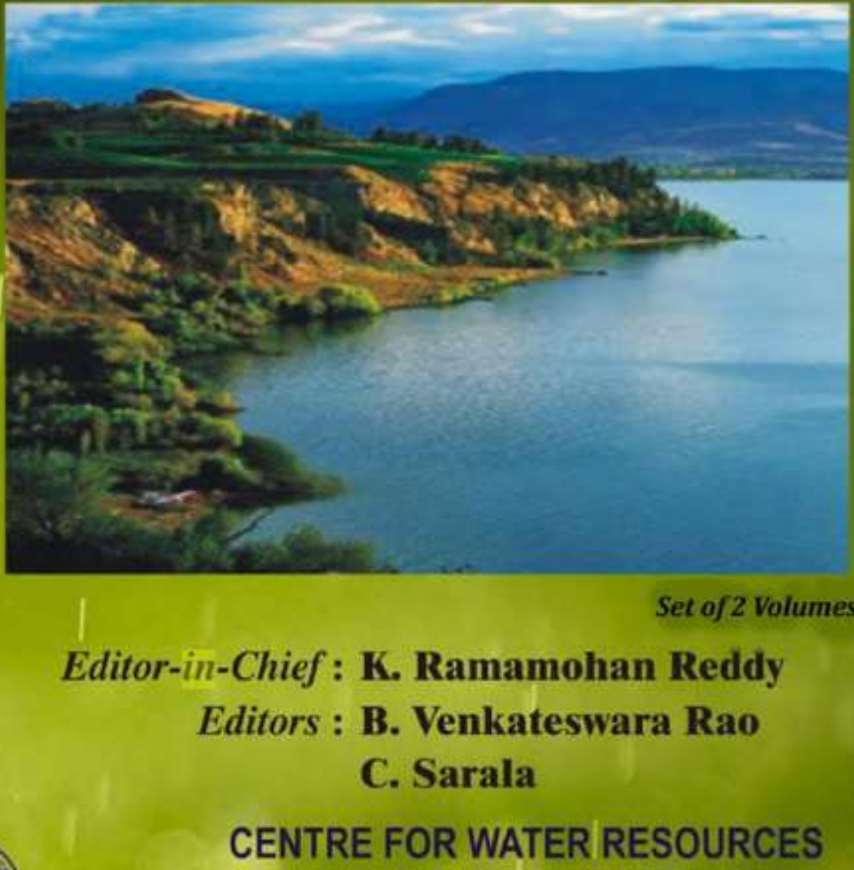
Proceedings of
4th International Conference on

HYDROLOGY AND WATERSHED MANAGEMENT

with a Focal Theme on

Ecosystem Resilience—Rural and Urban Water Requirements

(29th October to 1st November, 2014)



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CENTRE FOR WATER RESOURCES
Institute of Science and Technology
Jawaharlal Nehru Technological University Hyderabad
Telangana State, India

Comparative rainwater harvesting potential assessment in north-central Texas, US and West Bengal, India in farm-scale reservoirs

Pramod K Pandey[1] Sudhindra N Panda[2], Vinay K Pandey[3]
Department of Population Health and Reproduction, Vet Med Extension, University of California Davis, California, United States of America
[2] Department of Agricultural & Food Engineering, Indian Institute of Technology, Kharagpur, West Bengal, India
[3]BRSM College of Agricultural Engineering and Technology, Indira Gandhi Krishi Viswavidyalaya, IGKV, Raipur, Chhattisgarh, India

Abstract

Considering the increasing agricultural water demands, conservation of rainwater is crucial. Rainwater harvesting in farm-scale reservoirs can be a potential option for enhancing water resources for sustainable water management for agriculture in rainfed regions. In this study we exploited a water balance model for improving the understanding of rainwater harvesting potential in farm-scale reservoirs. The modeling study was executed using the climate data of Fort worth (north-central Texas), USA, and Kharagpur (West Bengal), India. Potential water storages in farm-scale reservoirs were evaluated in multiple soil and climate conditions. In addition, we assessed the potential impacts of seepage and evaporative losses on water storages in the reservoirs. The results of the study would be useful for understanding the rainwater harvesting potential in rainfed regions under various soil and climate conditions, and support stakeholders in making informed decisions.

