2013 | IPWE

6TH INTERNATIONAL PERSPECTIVE ON WATER RESOURCES & THE ENVIRONMENT

January 7-9, 2013 | Izmir, Turkey

CALL FOR PAPERS

ASCE-EWRI invites you to submit abstracts to IPWE 2013. This conference will cover a wide variety of topics on sustainable environmental and water resources management. While technical sessions will include topics on developed and developing countries, much of the focus of this conference will be on water resources and the environment in developing countries.

IMPORTANT DATES

ABSTRACT SUBMISSIONS DEADLINE:

June 17, 2012

AUTHOR REGISTRATION & FINAL PAPER DEADLINE:

October 1, 2012

CONFERENCE BEGINS:

January 7, 2013

STEERING COMMITTEE

Dr. Zekai Sen,
Conference Co-Chair
Istanbul Technical University, TURKEY

Dr. Latif Kalin,
Conference *Co-Chair*
Auburn University, USA

Dr. Mustafa M. Aral,
Tech. Program Co-Chair
Georgia Institute of Technology, USA

Dr. Orhan Gündüz,
Tech. Program Co-Chair
Dokuz Eylul University, TURKEY

The Environmental & Water Resources Institute of the American Society of Civil Engineers (ASCE-EWRI) looks forward to welcoming attendees to the 6th International Perspective on Water Resources & the Environment conference (IPWE 2013), January 7-9, 2013, Izmir, Turkey. Following the success of the 2012 conference in Marrakech, Morocco, EWRI looks forward to another noteworthy conference that brings together engineers, scientists, planners, economists and allied professionals from all over the world.

CONFERENCE THEMES

- Advanced Wastewater Treatment Technologies
- Artificial Groundwater Recharge
- Climate Change and Environmental Impacts
- Conflict Resolution in Interstate and International Water Disputes
- Droughts and Their Impacts on Water Resources
- Ecological Modeling and Assessment
- Effect of Urbanization on Water Resources and Water Quality
- Environmental Modeling and Assessment
- Flood Risks and Flash Floods
- Global Climate Change and Effect on Water Resources and Environment
- Green Energy Development and Management
- Groundwater Flow and Contaminant Transport
- Hazardous Waste and Solid Waste Management
- Hydroclimate
- Hydrologic and Hydraulic Engineering and Modeling
- Inter-basin Transfer of Water
- Irrigation Management and Land Reclamation
- Low Impact Development (LID)
- Management of Contaminated Aquifers
- Marine Outfalls and Waste Disposal Systems
- Rainfall and Runoff Harvesting
- Safety and Security of Environmental and Water Resources Infrastructure
- Saltwater Intrusion in Coastal Aquifers
- Seawater Desalination and Desalination Brine Outfalls
- Smart Technologies for Treatment of Plant Sludge
- Snow Hydrology
- Socio-economic Issues in Water Resources Development
- Surface Water Flow and Contaminant Transport
- Wastewater Reclamation and Reuse
- Water Management for Food Security and Sustainable Rural Development
- Water Quality Planning, Management, and Monitoring
- Water Resources Planning and Management
- Water Supply and Pricing
- Water Supply and Sanitation in Urban and Non-urban Areas
- Watershed Processes and Management
- Wetlands Restoration and Protection

Visit www.ipwe2013.org for more information on submissions and the themes/topics available at the conference.

IPWE 2013 is a conference organized and sponsored by the Environmental & Water Resources Institute (EWRI) of the American Society of Civil Engineers (ASCE), the Turkish Water Foundation, Dokuz Eylul University, Georgia Tech, and Auburn University.

ASCE AMERICAN SOCIETY OF CIVIL ENGINEERS

EWRI ASCE

TURKISH WATER FOUNDATION

DOKUZ EYLÜL ÜNİVERSİTESİ İZMİR 1982

Georgia Institute of Technology

AUBURN UNIVERSITY

Visit **www.ipwe2013.org** for more information!

http://www.springer.com/journal/12403

Exposure and Health
Editor-in-Chief: Meharg, A.A.
ISSN: 2451-9766 (print version)
ISSN: 2451-9685 (electronic version)
Journal no. 12403

Modeling Rainwater Harvesting Potential and Supplemental Irrigation Requirement of Rainfed Crops

Pramod K Pandey[a]*, Pieter van der Zaag[b], Michelle L Soupir[a], Vijay P Singh[c], Sudhindra N Panda[d], Laxmi N Sethi[e], Vinay K Pandey[f]

[a]Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, IA, USA

[b]UNESCO-IHE Institute for Water Education, Delft, Netherlands, Water Resources Section, Delft University of Technology, Delft, Netherlands

[c]Department of Biological and Agricultural Engineering, Texas A and M University, College Station, Texas, USA

[c]Department of Civil and Environmental Engineering, Texas A and M University, College Station, Texas, USA

[d]Department of Agricultural and Food Engineering, Indian Institute of Technology, Kharagpur, India

[e]Department of Agricultural Engineering, Assam University, India

[f]BRSM College of Agricultural Engineering and Technology, Indira Gandhi Krishi Viswavidyalaya, IGKV, Raipur, India

*Corresponding author: pkpandey@iastate.edu; +1 (915)-603-1650

Abstract

Rainfed agriculture substantially contributes to the total crop production of the world. Therefore, improving agricultural production in rainfed regions is crucially important to meet the world future food demand. This will require generating new water resources in areas, where limited water supply hinders crop production, i.e., in rainfed regions. A simple approach, such as rainwater harvesting during rainy season in a farm and applying stored rainwater to crops judicially, can be an option for enhancing the water availability in rainfed areas. Models capable of estimating rainwater harvesting potential can play a key role in designing suitable systems intended for rainwater conservation for agricultural purposes. To predict the rainwater harvesting potential for meeting the supplemental irrigation (SI) requirement of rainfed crops, we have developed a water balance model, which calculates the water availability in the on-farm reservoirs designed for rainwater harvesting. In addition the model estimates soil moisture in the cultivated field and the SI requirement of the crops. The tool developed here will be potentially useful in designing rainwater harvesting systems capable of improving crop production in rainfed regions.

