Investigation of the Impact of Commonland Protection on Water Resources in Rural India using Hydrogeological Methods

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ABSTRACT

Sustainable watershed management plans must view groundwater as a common pool resource for which stakeholders have a shared responsibility for both development and protection. While hydrologic monitoring methods and water balance models are commonly used to develop plans for managing the demands on water within a watershed, it is less common that these techniques are applied to understanding the impacts of commonland conservation and management activities. This lack of practical and quantitative tools for assessing the impacts of communal management activities may therefore erode the long-term community support for such activities. In this study we present a case study where simple monitoring strategies and volume balance methods are applied to understanding the impact of artificial groundwater recharge from a percolation pond in the Salri watershed of Madhya Pradesh, India. The percolation pond is formed by a dam constructed by villagers on commonlands to capture monsoon rainfall. Water seeps from the pond into the subsurface to be stored in aquifers downstream of the dam until it is needed in the dry season. We use a simple water balance model constrained by changes in water level in the pond to estimate the volume of water contributed to the subsurface from the pond as a result of the 2009-2010 monsoon to be about 1.3×10^5 m^3, or about twice the volume of the pond at its peak capacity. The volume of water contributed to groundwater by the pond is about 7% of the total rainfall occurring within the entire watershed or almost 30% of rainfall falling directly upstream of the dam. The pond also affects surface water flows in the watershed as flows immediately downstream of the dam run through November, whereas significant discharge at the outlet of the watershed ceased by the end of September. If it is assumed that the water captured by the dam would have previously been lost from the watershed as surface flow during the monsoon, then the intervention has reduced runoff from the watershed by about a factor of 1/3. This study shows that simple monitoring and modeling techniques makes it possible to determine the impact water harvesting has to conserve water resources and help improve the commonlands.

Key words: Water scarcity, Commonlands, Geo-hydrology, Water harvesting

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INTRODUCTION

Viewing water as a part of the commons is critical for achieving sustainable water management. Water is a resource that flows across individual property boundaries and lacks clearly defined ownership. As a result, the actions of individuals can strongly impact the good of the community. In particular, groundwater is an example of a resource that faces the classic tragedy of the commons; individuals can benefit by maximizing withdrawals, but uncontrolled pumping leads to a net loss of groundwater that degrades the environment and causes feedbacks that further reduce water availability for all within the watershed. To protect the commons, hydrologists regularly monitor the flows in a watershed to develop water balances that define management plans to restrict demands to sustainable levels.

In contrast, there is limited experience in understanding how conservation and management activities implemented on commonlands by communities impacts water availability in watersheds. In this case, it is typically uncertain whether the communal action required to implement water management strategies leads to significant net benefits for the commons or whether the benefits are received disproportionately by individuals. Such uncertainty can lead to erosion of community support for conservation activities, ultimately making the management of commonlands unsustainable. Parallel to the argument for developing science-based plans to manage demands in watersheds, hydrologic monitoring can also play an important role in building community confidence that leads to more sustainable watershed conservation and management activities.

This paper provides a case study for how water conservation efforts undertaken in the Salri watershed of Madhya Pradesh, India, affects the water balance. Specifically, we investigate the impact of artificial recharge from a percolation pond formed by capturing monsoonal runoff behind by a small earth dam, commonly known as a water harvesting structure. Water harvesting is an approach to enhancing local water resources that has received widespread attention in regions of India facing water scarcity (Sukhija, 1997). The effectiveness of these structures, however, is difficult to quantify given limited availability of technical infrastructure and expertise. Anecdotes by villagers suggest that the Salri structure keeps water levels in downstream wells higher for a longer period into the dry season. Despite this qualitative evidence, the volume of water recharged to groundwater remains poorly understood and contributes to uncertainty regarding best management practices for the reservoir and the overall value of the dam to the watershed. Simple methods for monitoring flows and quantifying reservoir performance are therefore essential for evaluating the value of the structure to villagers.

The scientific community has used tools like environmental tracers (Sukhija, 1997), water table fluctuations (Sharda, 2006), and chloride mass balances (Sharda, 2006) to quantify the impact of artificial groundwater recharge from water harvesting structures. These methods are effective, but can be difficult to apply broadly by non-expects. In contrast, simple volume balance methods can be performed with limited knowledge of local conditions. For instance, water level changes in a reservoir can be used to quantify contributions to groundwater (Sukhija, 2008; Oblinger et al., 2010). Water level measurements are an example of a measurement that can be readily collected through village-based monitoring programs, which can also be used help build community consensus, acceptance, and ownership for commonland conservation activities. Furthermore, reservoir volume balances can be performed using limited inputs that are generally available to the public through the internet (e.g., IWP, 2002), making widespread implementation possible.

The objective of this paper is to test the performance of a simple water balance model developed for the Salri water harvesting structure by Oblinger et al. (2010) using data collected by a low-tech, community-scale monitoring program during the 2009-2010 monsoon season. A direct product of the model is the estimated volume of water lost from the reservoir to the subsurface. This value provides a direct and quantitative measure of the impact of water harvesting in the watershed. However, to provide context for this volume, we also compare it to the amount of precipitation and streamflow in the watershed estimated from direct measurements. Providing both quantitative and relative measures of WHS impact provides villagers with information that can be easily comprehended to assist in developing management plans for the reservoir and encourage continued support for commonland management activities.

STUDY LOCATION

The research site is located in the Shajapur district of Madhya Pradesh, India (Figure 1). The approximate coordinates of the study area are 23.7^{o}N and 76.1^{o}E. The $2.56km^2$ study watershed is characterized by rolling hills, with a maximum elevation change of approximately 166 meters between the uplands in the southwestern portions of the watershed to the northeastern area of the watershed. Geology is characterized by the Deccan Basalts, primarily massive and columnar basalts overlain by up to ten meters of alluvial material and weathered basalt in low lying areas. Land use is primarily for agriculture, although the majority of the watershed is barren land with some small forests. Ephemeral streams, flowing only during and shortly after the monsoon season, originate in the uplands of the watershed and flow to a single channel that discharges to the northeast of the watershed.

