment tillage (contour strip cropping), contour barriers, basin system/ negarim system/ meskat system, pitting, and semi-circular bunds.

The technique of strip catchment tillage (contour strip cropping) consists of alternating rows of cultivated crops with rows of uncultivated grass or cover crops. The function of the uncultivated rows is to act as catchments to collect rainwater and then drain it to the cultivated rows next to them. This is shown in Figure 1.

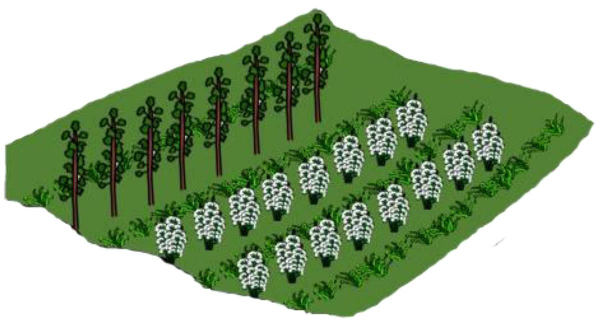

Figure 1 Schematic Diagram of Strip Catchment Tillage (Contour Strip Cropping)

Strip catchment tillage is reported to be applicable on slopes with a maximum of 2 % (Gowing et al. 1999) to 5 % gradient (Anschütz

[1] Loess soils are yellowish-brown unstratified sedimentary deposits of silt or loamy material which are usually silt-sized grains deposited by wind (Encyclopædia Britannica 2010).

et al. 2003), and the CA/CB ratio is typically less than or equal to 2:1. This technique is suitable for most crops and facilitates mechanisation (Gowing et al. 1999; Hatibu & Mahoo 1999).

Contour barriers are barriers constructed perpendicular to the slope along the contour lines (Figure 2).

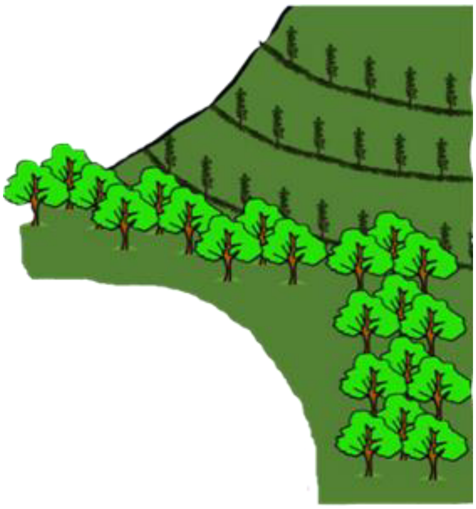

Figure 2 Schematic Diagram of Contour Barriers

Their function is to intercept rainfall as it flows down the slope and encourage infiltration into the soil. Simultaneously, they can be used as erosion reduction measures. They may be built from vegetative material (such as grass strips or trash lines), or mechanical materials (such as stone lines/earth bunds) (Anschütz et al. 2003; Gowing et al. 1999; Hatibu & Mahoo 1999).

Impermeable barriers such as earth bunds do not allow water to flow through them, but rather store water behind them. Semi-permeable barriers such as stone bunds, trash lines (built with straw, crop residues, brushwood) or live barriers (grass strips, contour hedges) are used to slow down and filter the runoff without ponding (Gowing et al. 1999). In most reviewed literature, contour barriers are usually applied on slopes with a maximum gradient of 5 %, although Mekdaschi Studer & Liniger (2013) claim contour bunds can also be applied on steeper slopes (up to 25 %) for soil as well as water conservation purposes. The CA/CB ratio is typically less than 3:1 (Hatibu & Mahoo 1999). Bund spacing varies from 2 – 5 m for earth bunds, to 15 – 30 m for stone lines (Gowing et al. 1999).

Basin systems are closed diamond or square basins (Figure 3) surrounded by low earth bunds, designed to contain and channel the water to the lowest point in the basin (cropping area), where trees are usually grown (Mekdaschi Studer & Liniger 2013).