Introduction

Currently, agricultural activities use approximately 75% of the world's total water consumption (Falkenmark and Rockström, 2004; Pandey et al., 2013). In current scenario, while water uses for household and industrial activities are outcompeted by water uses for agriculture, the demand for agricultural water is likely to enhance further in future. Increasing living standards and industrialization in many developing countries will certainly put additional pressure on existing water resources. Currently, ongoing drought and water scarcity faced by many developed and developing countries, which are potentially driven by climate variability, are serious concerns. To meet future agricultural water demands, enhancing water resources, and identifying the efficient methods of using water for agriculture are important for sustainable agriculture.

Future water crisis at global-scale is well emphasized in the Human Development Report (2010). A study by Rockström (2003) reported that by 2050, more than 59% of the world population will live in water stressed areas. Additional water (>5,500 km^3/yr) for consumptive water use will be needed by 2050 (Falkenmark and Rockström, 2006).

In many developing countries such as India, sub-Saharan Africa, where agriculture contributes considerably to the gross domestic product (GDP), limited water for agriculture will most likely impact economy as well as human wellbeing. Approximately 70% of people in India live in rural areas mainly depend on agriculture for their livelihoods. The GDP of many countries in sub-Saharan Africa relies excessively on agriculture. As an example, 47% of GDP of Ethiopia comes from agriculture, and shortage of water will heavily impact the economy of the country. Even in developed countries such as USA, extensive drought in 2012 has affected U.S. agriculture considerably (USDA-ERS, 2014)

Rainwater harvesting for meeting the agricultural water demands has been seen as an option in many countries. Approximately 94% of the agricultural land in sub-Saharan Africa is rainfed (McCartney and Smakhtin, 2010). More than 65% of agricultural land in Asia is rainfed. Approximately 80% of global cropland is rainfed. Rainfed cropland produces about 70% of the word’s food supply (Falkenmark and Rockström, 2004; Pandey et al., 2013), therefore, water requirement in rainfed regions cannot be ignored.

While contribution of rainfed agriculture to world’s food production is enormous, crop yield in rainfed crop land is often suffered by drought and uncertainty in rainfall. In many countries, such as in India, excessive amount of water is available during rainfall seasons, however, during dry seasons, limited water is available for agricultural, which results in poor crop yields, hence, economic losses.

Previous studies (Pandey et al., 2013; Rockström, 2003; van der Zaag and Gupta, 2008) have shown that providing supplemental irrigation to rainfed crop can increase crop yield substantially. van der Zaag and Gupta (2008) reported that rainfed crops have ability to get 50% of water need (out of 200 mm) from the moisture available in soil profile, however, additional 100 mm water is required to achieve full potential. Farm-scale rainwater harvesting reservoirs can potentially supply additional water in dry seasons. Many of previous studies have explored the options of using rainwater harvesting structures for meeting the supplemental water demand (Panigrahi et al., 2001; Pandey et al., 2006). In order to understand the full potential of rainwater harvesting in rainfed regions, additional studies focused on water availability and demand are needed. While field studies are crucial for generating such information, developing mathematical models for predicting supplemental irrigation requirement at various climate conditions, and understanding the water availability in on-farm reservoirs in dry and wet conditions can help in improving the understanding of rainwater harvesting system suitability in rainfed regions.

In this study, we extended our previous published work (Pandey et al., 2011; Pandey et al. 2013) to understand how seepage and evaporation control the water balance in rainwater harvesting structures. The model, which is already published elsewhere (Pandey et al., 2011), was used to predict the water storages in reservoirs under lined (no seepage) and unlined (with seepage). The objectives of this study are to understand the water losses (seepage and evaporation) from rainwater harvesting reservoirs in lined and unlined reservoirs; and compare the losses of two different climate conditions (i.e., Kharagpur, West Bengal, India, and Dallas-Fort worth, Texas, USA).

Methods

In this study a water balance model (Pandey et al., 2011) was exploited to assess the water balance in reservoirs. The model uses input parameters such as rainfall, solar radiation, soil characteristics, and temperatures to predict evaporation losses, runoff, seepage losses, and water storages in reservoirs. Readers are encouraged to refer two recently published studies (Pandey et al., 2013; and Pandey et al., 2011) for understanding the model details. A simple formulation for model is:

$$\frac{dV}{dt} = DR_i + Q_i - Eloss_i - Sloss_i \quad ......(1)$$

where $dV = (V_i - V_{i-1})$ is the change in water volume (m^3) in OFR at a given day; $dt = 1\ timestep = 1\ day$; i is day; V_i and V_{i-1} are stocks (volume); DR_i is the water gain through direct rainfall in OFR (m^3); Q_i is the runoff from land excluding the OFR (m^3); $Eloss_i$ is the water loss through evaporation (m^3) in OFR; and $Sloss_i$ is the water loss through seepage (m^3). Readers are encouraged to review model presented elsewhere (Pandey et al. (2011). Here we exploited the model in two locations: 1) Fort worth, Dallas, Texas, USA (Fig. 1); 2) Kharagpur,West Bengal India (Fig. 2).

