Estimating Water Balance of Small Reservoirs in Arid Regions: A Case Study from Kachchh, India

Deepesh Machiwal[1*], Devi Dayal[1] and Sanjay Kumar[2]

[1]ICAR-Central Arid Zone Research Institute, Regional Research Station, Kukma, Bhuj – 370 105, Gujarat, India

[2]Krishi Vigyan Kendra, ICAR-CAZRI, Bhuj – 370 105, Gujarat, India

*Email of the Corresponding Author: dmachiwal@rediffmail.com

Tel.: +91-2832-271238; FAX: +91-2832-271238

ABSTRACT

Quantification of hydrological processes is necessary for management of small reservoirs especially in arid regions characterized by hot climate, scanty rainfall magnitudes and large rainfall variability. This study focuses on estimating inflow and outflow components of a small reservoir situated in arid Kachchh region of Gujarat, India by developing a water balance model. Daily reservoir water levels were monitored for years 2012 and 2013. All water balance components, i.e. rainwater directly falling into reservoir, surface runoff, irrigation extractions, and evaporation and percolation, were either measured or estimated. Results indicated that rainfall has a fair control on amount of harvested runoff water. In year 2012, meagre rainfall (79 mm) could store 925 m^3 of water with 66 cm depth. In contrast, reservoir water levels were at 2.85 m depth in year 2013 with full capacity of 24879 m^3 when rainfall totalled to 291 mm. The mean percolation rate (0.14 cm-hr^{-1}), determined from 24-hours long-term infiltration tests, revealed that full storage will get depleted within 85 days. A major portion (51%) of storage was lost through evaporation and percolation, and only 21% stored water could be utilized for supplemental irrigation. This finding suggested that suitable measures need to be adopted to check evaporation and seepage losses from the reservoirs in arid regions for improved agricultural productivity. Moreover, results of this study may be useful for water resources managers and decision-makers to develop appropriate operational strategies for the reservoirs in the study area as well as in other arid regions of the world.

Key Words: Arid region; Evaporation; Percolation; Small reservoir; Water balance model; Water levels.

1. INTRODUCTION

People living in arid regions often have insecure livelihoods mainly because of relatively low magnitude and high variability of rainfall [32]. Rainwater harvesting (RWH) is being practised worldwide from the ancient times in order to meet the challenges of the scanty rainfall [36]. Small reservoirs, a proven tool of RWH systems, are the key to secure livelihoods and enhance crop yields in the water scarce regions [15, 23]. Reservoir water storage has become imperative to cope with water scarcity under the climate change scenario

[10, 24, 36]. In dry regions of India, the number of small reservoirs has shown 60% annual growth rate with 120,000 small reservoirs supplying irrigation water to more than 4.12 Mha land [7]. It is estimated that in India as a whole, small reservoirs supply water to 20% of irrigated lands [14]. However, small reservoirs, with less attention and lack of management, are mostly neglected in hydrological research [8, 21] mainly because of absence of enough information to understand their hydrological processes [1, 16]. Estimating the water balance and inflow/outflow components is a necessary requirement for agricultural reservoir water management. Oblinger et al. [22] developed a water balance model to estimate infiltration losses from small reservoirs using reservoir stage, rainfall and evaporation data in Madhya Pradesh, India. Results indicated that model-based infiltration was significantly higher than that obtained by observed changes in reservoir.

It is a general belief that the small reservoirs can only be successful as RWH systems when a large amount of monsoon flow is available, and hence, it is perceived that RWH may not be a dependable source of water supply in dry regions [25]. In the Indian arid regions, commonly-occurring high-intensity rainfall in short-durations [3, 9, 17] generate ample quantity of surface runoff in excess of reservoir storage. Thus, a large portion of runoff is lost as flowing downstream, and this may restrict the effective storage capacity of the small reservoirs to almost equal to their actual storage. Perhaps, these are the reasons that studies highlighting usefulness of the small reservoirs for arid regions could not be found in literature. But it can not be overlooked that the first ever example of the RWH in the world was found during Archaeological excavations of the Indus Valley civilization at Dholavira in the Great Rann of Kachchh, Gujarat, India [12], which is an extremely arid region.

Aridity is prevailing over the entire Kachchh region of Gujarat State, India, which is the second-largest district of the country. Historically, this arid district has been receiving scanty amount of annual rainfall with large variability over annual and spatial scales [19, 26, 29]. The large rainfall variability in the region is illustrated in Fig. 1, as an example, using 38-year (1988-2015) rainfall records available for a raingauge situated at Research Station of the Central Arid Zone Research Institute (CAZRI), Kachchh (Gujarat). It is apparent that the mean rainfall for 9-year (2003-2011) period is 599 mm $year^{-1}$ that is more than double of the mean of 8-year (1995-2002) and 4-year (2012-2015) periods, i.e. 222 and 237 mm $year^{-1}$, respectively. In general, an increase in the annual rainfall is observed after year 2002 [20]. In order to harvest and store the rainwater for supplemental irrigation, few small reservoirs, are constructed in the region. However, feasibility of these reservoirs could not be evaluated due to lack of knowledge about evolution of water storage. Therefore, this study was undertaken to identify and estimate the inflow and outflow components of a small reservoir of Kukma watershed, Gujarat, India, by developing a water balance model under data scarce conditions.

2. MATERIALS AND METHODS

2.1 Study Area Description

Kukma watershed, situated in Kachchh district of Gujarat (Fig. 2), is selected for the present study. The study area exists within 23°10′ to 23°14′ N latitude and 69°46′ to 69°49′ E longitude and is about 14 km away from Bhuj city. The watershed area is 71.12 ha, which encompasses campus of the CAZRI, Regional Research Station, Kukma, Gujarat. The area experiences a hot arid climate and receives an average annual rainfall of 389 mm (1988-2015). It is seen that a considerable portion ranging from 38 to 68% of the annual rainfall occurred in consecutive 2-4 days in the area [17]. On an average, the rainfall occurs in 13 rainy days with high potential evapotranspiration (1900 mm $year^{-1}$) [29].

2.2 Experimental Setup

Previously, runoff water generated from the short-duration and high-intensity rainfall in the study area, was quickly escaping with high velocity. In order to harvest and store this unutilized runoff water, a small reservoir of 20000 m^3 storage capacity was constructed in year 2001 at northwest corner of the CAZRI campus (Fig. 2). The stored water during first few years of reservoir construction was used for drinking and irrigation purposes. Presently, the reservoir water is utilized only to provide supplemental irrigation and the drinking water needs are met from the Narmada canal. It was observed that runoff in high rainfall years escape out of the area after filling the reservoir. Hence, the reservoir was expanded in years 2008 and 2009 to increase its storage capacity by 4803 and 4381.5 m^3, respectively. With these two extensions, reservoir size was 180 m × 90 m with less than 3 m depth and the gross storage capacity of the reservoir was 29184.5 m^3.