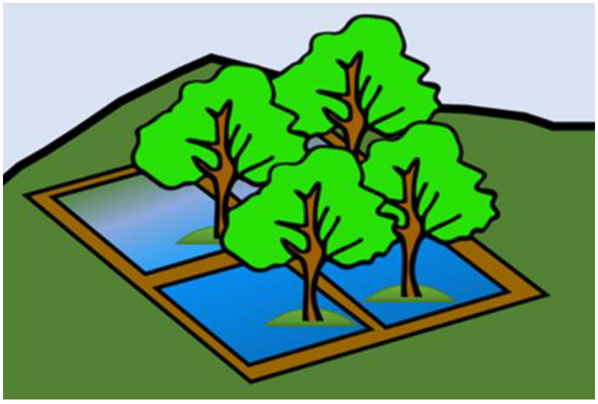

Figure 3 Arrangement of the Negarim System

To increase the production of runoff, vegetation in the catchment area is removed and soil is compacted. All revised sources agree that this method is relatively easy to apply on flat, as well as sloping, land. The CA/CB ratio typically ranges between 2:1 (Hatibu & Mahoo 1999) and 10:1, although in very flat and dry areas a ratio of 25:1 can be necessary. In addition to this, the basin area ranges from 10 m^2

to 100 m^2 (Gowing, Mahoo, Mzirai, & Hatibu 1999).

Semi-circular pits (about 30 cm diameter and 20 cm in depth for the case in West Africa) are dug into the ground and farm yard manure is added into the pits to serve as fertiliser. Seeds are sowed in the centre of the pits, and they experience constant growth due to the presence of water. This technique is suitable for areas where 350 – 600 mm of rainfall is available per year (Hatibu & Mahoo 1999). Experiments conducted by Zhang, Carmi & Berliner (2013) show that deep pits have less evaporation losses and are thus more efficient than shallow ones.

Semi-circular bunds consist of rows of semi-circular bunds arranged in a staggered manner (Figure 4).

Here, runoff is collected within the bunds of the upper rows and overflows into the subsequent bunds when they are full.

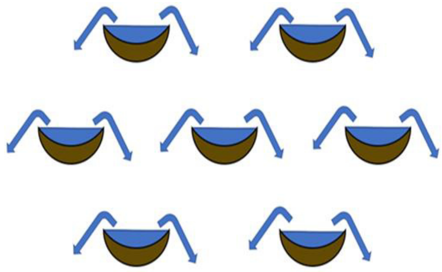

Figure 4 Schematic Diagram of Semi-Circular Bunds

Typical dimensions of each bund are semi-circles of 4 – 12 m radius, 30 cm height, 80 cm base width, 20 cm crest width and side slopes of 1:1.5 (Hatibu & Mahoo 1999).

In the following overview of the selection criteria for all described micro-catchment rainwater harvesting techniques is provided in Table 1.

Over the past forty years, micro-catchment rainwater harvesting has been a continuously present topic in research and practice. Several handbooks and guidelines concerning the implementation of rainwater harvesting have

Table 1 Selection criteria for the discussed micro-watershed harvesting techniques (Anschütz et al. 2003; Mekdaschi Studer & Liniger 2013)

	Rainfall (mm/a)	Slope (%)	Soil	Topography
Stone bunds	200 - 750	< 5	At least 1m deep and relatively permeable	Can be uneven
Contour strip cropping	200 - 750	< 5	At least 1m deep and relatively permeable	Can be uneven
Basin system	150 - 500	< 20	Free tree cultivation, the soil should be at least 1.5 - 2 m deep	Can be uneven
Earth bunds	200 - 600	< 25	Permeable soil types (e.g. loam)	Should be even
Pitting	350 - 600	< 2	Especially suited for degraded, crusted soil	Can be uneven
Semi-circular bunds	200 - 750	> 5	Any soil adequate for agricultural use	Should be even