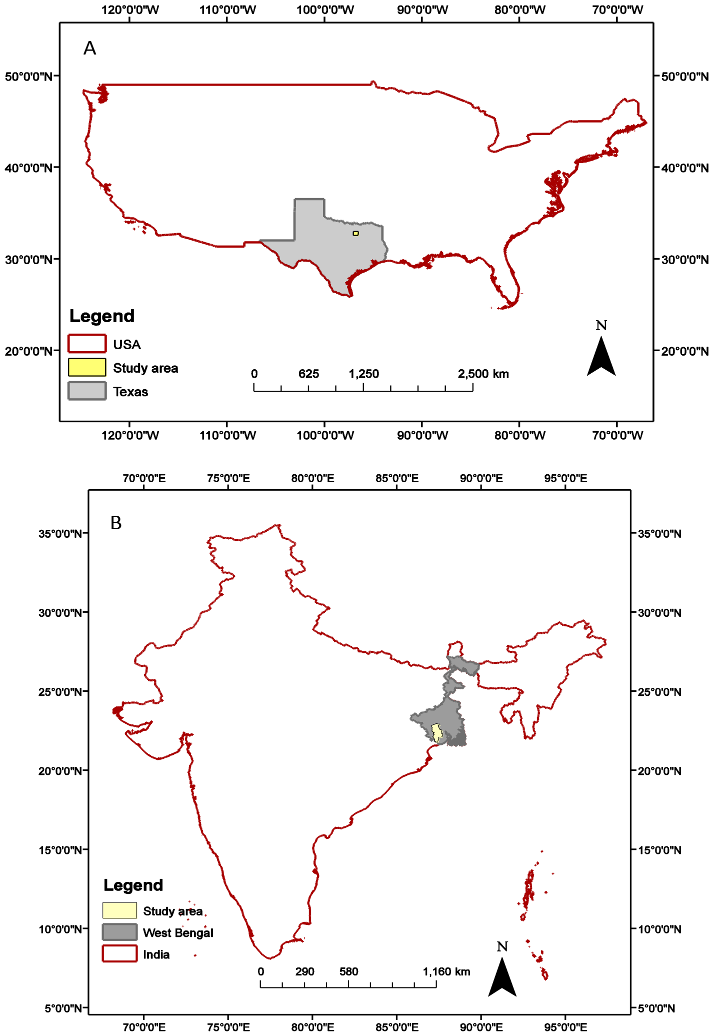

Figure 1. Study areas: A) Fort worth, Texas, USA; B) Kharagpur, West Bengal, India.

Climate data i.e., annual temperature and rainfall pattern is shown in Figure 2. The first location (Fig. 1) is a humid subtropical climate region. Coldest month is January and hottest month is July. Temperature varies from –1 ^{0}C to36 ^{0}C. The average annual precipitation is 942 mm. The most precipitation occurs in May (average of 116.3 mm). The second study area (Fig. 2) has a sub- humid, tropical savannah climate. The mean minimum and maximum air temperatures are 12 ^{0}C and 40 ^{0}C in January and May, respectively. The area receives about 1500 mm mean annual rainfall, about 75% of which is concentrated during the rainy season from June to September.