Keywords: rainfed agriculture; water balance model; supplemental irrigation; crop productions

Introduction

Rainfed agriculture dominates the world's food supply. For example, rainfed crops contribute approximately 60-70% to the world crop production (FAO, 2002). About 80% of the world agricultural land is rainfed. In some regions, such as sub-Saharan Africa, even more than 95% land is rainfed. In Asia more than 65% land is rainfed (FAO STAT, 1999). In many countries, for instance, sub-Saharan Africa, more than 60% population depends on rainfed agriculture, where rainfed farming produces 30-40% of the countries' gross domestic product (GDP) (World Bank, 1997).

Despite significant contributions to the world food production, and considerable potential for agricultural growth, rainfed agriculture suffers mainly due to poor crop yields. Except for a few exceptions, for example rainfed regions in the United States, which are highly productive; many of the rainfed regions around the world have the lowest crop yields. The average crop yield in rainfed regions is reported to be 1 t/ha (Rockstro□m, 2001); and improvement in rainfed crop yields is a key to enhance the food production as well as the economy of the rainfed areas, which critically depend on rainfall. Studies have shown that poverty and food are interlinked (Rockstr o□m et al., 2009), for an example, a majority (75%) of 1.2 billion extremely poor people (i.e., daily earning less than $1) live in rural areas, where the water availability is a serious issue.

Improving water resource management and rural development are important to alleviate poverty in many countries. Insufficient water resources for agricultural purposes are a stumbling block to development in many developing countries. Uncertainty in rainfall often hinders agricultural production. For example, previous studies have shown that the occurrence of dry spells (i.e., short periods of 2-4 weeks with no rainfall or the dry spells lasting 10-15 days) causes severe yield reductions (Steward, 1998; Sivakumar, 1992) in rainfed regions. Barron et al. (2003) assessed the probability of dry spells in semi-arid areas in Kenya and Tanzania, and reported minimum probability of 0.2-0.3 for a dry spell lasting more than 10 days for any time of the growing season of a crop; and 0.7 for a dry spell which occur during the sensitive flowering stage.

Mitigating the impacts of dry spell on agriculture will potentially improve crop production. Techniques, such as water harvesting and conservation tillage in semi-arid rainfed areas, have been found to be useful in controlling the impact of dry spells. Providing supplemental irrigation to crops during dry spells can lead to a considerable increase in water productivity (Rockstro□m et al., 2009; 2003). In principle, adopting the strategies which allow rainwater conservation (i.e., improving water holding capacity of soil, increasing infiltration, and enhancing water uptake of plants) will be an alternative for meeting the growing food demand of the world.

For example, a simple approach, such as rainwater harvesting in farm-scale reservoirs, and recycling it for supplemental irrigation to crops, is a viable option. A relatively old study by Evanari et al. (1971) showed that constructing multiple small water-harvesting ponds for collecting local runoff can be more useful for agricultural production compared to designing a large reservoir downstream. Other studies, which are relatively new, such as van der Zaag and Gupta (2008) and Pandey et al. (2011) have shown the improved sustainable gross return while using decentralized small reservoirs compared to a large reservoir downstream. In addition, these decentralized reservoirs can promote participatory irrigation. Recently integrated water management approach, which encourages water use associations (i.e., participatory irrigation) [e.g., Gunnel and Anupama, 2003; Mialhe et al., 2008], has been encouraged in many parts of the world, particularly in sub-Saharan Africa, to improve the water availability in rural areas.

These small reservoir systems (i.e., decentralized distributed small reservoirs) have been prevalent for centuries in many rural communities around the world, and water stored in the reservoirs was often used for providing irrigation to crops as well as for domestic purposes. Studies have shown that irrigation from farm-scale reservoirs is profitable particularly to small farmers (Palanisami and Meinzen-Dick, 2001; Balasubramanian and Selvaran, 2003). These ponds have been found to be useful in bridging dry spells in tropical savannah farming systems (Barron et al., 2003; Palanisami and Meinzen-Dick, 2001; Balasubramanian and Selvaraj, 2003).

The importance of these reservoirs in agriculture production in southern India is reported elsewhere (Rao and Chakraborti, 2000; Prasad et al., 1993; Mialhe et al., 2008). Besides improving the water availability for agricultural production, rainwater harvesting can also support aquaculture in rainfed regions. For example, Mohanty et al. (2002) used rainwater conservation as a tool for enhancing fish farming. The authors proposed a method (i.e., optimizing the weir height) for conserving rainwater for rice crop as well as refuge size to harvest the runoff for fish culture. Pandey et al. (2006) proposed designing on-farm reservoirs in paddy field for storing rainwater, which can be used for fish farming in the reservoirs as well as stored water can be recycled to crops (i.e., supplemental irrigation).

