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Opportunities in rainwater harvesting

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Abstract

Water scarcity is a major problem in many developing countries. Depending on precipitation intensity rainwater constitutes a potential source of drinking water. In addition, its proper management could reduce water and food crisis in some of these regions. Rainwater harvesting (RWH) is a technology where surface runoff is effectively collected during yielding rain periods. In order to support such technologies RWH systems should be based on local skills, materials and equipment. Harvested rainwater can then be used for rainfed agriculture or water supply for households. Unfortunately, rainwater might be polluted by bacteria and hazardous chemicals requiring treatment before usage. Slow sand filtration and solar technology are methods to reduce the pollution. Membrane technology would also be a potential disinfection technique for a safe drinking water supply.

Keywords: Rainwater harvesting; Rainfed agriculture; Rainwater treatment; Solar energy; Membrane filtration; Sand filtration

1. Introduction

One of the UN Millennium Development Goals is to reduce by half the proportion of people without sustainable access to safe drinking water. Another goal is to reduce by half the proportion of people who suffer from hunger. In some countries both goals are far from being fulfilled until 2015. One billion people do not have access to safe drinking water. According to the Food and Agriculture Organization (FAO) some 840 million people still suffer from undernourishment [1].

Most of the developing countries are classified as water-scarce countries which are characterized by low erratic rainfall, which results in high risk of droughts, intra-seasonal dry spells and frequent food insecurity [2]. Most of the rainfall events are intensive, often convective storms, with very high rain intensity and extreme spatial and temporal rainfall variability [2–4]. The ratio of rainfall to evaporation is often unsatisfactory. Rainfall often varies in a range of 200–600 mm/year from arid to semi-arid areas [5]. Potential evapotranspiration varies between 1500 and 2300 mm. This results in poor crops. The relation between rainfall and the potential evapotranspiration determines the growing period lasting about 2.5–4 month in semi-arid zones. Rainfall in the semi-arid areas exceeds potential evapotranspiration during 2–4.5 months only [5].

Fig. 1 indicates the partitioning of rainfall into different water flow components [5]. Soil evaporation accounts for 30–50% of rainfall, a value that might exceed 50% in sparsely cropped farming systems in semi-arid regions. Surface runoff is often reported to

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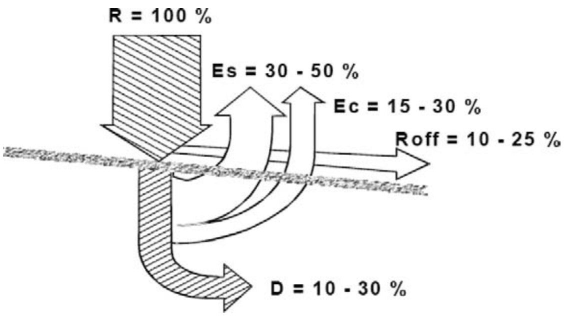

Fig. 1. General overview of rainfall partitioning in farming systems in the semi-arid tropics of sub-Saharan Africa. R, rainfall; Ec, plant transpiration; Es, evaporation from soil and loss by interception; Roff, surface runoff; D, deep percolation. Graphic from [5].

account for 10–25% of rainfall. The characteristics in dry lands of frequent, large and intensive rainfall events result in significant drainage, amounting to some 10–30% of rainfall [5].

Plant transpiration is reported to account for merely 15–30% of rainfall. The rest, between 70% and 85% of rainfall, is ''lost'' from the cropping system as soil evaporation, deep percolation and surface runoff. Fig. 1 thus indicates that there is a high risk of soil water scarcity in crop production, irrespective of spatial and temporal rainfall variability. In such a situation it is necessary to increase the amount of water available for agricultural purposes above the actual amount of direct rainfall [5]. Rainwater harvesting (RWH) may be a method to reduce water scarcity in such regions.

2. Rainwater harvesting techniques

Rainwater harvesting has a long tradition for thousands of years [6]. It is a technology used for collecting and storing rainwater from rooftops, land surfaces or rock catchments using simple techniques such as natural and/or artificial ponds and reservoirs. One millimeter of harvested rainwater is equivalent to one litre water per square metre. After collecting and storing the rainwater is a source in households for drinking, cooking, sanitation, etc., as well as for productive use in agriculture.