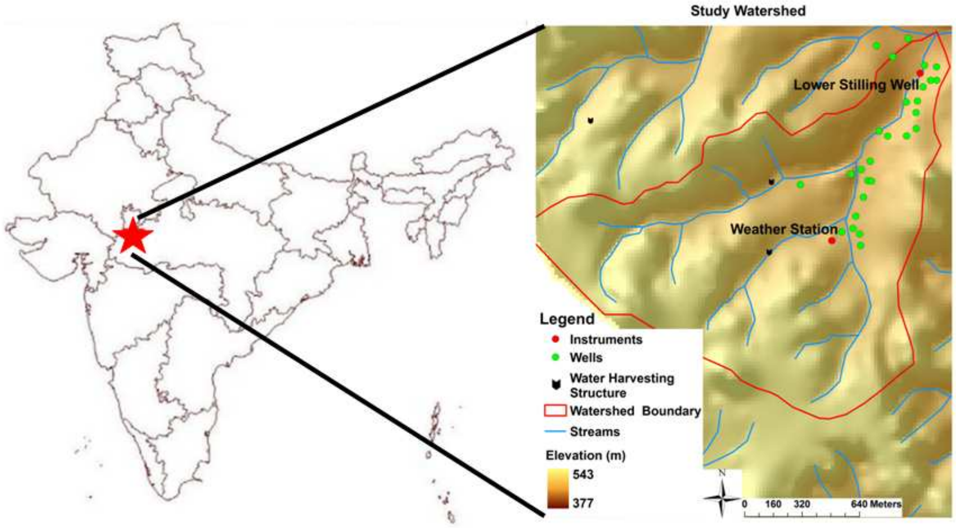

Figure 1: Location of the study watershed located in Madhya Pradesh, India.

Watershed development in the study area began in 1996, and one of the main projects was the construction of an earthen dam to capture monsoonal runoff. The structure was built on an ephemeral stream draining an upland area of approximately 0.64 km^2 (Oblinger et al., 2010). The length across the top of the dam is approximately 150 meters, and at capacity the reservoir extends approximately 350 meters upstream. The reservoir is currently a shared resource among all the members of the villagers for domestic use and watering livestock. No water is pumped from the reservoir for irrigation. Infiltrated water helps to recharge the groundwater system downstream of the WHS. The recharged water is accessed by large diameter wells and is used for irrigation, domestic use, and watering livestock.

Figure 2 illustrates a conceptual model for the relationship between the WHS and local geology of the watershed. The geologic interpretation of the area was obtained by combining use of geologic mapping, electrical resistivity surveys (Oblinger, 2008), observations of lithology in large diameter open wells, and electromagnetic induction surveys (Matz, 2010). It was found that the watershed is dominated by alternating layers of massive and columnar basalts. These are crystalline rocks in which water storage and transfer occurs primarily through fractures. Weathering and erosion leads to significant exposure of the basalt in the sloping uplands of the watershed, where the soils tend to be thin. In the lowland portion of the watershed, the weathered basalts reach an estimated thickness of up to ten meters. This weathered zone is overlain by a blanket of alluvial material, though the thickness of these deposits appears to vary significantly. Together the weathered basalt and alluvial deposits comprise a shallow aquifer system accessed by villagers using large diameter open wells.

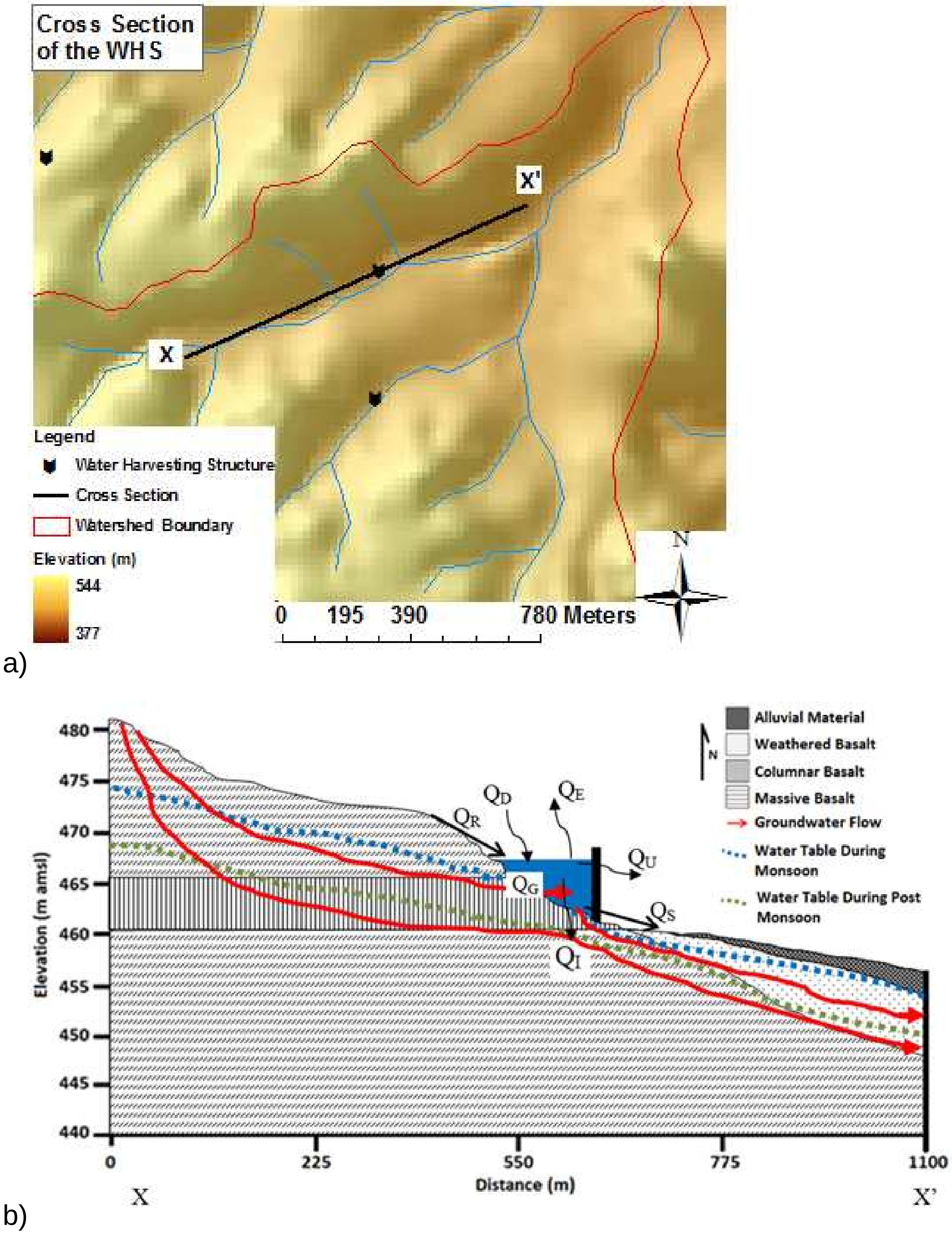

Figure 2: (a) Location of the geologic cross section used to develop the conceptual model for the WHS. (b) Conceptual model for the geology surrounding the WHS along section X to X'. The vertical exaggeration is approximately 11.3 times and the y-axis shows the elevation above mean sea level (amsl).