Considering the importance of rainfed agriculture, which will remain the dominant source of food supply (Parr et al., 1990; Rockstro□m, et al., 2003), managing water resources in rainfed regions for improving agricultural production is critical. Understanding water availability at the farm-scale catchment and developing techniques to capture rainwater for agricultural purposes can help find solutions for rainfed farming. Here we, therefore, have developed a modeling tool for improving our understanding of rainwater harvesting potential in rainfed regions. Many models have been developed in the past, which calculate runoff from rainfall (Roche, 1971; Chiew et al., 1994; Hughes, 1995); however, further studies are required to understand how this runoff can be captured in farm scale reservoirs and recycled it for agricultural production. The objective of this study is to develop a water balance model to calculate water storages in the on-farm reservoir (OFR) and supplemental irrigation requirement of crops. This study is important to improve the farm-scale rainwater harvesting systems and enhance the water availability in rainfed regions.

Material and Methods

Model

The conceptual model formulation used in this study is shown in Figure 1. Water storages in the OFR and soil moisture in the field were calculated. The OFR water storage was estimated using OFR water balance model, while soil moisture in the field was calculated by balancing the soil moisture in the field. Soil moistures were estimated under irrigated (i.e., with supplemental irrigation using the OFR storage) and rainfed conditions (no supplemental irrigation). Various components involved in simulation are described in detail elsewhere (Pandey et al., 2012).

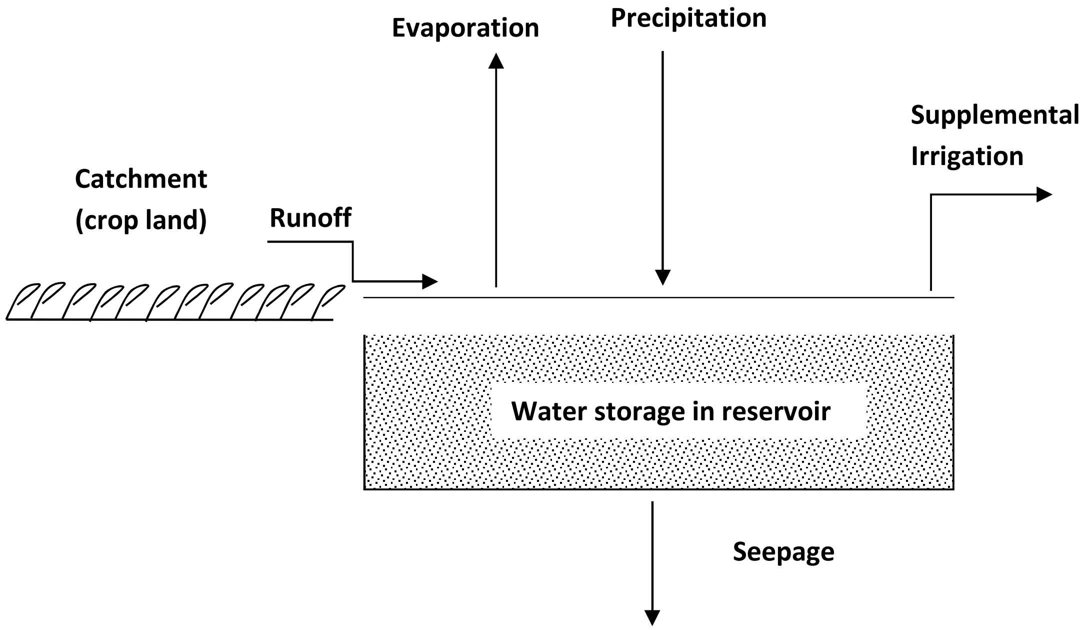

Figure 1. Conceptual water balance model used in simulation

The OFR water balance can be written as:

$$\frac{dW}{dt} = P - Q - E - S - SI \qquad (1)$$

The change in soil water of irrigated conditions can be written as:

$$\frac{ds}{dt} = P_{eff} - Q - ET_a - D + SI \qquad (2)$$

where *ds/*dt is the change in soil water (mm/day); *dw/dt* is the change in OFR water (mm/day); and $P_{eff,}$ Q, ET_a, E, D, SI, and S is the effective precipitation (daily rainfall minus 2 mm interception loss), runoff, actual evapotranspiraiton, evaporation, deep percolation, supplemental irrigation, and OFR seepage in (mm/day). Surface runoff was calculated for daily rainfall using the SCS curve number equation (USDA-SCS, 1972):

$$Q = \frac{(P_{eff} - 0.2s)^2}{P_{eff} + 0.8s} \qquad \text{R} > 0.2\text{s} \qquad (3)$$

$$Q = 0 \qquad \text{R} \leq 0.2\text{s} \qquad (4)$$

$$s = 254\left(\frac{100}{CN}\right) - 1 \qquad (5)$$

where Q is the daily surface runoff in mm, P_{eff} is the daily effective rainfall, s is retention parameter, and CN is the curve number. The s and CN values vary with soil, land use, slope, and management. Water losses as evaporation from OFR and evapotranspiration from field were estimated using the Penman method (1948, 1963). The formulation of evaporation was as (Singh and Xu, 1997; Shuttleworth, 1993):

$$E = ET_0 = \frac{\Delta}{\Delta+\gamma} \cdot \frac{R_n}{\lambda} \cdot \frac{\gamma}{\Delta+\gamma} \cdot \frac{6.43(f_u)D}{\lambda} \qquad (6)$$

where E is the evaporation (mm/day); R_n is the net radiation at the surface of water (MJ/m^2/d); Δ is the slope of saturation vapor pressure curve (kPa/ºC); γ the psychometric coefficient (kPa/ºC); λ is the latent heat of vaporization (MJ/kg); f_u is the wind function; and D is the vapor pressure deficit (e_s - e_a) in (kPa). The wind function was estimated as in the original Penman (1948, 1963) equation using $a_u = 1$, $b_u = 0.536$, and u, the wind speed, at a 2 m height (m/s). For open water surface, the reflection coefficient or albedo of 0.08 was used (Shuttleworth, 1993; Allen et al., 1998). Formulation for calculating evaporation from ponds is described by Pandey et al. (2011).