There are three major forms of RWH:

- In situ RWH, collecting the rainfall on the surface where it falls and storing in the soil.
- External water harvesting, collecting runoff originating from rainfall over a surface elsewhere and stored offside, both are used for agricultural RWH.
- Domestic RWH (DRHW), where water is collected from roofs and street and courtyard runoffs.

2.1. Agricultural RWH

Irrigation of rainfed crops by the use of RWH is a likely viable option to increase water productivity and therefore crop yields. Rainfed agriculture in arid and semi-arid areas contributes to up to 90% of the total cereal production of these regions [7]. However, in many countries, productivity remains low due to less than optimal rainfall characteristics, unfavourable land conditions and lack of proper management of these resources. Increasing productivity of rainfed areas could increase food security, improve livelihoods, and reduce irrigation frequency. Apart from the climate, the landscape must be suited for RWH agriculture. Following minimal requirements have to be fulfilled [1]:

- The landscape surface must be such that runoff is readily generated by rainfall.
- Differences in elevation must be present in the landscape surface. The runoff generated by rainfall must be allowed to flow and to be concentrated in the specially prepared parts of the landscape.
- The runoff receiving part must have sufficiently deep soils of suitable texture and structure to retain and store the received runoff water.

Storage can be achieved by various types of surface and sub-surface storage systems. The method of application differs according to the financial strength. Runoff collection may involve land alterations, soil compaction, etc., to increase the runoff from the catchment areas [5]. Following systems are common:

- Micro-catchment systems: They constitute specially contoured areas with slopes and berms designed to increase runoff from rain and concentrate it in a planting basin where it infiltrates the soil profile and is effectively ''stored'' therein. The water is available for plants but protected from evaporation. Micro-catchments are simple and inexpensive and can be rapidly installed using local materials and manpower. There are three types of micro-catchments: contour bench terraces, runoff strips, and micro-watersheds.

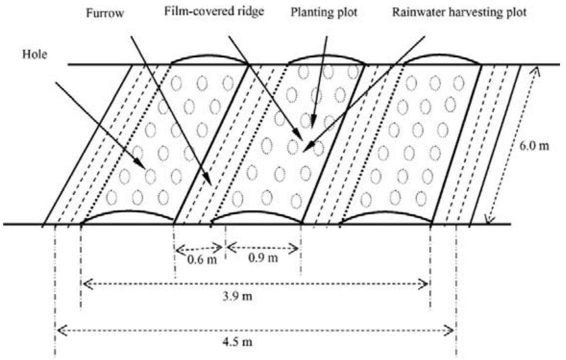

Fig. 2. Field cultivation by sowing in the holes of film-covered ridges. Graphic from [8].

- Sub-surface dams, sand dams or check dams: Water is stored under ground in an artificially raised water table or local sub-surface reservoir.
- Tanks of various forms made of plastic, cement, clay, soil, etc: They can be built underground or above ground, depending on space, technology and investment capacity.

Fig. 2 shows an example for field cultivation of RWH in a micro-catchment [8].

2.2. Domestic rainwater harvesting

For DRWH, rainwater is collected from rooftops, courtyards and low frequented streets and can be stored close to these. The storage tanks can be built underground or aboveground. The storage size depends on the requirements. Common tank shapes are cuboid, cylindrical or doubly curved. For storage smaller storage tanks made of bricks, stabilized soil, rammed earth, plastic sheets and mortar jars are common. For larger quantities rainfall water containers can be made of pottery, ferrocement, or polyethylene. The polyethylene tanks are compact but have a large storage capacity. The rainwater may be stored in underground tanks or above ground tanks [9] (see Fig. 3).

Precautions required in the use of storage tanks include provision of an adequate enclosure to minimise contamination from human, animal or other environmental contaminants, and a tight cover to prevent algal growth and breeding of mosquitoes. Open containers are not recommended for collecting water for drinking purposes.

The stored water is used for domestic purposes, garden watering and small scale productive activities. The main advantage of DRWH is to provide water right near the household, lowering the long distance walks burden of water collecting [9]. The costs for DRWH depend on the on-site requirements. Capital costs are high but neither operation nor maintenance usually involves significant expenditure. The investment costs depend on the size, the material and the situation whether the tank must be build underground or over ground. Storage costs for smaller tanks are low, e.g. for a 2 m^3 jar made from pottery or cement about 20–40£. The costs for a ferromagnetic tank with a size of about 20 m^3 are between 120 and 140£ [10].