been published (Anschütz et al. 2003; Malesu, Odour & Odhiambo 2007; Mekdaschi Studer & Liniger 2013) and many studies have been conducted concerning the improvement of efficiency of specific micro-catchment harvesting techniques (Farreny, Gabarrell & Rieradevall 2011; Gammoh 2013; Young et al. 2002; Zhang, Carmi & Berliner 2013). However, rainwater harvesting techniques are not as widely spread among farmers in semi-arid rural areas as expected. Young et al. (2002) argue that this can be attributed to the lack of technical knowledge, while others stress socioeconomic and policy factors, as well as a lack of community participation in the development and implementation of occurring projects (Oweis & Hachum 2006).

Rainwater Harvesting from Macro-Catchments

Rainwater harvesting from macro-catchments describes the utilisation of rainwater in an area different from the area in which rain falls. Other terms are macro-catchment water harvesting, water harvesting from long slopes or harvesting from external catchment systems (Mekdaschi Studer & Liniger 2013; Prinz 1996).

Macro-catchment harvesting is especially beneficial to buffer water shortages in arid, semi-arid and sub-humid zones with extended dry seasons and rainfalls that vary highly over time. In most cases, the harvested water is used for agricultural purposes. If there is a sufficient quantity of water with high quality, the harvested water can also be used for domestic purposes (Mekdaschi Studer & Liniger 2013).

Reviewing relevant literature on the topic, Mekdaschi Studer & Liniger (2013) concluded that the four main components of a macro-catchment water harvesting system are:

- catchment area,
- runoff conveyance system,
- storage system and
- application area.

The inclination of the catchment area varies from 5 to 50 % (Prinz 1996). Mekdaschi Studer & Liniger (2013) even include inclinations as low as 0 to 5 %. Often, the catchment area is located on a hill or mountain slopes, while the land cover can be manifold including cultivated or uncultivated land, roads or settlements. The size of the catchment area may vary between 0.1 to 200 ha, but usually does not exceed 2 ha (Mekdaschi Studer & Liniger 2013; Prinz 1996).

Runoff may be conveyed overland, or via rills, gullies or channels. Storage can be achieved in two ways: either the water is directly diverted onto the respective application area, and thus stored in the soil profile; or it is diverted into a specially designated reservoir, where it is stored until needed at the application area. Such reservoirs include open storage (e.g. in farm ponds or via different kinds of dams) or closed storage (e.g. via groundwater dams or in below-ground tanks and reservoirs) (Mekdaschi Studer & Liniger 2013).

The application area (mostly farmland) is either terraced or located on flat terrain (Mekdaschi Studer & Liniger 2013; Oweis, Prinz & Hachum 2001). The ratio between the size of the catchment area and the application area usually lies between 10:1 and 100:1 (Mekdaschi Studer & Liniger 2013; Prinz 1996).

The main differences between macro- and micro-catchment water harvesting are the size of the catchment area and its location (Mekdaschi Studer & Liniger 2013). In micro-catchment harvesting, runoff is trapped within the application area. As mentioned before, this is not the case in macro-catchment harvesting. Additionally, as opposed to the typical sheet or rill flow of micro-catchments, runoff of macro-catchments is usually turbulent and occurs as a channel flow (Mekdaschi Studer & Liniger 2013; Oweis, Prinz & Hachum 2001). Furthermore, macro-catchment systems have a lower runoff efficiency than micro-catchment systems, meaning that, relative to the size of the catchment area, in macro-catchments much less runoff can be captured (a maximum of 50 % of the annual rainfall) (Oweis, Prinz & Hachum 2001).

Mekdaschi Studer & Liniger (2013) point out that the distinction between floodwater and macro-catchment harvesting practices is often difficult and mainly depends on the size of the applied technology. However, floodwater harvesting is generally not considered as a practice of rainwater harvesting (Mekdaschi Studer & Liniger 2013; Prinz 2002), and is therefore not included in this literature review.