The reservoir storage was usually withdrawn at end of monsoon season from two outlets by using diesel-operated 5 hp centrifugal pumps. The extracted water was supplied as supplemental irrigation to wheat and barley crops grown in 3-4 ha. The water was conveyed from reservoir to field inlets through flexible section pipes, and thereafter, flooding irrigation method was used.

2.3 Topographic Survey of Reservoir

A topographic survey of the reservoir was performed in June 2012 with 2.5 m × 2.5 m grid size to develop 2-dimensional contour map and depth-capacity curve. The survey was conducted in reservoir submergence area by recording reduced levels (RLs) of 2675 stations with reference to bench mark using Auto Level. Point RLs were then spatially interpolated by using kriging technique, which is the best interpolation method in hydrogeology [13]. Also, reservoir storage volumes were computed for every 1-cm depth by using extended trapezoidal formula in SURFER software [33] as shown in Eqns. (1) and (2). The depth and storage volumes were used to develop depth-capacity curve for the reservoir.

$$A_i = \frac{\Delta x}{2}\left[RL_{i,1} + 2RL_{i,2} + 2RL_{i,3} + \ldots + 2RL_{i,n-1} + RL_{i,n}\right] \quad (1)$$

$$\text{and } V = \frac{\Delta y}{2}\left[A_1 + 2A_2 + 2A_3 + \ldots + 2A_{n-1} + A_n\right] \quad (2)$$

where, A_i = weighted area of station points coming in grid nodes of i^{th} row, V = water storage volume, $RL_{i,j}$ = reduced level of grid point in i^{th} row and j^{th} column, Δx and Δy = grid column and row spacing, respectively.

2.4 Recording Rainfall and Evaporation

In this study, daily rainfall was measured by using non-recording type raingauge installed nearby the reservoir. The volume of rainwater directly falling inside the reservoir on a particular day was estimated from the following expression:

$$R_t = 10^{-3} \times A \times P_t \quad (3)$$

Where, R_t = rainwater received inside the reservoir on t^{th} day (m^3); A = open surface area of the reservoir that receives the rainfall (m^2); and P_t = rainfall depth (mm) on t^{th} day.

There are many methods to estimate evaporation losses from an open or free water surface [2, 27, 34]. Depending upon the data availability, this study selected Class-A evaporation pan method for estimating reservoir evaporation losses. Daily evaporation rate from the reservoir was determined by converting pan evaporation (E_{pan}) to reservoir evaporation (E_{res}), and then volume of water evaporated from the reservoir (E_t) on a particular day was computed by using the following expressions:

$$E_{res} = k_{pan} \times E_{pan} \quad (4)$$

$$E_t = 10^{-3} \times E_{res} \times A_{res,t} \quad (5)$$

Where, k_{pan} = annual pan coefficient, $A_{res,t}$ = reservoir surface area responsible for evaporation on that day. The effective surface areas of the reservoir were obtained from the topographic survey results.

2.5 Monitoring of Reservoir Water levels

Analysis of reservoir water levels enhances knowledge about the hydrologic processes with a minimum of field measurements, and is also important indicator of climate change [35]. Daily water levels were monitored during dry periods in 2012 and 2013 by installing one wooden scale of 3 m height with nearest 1-cm accuracy. The scale was installed at lowest elevation in the reservoir bottom to enable monitoring even during low storage.

In this study, amount of runoff inflow was estimated indirectly based on reservoir water level changes using the depth-capacity curve. The runoff volumes were determined by subtracting amount of rainwater falling directly in the reservoir from the total inflow.

2.6 Estimating Amount of Water Extracted for Irrigation Purpose

Volumetric method was adopted for estimating reservoir water extraction for irrigating rabi season crops. The average pump discharge at two outlets was measured based on 2-3 daily observations and pump operational hours were recorded. Water extraction quantities (I_i) from the i^{th} outlet for entire crop season were estimated from following formula:

$$I_i = \sum_{j=1}^{n_i} q_{ij} \times d_{ij} \tag{6}$$

Where, q_{ij} = pump discharge at i^{th} outlet on j^{th} day (m^3/hour), d_{ij} = operational pumping hours at i^{th} outlet on j^{th} day (hours), n_i = number of days when pump at i^{th} outlet was operated during a crop season, and i = outlet number, i.e. 1 or 2.

2.7 Measuring Infiltration Rate from Reservoir Bottom

Infiltration rate may resemble the rate of water entry to subsurface from the bottom of the reservoir, thus, may represent the percolation rate. It is well-known fact that estimation of this groundwater inflow component, or potential recharge, always includes uncertainties [28]. Water infiltrating rates were determined by conducting double ring infiltration tests at nine sites for 315 to 540 minutes durations. Diameters of the inner and outer rings were 30 and 60 cm, respectively. Of the total nine tests, four tests were prolonged for more than 24 hours varying from 1463 to 1583 minutes in order to predict long-term percolation rates. The rate of fall of water was measured in the inner ring while water head was maintained at the same level in the outer ring to reduce the flow divergence due to unsaturated lateral flow, which is the largest source of error in ring infiltration tests [4]. Water depth inside the ring was kept as minimum as possible to further minimize the divergence [4].

2.8 Water Balance Modeling of Reservoir

The water balance models are widely-used for estimating groundwater inflow or recharge due to their straightforward implementation and relatively low-cost [5, 11, 18, 31]. A schematic diagram of reservoir water balance is shown in Fig. 3. The reservoir water balance modeling was accomplished by including inflow and outflow components as shown in Eqn. (7) that was run for daily time step for two years, i.e. 2012-2013 by incorporating all component values computed/estimated by using the earlier-described procedures.

$$(R_t + RO_t) - (I_t + P_t + E_t) = \Delta WL_t \tag{7}$$

Where, R = rainwater falling directly into reservoir (m^3), RO = surface runoff entering into reservoir (m^3), I = water abstracted for supplemental irrigation (m^3), P = water percolating down (m^3), E = water lost due to evaporation (m^3), and ΔWL = water level fluctuation (m^3) occurring between t^{th} and $(t+1)^{th}$ time steps. In this study, the model was run at daily time step (t).