Fig. 4 shows the water demand satisfied by a tank as compared to its size. The benefit of a tank is not strictly proportional to its size. The reason is that a smaller tank will be filled and emptied often whereas a larger tank will only be cycled rarely [10].

Fig. 3. Left: 30 m^3 RWH from ferrocement, underground (picture by Papenfus from [9]); right: bamboo tank developed by ARTI in Pune, India, uses a polythene sheet in a basket structure traditionally used for grain storage. Picture from [10].

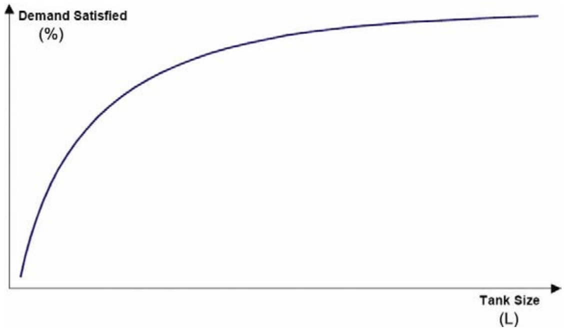

Fig. 4. Benefits of tank sizing. Graphic from [10].

3. Quality of harvested rainwater

Pure rainwater is mostly low polluted depending on the quality of the atmosphere. Atmospheric pollutants including particles, microorganisms, heavy metals and organic substances, accumulate on the catchment areas as dry deposition and are washed out from the atmosphere during rainfall events. Rainwater in rural areas – being situated far from atmospheric and industrial pollution – is fairly clean except for some dissolved gases. On the other hand urban areas are characterized by a high traffic and industry impact and are therefore contaminated by particles, heavy metals and organic air pollutants.

In addition, the catchment surfaces themselves may be a source of heavy metals and organic substances. Low or not polluted rainwater can be collected from roofs constructed with tiles, slates and aluminium sheets [11]. Roof tied with bamboo gutters are least suitable because of possible health hazards. Similarly, zinc and copper roofs or else roofs with metallic paint or other coatings are not recommended because of high heavy metal concentrations.

It was found that the measured inorganic compounds in the rainwater harvested from most roof-yard catchment systems generally matched the WHO standards for drinking water, while the concentrations of some inorganic compounds in the rainwater collected from road surfaces appeared to be higher than the guideline values for drinking water, but generally not beyond the maximum permissible concentrations [12].

If the catchment areas are roads the rainwater may be polluted by heavy metals originating from brakes and tires, and by organic compounds like polycyclic aromatic hydrocarbons (PAH) and aliphatic hydrocarbons from incomplete combustion processes. To apply drinking water quality the removal of these hazardous compounds is necessary.

Bacteria, viruses and protozoa may originate from faecal pollution by birds, mammals and reptiles that have access to catchments and rainwater storage tanks [13,14]. The presence of microbial indicators and pathogens has been found to vary greatly with reported counts up to thousands CFU/100 mL [12,14,15]. Sazakli et al. analyzed three widely used bacterial indicators [14]. They found coliforms in 80.3% of rainwater samples, *Escherichia coli* and enterococci in 40.9% and 28.8%, respectively. Therefore, harvested rainwater is often unsuitable for drinking without any treatment. Disinfection should then be applied to improve microbiological quality.

4. Rainwater treatment for DRWH

The basic requirement for developing countries is a practicable treatment method which is inexpensive. A first improvement of rainwater quality can be achieved by cut off the first flush of a rain event, e.g. by first flush water diverters. They are easily to install, operate automatically and available in a number of different sizes to suit different requirements. In addition to the improvement of rainwater quality they reduce the tank maintenance.

For disinfection the most common and easily applicable practice is chlorination. Chlorine can be applied for the deactivation of most microorganisms and it is relatively cheap. Chlorination has to be applied after removal of the harvested rainwater from the storage tank, because chlorine may react with organic matter which settled to the bottom of the tanks and form undesired by-products [16]. Chlorination should meet the amount of 0.4–0.5 mg/L free chlorine and can be done by chlorine tablets or chlorine gas. One limit of disinfection by chlorination is that some parasitic species have shown resistance to low doses of chlorine.