DEVELOPMENT OF THE RESERVOIR WATER BALANCE

The development of a water balance for the reservoir is critical for quantifying water availability. Additionally, quantifying the reservoir behavior is important for assessing its impact on the watershed. Knowing the flows to and from the structure can empower villagers to enable management of the shared surface and groundwater resources in the watershed. Furthermore, as villagers assist in monitoring efforts, they are playing an active role in better understanding the water resources in the village.

Flows into the structure are groundwater (Q_G), runoff (Q_r), and direct precipitation (Q_d). Flows out of the structure are evaporation (Q_e), water lost via the spillway (Q_s), domestic use (Q_U), and infiltration (Q_I). Groundwater flows into the structure at the contact between the columnar and massive basalts as well as via groundwater discharge up gradient of the structure from localized springs (Q_G). Water is lost as infiltration to the weathered basalts underlying the reservoir (Q_I) and may either recharge downstream aquifers or be discharged as surface water. Precipitation provides water to the structure as runoff from the upland area of the watershed that drains into the reservoir (Q_r), as well as water falling directly on the surface (Q_d). During the post monsoon and dry season rainfall is generally less than 10mm. Outflow from the WHS occurs as water lost to the spillway when the reservoir reaches the maximum capacity (Q_S) as well as direct evaporation from the surface of the reservoir (Q_E). Domestic use (Q_U) includes water withdrawn from the reservoir for use by villagers and the livestock of the area.

Given these flows, Oblinger et al. (2010) developed a simple volumetric water balance for the reservoir:

$$\frac{dV(h)}{dt} = Q_G + Q_r + Q_d - [Q_e + Q_I + Q_U + Q_S] \qquad \text{(Eq.1)}$$

The balance between inflows (positive) and outflows (negative) to the reservoir equate to the observed changes in reservoir storage. Here the change in storage is given by the time derivative of the reservoir volume V(h), which is a function of the stage, h.

Simple models are used to link each of the flows in Eq.1 to processes in the watershed. For example, Oblinger et al. (2010) use Darcy's law to quantify the flow of groundwater into the reservoir and the infiltration flux out of the reservoir. A simple approach, known as the Φ approach, is also used to quantify runoff to the reservoir as a fixed fraction of rainfall specified by the parameter Φ (Bedient and Huber, 2002). When these simple relationships describing each flow are substituted back into Eq.1, the following equation for the reservoir balance results:

$$\frac{dV(h)}{dt} = c_1 \Delta H_G + \Phi A_U R - c_2 (h - H_1) + A_{WHS}(h)(R - E) - Q_u - Q_s \qquad \text{(Eq.2)}$$

This equation is discretized in time to provide an explicit solution for the volume of the reservoir:

$$V(h_{i+1}) = (c_1 \Delta H_G + \emptyset A_U R_i - c_2(h_i - H_l) + A_{WHS}(h_i)(R_i - E_i) - Q_U - Q_s)\Delta t + V(h_i) \quad \text{(Eq.3)}$$

where $V(h_{i+1})$ is the predicted reservoir volume for time step i+1, and $V(h_i)$ is the volume at the current time step.

Water usage, rainfall, and evaporation, Q_U, R_i, and E_i, respectively, drive the model and must be known for a given study watershed. The volume of water required for human and livestock use must be obtained from local studies or surveys, either given by an outside organization or done through village meetings. In the study watershed villager demand is approximately $0.5 \times 10^4 m^3$/year (Oblinger et al., 2010), which is 8% of the maximum reservoir volume ($6.5 \times 10^4 m^3$). Since not all water is taken from the WHS, the WHS is not full year round, and the magnitude of the demand is relatively small compared to the other flows in this study, it is neglected when running the model. Rainfall data can generally be obtained from nearby weather stations or from community based monitoring. Direct measurements of evaporation are more difficult to obtain, but can be estimated from temperature and humidity data. Overall, rainfall and evaporation data can be collected by villagers, recorded, and used in the above model.

The function $A_{WHS}(h_i)$ in Eq.3 is the surface area of the WHS for a given stage, h_i, and should be obtained directly from detailed topographic surveys or estimated from the reservoir geometry. It is assumed that the area of the watershed upstream of the dam contributing to surface runoff (A_U) can be determined from topographic data. Losses of water through the spillway (Q_S) are not specified directly, but rather obtained from calculated volume changes that exceed the reservoir capacity. The length of the time step used in the model is Δt.

All of the known parameters which drive the volume balance model can be collected by the villagers. Villagers can monitor the amount of rainfall within the watershed and can record the temperature in order to determine the rate of evaporation. Village meetings can be held to determine average household water usage. Lastly, in order to determine the area of the structure, surveying can be done with the use of measuring tapes and a builder's level.

There are six unknown parameters in the model related to specific characteristics of the study area that must be estimated from observations of the reservoir behavior. These parameters control the groundwater inflows (c_1, α, β), surface runoff (Φ), and reservoir seepage losses (c_2, H_l). The parameter c_1 is the effective hydraulic conductance controlling groundwater inflows to the reservoir. This conductance is equivalent to AK/L, where A is the cross-sectional area of flow into the reservoir, L is the average length of the flow path between the upstream recharge area and the location of groundwater discharge, and K is the effective hydraulic conductivity of the upstream area. Due to the ephemeral nature of flows in the watershed, Oblinger et al. (2010) modeled the head difference driving groundwater inflows to the reservoir (ΔH_G) as a step function describing groundwater flow into the structure before, during, and after the monsoon season. Given that the reservoir is initially dry, flow before the monsoon starts (t_S) is fixed at zero, i.e., $\Delta H_G = 0$ when $t<t_S$. From the start of monsoon to the end of monsoon (t_E) it is assumed that the groundwater flow contribution is dominated by transmission from recharge areas and therefore relatively constant. As a result, the head difference in this period, $t_S<t<t_E$, is fixed to a constant value, i.e., $\Delta H_G = \alpha$. After the monsoon when $t>t_E$, groundwater discharge results from decreases in aquifer storage, the effect of which is approximated by an exponentially decaying head difference governed by a decay constant β, i.e., $\Delta H_G = \alpha e^{-\beta(t-t_E)}$. Seepage losses from the reservoir are likewise controlled by the product of a hydraulic conductance parameter, c_2, and the head difference between the reservoir and a downstream aquifer, $h-H_I$. Based on direct observations in the study area it was assumed that the downstream head H_I can be treated as a constant; however, this assumption must be reviewed for other watersheds.