3. RESULTS AND DISCUSSION

3.1 Depth-Capacity Curve of Reservoir

The reservoir storage capacity was computed for the entire depth at every 1-cm interval, which was later utilized to develop depth-capacity curve as shown in Fig. 4. It is seen that the reservoir can store 24879 m^3 of rainwater at the maximum storage depth of 2.85 m. It is worth-mentioning that the reservoir capacity was reduced by 4305.5 m^3 over 12-year period due to sedimentation [17]. It is derived from Fig. 4 that the depth-capacity relationship is approximately exponential at low storage depths, which becomes linear at large storage depths. This characteristic of the depth-capacity curve may be well-understood from the shape and size of the reservoir where the initial water quantities get spread over submergence area with little increase of water depth. Once the submergence area is completely covered then further water quantities inclines the storage depth quickly. In arid regions with high evaporation losses, the ratio of surface area to reservoir water depth should be as small as possible. However, reservoir bottom in this study could not be dug beyond 2-3 m depth from surface due to existence of a relatively impermeable layer. Hence, the reservoir capacity could be increased by making two separate extensions, which were clearly revealed in three-dimensional model of the reservoir [17].

3.2 Inflow Components of Reservoir Water

In year 2012, only 79 mm rainfall occurred in the area that could not generate adequate surface runoff to flow into the reservoir. On the other hand, rainfall of 291 mm in 2013 produced ample quantity of the surface runoff that filled up the reservoir up to the maximum storage capacity. The depth-capacity curve revealed that the surface area of the reservoir corresponding to the maximum storage depth of 2.85 m is 15145 m^2. Thus, amount of inflow water directly received from rainfall falling inside the reservoir was computed as 1198 and 4421 m^3 in years 2012 and 2013, respectively. Contribution of the surface runoff to inflow component was zero in year 2012 whereas a storage volume of 20458 m^3 of water was supplied from the runoff in year 2013.

3.3 Hydrographs of Reservoir Water Level

Daily reservoir storages were determined using the water levels monitored during dry periods through the depth-capacity curve. The daily water level fluctuation was computed by taking

difference of two consecutive daily readings of the reservoir water levels. Monitoring was started on 8-September in 2012 and on 4-October in 2013, and it was continued up to December. Hydrographs of reservoir storages along with bar charts of water level fluctuation or daily total water loss for years 2012 and 2013 are shown in Figs. 5(a,b). It is seen from Fig. 5(a) that storage of 925 m^3 rainwater was stored in year 2012 with 66 cm depth in response to rainfall of 79 mm. In contrast, reservoir stage attained the water depth of 2.85 m with the maximum storage of 24879 m^3 in year 2013 when rainfall totalled to 291 mm (Fig. 5b). Because of less number of rainy days in year 2012, the reservoir storage showed a continuous decrease since start of monitoring (Fig. 5a). Hence, the stored rainwater was completely lost within a short-period of 75 days mainly due to high evaporation and arid climatic conditions. In Fig. 5(a), the negative water loss for two days is due to rise of reservoir water stage resulting from rainfall occurrences on 11^{th} and 12^{th} September 2012. The mean water depletion rate was observed to be 0.875 cm day^{-1} during October 2013, without any water extraction. However, the mean depletion rate for three months (October-December) of 2013 was observed as 1.11 cm day^{-1} when a large proportion of storage was extracted for irrigation. On comparing the rainfall and reservoir storages of two years, it is revealed that the rainfall in year 2012 was only 27% of that in year 2013, which resulted in decline of the storage in year 2012 by 96% of that in year 2013.

3.4 Water Withdrawals for Supplemental Irrigation

Discharge of diesel-operated pump at first outlet varied from 16.37 to 19.97 $m^3\ hr^{-1}$ with the mean value of 18.75 $m^3\ hr^{-1}$ whereas the same at second outlet ranged between 6.14 and 7.08 $m^3\ hr^{-1}$ with a mean of 6.70 $m^3\ hr^{-1}$. Water extracted at first outlet was utilized to irrigate wheat crop and that from second outlet was used for irrigating barley crop. Daily mean operational hours for first and second pumps were 7.56 and 7.37 hours, respectively in 2013. Thus, water extraction from first and second outlets was 3829.35 and 1282.68 m^3, respectively with a sum of 5112.02 m^3 for year 2013.

3.5 Water Lost Due to Evaporation

Daily readings of evaporation pan were multiplied by pan coefficient value of 0.90 considered for the arid climate of the area. The evaporated water depths were converted to volumetric terms by multiplying them with evaporating surface areas. Water surface areas for every 1-cm water depth were computed by using trapezoidal formula through SURFER software. Water quantities lost in the form of evaporation varied from 0.009 to 18.42 $m^3\ day^{-1}$ and from 30.78 to 103.20 $m^3\ day^{-1}$ in years 2012 and 2013, respectively. The mean daily evaporation losses accounted for 5.53 and 60.11 m^3 in 2012 and 2013. Relatively high daily evaporation losses in year 2013 were observed due to large surface area of reservoir storage and long-duration water availability in comparison to that in year 2012. Comparatively large values of surface area-to-volume ratio are indicative of large evaporation per unit of storage

[36]. Thus, it is suggested to adopt appropriate measures to prevent or check evaporation of harvested rainwater in arid regions.

3.6 Groundwater Inflow Component

Results of infiltration tests are summarized in Table 1. It is seen from Table 1 that the initial infiltration rate varies widely among the sites ranging from 0.1 to 66 cm hr^{-1}, which is attributed to the large spatial variations of soil moisture content and soil properties. However, the basic infiltration rate for the short-term infiltration tests is somewhat less variable ranging from 0.05 to 4.2 cm hr^{-1} (or 1.2 to 100.8 cm day^{-1}) with the spatial mean of 0.66 cm hr^{-1} (15.87 cm day^{-1}) (Table 1). It is observed that the higher side range of the basic infiltration rate may not practically exist; otherwise, with fast-depleting water levels the completely filled reservoir will get emptied within a short-span of 18 days. Therefore, infiltration tests at four sites were prolonged for more than 24 hours, and it was noticed that the basic infiltration rate got declined by 21, 49, 59 and 72% of that obtained from the short-term infiltration test at the same sites. Dickenson and Bachman [6] also observed that the infiltration rate declines to a minimum value after 4-5 days of ponding. The infiltration rates for the long-term tests varied from 0.057 to 0.318 cm hr^{-1} (or 1.37 to 7.63 cm day^{-1}) with the mean of 0.14 cm hr^{-1} (Table 1). With the mean percolation rate, the maximum water depth of 2.85 m will get depleted within 85 days and that seems to be reliable. The long-term infiltration rate may possibly represent the depletion rate at which the stored water can percolate down from the reservoir bottom. On comparing the results of both the short- and long-term tests, it can be inferred that the stored water inside the reservoir initially percolates down at a little faster rate as it enters the reservoir, and subsequently the percolation rate slows down continuously over the course of time mainly because of constantly reduced water head. Thus, looking at variability at both the spatial and temporal scales and uncertainty involved in estimation of the water percolation as reported in few studies, e.g. Sivapragasam et al. [30], the groundwater inflow or percolation losses in this study were estimated by considering it as a residual term in the water balance model.