Slow sand filtration is a cheap method to improve the bacteriological quality of water [17,18]. Slow sand filters rely on biological treatment rather than physical filtration processes for successful performance. The filters are carefully constructed using graded sand layers with the coarsest fraction on top and the finest

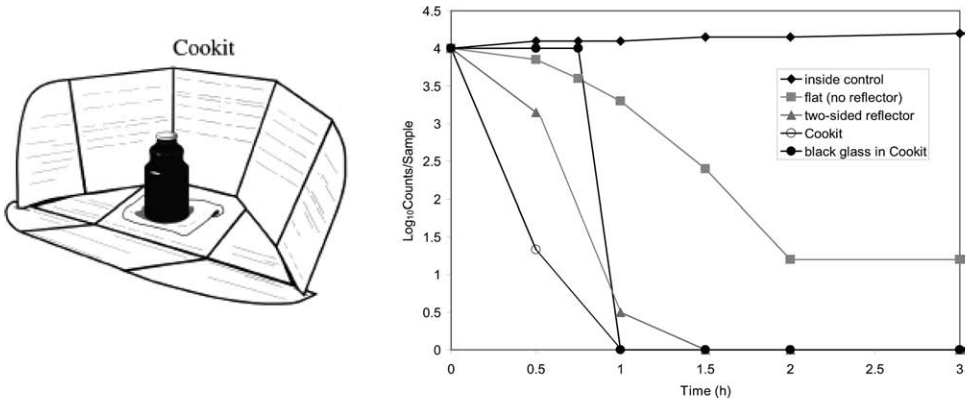

Fig. 5. Left: Cookit black jar 1.4 L, right: solar inactivation of *Escherichia coli*. *E. coli* counts/sample are shown as CFU/mL. Graphic from [23].

at the base. Filtration efficiency depends on the development of a thin biological layer, i.e. a biofilm, on the filter surface. An effective slow sand filter may remain in service for many weeks or even months if the pretreatment is well designed and produces water with a very low nutrient level available which physical treatment methods rarely achieve. In order to be effective, a constant flow of water through the filters is essential [17]. Slow sand filters are already in use in developing countries. A limit of slow sand filters is that they can only reduce microorganisms.

Pasteurization by solar technology is also known as a cheap disinfection method [19–22]. It can be achieved by combining UV-A radiation with heat. Since the sun is a free natural source of energy plentiful in most developing countries, this technique seems to be a reliable and effective low cost treatment method for harvested rainwater. Pasteurization by solar technology can be achieved in plastic bottles or bags (batch) or continuous flow (SODIS) reactors. It is most effective with a water temperature of at least 50°C which can be easily accomplished by sun energy [19,20]. Fig. 5 demonstrates solar inactivation of *E. coli* with time in different bottle systems with and without reflector and a special reflector system called Cookit developed by Solar Cookers International (SCI) [23]. A Cookit consists of plates of aluminium foil being laminated onto cardboard folded at three locations to create the vertical reflective section, the middle section, which holds the black jar (optimal volume: 1–5 L, costs circa 15£), and the front section, which is adjusted to reflect the maximum amount of sunshine onto the jar (scheme see Fig. 5, left site).

Compared to solar inactivation of *E. coli*, it took 2.4 times as much solar energy to inactivate *Candida* sp., *Geotrichum* sp. and spores of *Aspergillus flavus* and 6.4 times as much to inactivate *Penicillium* spores [23].

The solar batch technology is sufficient for small households while the solar water disinfection respectively pasteurization as continuous flow system (SODIS reactor) can produce around 100 L of disinfected water per square metre of solar collector and day [21]. Solar technology is limited when the concentration of suspended solids is more then 10 mg/L. In this case, other techniques for elimination of the particulate matter like filtration may be added.

For removal of hazardous substances from rainwater filtration techniques are common. A part of these substances are particle-bound. These suspended particles may be removed by filtration. The most common type of filter is a rapid sand filter. Water moves vertically through sand which often is covered by a layer of activated carbon or anthracite coal. The top layer removes organic compounds, which contribute to taste and odour. The pore space between sand particles is larger than the smallest suspended particles, so simple filtration in most cases is not sufficient. Most particles pass through surface layers but are trapped in pore spaces or adhere to sand particles and biofilms on their way through the filter. Effective filtration therefore is enhanced with the depth of the filter. This property of the filter is the key to its operation: if the top layers of sand were to remove all the particles, the filter would quickly clog.

Metal membrane filters (1 μm and 5 μm) also appear suitable to clarify rainwater up to utilization quality. Ozon bubbles as well as aeration on the feed side was considered to reduce membrane fouling and inactivate microorganism [24]. The major fouling problem is pore blocking.