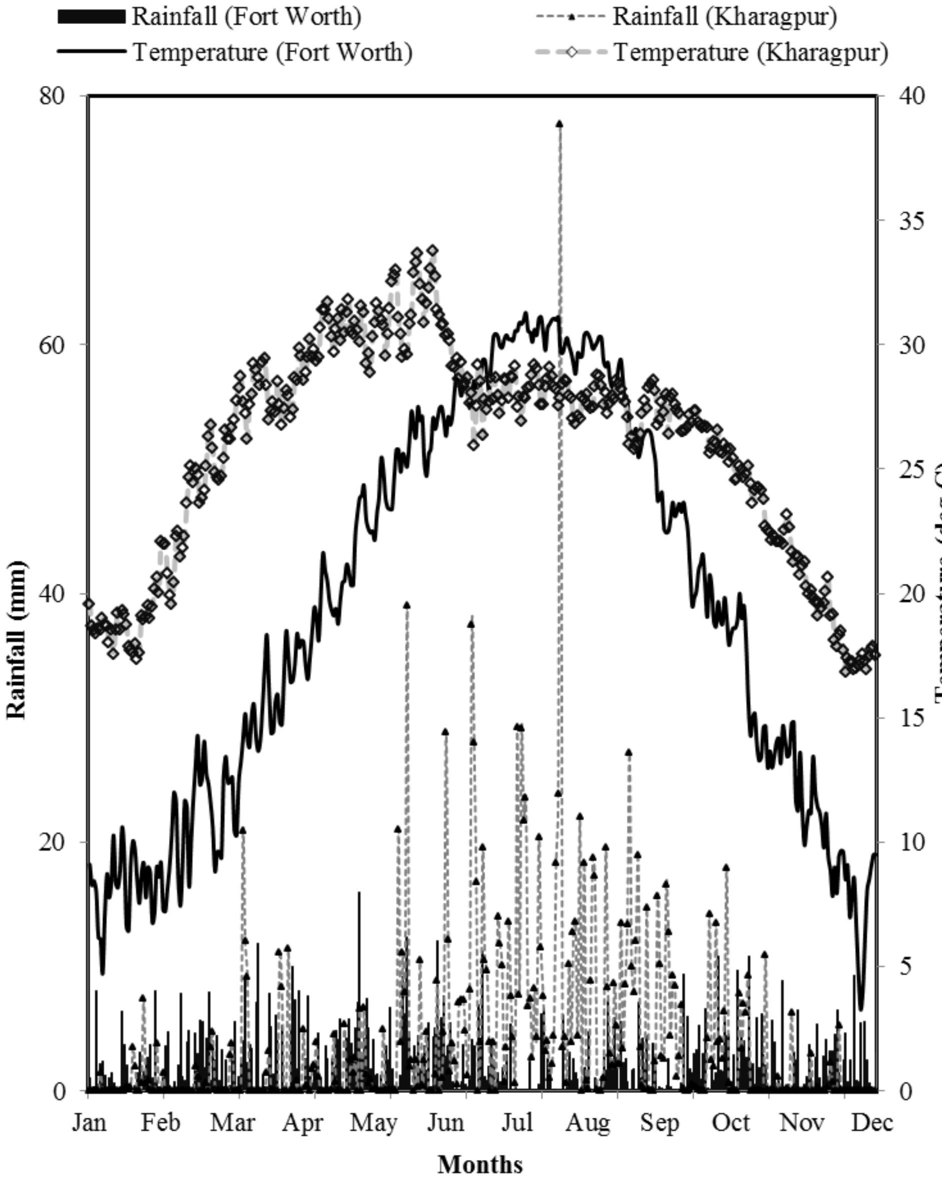

Figure 2: Climate of Forth worth Texas, USA and Kharagpur, West Bengal, India

Results and Discussion

The simulations were performed to understand the water storages in the reservoirs in two conditions: 1) when reservoir was subjected to seepages losses; 2) when reservoir was not subjected to seepages losses i.e., reservoir was lined. Figure 3 shows the simulation results for the first location, Fort worth, Texas, USA. Figure 3 shows water storages (m^3) in reservoir (reservoir size of 10% of the farm area). Farm area was set to 1 ha. Figure 3A shows the lined and unlined water storages at saturated hydraulic conductivity (K_{sat}) of 0.64 cm/hr, and Figure 3B shows the water storage results, when saturated hydraulic conductivity (K_{sat}) was set to 1.3 cm/hr. As shown in Figure 3A, when saturated hydraulic conductivity was set to 0.64 cm/hr, water storages in unlined reservoir was greater than the water storages in unlined reservoir at greater saturated hydraulic conductivity(K_{sat}) of 1.3 cm/hr (Fig. 3B).