3.7 Accounting of Inflow and Outflow Components

Values of all inflow/outflow components of the reservoir water balance model are summarized in Table 2 for years 2012 and 2013. It is seen from Table 2 that inflow in year 2012 was only contributed by 79 mm rainfall directly falling inside the reservoir, which accumulated 1198 m^3 of storage water. This storage was lost without any utilization due to evaporation (655 m^3) and percolation (475 m^3) losses, thus, totalling to outflow component of 1130 m^3 with left storage of 68 m^3. In contrast, rainfall amount of 291 mm in year 2013 could generate the sufficient runoff. The directly falling rainwater (4421 m^3) and surface runoff (20458 m^3) cumulatively (24879 m^3) filled the reservoir up to its maximum capacity. Of the total inflow, 5112 m^3 of water was utilized for irrigating wheat and barley crops, and 7529

and 5290 m^3 of water was lost as percolation and evaporation losses, respectively. At the end of monitoring in 2013, there was storage of 6948 m^3 of water inside the reservoir.

3.8 Comparative Evaluation of Components

Relative proportions of all inflow and outflow components for two years were evaluated by plotting pie diagrams as shown in Figs. 6(a,b). It is apparent from Fig. 6(a) that 100% of the inflow was contributed by the rainwater directly falling into the reservoir in year 2012 but storage was very less. Conversely, in year 2013, 82% of the inflow was received from surface runoff, and only 18% was added by the direct rainwater (Fig. 6b) although the absolute storage volume contributed by the direct rainfall was more than that in year 2012. This finding suggests that increasing the rainfall magnitude by little amount may cause large reservoir storages because surface runoff generated in reservoir catchment outside submergence area also contribute to the inflow. It is further seen from Fig. 6(a) that 94% of storage in 2012 was lost through evaporation (54%) and percolation (40%). However, in year 2013, evaporation and percolation losses accounted for 21 and 30% of storage, respectively, and 21% water was utilized for supplemental irrigation (Fig. 6b). Almost similar findings were reported by Fowe et al. [8] where less than 20% of the available water was withdrawn for various uses from a small reservoir in Burkina Faso, West Africa along with evaporation and percolation losses accounting for 60 and 30%, respectively. It is interesting to notice that relative proportion of percolation loss is higher than evaporation loss in 2013, which is contrasting to their relative proportions in 2012. This can be explained by the fact that in year 2013, the reservoir storage was at the maximum capacity with complete coverage of submergence area that allowed relatively large quantities of water to percolate down. In addition, full water storage created higher or taller water heads, which may have enforced the water entries in subsurface of the reservoir. Also, extraction of 21% of the stored water for irrigation purpose in year 2013 may be responsible for disturbing the relative proportions of percolation and evaporation, which would be definitely different from that obtained if none of the water were withdrawn for irrigation. A general perception is that evaporation losses in the region are much higher than percolation losses. A future study with detailed investigations may be undertaken to find exact ratio of evaporation and percolation losses in the reservoir.

4. CONCLUSIONS

This study determined water balance components of a small reservoir situated in arid Kachchh region of India, in order to obtain necessary information required for better management of the water resources. It was revealed that in an average or surplus rainfall year, more than 80% of the total reservoir storage is received from the surface runoff. In two years, 73% reduction in the annual rainfall resulted in 96% of the water storage indicating a fair control of rainfall on the amount of reservoir storage. The water balance of the reservoir showed that only 21% of harvested rainwater could be withdrawn for providing supplemental irrigation to wheat and barley crops; however, an equal proportion of the water was lost

through evaporation and 30% was percolated down as groundwater inflow. Thus, there is scope for increasing the water use efficiency by reducing the evaporation and percolation losses. In arid regions, large wind velocity and extremely high air temperatures are responsible for losing significant portion of reservoir storage through evaporation, and therefore, suitable treatment methods such as spreading of thin layer of plastic sheets, chemicals and/or bio-substances need to be employed to conserve water for relatively longer period. Moreover, results of this study can be useful for water resources managers and decision-makers in order to formulate appropriate policies for the efficient planning and management of small reservoirs in the arid regions. The results can also be considered as the first information needed for understanding hydrological processes acting on the reservoir system for optimizing the reservoir operations, and may be valuable to decide satisfactory activities undertaken for conserving the rainwater storage against the evaporation and percolation losses. Finally, this study emphasizes the importance of the monitoring of the water levels in small reservoirs in hydrological research especially in dry areas of the data scarce regions.

ACKNOWLEDGEMENTS

Authors gratefully acknowledge the support and necessary facilities provided by the Director, ICAR-Central Arid Zone Research Institute (CAZRI), Jodhpur for carrying out this study. They also wish to thank the editor and three anonymous reviewers whose valuable and encouraging comments helped improving earlier version of this manuscript.

REFERENCES

1. Adwubi A, Amegashie BK, Agyare WA, Tamene L, Odai NS, Quansah C, Vlek P (2009) Assessing sediment inputs to small reservoirs in Upper East Region, Ghana. Lakes & Reservoirs Research and Management, 14: 279-287.
2. Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration: Guide-lines for computing crop water requirements. In: Irrigation and Drainage, Paper 56. Food and Agriculture Organization, Rome, Italy.
3. Athawale RN (2003) Water Harvesting and Sustainable Supply in India, published for Environment and Development Series, Centre for Environment Education, Rawat Publications, Jaipur and New Delhi.
4. Bouwer H, Back JT, Oliver JM (1999) Predicting infiltration and ground-water mounds for artificial recharge. J Hydrol Eng, ASCE, 4(4): 350-357.
5. Crosbie RS, Binning P, Kalma JD (2005) A time series approach to inferring ground water recharge using the water table fluctuation method. Water Resour Res, 41, W01008. doi:10.1029/2004WR003077
6. Dickenson, JM, Bachman, SB (1994) The Optimization of Spreading Groundwater Operations. In: Proceedings of the Second International Conference on Artificial Recharge of Groundwater, A. Ivan Johnson and R. David G. Pyne (Editors), ASCE Publications, pp. 630-639.
7. Downing JA, Prairie YT, Cole JJ, Duarte, CM, Tranvik LJ, Striegl RG, McDowell, WH, Kortelainen P, Caraco NF, Melack JM, Middelburg JJ (2006) The global abundance and size distribution of lakes, ponds, and impoundments. Limnol Oceanogr, 51(5): 2388-2397.