For drinking water membrane filter systems with a pore size of 0.1 μm use low-pressure membrane filters in linear arrays of multiple modules. Protozoa, bacteria, algae and other microorganisms can be effectively removed. A membrane module functions like a fine-meshed sieve. It consists of some 10,000 porous plastic fibers that form a web within a cylindrical housing. A pump propels contaminated water from the outside of the module through the membrane to the inside. Any particle exceeding 0.1 μm – which includes all bacteria – literally gets stuck. However, the treated water may still contain some viruses. With dimensions of less than 100 nm, viruses are small enough to slip through even tiny pores. The filter systems are therefore coupled with a disinfection system [25].

The investment costs for filters depend on the requirements, the material, the size and the pore size. Filters require a lot of maintenance.

A new technique developed at Fraunhofer Institute provides rainwater treatment with rotating disc filters with a ceramic membrane. With a pore size of 0.06 μm bacteria and viruses are safely removed. This new technique is expensive and may only be suitable for central treatment of rainwater [26].

5. Problems and constraints hampering RWH

Even though RWH is a helpful technique for areas with scarce water resources there are some problems hindering the integration and implementation. Often the technology used is inadequate to meet the requirements of the region or else is too expensive. Sometimes there is a lack of acceptance, motivation and involvement among users. Hydrological data and information for confident planning, design and implementation of RWH systems are missing. Additionally there is often an insufficient attention to social and economic aspects such as land tenure and unemployment. Often the people's knowledge with regard to RWH and use is inadequate and outdated giving away the benefits of rainwater resources. Absence of long-term government strategies is also a handicap [23]. In some regions DRWH is in fact illegal if water legislation is strictly applied [9]. Therefore a lot of development work has to be done in this matter. Geographic information systems (GIS)-based models, which combine physical, ecological and socio-economic data, might contribute to assess the suitability of a given area to RWH. Potential areas might thus be identified [7,27–29].

6. Conclusions

Rainwater harvesting seems to be a beneficial method for minimizing water scarcity in developing countries. It is essential that local materials and manpower is to be used to spot catchment areas and build up harvesting systems. For agricultural use most of the harvested water can be stored underground in natural systems protecting it from evaporation. On the other hand, rainwater harvested for domestic use may be polluted by bacteria and hazardous substances requiring a vigilant choice of the catchment area. For disinfection purposes there are many techniques available, some of these utilizing natural sources such as solar energy. GIS technology might enhance locating potential areas for RWH.

References

[1] United Nations Educational Scientific and Cultural Organisation, Official Homepage 2008, www.unesco.org.
[2] S.N. Ngigi, What is the limit of up-scaling rainwater harvesting in a river basin? Phys. Chem. Earth, 28 (2003) 943–956.
[3] H.J. Bruins, M. Evenari and U. Nessler Rainwater-harvesting agriculture for food production at aride zones: the challenge of the African famine, Appl. Geography, 6 (1986) 13–32.
[4] L. Shanan, N.H. Tadmor and M. Evenari, Runoff farming in the desert. III. Micro-catchments for the improvement of desert range, Agronomy J., 62 (1970) 695–699.
[5] M. Falkenmark, P. Fox, G. Persson and J. Rockström, Water Harvesting for Upgrading of Rainfed Agriculture, SIWI Report 11, Stockholm International Water Institute, Sweden, 2001, ISBN: 91-974183-0-7.