Surface runoff to the reservoir is controlled by the parameter Φ, which is the fraction of rainfall that directly goes to runoff. Since Φ is a constant value during the entire study period, it cannot represent varying runoff conditions. This is a potential problem with the model since it is expected that Φ should be low before and after the monsoon season when there is a large amount of soil storage available, and Φ should be higher during the monsoon as the soils are saturated (U.S. Soil Conservation Service, 1986). Having a constant value of Φ is therefore a limitation of the Oblinger et al. (2010) model.

COLLECTED DATA FROM 2009-2010 MONSOON SEASON

Installation of various hydrologic monitoring instruments, including a weather station, stream gauging stations to measure runoff, and a gauge to measure the reservoir level, was carried out by the Foundation for Ecological Security, Clemson University, and the villagers of Salri in May of 2009. Data was then collected throughout the 2009-2010 monsoon season which is critical for quantifying the commonland water resources shared by the villagers. With the efforts of all three groups, the data collected provided enough information to determine the effectiveness of the WHS and also help to determine water resources throughout the year.

In order to determine the volume of water that the reservoir can hold during the monsoon season, the bathymetry of the reservoir was surveyed using differential GPS during field work conducted in 2007 (Oblinger, 2008). The elevation data were interpolated using a geographic information system to yield a smoothed map of bottom elevations (Figure 3). The deepest point of the reservoir is 421.8 meters above sea level, and a spillway to prevent overtopping of the dam is at approximately 427.4 meters, making the maximum depth of the structure 5.6 meters. The interpolated reservoir geometry was then used to model relationships between the stage, surface area, and volume of water stored in the reservoir. A power function is used to estimate the volume (V) from the stage (h) and a quadratic equation is used to estimate the surface area from the stage (Oblinger et al., 2010).

$$V(h) = 973.56\ h^{2.4225},\ R^2 = 1.00; \qquad \text{(Eq.4a)}$$
$$A_{WHS}(h) = 768\ h^2 + 2277\ h,\ R^2 = 0.988 \qquad \text{(Eq.4b)}$$

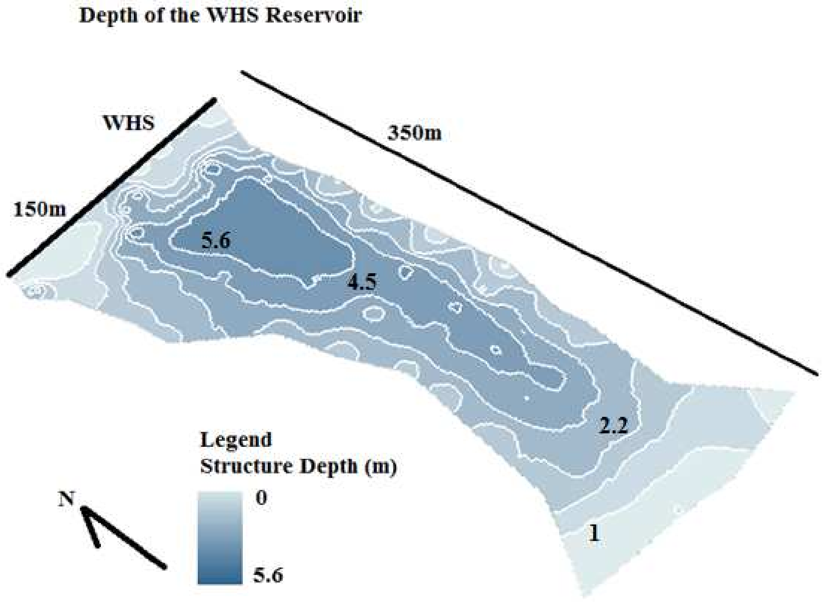

Figure 3: The total depth of the reservoir as determined from the GPS survey.

The reservoir stage was monitored using a calibrated concrete gauge installed on the upstream side of the dam. The gauge was calibrated with the use of a measuring stick and a builder's level. Markings were made in 10cm increments of vertical distance along the length of the gauge relative to the lowest point in the reservoir, which selected as a datum where it was specified as zero meters depth (Figure 4). Visual observations were collected by reading the numbers off of the gauge from the top of the dam approximately every week starting in May 2009 through September, and then readings were taking approximately every month till the structure was empty in April 2010 (Figure 5). Villagers were able to assist in the collection of the stage data throughout the data collection period.

Figure 4: Calibrated gauge on the upstream side of the reservoir used to determine the stage of reservoir.