8. Fowe T, Karambiri H, Paturel J-E, Poussin J-C, Cecchi P (2015) Water balance of small reservoirs in the Volta basin: A case study of Boura reservoir in Burkina Faso. Agr Water Manage, 152: 99-109.
9. Garg SK (1987) Hydrology and Water Resources Engineering, Khanna publishers, Delhi, pp.110-181.
10. Gunnell Y, Krishnamurthy A (2003) Past and present status of runoff harvesting systems in dryland peninsular India: a critical review. Ambio, 32(4): 320-324.
11. Healy RW, Cook PG (2002) Using ground water levels to estimate recharge. Hydrogeol J, 10: 91-109.
12. Kavarana G (2006) The value of a raindrop. Traditional RWH systems, particularly in the arid and semiarid regions of Rajasthan and Gujarat. In: Edmunds, W.M. and Cardona, C. (editors), Final Report of UNESCO G-WADI meeting on water harvesting, Aleppo, Syria, 20-22 November 2006, p. 49-57.
13. Kitanidis PK (1997) Introduction to Geostatistics: Applications in Hydrogeology. Cambridge University Press, New York, 249 pp.
14. Li Q, Gowing J (2005) A daily water balance model approach for simulating performance of tank-based irrigation systems. Water Resour Manag, 19: 211-231.
15. Liebe J, van de Giesen N, Andreini M (2005) Estimation of small reservoir storage capacities in a semi-arid environment – a case study in the Upper East Region of Ghana. Phys Chem Earth, 30(6-7): 448-454.
16. Liebe JR, van de Giesen N, Andreini M, Walter MT, Steenhuis TS (2009) Determining watershed response in data poor environments with remotely sensed small reservoirs as runoff gauges. Water Resour Res, 45, W07410, http://dx.doi.org/10.1029/2008WR007369.
17. Machiwal D, Dayal D, Kumar S (2015) Assessment of reservoir sedimentation in arid region watershed of Gujarat. Journal of Agricultural Engineering, ISAE, 52(4): 40-49.
18. Machiwal D, Jha MK (2015) GIS-based water balance modeling for estimating regional specific yield and distributed recharge in data-scarce hard-rock regions. Journal of Hydro-environment Research, 9(4): 554-568.
19. Machiwal D, Kumar S, Dayal D (2016) Characterizing rainfall of hot arid region by using time series modeling and sustainability approaches: a case study from Gujarat, India. Theor Appl Climatol, 124(3): 593-607.
20. Machiwal D, Kumar S, Dayal D, Mangalassery S (2016) Identifying abrupt changes and detecting gradual trends of annual rainfall in an Indian arid region under heightened rainfall rise regime. Int J Climatol, accepted.
21. Mustapha MK (2009) Problems, challenges and management of small, shallow tropical African reservoirs: a case study of Oyun Reservoir, Offa, Nigeria. International Journal of Lakes and Rivers, 2(1): 163-174.
22. Oblinger JA, Moysey SMJ, Ravindrinath R, Guha C (2010) A pragmatic method for estimating seepage losses for small reservoirs with application in rural India. J Hydrol, 385: 230-237.
23. Oweis T, Hachum A (2006) Water harvesting and supplemental irrigation for improved water productivity of dry farming systems in West Asia and North Africa. Agr Water Manage, 80(1-3): 57-73.
24. Pandey DN, Gupta AK, Anderson DM (2003) Rainwater harvesting as an adaptation to climate change. Curr Sci India, 85(1): 46-59.

25. Pisharoty PR (1990) Characteristics of Indian Rainfall, Monograph, Physical Research Laboratories, Ahmedabad.

26. Raju KCB (1995) Strategies to combat drought in Kutch. Workshop on Strengthening of Community Participation in Disaster Reduction and Role of NGOs organized by Vivekanand Research and Training Institute, Mandvi, during January 13-15 at New Delhi.

27. Rosenberry DO, Winter TC, Buso DC, Likens GE (2007) Comparison of 15 evaporation models applied to a small mountain lake in the northeastern USA. J Hydrol, 340: 149-166.

28. Scanlon BR, Healy RW, Cook PG (2002) Choosing appropriate techniques for quantifying groundwater recharge. Hydrogeol J, 10: 18-39.

29. Singh S, Kar A (1996) Integrated Natural and Human Resources Appraisal for Sustainable Development of Kachchh District. Central Arid Zone Research Institute, Jodhpur.

30. Sivapragasam C, Vasudevan G, Maran J, Bose C, Kaza S, Ganesh N (2009) Modeling evaporation-seepage losses for reservoir water balance in semi-arid regions. Water Resour Manag, 23: 853-867.

31. Sophocleous M (1991) Combining the soil water balance and water level fluctuation methods to estimate natural ground water recharge: practical aspects. J Hydrol, 124: 229-241.

32. Stevenson K (2000) The Role of Small Dams in Improving Rural Livelihoods in Semi-Arid Areas. Care Stakeholder Workshop 29-31 August 2000, Masvingo, Zimbabwe.

33. SURFER (2003) Surface Mapping System. Surfer version 8.03, Golden Software, Inc., Colorado. www.goldensoftware.com.

34. Tanny J, Cohen S, Assouline S, Lange F, Grava A, Berge D, Teltch B, Parlange MB (2008) Evaporation from a small water reservoir: direct measurements and estimates. J Hydrol, 351: 218-229.

35. Vuglinskiy V (2009) Water Level - Water level in lakes and reservoirs, water storage. Assessment of the Status of the Development of the Standards for the Terrestrial Essential Climate Variables. Report of Global Terrestrial Observing System, Rome, 17p.

36. Wisser D, Frolking S, Douglas EM, Fekete BM, Schumann AH, Vörösmarty CJ (2010). The significance of local water resources captured in small reservoirs for crop production - A global-scale analysis. J Hydrol, 384: 264-275.

Table 1. Results of infiltration tests conducted at nine sites for short duration and at four sites for long duration

Site	Test Duration	Initial Infiltration Rate	Basic Infiltration Rate		Test Conducted During
		cm hr^{-1}	cm hr^{-1}	cm day^{-1}	
S_1	9 hr	0.1	0.05	1.20	Feb-2012
S_2	8 hr	18	0.2	4.80	Feb-2012
S_3	7 hr	18	0.1	2.40	Feb-2012
S_4	7 hr 34 min	18	0.4	9.60	Apr-2013
S_5	7 hr (26 hr 9 min)	36	0.4 (0.318*)	7.632*	Apr-2013
S_6	6 hr	66	4.2	100.8	Apr-2013
S_7	7 hr 16 min (26 hr 23 min)	30	0.2 (0.102*)	2.448*	Apr-2013
S_8	6 hr 36 min (25 hr 31 min)	30	0.2 (0.082*)	1.968*	Apr-2013
S_9	5 hr 15 min (24 hr 23 min)	24	0.2 (0.057*)	1.368*	Apr-2013

Note: * and bracketed figures indicate information for the long-duration (24 hours) tests.

