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Evaluation of Percolation Tanks in a Semitropical Watershed in India using SOFTANK model

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ABSTRACT

Watershed development projects in India have proved their utility in making more water available for drinking and crop production and conserving the soil resources in the fragile rural ecosystems. Water harvesting structures viz. nala bunds, percolation tanks, farm ponds are the main structures which create surface water and groundwater storages in watershed. These structures are effective in creating more surface and groundwater resources but there is lack of an analytical tool for designing these structures optimally. This often results in non optimal rainwater harvesting through these structures.

The combination of one or more harvesting structures in watershed is referred to as watershed based tank system in this paper. These systems have some unique characteristics and requirements. While designing the tank system one has to decide the number of tanks, their locations and type. Tank type depends on the orientation of command area around the tank. The in situ treatments like CCT in the catchments of these tanks affect the inflow to the tank. To avoid upstream-downstream conflict some portion of runoff needs to be allowed to go downstream of the watershed. SOFTANK (Simulation Optimization For Tanks) model has been developed which takes into account all these characteristics. This paper discusses the SOFTANK model and its application for evaluation of percolation tanks in the Pimpalgaon Ujjaini watershed in the scarcity region of the Maharashtra state of India.

In Pimpalgaon Ujjaini watershed there are two tanks at stream point No 3 and 6 with capacities of 695877 and 216937 m³ (total storage capacity 912814 m³). These tanks are used for groundwater recharge only. The water balance analysis of two percolation tanks of Pimpalgaon Ujjaini watershed was carried out with the SOFTANK model for 29 years (1975 to 2003). Model showed that 42% runoff is harvested by the tanks and 58% goes out of the watershed. Seepage was the major (84%) outflow component from the tanks. The tanks are overdesigned and therefore any in situ soil water conservation works in the catchments of these tanks should be discouraged.
INTRODUCTION

Land and water resources development on watershed basis has offered sustainable approach for rainwater harvesting and resources conservation. Indian watershed development programmes started from late 80s to develop semi-arid areas that the green revolution bypassed. By the late 90s watershed development became the focal point for rural development in the country, with an annual budget of over $450 million (Kerr, 2002).

Due to the advent of watershed approach to the management of land and water resources, rainwater harvesting tanks i.e. nala bunds, check dams, percolation tanks, farm ponds are planned as an integral component of the watershed (Fig 1). Due to the different nature of watershed based tank systems from stand-alone tank systems, the existing approaches of design of isolated tank systems (Palmer et al 1982, Panigrahi and Panda,2003, Srivastava, 1996) can not be used for designing watershed based tank system. At present they are designed based on local experience and some empirical guidelines for these structures for different regions of India can be found in Samra et al (2002). This often results in non-optimal rainwater harvesting through these structures. Therefore a new methodology is proposed for the design of watershed based tank systems on the concept of Integrated Water Storage System (IWSS) in the watershed.

Unique features of watershed based tank system

Watershed based tank system has some unique features which are described below. These features have been considered in the proposed methodology of tank design.

1 Integrated water storage system (IWSS)

Water can be stored in the watershed for crop production in three storage media- soil, surface tanks and aquifer. There are different techniques of rainwater harvesting which can be adopted to make use of these three storages. For example in-situ RWH techniques like tillage practices, trenches etc make use of the soil medium to store the harvested rainwater. Part of the rainfall that is in excess of the storage capacity of these practices flows downstream as surface runoff. This runoff is harvested by ex situ RWH techniques like nala bunds, irrigation tanks, and percolation tanks. Part of the water harvested by in situ RWH practices and ex situ RWH practices flows down the soil medium as deep percolation and joins the groundwater table. This groundwater and surface water stored in the tanks is used for irrigating the crop in the watershed. Thus three storage media are interlinked in the watershed and changes in one storage medium affects the storage in another medium. This affects the tank design. Hence integration of these storages is imperative and is referred to as IWSS in this study.
2 Effect of in-situ RWH practices on storage capacity of tanks
Tanks are constructed along with other in-situ rainwater harvesting (RWH) practices like bunds, trenches, ridges to harvest maximum possible rainfall in the watershed (Fig 1). These in-situ practices harvest considerable volume of water, reducing the flow to the tanks; increasing soil water storage and groundwater recharge (Chittaranjan et al., 1997, MPKV, 2002). This reduces the capacity requirements of the tanks. This aspect has been considered in the methodology for designing tanks.

3. Upstream-downstream conflict
When watershed development works are undertaken there is no consideration to the downstream release of water. The works are undertaken with intention to harvest almost all the runoff in the watershed. This gives rise to upstream-downstream
conflict since all the watersheds are nested and development in upper watershed may result in less water available for lower watershed. There is growing debate on upstream-downstream conflict in the Indian watershed development programme (Sakthivadivel and Scott, 2005; Sikka and Paul, 2005) and this aspect has been considered in the proposed methodology by introducing upstream receipt (USR) and downstream release (DSR) criteria. This facilitates design of tank system for the given DSR criterion. For example when tanks are designed for 30% DSR, tanks harvest 70% runoff generated in the watershed and 30% goes downstream of the watershed for downstream users or ecological reasons.