The actual evapotranspiration (ET_a), the amount of water consumed by a crop (i.e., the amount the crop transpires through the leaves) and the amount of water the soil evaporates, was estimated from reference evapotranspiration (ET_0) using the FAO method (1977). Transpiration from leaves and evaporation from soil were lumped together to have simple simulations. ET_a is a function of crop characteristics, crop growth stages, climate conditions (i.e., length of day, temperature, wind, sunshine, cloudiness), and the available soil moisture in the field. It was estimated as:

$$ET_a = K_c \times ET_0 \qquad (7)$$

where K_c is the crop coefficient. In the ET_a simulation, we used K_c of dry bean. Daily K_c was estimated from the values for different crop growth stages (FAO 1979) by fitting the polynomial line for two 100-day cropping seasons (20-119 and 165-264 Julian Days). The crop coefficient of the four growth stages: initial (25 days); crop development (25 days); midseason (30 days); and late seasons (20 days) were incorporated for daily K_c estimation. The K_c value for bean crop varied from 0.15 (initial stage) to 0.56 (late season) with a maximum of 1.19 during the midseason.

Soil was considered as a reservoir for water storage and that water can be used by plant roots (i.e., available moisture (*AM*)). The change in *AM* for plant growth was estimated as:

$$\frac{d(AM)}{dt} = RAM + NRAM \qquad (8)$$

where *d(AM)/dt* is the change in *AM* (mm/day); *RAM* is the readily available moisture (mm/day), which is the portion of the available soil water that is relatively easily available for plant use. The remaining water (i.e., AM – RAM) was the non-readily available moisture (NRAM). The *NRAM* value (mm/day) can be used by plants; however, plants will suffer from yield reduction. Water in excess of field capacity drained from the root zone was considered as a water loss through deep percolation. The deep percolation was estimated using the method described elsewhere (Temeszen et al., 2007).

Model Input

Catchment area, reservoir area, curve number, depth of reservoir ground water depth, saturated hydraulic conductivity, RAM, NRAM, minimum supplemental irrigation requirement (SI), and irrigation efficiency were the major input parameters required for simulation. Model inputs are described in detail by Pandey et al. (2012). Here we have used a catchment area of 10 ha, and the reservoir area (i.e., % of catchment area) was 10%. The curve number (CN) was 88, and depth of reservoir was 2.5 m. The ground water depth was set at 6 m, and the saturated hydraulic conductivity was 0.33 cm/hr. The initial RAM and NRAM values were 48 mm and 72 mm, respectively. The SI value was 24 mm, and irrigation efficiency was 67%.

Model application

The model was applied to a rainfed location (experimental study at Agricultural and Food Engineering Department, Indian Institute of Technology, Kharagpur) in India shown in Figure 2. The study area has a sub-humid and tropical savannah climate. The mean minimum and maximum air temperatures are 12 ^{0}C and 40 ^{0}C in January and May, respectively. The annual average total rainfall is approximately 1500 mm, 75% of which occurs during the rainy season (June to September). Rainfed crops, such as rice, wheat, and mustard, are the major crops in the study area. Commonly, rice crop is grown in the monsoon season. Rice crop is grown in approximately 90% of the total cultivated area. Crops which require low levels of water, such as mustard, are grown after rice crop harvesting, depending on the soil moisture conditions in the field. The climate data (i.e., rainfall, temperature, wind speed, and humidity etc.) were obtained from Department of Physics and Meteorology, Indian Institute of Technology, Kharagpur. Global solar radiation data were obtained from Solar Radiation Handbook (2008), Solar Energy Center, MNRE, Indian Meteorological Department. Details of climate data used in this study are described elsewhere (Pandey et al., 2011).