[6] R.A. AbdelKhaleq and I.A. Ahmed, Rainwater harvesting in ancient civilization in Jordan, Water Sci. Technol.: Water Supply, 7 (2007) 85–93.
[7] J. Mwenge Kahinda, J.R. Boroto and A.E. Taigbenu, Developing and integrating water resources management and rainwater harvesting systems in South Africa, in: Proceedings of the 12th SANCIAHS Symposium, Johannesburg, South Africa, 2005.
[8] G. Xiao, Q. Zhang, Y. Xiong, M. Lin and J. Wang, Integrating rainwater harvesting with supplemental irrigation into rain-fed spring wheat farming, Soil Tillage Res., 93 (2007) 429–437.
[9] J. Mwenge Kahinda, A.E. Taigbenu and J.R. Boroto, Domestic rainwater harvesting to improve water supply in rural South Africa, Phys. Chem. Earth, 32 (2007) 1050–1057.
[10] Development Technology Unit, Recommendations for designing Rainwater Harvesting system tanks, Domestic Roofwater Harvesting Research Programme, O-DEV Contract No. ERB IC18 CT98 027, Milestone A6: Report A4, University of Warwick, 2001.
[11] J.E. Gould, Rainwater Catchment Systems for Household Water Supply, Environmental Sanitation Reviews, No. 32, ENSIC, Asian Institute of Technology, Bangkok, 1992.
[12] M. Yaziz, H. Gunting, N. Sapiari and A. Ghazali, Variation in rainwater quality from roof catchment, Water Res., 23 (1989) 761–765.
[13] C.A. Evans, P.J. Coombes and RH. Dunstan, Wind, rain and bacteria: the effect of weather on the microbial composition of roof-harvested rainwater, Water Res., 40 (2006) 37–44.
[14] E. Sazakli, A. Alexopoulos and M. Leotsinidis, Rainwater harvesting, quality assessment and utilization in Kefalonia Island, Greece, Water Res., 41 (2007) 2039–2047.
[15] K. Zhu, L. Zhang, M. Liu and H. Chen, Quality issues in harvested rainwater in arid and semi-arid Loess Plateau of Northern China, J. Arid Environ., 57 (2004) 487–505.
[16] G. Gordon, L. Adam and B. Bubnis, Minimizing chlorate ion formation, J. Am. Water Works Assoc., 87 (1995) 97–106.
[17] E. Fewster, A. Mol and C. Wiessent-Brandsma, The long term sustainability of household bio-sand filtration, in: Proceedings of the 30th WEDC International Conference, Vientiane, Laos PDR, 2004, pp. 1–3.
[18] G. Palmateer, D. Manz, A. Jurkovic, R. McInnis, S. Unger, K.K. Kwan and B.J. Dutka, Toxicant and parasite challenge of Manz intermittent slow sand filter, Environ. Toxicol., 14 (1999) 217–225.
[19] M. Wegelin, S. Canonica, K. Mechsner, T. Fleischmann, F. Pescaro and A. Metzler, Solar water disinfection: scope of the process and analysis of radiation experiments, J. Water Supply: Rese. Technol. – Aqua, 43 (1994) 154–169.
[20] T.M. Joyce, K.G. McGuigan, M. Elmore-Meegan and R.M. Conroy, Inactivation of fecal bacteria in drinking water by solar heating, Appl. Environ. Microbiol., 62 (1996) 399–402.
[21] B. Sommer, A. Marino, Y. Solarte, M.L. Salas, C. Dierolf, C. Valiente, D. Mora, R. Reichensteiner, P. Setter, W. Wirojanagud, H. Ajarmeh, A. Al-Hassan and M. Wegelin, SODIS – an emerging water treatment process, J. Water Supply: Res. Technol. – Aqua, 46 (1997) 127–137.
[22] R. Khaengraeng and R.H. Reed, Oxygen and photoinactivation of *Escherichia coli* in UVA and sunlight, J. Appl. Microbiol., 99 (2005) 39–50.
[23] N. Safapour and R.H. Metcalf, Enhancement of solar water pasteurization with reflectors, Appl. Environ. Microbiol., 65 (1999) 859–861.
[24] R.H. Kim, S. Lee and J.O. Kim, Application of a metal membrane for rainwater utilization: filtration characteristics and membrane fouling, Desalination, 177 (2005) 121–132.
[25] Siemens Water Technologies, Membranetechnology – worth a closer look, Membr. Evol., 4 (2006) 1–5.
[26] M. Mohr, Water house Knittlingen: semi-centralized technique in a development area, in: Proceedings of the 11th Colloquium on Municipal Wastewater and Waste Treatment, Fraunhofer Institute, Stuttgart, Germany, 2006, pp. 1–10.
[27] J. Rockström, Water resources management in smallholder farms in eastern and southern Africa: an overview, Phys. Chem. Earth, 25 (2000) 275-283.
[28] B.P. Mbilinyi, S.D. Tumbo, H.F. Mahoo and F.O. Mkiramwinyi, GIS-based decision support system for identifying potential sites for rainwater harvesting, Phys. Chem. Earth, 32 (2007) 1074–1081.
[29] J. Mwenge Kahinda, J. Rockström, A.E. Taigbenu and J. Dimes, Rainwater harvesting to enhance water productivity of rain-fed agriculture in the semi-arid Zimbabwe, Phys. Chem. Earth, 32 (2007) 1068–1073.