4 Tank type:  
It has been observed that when a tank is constructed the water from the tank may be used to the downstream command area or the water may be lifted for irrigation to the upstream catchment area or the combination of both these cases. This changes the command area of the tank and the catchment-command hydrology. This aspect has been incorporated by introducing ‘tank type’ here. Based on the orientation of command area tank may be of any of the following tank types.

1. Tank type 1: Command area on the downstream side of the tank
2. Tank type 2: Command area on the upstream side of the tank (This also serves as catchment area of the tank)
3. Tank type 1: Command area on both i.e. upstream and downstream side of the tank

A check dam on the nala with command area on the downstream side comes under tank type-1. A farm pond at the end of the field slope comes under tank type-2 and a percolation tank may come under tank type 2 or 3.

5 Tank strategy  
Tank strategy for watershed as proposed in this methodology is a strategy that defines number of tanks, their locations on the stream and their types. In watershed, there are certain locations on the main drainage line (referred to as ‘stream points’ in the methodology), which are suitable for construction of a tank. When these stream points are known next question is “How many tanks and where to place them on these stream points?” For example if only one tank is to be built, it may be located on any of the stream points. The location of the tank has relationship with the tank type discussed above. Hence based on the number of tanks, their locations and types there is a certain number of combinations for the given number of stream points. Each of these combinations is one ‘tank strategy’. For there is only one tank strategy when there is one stream point at the outlet of the watershed. There are 7 tank strategies for 2 stream points 31 for 3, 127 for 4 and 511 for 5 stream points.

Once the tank strategy is defined each tank has to be assigned the fields in its catchment and command areas. As the tank type changes the command area and its corresponding fields change. Catchment fields receive inflows in the form of rain and runoff whereas command fields receive inflows in the form of irrigation in addition to rain and runoff. If the tank is at the outlet of the watershed, it has to be of Type-2.
In a series of tanks, the topmost tank will not have excess runoff from the upstream tanks whereas lower tanks will have excess runoff from the upper tanks. The concept of tank strategy facilitated this kind of analysis and methodology includes dynamic allocation of fields to the catchment and command area of tanks. As the tank strategy changes the field allocation to the catchment and command area of tanks changes.

**METHODOLOGY FOR OPTIMUM DESIGN OF TANK SYSTEM**

A comprehensive methodology has been developed for the optimum design of tank system for the watershed. The methodology is based on three important water balances in the watershed i.e. field water balance, tank water balance and groundwater balance. The tank system for the watershed is optimised for maximum net benefits. At the beginning fields are allocated to ‘stream points’. Stream point is defined here as a point on the stream at which tank location is preferred. Tank strategies are generated based on the number of stream points. Catchment and command field allocation is performed for each tank strategy. Initial tank capacity is determined with the design runoff depth (DRD). Simulation then starts from the first (or selected) tank strategy. A downstream release (DSR) criterion is given before the simulation. The DSR criterion in this research is the annual volume of water that passes the watershed outlet as per cent of annual volume of runoff generated in the watershed. For example a DSR of 30% means tanks will harvest 70% of the runoff generated in the watershed and remaining 30% will go downstream out of the watershed. Tank system is designed for this DSR. In simulation field, tank and groundwater balances are simulated simultaneously on daily basis. At the end of simulation, output DSR is obtained. This DSR is compared with the input DSR ± deviation (e.g. 30 ± 10). Since the output DSR is the result of simulation and depends upon many factors like tank size, water use, climate etc., this DSR may or may not match with the input DSR. If DSR criterion is not met, tank capacity is increased (or decreased) and simulation performed again. The procedure is repeated till the DSR criterion is met. When the DSR criterion is met, project economics for the tank strategy is performed. In this way all tank strategies are simulated. The conceptual flowchart of the methodology is shown in Fig 2.

**The SOFTANK model**

The comprehensive methodology of optimum design of tank system was converted into computer code in C language, which resulted into computer model SOFTANK. This model provides an analytical tool for studying different aspects of tank system design in the watershed. The model can be operated in four different modes i.e. calibration, evaluation, simulation and optimisation mode as described below.