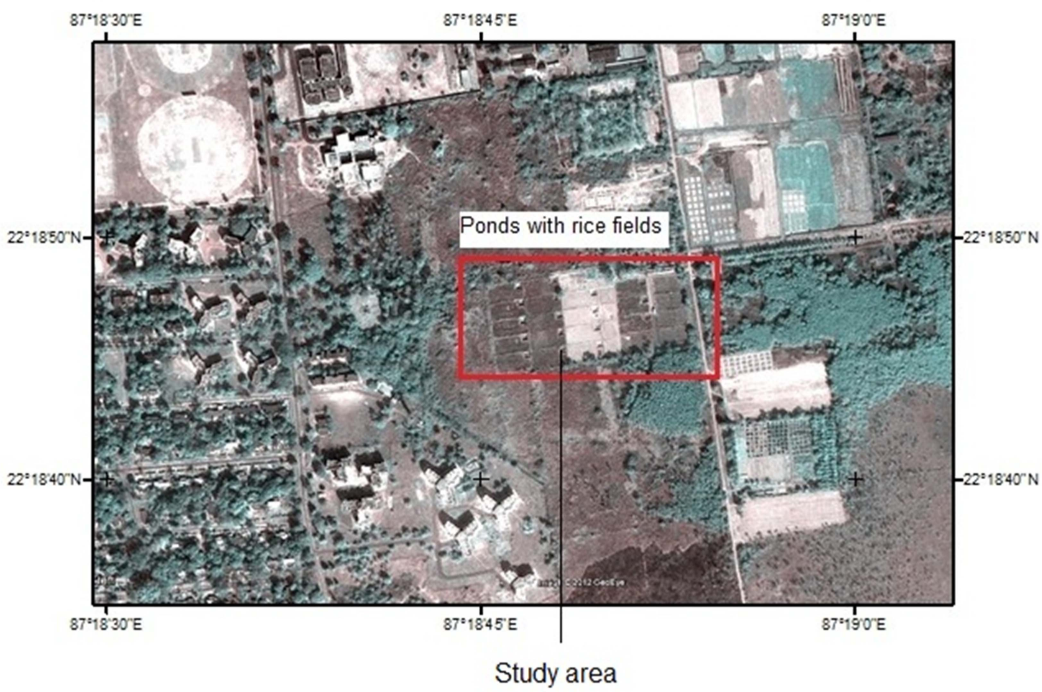

Figure 2. Map shows the location of the study area used for water balance simulation

Results and Discussion

Water balance in OFR (i.e., water storages) and field (i.e., available soil moisture) was simulated. Figure 3A shows precipitation (secondary y-axis) and the OFR water storage (primary y-axis). The OFR size was 10% of the catchment area of 10 ha. The length and width of OFR was 100 m × 100 m (total area of 100, 00 m^2). The depth of OFR was 2.5 m. The total annual rainfall in the study area was 1460 mm and the effective rainfall was 1128 mm. The maximum daily effective precipitation was 75.7 mm. The change in water storage shown in Figure 1 was estimated using equation 1. The OFR water volume varied from 0 to 15,440 m^3. The water depth in OFR varied from 0 – 1.5 m with an average depth of 0.8 m. The daily average water volume in OFR was 7,868 m^3. The water storage in OFR followed the pattern of rainfall variation (i.e., water availability in the OFR was greater during the monsoon season).

The total runoff from the field (i.e. catchment) was 234 mm (16% of precipitation). Approximately 11,282 m^3 of water in OFR was received as direct precipitation on OFR, while 21,044 m^3 of water in OFR was received as runoff from the field (i.e., 1.9 times the water received as direct precipitation in OFR). The total water of 32,327 m^3 was conserved (i.e., harvested) in OFR, which was potentially lost from the farm without OFR. Figure 3B shows evaporation and seepage losses from OFR. About 16,199 m^3 of water was lost as evaporation from the OFR water surface, and 15,557 m^3 was lost as seepage from OFR. The maximum daily seepage was 53.3 m^3, while the maximum evaporation loss was 73.3 m^3. The water loss from seepage was 96% of the water loss from evaporation. Considering the large amount of water losses through seepage, a provision, such as OFR lining (i.e., to reduce the seepage loss), may potentially improve the water availability in an OFR. Previous studies (Panigrahi et al., 2001; Pandey et al., 2006) have reported relatively greater water availability in OFRs when OFRs were lined compared to unlined OFRs.

Figure 4A shows actual evapotranspiration (ET_a) from the cultivated land (total area under cultivation was 1ha). ET_a was simulated for the whole year, which includes two cropping