Table 2. Inflow and outflow components for water balance model of reservoir for two years

Water Balance Component	**Quantity (m^3)**	
	Year 2012	**Year 2013**
Direct Rainfall	1198	4421
Surface Runoff	0	20458
Total Inflow	**1198**	**24879**
Irrigation Extractions	0	5112
Percolation losses	475	7529
Evaporation losses	655	5290
Reservoir Storage	68	6948
Total Outflow	**1198**	**24879**

Figure Caption

Fig. 1. Bar charts of annual rainfall and number of rainy days for 28-year (1988-2015) period recorded at Regional Station of the Central Arid Zone Research Institute in Kachchh, Gujarat, India

Fig. 2. Location map of the study area

Fig. 3. Schematic of reservoir water balance model

Fig. 4. Depth-capacity curve of the reservoir

Fig. 5. Water level hydrographs and barcharts of daily water loss from reservoir in years (a) 2012 and (b) 2013

Fig. 6. Relative proportions of the inflow/outflow components illustrating reservoir water balance for years (a) 2012 and (b) 2013

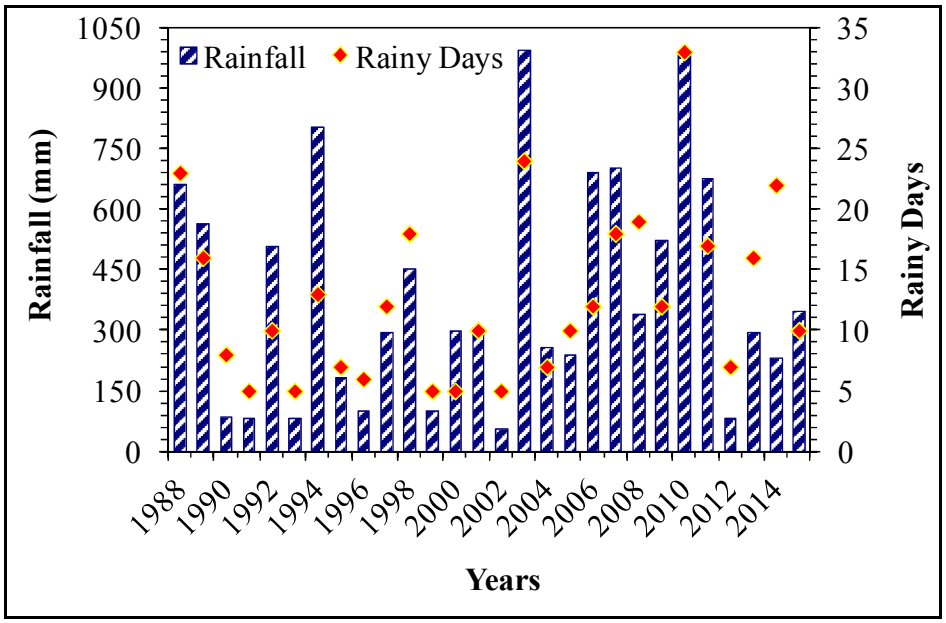

Rainfall
Rainy Days
Rainfall (mm)
Rainy Days
Years
1050
900
750
600
450
300
150
0
35
30
25
20
15
10
5
0
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014