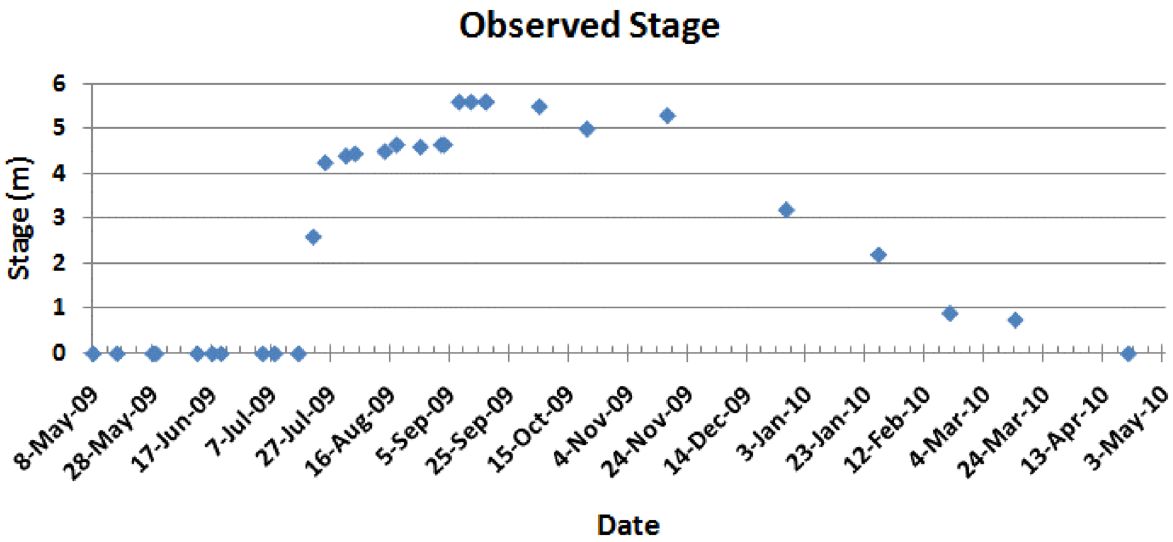

Figure 5: Observed stage from the reservoir.

Precipitation data were collected during the 2009 monsoon season using a tipping bucket rain gauge manufactured by Onset Computers (Model No. S-RGB-M002) installed at a weather station located in the watershed. The data are aggregated from 15 minute observations to half-hour totals for use in the model and shown in Figure 6 as monthly totals. The total amount of rainfall observed over the one year study period was 707mm, which gives a total volume of water falling over the watershed of approximately 1.8×10^6 m^3.

Monthly evaporation was estimated using the Thornthwaite-Mather method (Thornthwaite and Mather, 1957) based on temperature data collected from a temperature probe manufactured by Onset Computers (Model No. S-TMB_002) which was installed on the weather station (Figure 7; Figure 8). Since the Thornthwaite-Mather approach gives an estimate of potential and actual evapotranspiration, the calculation of potential evapotranspiration is used, as the maximum amount of water can be lost as direct evaporation when water is present in the reservoir. These values were disaggregated to half-hour values by equally distributing the total evaporation evenly across each month. Although precipitation and temperature data collection was automated in the study watershed, a small rain gauge and thermometer in the village would serve just as well for data collection.

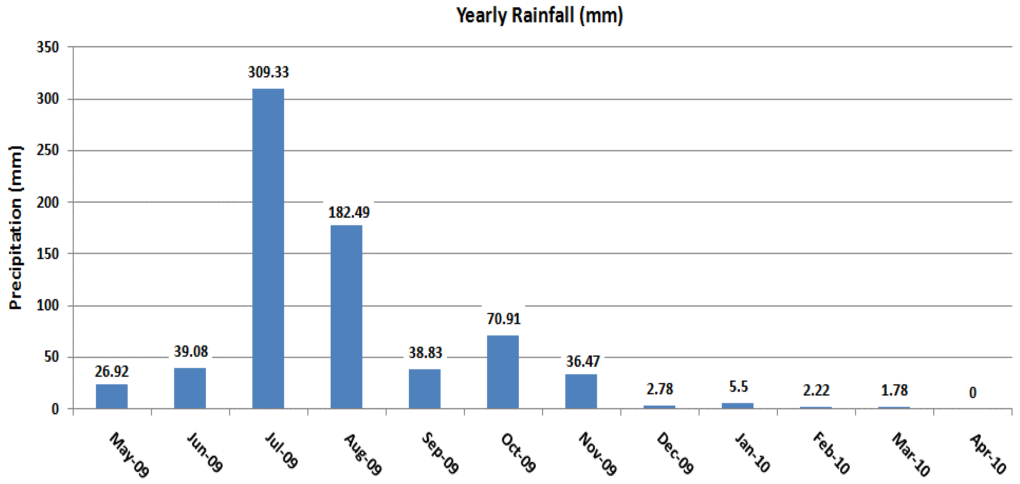

Figure 6: Monthly rainfall totals for the watershed.

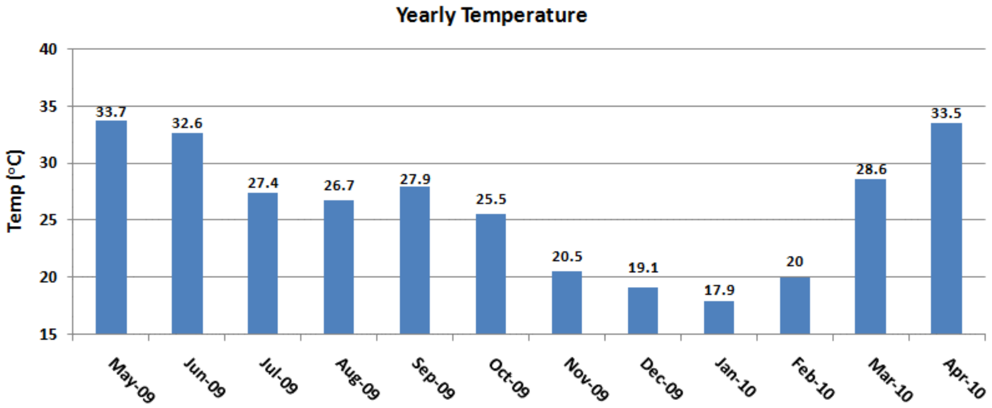

Figure 7: Yearly high temperature values used in the calculation of evaporation.

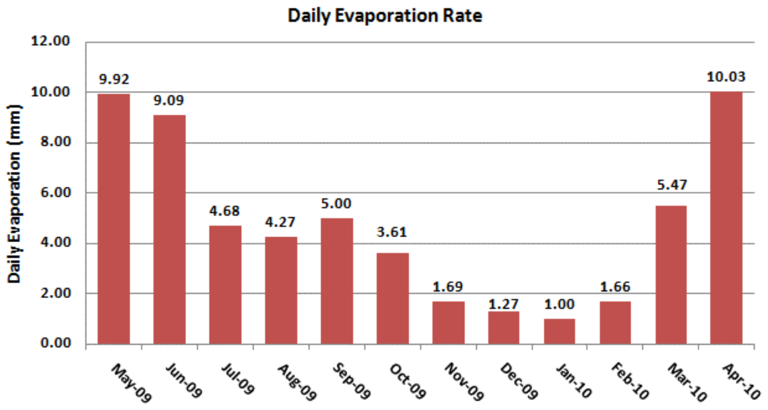

Figure 8: Daily evaporation rates for each month of the study period.