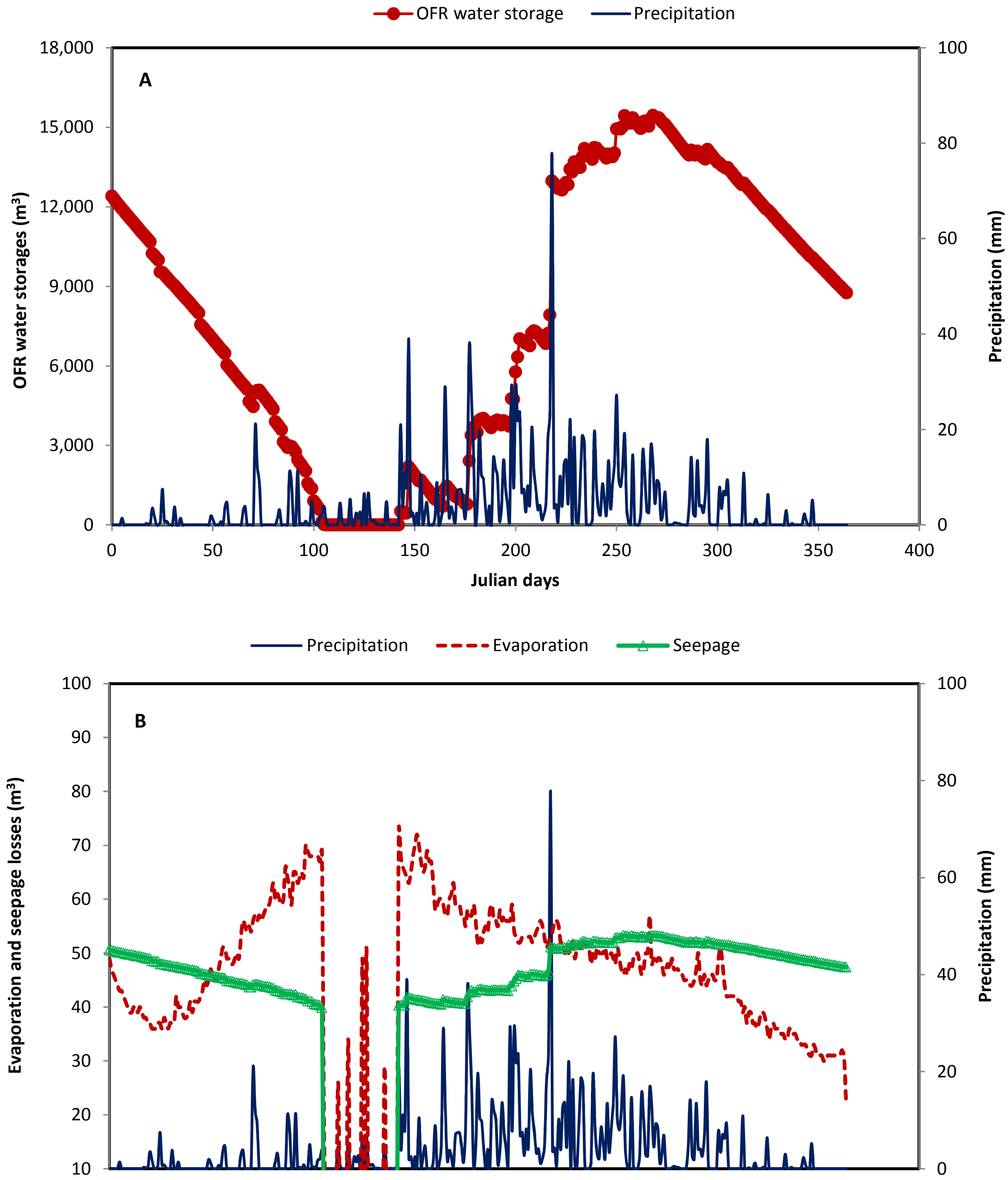

Figure 3. Water balance in OFR. 3A) red line with red markers indicates water storages in OFR, and blue line indicates precipitation; 3B) green line with triangle markers indicates seepage, and dotted red line indicates evaporation from OFR. Blue line indicates precipitation.

seasons (i.e., first cropping season between 20 and 119 Julian days, and the second cropping season between 165 and 264 Julian days). ET_a varied from 0 – 7.4 mm/day with an average of 1.2 mm/day. The total ET_a was 1020 mm, which includes the ET_a loss from RAM (readily available moisture) and NRAM (non-readily available moisture). ET_a from RAM and NRAM was 888 and 132 mm (estimated using equation 8), respectively. The variation in the available soil moisture is shown in Figure 4B. To increase the available soil moisture, the OFR water was recycled as supplemental irrigation (SI) to the cultivated area. The SI application is shown in Figure 4B.

The soil moisture of cultivated area varied from 0 – 120 mm. The average soil moisture over the year was 2.4 mm. The soil moisture in the first cropping season (i.e., from 20 to 119 Julian days) was lower than that of the second cropping season (i.e., from 165 to 264 Julian days) (Figure 4B). The elevated soil moisture in the second season was primarily caused by precipitation. In the second season, relatively large precipitation alleviated the need for SI. The water volume of 4,320 m^3 was applied to the field as SI. In the first season a total of 3,960 m^3 was used as SI, while in the second season 360 m^3. In the second cropping season usually monsoon rainfall can provide potentially enough water to grow crops (except a few dry spells), while in the first cropping season the SI role was critical in maintaining the moisture content of the soil. For example, 92% of the total SI was used in the first season, while only 8% in the second season. The impact of SI in increasing the soil moisture is shown in Figure 4B.

This simple model provided important information on the soil moisture variation in the cultivated land (Fig 4B), supplemental irrigation requirement (Fig 4B), and water storages in OFR (Fig 3A). In addition, the model also produced other water balance parameters, such as evaporation from OFR, seepage loss from OFR (Fig 3B), and ET_a from the cultivated area (Fig 4A). Results of the model can be useful in managing water resources (i.e., rainwater) in rainfed areas and recycling it to the cultivated area for irrigation purposes. The model can also calculate the timing when supplemental irrigation is required. This information is crucial for deriving the approaches useful for improving crop production in areas where rainfall is the primary source of water for agriculture. Results presented here are produced from the model simulation; additional work, such as validating the prediction, is needed. Although the fundamentals used in the simulation are sound, verifying predictions using experimental data will help improve the model's capability.

In summary, the model presented here has capability of simulating the rainwater harvesting potential in rainfed regions, i.e., it can predict the impact of rainwater harvesting in rainfed agriculture. The model predicts water storages in OFR, potentially recharged water (i.e., ground water recharge through seepage), and evaporation from the OFR water surface areas. The model also predicts actual evapotranspiration from cultivated land, soil moisture in the field, and the supplemental irrigation requirement. Currently this model was formulated for small landholdings; however, it can be applied at watershed scale with modification.