1. **Calibration mode**

In calibration mode the existing watershed data are used for running the model. Calibration can be performed for infiltration, runoff and groundwater level. Estimated values of these parameters are compared with the observed values. If the values deviate, estimated values are modified by adjusting a calibration parameter till the observed and estimated values agree. This is done with root mean square error (RMSE).
2. Evaluation mode
In evaluation mode the model is used to evaluate the existing tank strategy for its performance assessment. The changes in the tank strategy or irrigation strategy can be suggested to improve the performance of the existing tank system in the watershed. In evaluation mode the model reads the existing tank dimensions and hence tank dimensions are not optimised. Existing irrigation and crop practices are input to the model.
3. Simulation mode
SOFTANK can be used in simulation mode to simulate a particular tank strategy or all the tank strategies for the watershed. In this mode, tank dimensions are optimised for the given watershed data and DSR criterion. Model gives one optimum tank strategy for each year in this mode. Different management options can be simulated and compared in the simulation mode.

4. Optimisation mode
Simulation mode gives the best tank strategy for each year based on the maximum net benefits. In optimisation mode, the model selects these best tank strategies generated in the simulation mode and evaluates these strategies for other climatic data years. The tank strategy giving maximum net benefits with output DSR within the range of input DSR is selected as the stable ‘optimum tank strategy’ for the watershed.

CASE STUDY DESCRIPTION
The Pimpalgaon Ujjaini watershed in Ahmednagar district of Maharashtra state was selected for the application of the SOFTANK model. The salient features of the watershed are described below.

Pimpalgaon Ujjaini watershed
Pimpalgaon Ujjaini watershed with an area of 1326 ha is located 15 km northeast from Ahmednagar (latitude 74.05 east and longitude 18.15 north). There are two tanks on two streams in the watershed. The tanks are mainly used for groundwater recharge and called as percolation tanks. Water is not used directly from the tanks for irrigation purpose. Common cereal, pulses and oilseed crops are grown in the command of the percolation tanks in the watershed with irrigation by groundwater. The Groundwater Project of Mahatma Phule Krishi Vidyapeeth (MPKV) conducts the water balance study in the watershed. The location of the watershed is shown in Fig 3 and the map of watershed in Fig 4.

The climate of the region is usually hot and potential evaporation is about 1800 mm. The mean annual rainfall for the region is 642 mm, most of which falls in four months of monsoon i.e. from July to October. Rainfall starts in late June to early July. There is however, recession during late July and early August. Again, there is good rainfall in late August and September. The rainfall totally recedes by mid-October. This is the usual pattern found in the drought prone area of Maharashtra state. Breaks in monsoon are normally experienced during late July and August. These dry spells occur during kharif season and hence kharif season is considered as risky for rainfed crop production (Patil et al., 1981).
Figure 3: Location of Pimpalgaon Ujjaini watershed

Figure 4: Map of Pimpalgaon Ujjaini watershed
Data
The daily values of climatic parameters available at Rahuri from 1975 to 2004 were used for calibration and application of the SOFTANK model for Pimpalgaon Ujjaini watershed. Watershed data included data on stream points, fields, crops, soils, tanks, and groundwater. The watershed is comprised of 447 fields. These fields were allocated to different stream points based on their z-coordinates. The soils in the watershed ranged from very shallow to very deep and from sandy loam to clay in texture. Hydrologic soil groups in the watershed belonged to hydrologic soil group B, C and D. Soils in the watershed vary in depth, colour and other morphological characteristics. Common crops in the watershed are sorghum, pearl millet, wheat, gram and fodder. Fields are used for single kharif cropping or single rabi cropping or double cropping. Most of the area downstream of the percolation tanks comes under double cropping system. The area in the catchment of the tanks is mostly with shrubs. There are two percolation tanks one each on the two streams in the watershed. These tanks are used for recharging the groundwater only. Water is not used from storage of the tanks for irrigation. The details of the percolation tank are given in Table 1. These tanks are of embankment type with irregular shape of the reservoir. This shape was approximated to the square prism shape in the analysis. Seepage rate for both the tanks was considered as 24 mm/day (Groundwater Project, MPKV 2000). There are number of wells in the watershed. Data on groundwater levels of nine wells were used for the calibration of the model for the watershed.

Table 1: Details of percolation tanks in Pimpalgaon Ujjaini watershed

<table>
<thead>
<tr>
<th>Percolation tank No.</th>
<th>Water spread area (ha)</th>
<th>Storage capacity (ha-m)</th>
<th>Catchment area (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank I</td>
<td>20.5</td>
<td>69.6</td>
<td>297.41</td>
</tr>
<tr>
<td>Tank II</td>
<td>11.5</td>
<td>21.6</td>
<td>279.40</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSION
The SOFTANK model was used to evaluate the existing percolation tank system in the Pimpalgaon Ujjaini watershed and the results are discussed below.

Evaluation of existing tank system
The detail water balance of the watershed has been analysed for evaluating the existing tank system and discussed below.