RESERVOIR SIMULATION RESULTS

Simulations of the reservoir response over the 2009-2010 monsoon are calculated using the volume-balance model described by Equation 3. Half-hour time steps are used to simulate the reservoir behavior for a period of 349 days starting on May 8, 2009 and ending on April 21, 2010. The precipitation and evaporation values shown in Figures 6 and 8 are used to drive model predictions over this period.

Oblinger et al. (2010) originally used a Monte Carlo sampling strategy combined with a non-linear optimization algorithm (the function *lsqnonlin* in MATLAB; Coleman and Li, 1996) to calibrate model parameters using stage data observed from September through December in 2007 (Table 1). Figure 9 shows these authors obtained a good match between the observed and predicted stage values. Because the data were collected primarily after the monsoon, however, they were more representative of drainage conditions than the inflows to the reservoir. As a result, the histograms in Figure 10 show that the model parameters controlling groundwater inflow (i.e., c_1, α, and β) are not well constrained by this data. In contrast, the parameters controlling seepage from the reservoir (i.e., c_2 and H_l) are relatively well constrained.

Parameter	**Calibrated Value**
α	38.6 (m)
β	0.027 (1/hour)
Φ	0.189 (-)
c_1	18.9 (m^2/hour)
c_2	2.76 (m^2/hour)
H_l	2.78 (m)

Table 1: Calibrated model parameters for the reservoir flows (Oblinger, 2010).

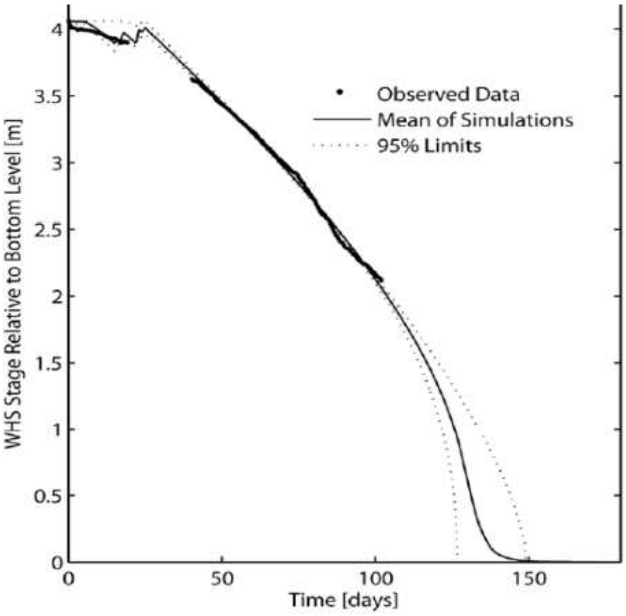

Figure 9: Predicted and observed stage over the 2007 monsoon. The model was calibrated using data shown (Oblinger et al. (2010).

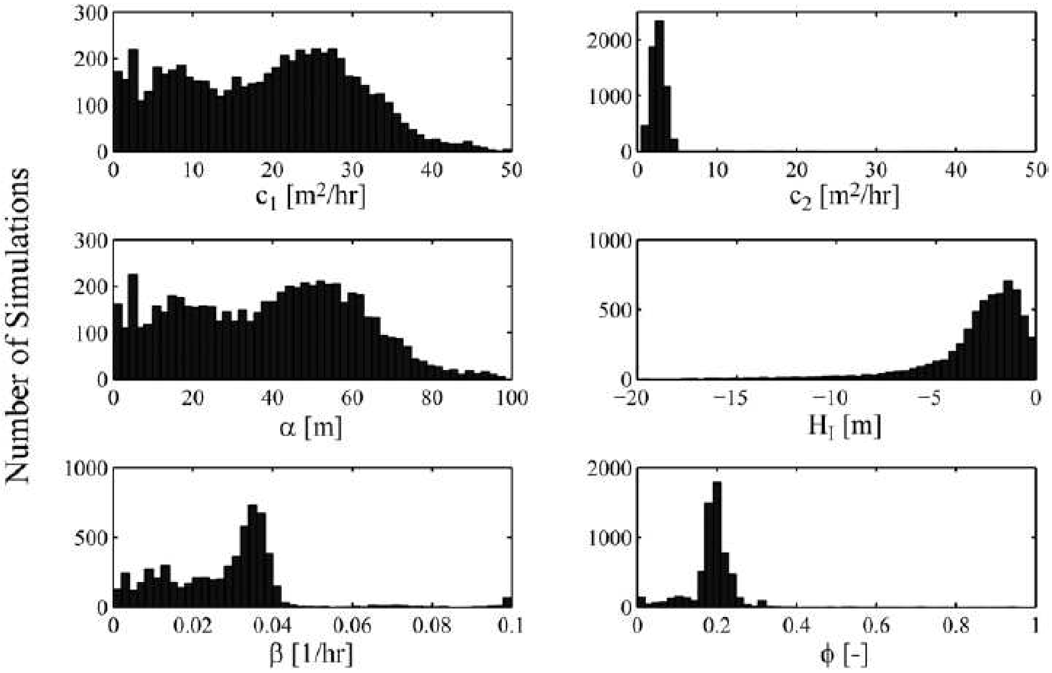

Figure 10: The histograms of model parameters leading to a good fit of data from the 2007 monsoon data show that the groundwater inflow parameters are better constrained than the seepage parameters (based on results of Oblinger et al., 2010).

Figure 11 shows the response of the reservoir to the 2009-2010 monsoon as predicted by the volume balance model with parameters calibrated by Oblinger et al. (2010). The true stage and model predictions are similar but they are not a perfect match. The root mean squared error (RMSE) between predicted stage and actual stage is 0.74 meters. The reservoir is predicted to fill slightly faster than observed in the field during the onset of the monsoon. The reservoir is then predicted to remain at capacity until the stage starts to decrease at the end of the monsoon season in September, at which point the model indicates the flow of groundwater into the structure starts to decrease (Figure 11). After monsoon the reservoir drainage is consistent between the model predictions and observations, except for March 17, 2010 when a rainfall event occurred and the observed stage is higher than the predicted stage.