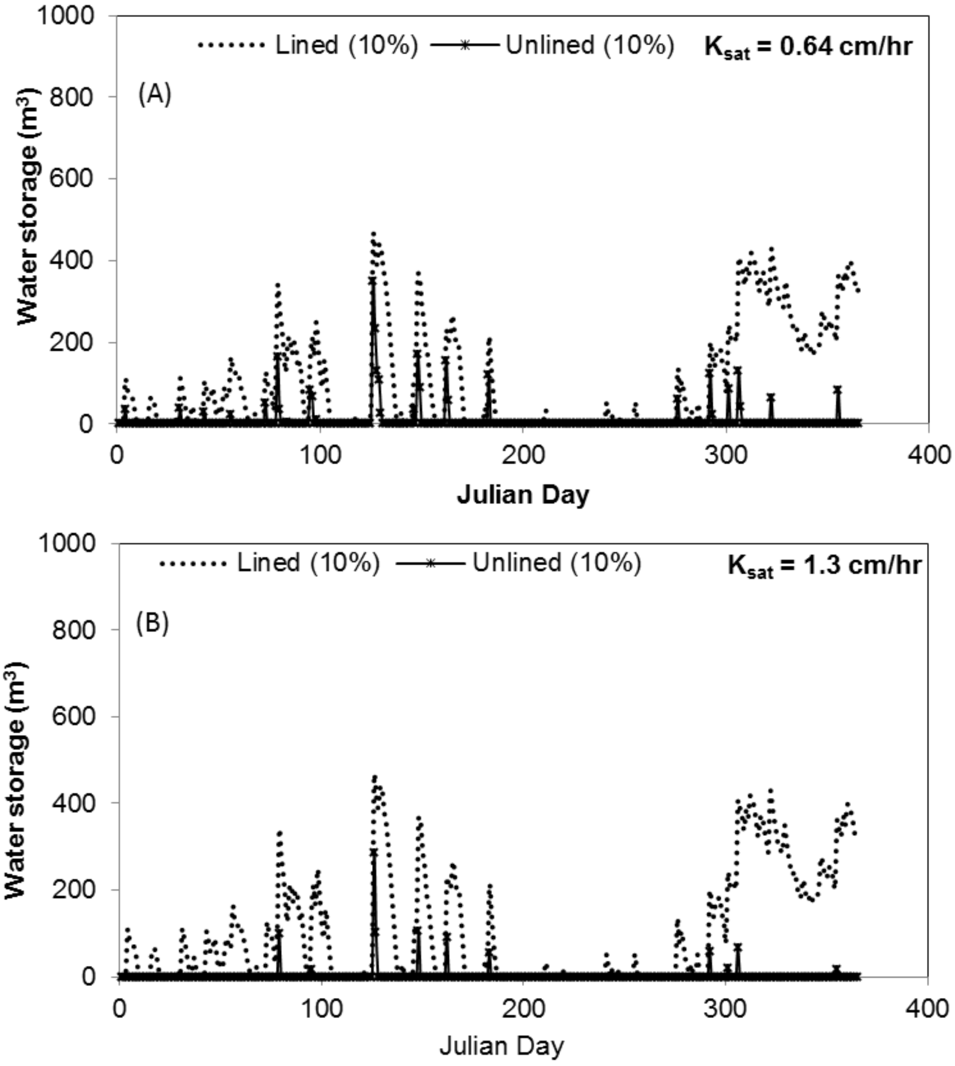

Figure 3: Water storages in lined and unlined reservoir in Fort worth, Texas, USA.

Compared to unlined reservoirs, water storages in lined reservoirs was considerably greater (Fig. 3A and Fig. 3B). The difference between unlined reservoir water storages and lined reservoir storages was greater when pond bottom's saturated hydraulic conductivity was set to 1.3 cm/hr. As shown in Figure 3B, water storage was only occasional at higher saturated hydraulic conductivity, while at lower saturated hydraulic conductivity (Fig. 3A), unlined reservoir showed relatively greater water storages. Simulation results showed that water storages in unlined reservoir will most likely be minimal due to excessive seepage and evaporation in location 1. However, if the reservoirs are lined (no seepage losses), then the water storages in lined reservoirs will be greater than the unlined reservoirs. Similar simulation was performed for the second location i.e., Kharagpur, India to understand the water storages in lined and unlined reservoirs, which is shown in Figure 4.