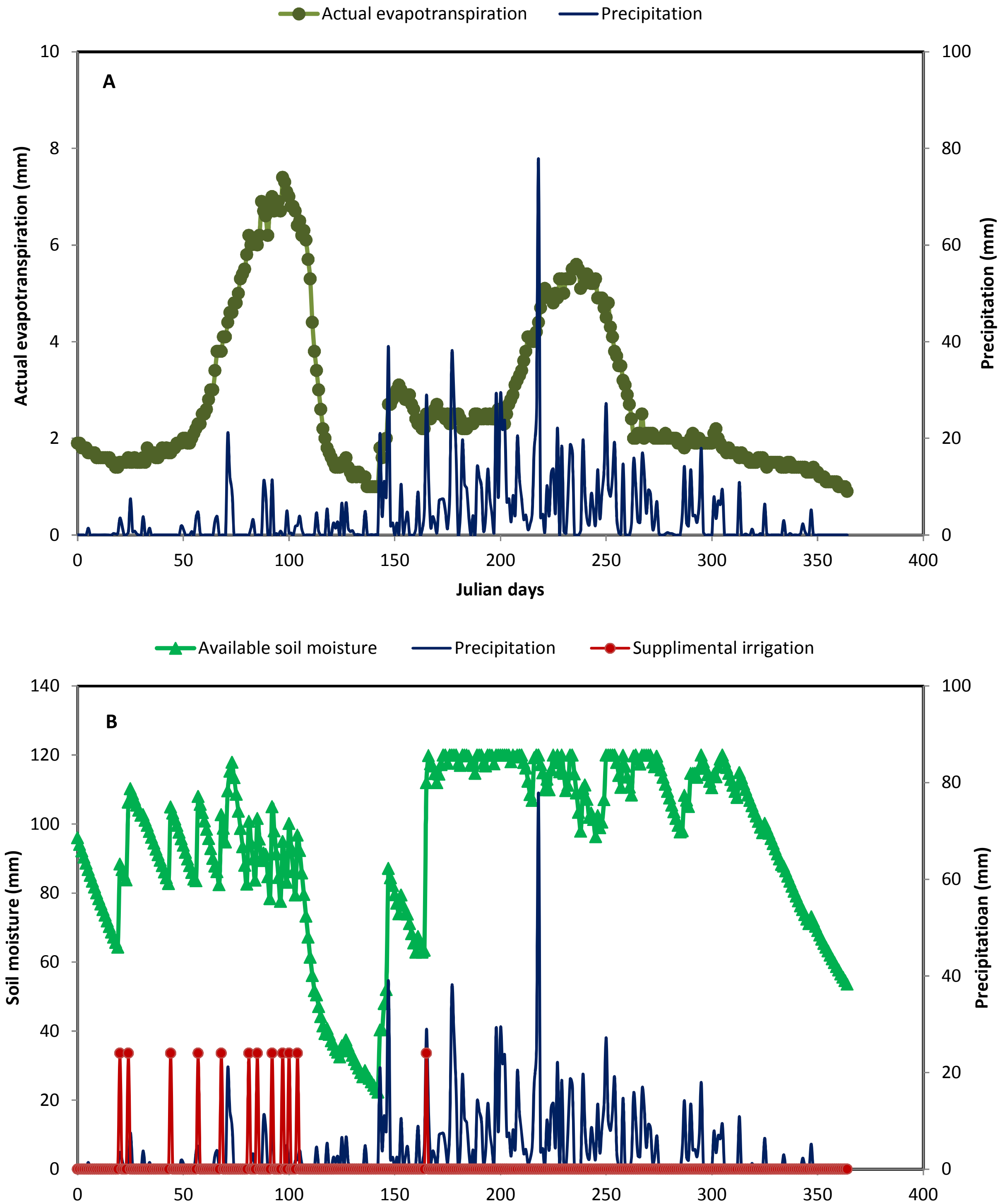

Figure 4. Water balance in the cultivated area. 4A) dark green line with green markers indicates the actual evapotranspiration in the cultivated area, and blue line indicates precipitations; 4B) green line with triangle markers indicates available soil moisture in cultivated field, and red line with red markers indicated supplemental irrigation (SI). Blue line indicates precipitations.

Conclusions

Here we have developed a water balance model to understand the rainwater harvesting potential for meeting the supplemental irrigation requirement in rainfed regions. The model estimates the water storage in the rainwater harvesting ponds (i.e., on-farm reservoirs (OFR)), available soil moisture in the cultivated field, and supplemental irrigation requirement of crops. Results show that the model will be applicable in designing OFR and harvesting rainwater in rainfed regions. Predictions of available soil moisture in the cultivated field can be applicable in making the decision when supplemental irrigation is needed. The model also estimates if the water storages in OFR are sufficient or not for meeting the crop SI requirement. The model developed here will be applicable in designing the rainwater harvesting systems for conserving rainwater, which can be recycled to croplands as SI for improving agricultural production in rainfed regions.

References

Allen, R.G., Pereira, L.S., Raes D., and Smith, M. (1998). Crop evapotranspiration: guidelines forcomputing crop water requirements. FAO Irrigation and Drainage Paper, 56, Rome, 300 pp.

Balasubramanian, R., and Selvaraj, K. N. (2003). Poverty, private property and common pool resource management: The case of irrigation tanks in south India, Working Pap. 2-03, 61 pp., S. Asian Network for Dev. And Environ. Econ., Kathmandu.

Barron, J., Rockstro□m, J., Gichuki, F., and Hatibu, N. (2003). Dry spell analysis and maize yields for two semi-arid locations in East Africa. Agric For Meteorol 117: 23– 37. doi:10.1016/S0168-1923(03)00037-6.

Chiew, F. H. S., and McMahon, T. A. (1994). Application of the daily rainfall–runoff model MODHYDROLOG to 28 Australian catchments. J. Hydrol. 147, 1–36.