The main advantages of macro-catchment rainwater harvesting are (Mekdaschi Studer & Liniger 2013):

- Enhanced crop yields,
- Increased availability of water for domestic and agricultural uses throughout the year,
- Improved food security, as risk of crop failure during dry periods is reduced,
- Improved protection against soil erosion and flooding, as excess runoff water is captured.

While the main disadvantages are:

- Water stored in open storage facilities may dry out during dry season due to seepage and evaporation (Mekdaschi Studer & Liniger 2013),
- Open storage systems may also pose health risks, as animals could contaminate the stored water or disease vectors could breed in it (Mekdaschi Studer & Liniger 2013),
- Water rights of the various users within the catchment as well as up- and downstream of it might be restricted. To prevent this, an integrated approach including all stakeholders for the development of the watershed is recommended (Oweis, Prinz & Hachum 2001).

In summary, macro-catchment rainwater harvesting schemes have similar benefits as their micro-catchment counterparts. However, the macro-catchment is more complex due to its dimensions; thus a holistic approach is needed.

Selected Techniques

There are several techniques for rainwater harvesting from macro-catchments, which can be applied to rural areas. Gowing et al. (1999) and Hatibu & Mahoo (1999) present the following techniques, which are used in semi-arid regions of Tanzania: hillside systems, streambed systems, ephemeral stream diversion and storage systems.

Hillside systems are a way to improve the runoff catchment uphill areas by constructing cross-slope barriers and basins using earth –

just like micro-catchment contour barriers and basin systems – but with a greater external catchment area, as shown in Figure 5. An alternative to this technique is the construction of hillside conduits. These conduits intercept the runoff and convey it away from infertile land to provide additional irrigation to arable land.

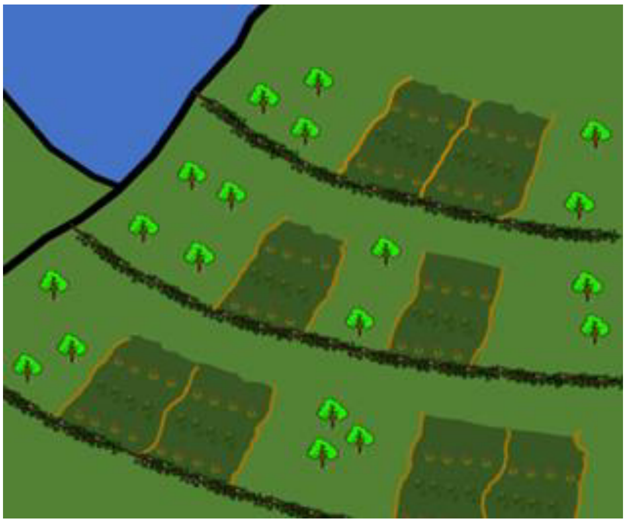

Figure 5 Hillside System Example

Stream-bed systems use barriers that can be made from permeable materials such as earth banks or stone dams. These barriers intercept the runoff and convey it across valleys, thereby enhancing infiltration and crop production.

As the name implies, ephemeral stream diversion systems divert water from an ephemeral stream and convey it to cropland. The system comprises a diversion structure and a distribution system. One system to distribute the water within the cropped land are cascades made from semi-circular or trapezoidal bunds (Figure 6). When the top basin is filled, the water cascades into the next sections. The second system divides the field into many enclosed basins, where the water is distributed

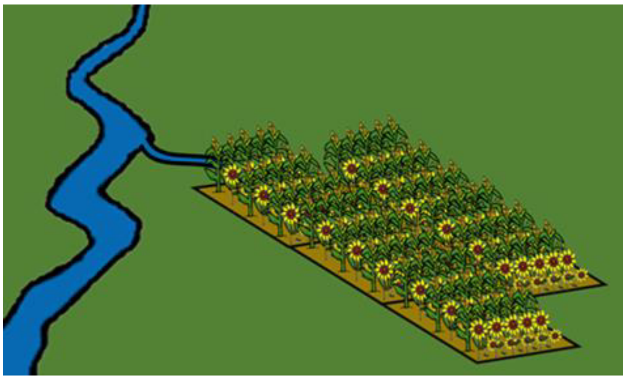

Figure 6 Ephemeral Stream Diversion

either by a channel or a basin-to-basin flow. However, a drawback of this system is the possibility of the diversion structures being washed away by intense flooding.