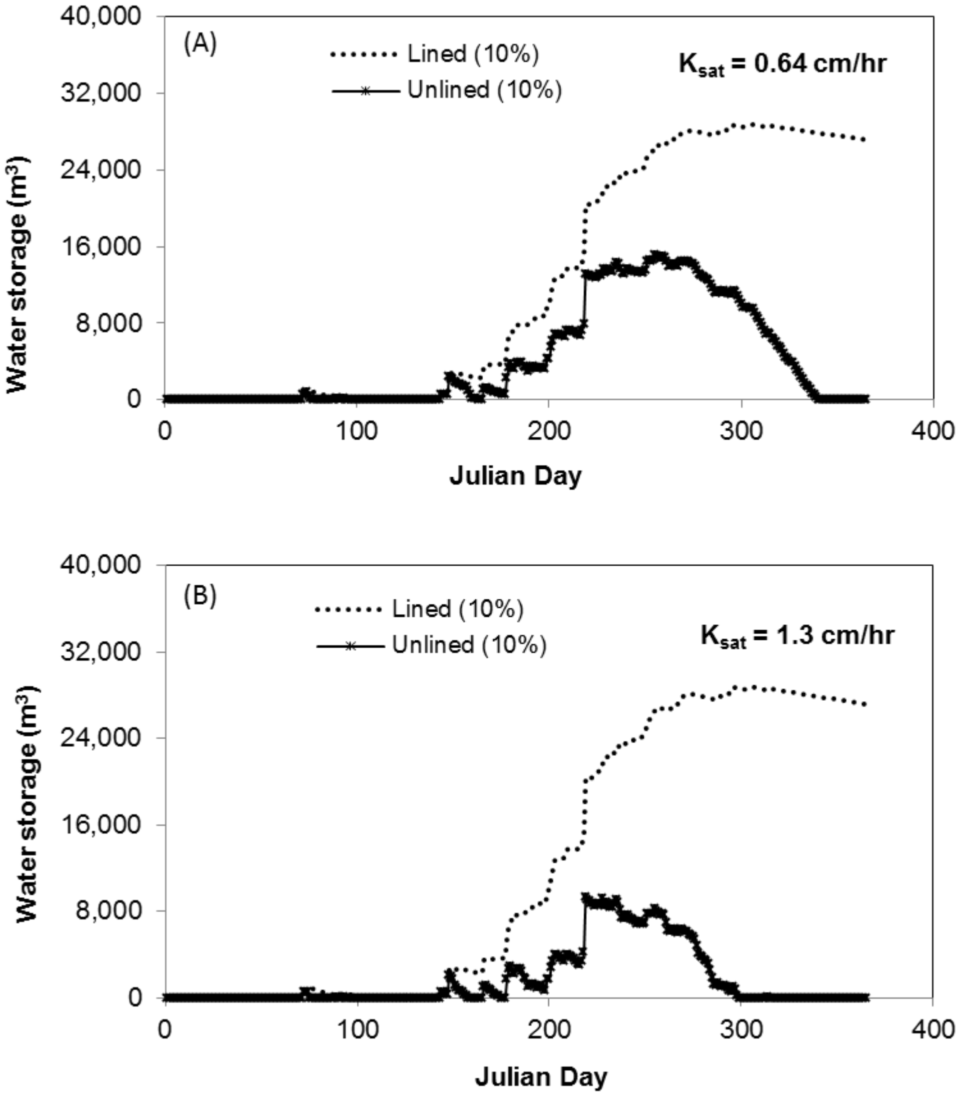

Figure 4: Water storages in lined and unlined reservoirs in Kharagpur, West Bengal, India

Figure 4A shows variation in water storages in lined and unlined reservoirs at K_{sat} of 0.64 cm/hr, and Figure 4B shows variation in water storages in lined and unlined reservoir at K_{sat} of 1.3 cm/hr. Similar to the first location, water storage in lined reservoirs were greater than the unlined reservoirs. Difference between water storages in lined and unlined reservoir was lower at K_{sat} of 0.64 cm/hr compared to K_{sat} of 1.3 cm/hr potentially due to excessive water losses through seepages.

While comparing the results of Figure 4 and 3, an obvious observation is that water storages in both lined and unlined reservoirs were significantly different in two locations. At the second location (Kharagpur, India), water storages in both lined and unlined reservoirs were greater than the first location (Dallas Fort worth, Texas). These results indicate that the rainwater harvesting potential may vary from one climate condition to other. As shown in the Figure 3A and 3B, water storages in the unlined pond (in the first location) was observed occasionally, while in the second locations, water storages in unlined ponds were considerably greater than the first location. In the second location, water storage in unlined ponds was substantially higher than the first location in both K_{sat} conditions.