Field water balance
There are 447 fields in Pimpalgaon Ujjaini watershed with an area of 1326 ha. Out of this 334.92 ha was under single cropping, 410.14 ha under double cropping, 490.84 ha was barren and 90 ha occupied under two tanks. Field water balance involved computation of various inflows to and outflows from the field. (Fig 5). Annual rainfall was 541.25 mm. Runoff was 21.5% of rainfall. Evapotranspiration and deep percolation contributed 67.5% and 15.8% of the total outflow respectively. Deep percolation was 20.5% of the rainfall.
Tank system water balance

There are two percolation tanks on two streams in the watershed. Total storage capacity of two tanks is 91.2 ha-m. Tank system water balance components for 29 years are shown in Fig 6. Inflow ranged from 0.13 to 1.86 times the total storage capacity of tank system with an average (29 years) of 0.82. Major portion of this inflow was lost as seepage which accounted for 83.6% of the total outflow from the tank. Other loses were evaporation (13.6%) and overflow (2.6%). There was no carry over storage from the tanks. Though the overflow from the tanks was less, average DSR from the watershed was 58.5% since the tanks were at the middle of the watershed and area of watershed downstream of tanks contributed directly to the DSR. There was no irrigation from the tanks since tanks were used for groundwater recharge only.

Figure 5: Components of field water balance for Pimpalgaon Ujjaini watershed

Figure 6: Tank system water balance components for Pimpalgaon Ujjaini watershed
**Tank water balance**

Tank water balance components of individual tanks are given in Table 2. Tank capacities were 69.60 and 21.70 ha-m. In tank No.1 annual inflow was less than the tank capacity whereas in tank No 2 annual inflow exceeded tank capacity. Of the total inflow, evaporation was about 15% in both the tanks whereas seepage was 85% in Tank No.1 and 74% in Tank No.2. There was no overflow from tank No.1.

<table>
<thead>
<tr>
<th>Tank No.</th>
<th>Capacity M$^3$</th>
<th>Inflow m$^3$</th>
<th>Overflow m$^3$</th>
<th>Evaporation m$^3$</th>
<th>Seepage m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>695877</td>
<td>424172.2</td>
<td>0.00</td>
<td>60302.8</td>
<td>362280</td>
</tr>
<tr>
<td>2</td>
<td>216938</td>
<td>326924.9</td>
<td>33789.2</td>
<td>41983.9</td>
<td>250001</td>
</tr>
</tbody>
</table>

**Groundwater balance**

In estimating the groundwater balance it was assumed that underground storage volume is available below the watershed confined by bed rock at the lower boundary and ground surface as the upper boundary. Deep percolation from fields, seepage from tanks recharge this storage volume and water is withdrawn for irrigation and other use from the storage. In addition water from adjoining area may join this storage volume and water may flow outside the storage volume as groundwater flow. In the PU watershed, irrigation was scheduled at 28 days in rainy season and 21 days in post rainy season with an irrigation application depth of 55 mm. Irrigation application efficiency was taken as 70%. Source of irrigation was open dug wells. There were 85 open dug wells in the watershed. Other use was estimated from the number of household units in the watershed. Field recharge and tank recharge were found to be 71 and 29% respectively. Groundwater flow was 33.26% of the total groundwater outflow whereas irrigation and other use contributed 65.53 and 1.21% respectively. The contributions of groundwater recharge and withdrawal components are shown in Fig 7.

![Figure 7: Contributions of groundwater recharge and withdrawal components for Pimpalgaon Ujjaini watershed](image-url)
The watershed water balance gave the detail analysis of the all the inflows to and outflows from the watershed. The two percolation tanks harvested 42% of the runoff and 58% went out of the watershed. Runoff was 21.5% of the rainfall and 20.5% of the rainfall contributed to the groundwater recharge. Major portion (83.6%) of the inflow to the tanks contributed to groundwater recharge, but major recharge to groundwater was through fields (71%) as compared to tanks (29%). Due to groundwater irrigation, groundwater withdrawal formed the major outflow (65.5%) from the groundwater storage. Though the investment in tanks was found economical (BC ratio 1.34), the tanks were overdesigned since inflow/capacity ratio was 0.82. Hence any treatment (like CCTs) in the catchments of these tanks should be discouraged.

CONCLUSION
The SOFTANK model offers a comprehensive analytical tool for studying the detail water balance of watershed based water harvesting tanks. It incorporates many new features which are unique to the watershed based tank system. The model can be used to evaluate the existing tank system. The existing tank system can be improved by running alternate management scenarios with the help of simulation utility of the model. An optimum tank system can be suggested for new watershed projects with the help of optimisation utility of the model. In this paper only the evaluation utility of the model is discussed. The model gave the detail water balance of the watershed and showed that 42% runoff is harvested by the tanks and 58% went out of the watershed. The tanks were economical but overdesigned and therefore any treatment in the catchments of these tanks which will reduce the inflow to the tanks should be discouraged.

REFERENCES