Figure 1

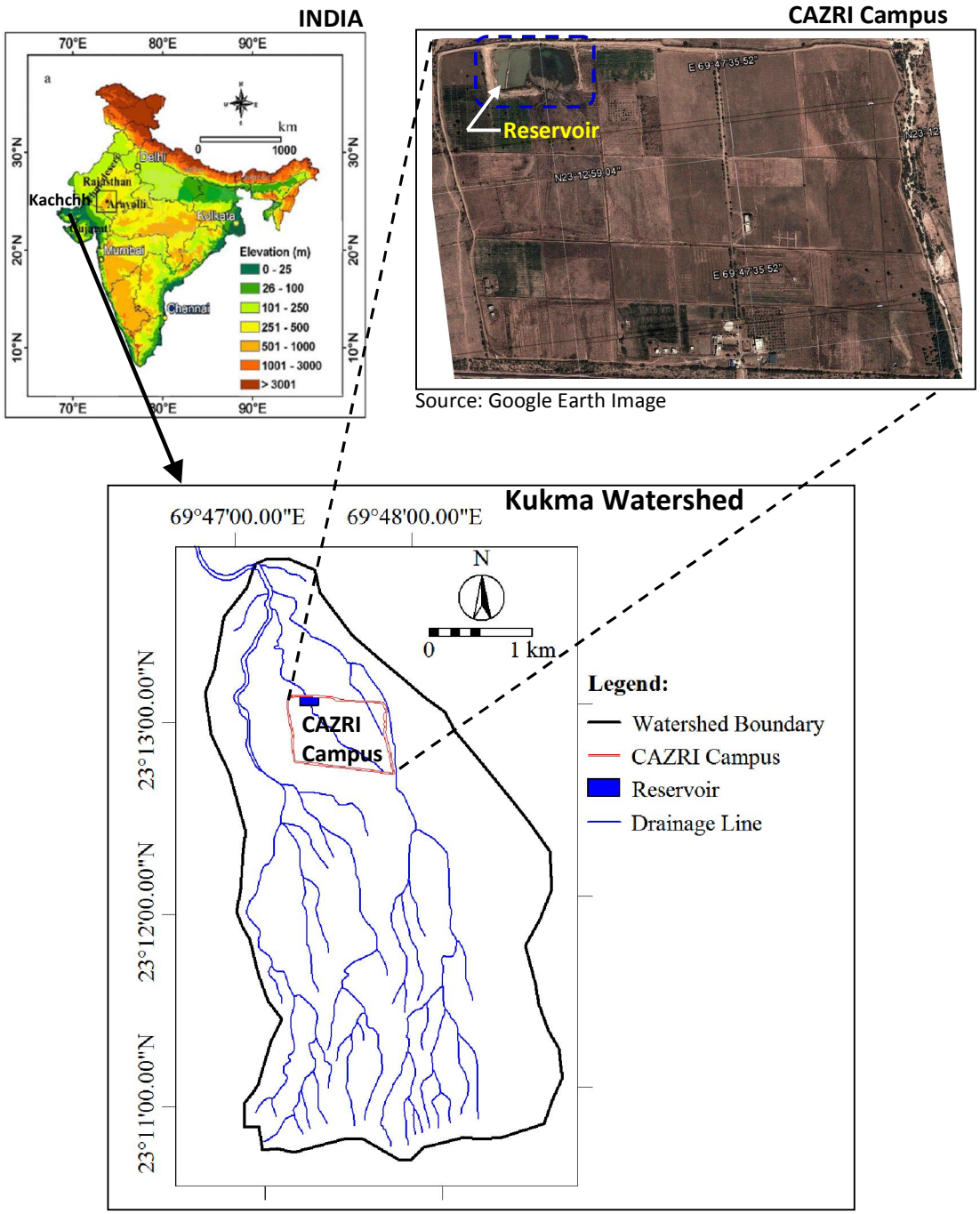

INDIA
70°E
80°E
90°E
30°N
20°N
10°N
km
0
1000
Delhi
Rajasthan
Kachchh
Aravalli
Kolkata
Mumbai
Chennai
Elevation (m)
0 - 25
26 - 100
101 - 250
251 - 500
501 - 1000
1001 - 3000
> 3001
CAZRI Campus
Reservoir
E 69 47 35.52"
N23 12'59.04"
Source: Google Earth Image
Kukma Watershed
69°47'00.00"E
69°48'00.00"E
23°13'00.00"N
23°12'00.00"N
23°11'00.00"N
N
0
1 km
CAZRI Campus
Legend:
Watershed Boundary
CAZRI Campus
Reservoir
Drainage Line

Figure 2

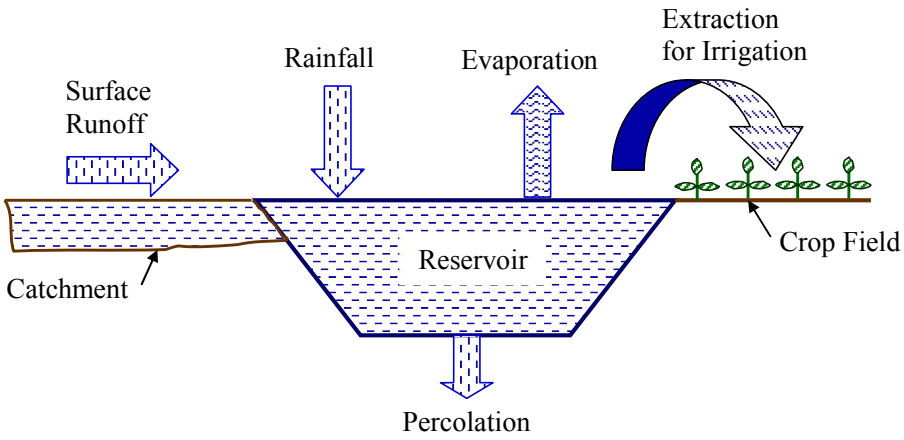

Extraction
for Irrigation
Rainfall
Evaporation
Surface
Runoff
Crop Field
Reservoir
Catchment
Percolation

Figure 3

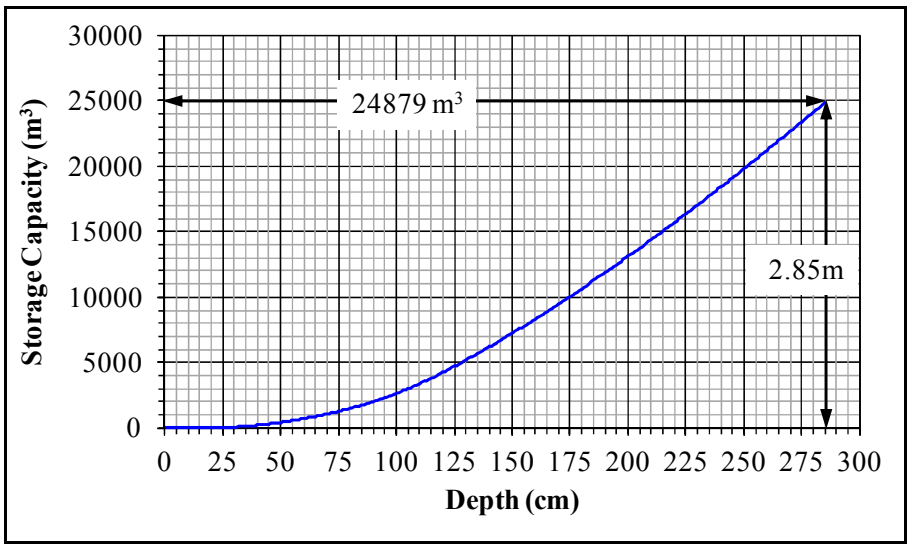
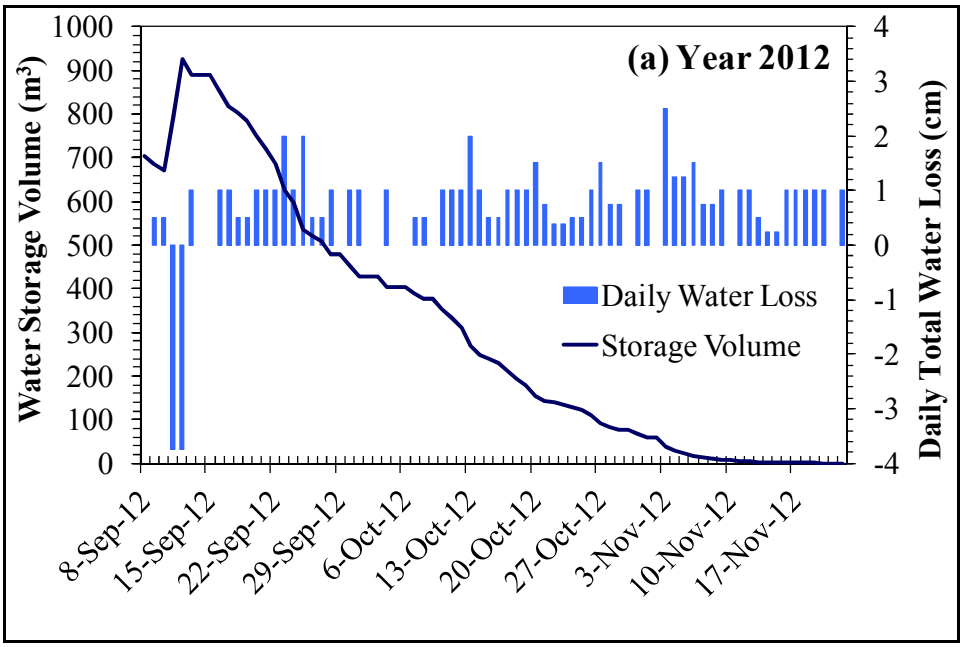