Storing the runoff obtained by the aforementioned techniques is important, as the runoff yield can be quite high. Reservoir systems and groundwater recharge are simple solutions for this. However, there are some drawbacks related to the use of reservoirs such as the evaporation and seepage of the stored water.

Studies on the Performance of Macro-Catchment Harvesting Systems

Different authors have investigated the performance of macro-catchment systems. The hydrological processes in-use in Tunisia at hillside systems, called 'tabia' are presented by Nasri et a. (2004), who cite a specific case where the runoff catchment for four tabias was investigated over four years. They concluded that the investigated system has many advantages, such as the decrease of flood risks due to a reduction in hillslope runoff. The crop area can be supplied with water by the tabias' runoff catchment. The remaining water in the tabias is infiltrated, thereby promoting groundwater recharge.

Mzirai & Tumbo (2010) conducted research on rainwater harvested by macro-catchment in Tanzania by measuring the obtained runoff from a given catchment basin into a water restricted cropped area. Although the research obtains good results regarding runoff availability, the authors did not specify in detail the technique used for the macro-catchment.

Kajiru et al. (1999) conducted research on the performance of agricultural rainwater harvesting by means of macro-catchments. However, the methodology is specific to the plotted land rather than to the catchment area.

In comparison to previous research, Mekdaschi Studer & Liniger (2013) compiled guidelines regarding water harvesting and provide a description, with images, of the possible techniques to be used for macro-catchment RWH. The following list adds to the techniques previously described in this section:

- Hillside runoff,
- Stream bed systems,
- Road runoff,
- Gully plugging,
- Cut-off drains,
- Ephemeral stream diversion,
- Large semi-circular or trapezoidal bunds,
- Water storage.

Mekdaschi Studer & Liniger (2013) offer measurements and ratios for the rainwater harvesting techniques presented, as well as water storage. Real life examples are also shown, providing a tangible experience of what this arrangement would look like. The guideline presents thoroughly three case studies in India, Zambia and Kenya. However, there is a significant focus on the water storage section, which falls out of scope of this literature review.

Conclusion

Water remains a fundamental requirement for adequate food production in agriculture. In this literature review, micro and macro-catchment land-based rainwater harvesting techniques have been identified as being suitable for providing this important resource. Based on the findings, it was discovered that micro-catchment rainwater harvesting systems encourage the storing of water in the root zone of planted crops, through the channelling of collected surface runoff to a cropped basin. The main advantage is the increased groundwater recharge through percolation, but it also serves as a preventive measure against soil erosion and flood hazard by ensuring reduced infiltration losses. Therefore this method can be used to construct highly resilient small-scale farms. In addition, macro-catchment rainwater harvesting also provides a sustainable source of water, and often has a runoff conveyance system, as well as an interposed reservoir. With this land-based technique, harvested rainwater is utilised in an area different from the one it falls onto; this is of great benefit in regions with extended dry seasons and erratic rainfall. Rainwater harvested from macro-catchments is for agricultural purposes: to enhance crop yields, improve food security, as well as to increase the protection against soil erosion and flooding. Subsequently, if the harvested rainwater from this system is of high quantity and quality, rainwater from macro-catchments can be used for domestic purposes. Indeed, both land-based rainwater harvesting systems contribute to a reduction in soil erosion and flood occurrence, improve food security and allows for groundwater recharge. All-in-all, even though climate change and anthropogenic activities threaten the availability of water as a resource in already arid and semi-arid regions, the literature reviewed strongly suggests that the implementation of land-based rainwater harvesting systems can help to increase agricultural productivity, and thus food availability. Therefore, a wider spread on knowledge on these techniques and participatory implementation concepts are necessary to implement these benefits globally.

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