In unlined reservoir, water storages in the second location varied from 0 to 9298 m^3 at K_{sat} of 1.33 cm/hr, and from 0 to 15126 m^3 at K_{sat} of 0.64 cm/hr. In lined reservoir, water storages at K_{sat} of 0.64 cm/hr and K_{sat} of 1.33 cm/hr varied from 0 to 28763 m3. In the first location, unlined reservoir water storages varied from 0 to 350 m^3 at K_{sat} of 0.64 and 0 to 285 m^3 at K_{sat} of 1.33 cm/hr. In lined reservoir, water storages varied from 0 to 464 m3 at K_{sat} of 0.64 cm/hr, and K_{sat} of 1.33 cm/hr.

Comparing the unlined water storage scenarios in these two locations, the maximum water storages in the second location was 32 times greater than the first location at K_{sat} of 1.33 cm/hr. At K_{sat} of 0.64 cm/hr, maximum water storage in the second location was 43 times greater than the first location. In lined condition, water storage in the second location was considerably greater than the first location (Figs. 3 and 4). For example, maximum water storages in the second location were 62 times greater than the water storages in the first location. In lined condition, reservoir bottom was completely lined; therefore, K_{sat} values did not affect water storages.

The deviation in water storages of these two locations is mainly due to rainfall pattern (Figure 2). As shown in the Figure, monsoon rainfall in second location was considerably greater than the first location. In the second location, monsoon, concentrated on July to September, provided excessive amount of rainfall, which resulted in enhanced water storages in both lined and unlined ponds. In the first location, although the rainfall was distributed throughout the year, but the intensity of the rainfall was considerably lower compared to the second location, which resulted in poor runoff as well water storages in lined and unlined reservoirs. In both lined and unlined reservoirs, water storages were low in the first location. Seepage and evaporation losses in the first location resulted in poor water availability in the reservoirs.

In order to compare the evaporative and seepage water losses, a water balance scenario for both lined and unlined reservoirs was performed. Results indicated that 32% of total water input in unlined reservoir of the first location was lost as seepage at K_{sat} of 0.64 cm/hr. At K_{sat} of 1.33 cm/hr, approximately 35% of total water input was lost as seepage.

In second location, at K_{sat} of 0.64 cm/hr, evaporation loss was 68% of the total water input. At higher K_{sat} (1.33 cm/hr), evaporation loss was 64% of the total water input. The change in evaporation losses corresponding to K_{sat} was due to the fact that at lower K_{sat}, water availability was greater in the reservoirs, causing increased evaporation.

Similar scenario (i.e., comparative evaporative and seepage water losses) was executed for the second location. Results showed that at K_{sat} of 0.64 cm/hr, seepages loss was 72% of total water input in unlined reservoir. At K_{sat} of 1.33

cm/hr, seepage loss was 76% of the total water input in unlined reservoir. Evaporation loss was 28% of total water input at K_{sat} of 0.64 cm/hr, while 24% at K_{sat} of 1.33 cm/hr. In lined reservoir of the first location, around 97% of total water input was lost due to evaporation. In the second location, about 33% of the total water input in reservoir was lost as evaporation indicating evaporation was dominant in the first location, while seepage was dominant in the second location.

In summary, results of this study indicate that rainwater harvesting potential will change depending on climate conditions. Lined reservoirs were more effective in terms of water storages compared to the unlined reservoirs. In the second location, where monsoon season provides a greater amount of rainfall, water storages were considerably greater than the first location, where average annual rainfall was approximately 62% of the second locations.

Conclusions

This study was carried out to understand the rainwater harvesting potential in farm-scale reservoirs under two different climate conditions (Fort worth, Texas, USA; and Kharagpur, West Bengal, India). The effect of seepage and evaporation water losses on water storages was estimated. Simulation results indicated that lined reservoirs were more effective in water storages compared to the unlined reservoirs. However, the water storages in the reservoirs varied from one location to another depending on the rainfall. In the first location (Fort Worth, Texas), evaporation was dominant source of water loss, while in the second location (Kharagpur, West Bengal), seepage was the main source of water loss. We anticipate that the results will be useful for deriving future studies targeted for understating the rainwater harvesting potential in different climate conditions.

Acknowledgment

Authors thank to Agricultural and Natural Resources (ANR), University of California Davis, California, USA for the support.

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