30000
25000
20000
15000
10000
5000
0
Storage Capacity (m³)
24879 m³
2.85m
0 25 50 75 100 125 150 175 200 225 250 275 300
Depth (cm)

Figure 4


(a) Year 2012
Water Storage Volume (m³)
Daily Total Water Loss (cm)
Daily Water Loss
Storage Volume
1000
900
800
700
600
500
400
300
200
100
0
4
3
2
1
0
-1
-2
-3
-4
8-Sep-12
15-Sep-12
22-Sep-12
29-Sep-12
6-Oct-12
13-Oct-12
20-Oct-12
27-Oct-12
3-Nov-12
10-Nov-12
17-Nov-12

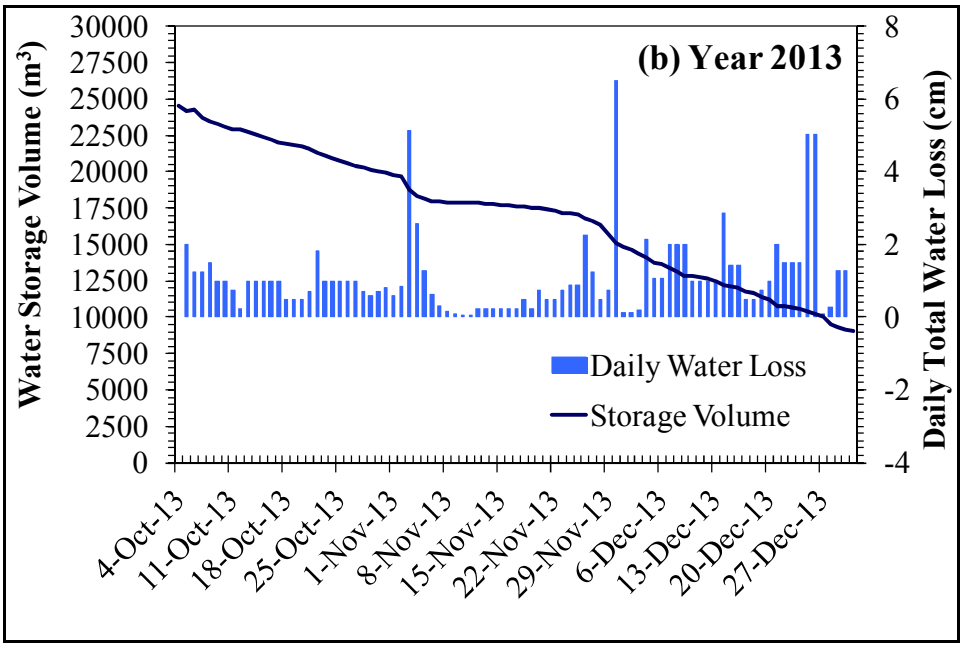

(b) Year 2013
Water Storage Volume (m³)
Daily Total Water Loss (cm)
Daily Water Loss
Storage Volume
30000
27500
25000
22500
20000
17500
15000
12500
10000
7500
5000
2500
0
8
6
4
2
0
-2
-4
4-Oct-13
11-Oct-13
18-Oct-13
25-Oct-13
1-Nov-13
8-Nov-13
15-Nov-13
22-Nov-13
29-Nov-13
6-Dec-13
13-Dec-13
20-Dec-13
27-Dec-13

Figure 5

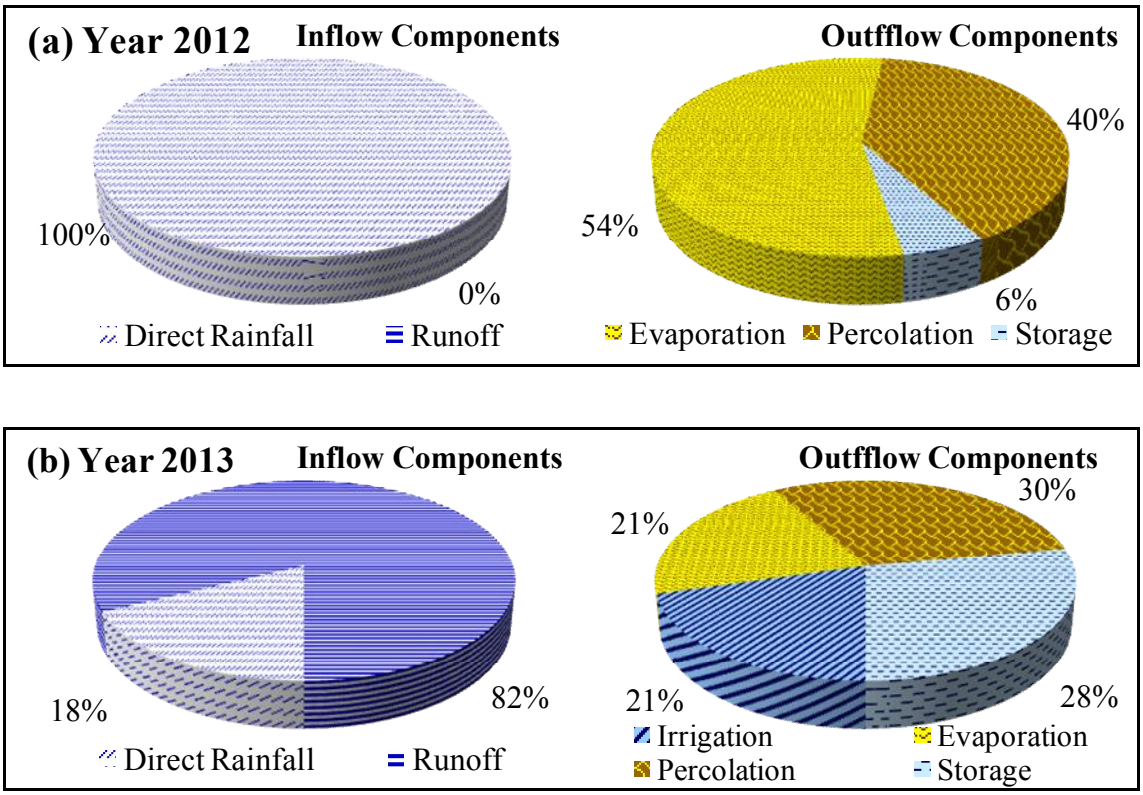

(a) Year 2012
Inflow Components
Outfflow Components
100%
0%
54%
40%
6%
Direct Rainfall
Runoff
Evaporation
Percolation
Storage
(b) Year 2013
Inflow Components
Outfflow Components
18%
82%
21%
30%
21%
28%
Direct Rainfall
Runoff
Irrigation
Evaporation
Percolation
Storage

Figure 6