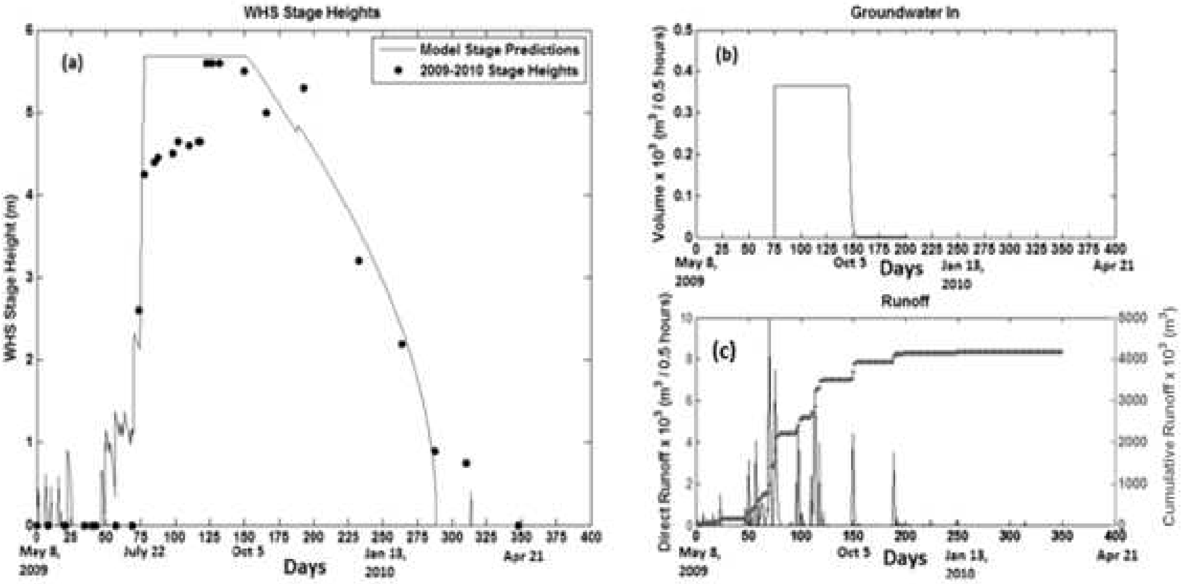

Figure 11: **(a) Predicted and true stage of the reservoir during the study period using the original model parameters as found by Oblinger et al. (2010). Volume of groundwater (b) and runoff (c) predicted to enter the structure by the model.**

Since the model simulations of the reservoir obtained using the calibrated model parameters from Oblinger et al. (2010) do not exactly predict the 2009-2010 stage data, it is necessary to determine which parameters might cause the poor fit. Potential problems could be related to parameters controlling groundwater inflow and runoff parameters, which together control how the structure fills, infiltration parameters controlling the draining of the structure, or errors in the user supplied parameters, mainly evaporation and precipitation.

Each of these potential problems was investigated by Matz (2010), and it was found that the errors between the stage predicted over 2009-2010 using the model parameters of Oblinger et al. (2010) and the true stage is caused primarily by incorrect values for the reservoir inflow parameters rather than infiltration parameters. Additionally, Oblinger et al. (2010) found that the seepage parameters were well constrained during model calibration compared to the inflow parameters. Furthermore, we have found that errors in rainfall and evaporation are not the cause for the misfit between the predicted and true stage. Matz (2010) showed that an improved fit to the reservoir data could be obtained by adjusting the model parameters controlling inflows to the water harvesting structure. After manually adjusting the inflow parameters of the water balance, it was found the stage could be estimated with a RMSE of 0.53 meters (Matz, 2010). Although the model parameter values from the Salri watershed may not be applicable to all watersheds, it is a straight forward process to adjust these values to get a good fit between the predicted and true stage at any site. The methodology behind the model can therefore be transferred to many watersheds in the region to better assess the impact of water harvesting and better manage the reservoir between all users.

IMPLICATIONS OF THE WHS VOLUME BALANCE

The ultimate purpose of fitting the WHS model to observed stage data is to determine the impact of water harvesting within the watershed. Based on the model results, the amount of water lost to infiltration is approximately $1.3\text{x}10^5 m^3/yr$, or about 2 times the maximum volume of the reservoir ($6.5\text{x}10^4 m^3$). This result is obtained using both the original parameters from Oblinger et al. (2010) and the adjusted model parameters from Matz (2010). Since only the inflow parameters of the reservoir model were adjusted during Matz's model calibration, the parameters controlling reservoir losses to the subsurface are consistent between these authors. In general, we suggest that fitting reservoir drainage data is most important for obtaining meaningful estimates of groundwater recharge needed to assess the impact of the WHS within the watershed, at least in situations where a long-term dry period occurs, e.g., during the dry season.

To further assess the impact of the WHS in the watershed, stream flows were monitored over the monsoon at two locations downstream of the reservoir. The first station was a v-notch weir installed approximately 300 meters downstream from the WHS that is used to evaluate seepage losses from the reservoir discharged as surface water. The second station was a stream gauge installed to monitor total flows discharging at the outlet of the watershed. In both cases stream levels were monitored using logging pressure transducers, which were subsequently converted to flow using either the standard charts for the v-notch weir or, for the second station, using a rating curve measured at the discharge point. Both stations provide continuous readings of streamflow throughout the monitoring period.

Monthly discharge was found to be higher at the upstream station near the WHS after monsoon in September, October, and November (Table 2). This result suggests that water leaving the WHS is captured before it can leave the watershed, i.e., in addition to water lost directly to groundwater, water lost from the WHS as surface flow is also recharged to the shallow aquifer well downstream from the WHS. This idea is supported by Figure 12 which shows flow measurements obtained using an in-stream current meter at four locations along the course of the stream in the watershed. The decrease in flow between stations 3 and 4 indicates that water is being lost from the stream to the shallow aquifer.

Table 2: Discharge from the v-notch weir and the lower stream gauge.