Evanari, M., Shanan, L., and Tadmor, N. H. (1971) The Negev, the Challenge of a Desert. Harvard University Press, Cambridge, Massachusetts.

FAOSTAT (1999). http://apps.fao.org/page/collections?subset=agriculture.

FAO (2002). Agriculture: Towards 2015/2030. Technical Interim Report, Economic and Social Department, FAO, Rome. http://www.fao.org/es/esd/at2015/toc-e.htm.

Gunnell, Y., and Anupama, K. (2003). Past and present status of runoff harvesting systems in dryland peninsular India: A critical review, Ambio,32, 320 – 324, doi:10.1639/0044-7447(2003)032[0320:PAPSOR]2.0. CO;2.

Hughes, D.A. (1995). Monthly rainfall–runoff models applied to arid and semi arid catchments for water resource estimationpurposes. Hydrol. Sci. J. 40 (6), 751–769.

Mialhe, F., Gunnell, Y., and Mering, C. (2008). Synoptic assessment of water resource variability in reservoirs by remote sensing: general approach and application to the runoff harvesting systems of South India, Water Resour Res **44** (2008), p. W05411.

Mohanty, R. K., Mishra, A., Verma, H. N., and Brahmanand, P. S. (2002). Rainwater conservation and rice-fish integration for enhancing land and water productivity. Water Technology Center for Easter Regions, Bhubaneswar, India. Research Bulletin, Publication No. 11.

Palanisami, K., and Meinzen-Dick, R. (2001) Tank performance and multiple uses in Tamil Nadu, south India. Irrig Drain Syst 15: 173–195.

Pandey P. K., Panda, S. N., and Panigrahi, B. (2006). Sizing on-farm reservoirs for crop-fish integration in rainfed farming systems in Eastern India. Biosyst Eng 93**:** 475–489.

Pandey, P. K., Soupir, M. L., Singh, V. P., Panda, S. N., and Pandey, V. (2011). Modelling rainwater storage in distributed reservoir systems in humid subtropical and tropical savannah regions. Water Resour Manage 25: 3091-3111. DOI 10.1007/s11269-011-9847-5.

Pandey P. K., van der Zaag, P., Soupir, M. L., Singh, V. P., and Panda, S. N. (2012 Under Review). Predicting supplemental irrigation and potential rainwater harvesting in rainfed regions. Water Resour Manage.

Panigrahi, B., Panda, S. N., and Mull, R. (2001). Simulation of water harvesting potential in rainfed ricelands using water balance model. Agricult Sys 69: 165-182.

Parr, J. F., Stewart, B. A., Hornick, S. B., and Singh, R.P. (1990). Improving the sustainability of dryland farming systems: a global perspective. In: Singh, R.P., Parr, J.F. and Stewart, B.A. (eds) Advances in Soil Science, Vol. 13, Dryland Agriculture Strategies for Sustainability. New York, USA, pp. 1–8.

Prasad, K. S. S., Gopi, S., and Rao, R. S. (1993). Watershed prioritization using remote sensing techniques—A case study of the Mahbubnagar district, Andhra Pradesh, India, Int. J. Remote Sens., 14, 3239– 3247, doi:10.1080/01431169308904438.

Rao, V. V., and Chakraborti, A. K. (2000). Water balance study and conjunctive water use planning in an irrigation canal command area: A remote sensing perspective, Int. J. Remote Sens., 21, 3227 – 3238, doi:10.1080/014311600750019859.

Roche, M. (1971). Les divers types de mode`les de´terministes. La Houille Blanche 2, 111–128.

Rockström, J. (2001). Green water security for the food makers of tomorrow: windows of opportunity in drought-prone savannahs. Water Science and Technology 43(4), 71–78.

Rockstro□m, J., Barron, J., and Fox, P. (2003). Water productivity in rain-fed agriculture: Challenges and opportunities for smallholder farmers in drought-prone tropical agro-ecosystems in Water Productivity in Agriculture: Limits and Opportunities for Improvements, edited by J. W. Kijne, R. Barker, and D. Molden, pp. 145–162, CABI, Publ., Oxon, Mass.

Rockstro□m, J., Falkenmark, M., Karlberg, L., Hoff, H., Rost, S., and Gerten, D. (2009). Future water availability for global food production: The potential of green water for increasing resilience to global change. Water Resour Res 45: W00A12. doi:10.1029/ 2007WR006767.

Shuttleworth, W.J. (1993). In: Maidment, D.R. (Ed.), Evaporation. McGraw-Hill, New York, pp. 4.1–4.53 (Chapter 4).

Singh, V. P., and Xu, C. Y. (1997). Evaluation and generalization of 13 mass transfer equations for determining free water evaporation. Hydrolog Process 11: 311–323.

Temesgen, M., Rockstr□om, J., Savenije, H. H. G., and Hoogmoed, W. B. (2007). Assessment of strip tillage systems for maize production in semi-arid Ethdipia:effects on grain yield and water balance. Hydrol. Earth Syst 4: 2229-2271.

US Soil Conservation Service (1972). In: SCS National Engineering Handbook, sect. 4. SCS, Washington, DC.

van der Zaag, P., and Gupta, J. (2008). Scale issues in the governance of water storage projects. Water Resour Res 44: W10417, doi:10.1029/2007WR006364.

World Bank (1997) .World Development Report, 1997. World Bank, Washington, DC.