Date	Discharge V-notch (m^3/month)	Discharge lower gauge (m^3/month)
July 2009	11	$1.0\text{x}10^5$
August	$1.0\text{x}10^4$	$1.1\text{x}10^5$
September	$9.3\text{x}10^4$	$6.1\ \text{x}10^4$
October	$4.4\text{x}10^4$	510
November	$8.1\text{x}10^4$	8
December	0	0
Total	***$2.3\text{x}10^5$***	***$2.7\text{x}10^5$***

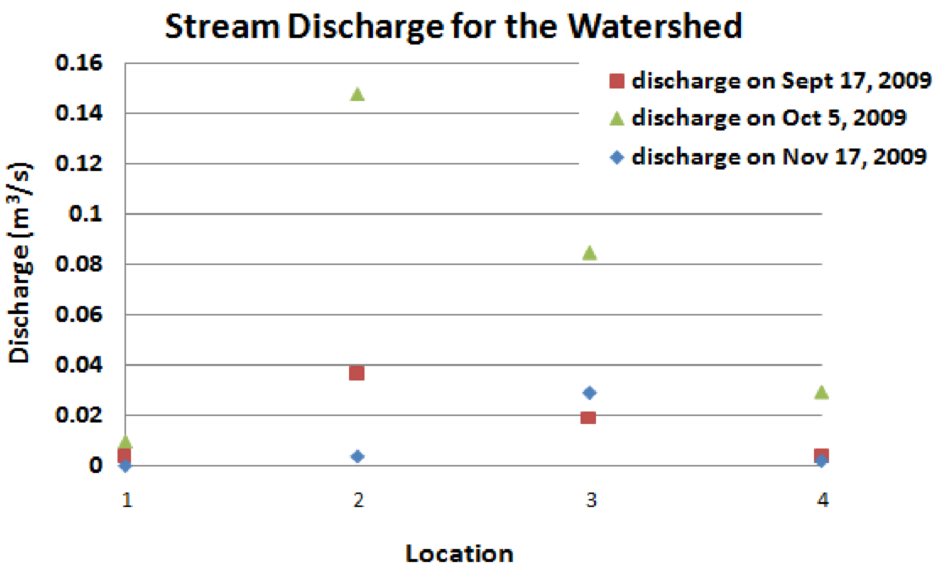

Figure 12: Stream gauging done at various locations throughout the watershed. Location 1 is in the upper watershed, location 2 is downstream of the v-notch weir by approximately 150m, location 3 is upstream of the bottom of the watershed by 200m and location4 is the lower stream gauge.

Given that the reservoir infiltrates 1.3x10^{5}m^3 of water per year, it is possible to compare the estimated volume of water infiltrated to the total rainfall and runoff volumes for the watershed (1.8x10^{6}m^3 and 2.7x10^{5}m^3, respectively). With the structure present, approximately 15% of the rainfall is lost as runoff in the stream at the outlet of the watershed. If the structure was not present, then the water captured would primarily be lost as runoff from the upland region of the watershed, making the streamflow approximately 22% of the total rainfall. Therefore, the structure reduces the yearly streamflows from the watershed by about 30% with this water apparently being diverted to local groundwater storage.

Another major aspect of the volume balance model is to predict the amount of time water remains in the structure. It is seen from the true data the structure is empty on April 21, 2010, 349 days after the start of data collection, which began on May 8, 2009. If it can be predicted how long water will last in the structure, people can better manage the resource, and can determine if they need to limit their water use from downstream wells in order to preserve water resources during the peak of the dry season. Each different variation during the model parameter sensitivity analysis shows the structure goes dry on March 17, 2010, 35 days before the structure actually goes dry, underestimating the net impact the WHS has on water availability in the watershed.

CONCLUSIONS

Data collected from a watershed located in Madhya Pradesh, India during 2009-2010 was used to test a simple, reservoir volume balance model as developed by

Oblinger et al. (2010). The parameters of the model that control the inflow and outflow of water from the reservoir were originally calibrated by Oblinger et al. (2010) with field data collected during 2007. Since field data from Oblinger et al. (2010) is only from the end of the monsoon season, the parameters that quantify the inflows were poorly estimated, whereas the flows that quantify the draining of the structure were better constrained. Due to inaccurate inflow parameters, the prediction of stage with the original model parameters did not accurately represent the behavior of the reservoir in 2009-2010. In order to better predict the stage, model inflow parameters were adjusted manually. These manual adjustments provided a better fit between the true and predicted stage.

Since the model parameters can be adjusted manually and the analysis is a simple process, the volume balance can be applied to multiple WHS in the region to predict the stage of the reservoir, as well as the residence time of water. After knowing the stage and residence time, villagers can predict how long water will last into the dry season depending upon the yearly rainfall totals. This information then gives an estimate of when surface water will no longer be available, making groundwater the only supply of water for the area. From this information, villagers can better manage their surface water resource and determine water availability from the reservoir throughout the year.

One of the main goals of the volume balance is to investigate the impact of water harvesting on the commons. Overall, infiltration is higher in the watershed with the presence of the WHS, which provides more water to downstream wells. It was found that with the structure approximately two times the maximum volume of the reservoir is infiltrated into the subsurface. Without the structure, the only water for infiltration would be natural and approximately 21% of rainfall would be lost as streamflow. Since the structure has been built, the infiltration rate is larger, streamflow is only 15% of precipitation, and more water is provided downstream for a longer period of time than if the structure was not present. Even if the model parameters do not exactly fit the observed stage data, infiltration is higher, and the impact of the WHS on the watershed is positive.

One key component in the development of the water balance is the data required to drive the model and the villager participation to collect data. Villager participation is crucial in this regard, as the installation of the instruments and gauges, the safe keeping of these instruments, and some data collection would have been impossible without the efforts of the village. When more villagers begin to engage in the project and see the benefits from the research done, they start to take ownership of the project. When this occurs, management practices can be put into place to help better utilize the commonlands shared by everyone.

Overall in the Salri watershed, water scarcity would be much higher if not for the WHS. With the participation of the villagers for instrument installation, data collection, the analysis for the water balance model, shows higher infiltration than if the structure was not present. Furthermore, the model predicts the residence time of water within 35 days. Lastly, higher stream flows directly below the WHS during the post monsoon season indicate more water is present as surface and groundwater with the WHS. The WHS has had a positive impact on the commonlands shared by the villagers of Salri. With the knowledge gained from the study, best use practices for water in the Salri watershed can be put into place to ensure water is a shared common good which can be used by all in a sustainable manner.

ACKNOWLEDGEMENTS

We thank Geoscientists *Without* Borders© for providing the funding for this research. Field contributions by Meenakshi Choudhary, Chiranjit Guha, and the staff of the FES Ujjain field office have been crucial to the success of the project along with outside assistance from Sudershan Gangrade and the villagers of Salri.

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