Structure-scale impact of widespread managed aquifer recharge in Gujarat, India

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$EVWUDFW The state of Gujarat is located in an arid to semi-arid region in western India. Drinking water and irrigation demands are highly dependent on groundwater resources. In the second half of the last century, the state has witnessed aquifers depletion due to a rapid development of abstraction wells and expansion of irrigated areas. However, different studies reported a significant increase in the water levels occurring from the last decade. There is still a lack of scientific evidence regarding the causes of this groundwater recovery, and different authors have proposed different possible drivers. This work is part of a project which aims to assess the impact of managed aquifer recharge (MAR) on groundwater storage through a multi-scale analysis. This thesis focuses on the development of a tool to study MAR performances at the structure scale for check dams. Based on a field visit and literature review, a conceptual model is developed from analytical equations. This model reveals that check dams are able to store and infiltrate a significant amount of water captured during runoff events. The efficiency of these structures is dependent on their geometry, the hydrogeological setting, maintenance practices, annual precipitation and its distribution during the monsoon season. It is also found that induced recharge by groundwater abstraction from wells located nearby check dams, can enhance their recharge potential up to 20%. In order to validate the model, a simulation is run for a check dam analysed by Dashora et al. (2017) in the years 2014 and 2015. For one of the simulated hydrogeological settings, the fitness with the observations reveals a coefficient of determination R^2 of 0.939 in 2014 and of 0.867 in 2015. It is therefore proved that the tool developed in this work can be used to analyse and predict the hydrological behaviour of check dams in the presence of site-specific data. Also, this tool has the potential to be implemented in a catchment-scale analysis to assess the cumulative effect of the widespread implementation of MAR.

1. Introduction

Over the last half of the century, the intense use of groundwater worldwide has resulted in aquifer depletion and the rise of other environmental issues, such as stream depletion, saline intrusion and land subsidence (Konikow and Kendy, 2005). Governments, organisations, scientists and communities are currently focusing on finding alternative solutions to preserve and sustainably manage groundwater resources. Some of these solutions fall into the category of so-called Managed Aquifer Recharge (MAR) practices. These practices consist of water supply based measures aimed to maintain, enhance and secure groundwater bodies (Dillon et al., 2018).

Gujarat is one of the driest and most water-stressed states of India, with 90% of rainfall concentrated in the monsoonal months (Shah, 2014). Due to the rapid expansion of irrigated agriculture, from the 1960s onwards the state has witnessed an escalating groundwater depletion (Bhatia, 1992). In response to this crisis, the government's actions focused on controlling water use and increasing groundwater recharge. This second aspect was tackled with the promotion of decentralised MAR.

In the last few years however, studies have reported some regional aquifer replenishment, with an increasing trend in the groundwater levels starting from years 2002-2004. These results come from GRACE (Gravity Recovery and Climate Experiment) data (Asoka et al. 2017), and monitoring records from local observation wells (Bhanja et al., 2017).

There is not yet unanimity among the scientific community regarding the causes of this groundwater replenishment. The main drivers which have been suggested by different authors are: the change in rainfall patterns, the change in energy policies by the government, the import of surface water from the Sardar Sarovar dam and finally the widespread implementation of MAR systems (Kumar and Perry, 2018, Bhanja et al. 2017, Gupta 2012, Jain 2012).

Because of this lack of clarity and the scale and intensity of MAR implementation, this region offers a unique opportunity to assess the large-scale impact of this technique as well as the effects on local communities.

The objective of this work is therefore to provide a tool that can be used to analyse MAR performances in terms of *i)* infiltration, *ii)* evaporation and *iii)* induced recharge by abstraction wells. This tool has two main roles: to be used to quantify recharge capacity of specific structures, and to be integrated into a catchment-scale model to analyse the overall impact of the widespread implementation of check dams.

The type of structure analysed in the current study is showed in Figure 1 and will be referred here as “check dam”. This system is an in-channel modification type of MAR, and it consists of a physical barrier constructed from earth or masonry material within the channel of ephemeral streams or rivers. This barrier retains water coming from surface runoff and allows more time for infiltration, therefore improving groundwater recharge (Renganayaki and Elango, 2013).

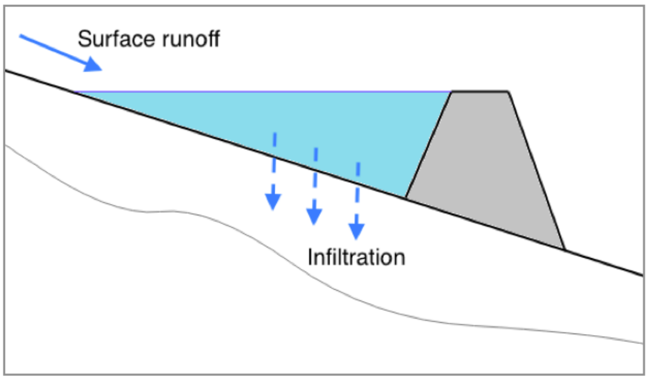

Figure 1: In-channel modification MAR (“*check dam*”)

2. Literature review

An integrated assessment of the overall impact of widespread MAR in semi-arid areas is highly critical. By capturing surface runoff, these structures have the potential to lead to inequitable access to water resources, as downstream users can be negatively affected (Batchelor and Singh, 2002). Studies have highlighted some of the limitations of check dams, such as low reliability in dry years and negative hydrological impacts for downstream areas (Kumar et al., 2008). However, the arguments for or against these structures have not been substantiated through integrated and comprehensive large-scale impact assessments (Glendenning et al. 2012). Studies have focused on the estimation of recharge potential of MAR using four different main techniques: water balance (Glendenning and Vervoort, 2010), water table fluctuation (Sharda et al., 2006), remote sensing (Becker 2006, Sharma and Thakur 2007) and tracers (Sharda et al. 2006, Stiefel et al. 2009).

Gore et al. (1998) used a catchment-scale groundwater model to estimate the influence of check dams in Wagarwadi watershed, situated in a basaltic formation in the state of Maharashtra, India. Through model calibration from 16 observation wells, they estimated the additional recharge due to MAR structures as 2% of annual average rainfall (leading to an increase of 16% in the total groundwater recharge).

Sharda et al. (2006) conducted a study to estimate potential recharge of different storage structures in a hard-rock aquifer in eastern Gujarat by combining water table fluctuation and chloride mass balance methods. They found that a power function was the best empirical equation to represent the relationship between the structure’s depth and potential recharge. They estimated the maximum groundwater recharge of these structures to be between 7.3% and 9.7% of the annual average rainfall.

Sharma and Thakur (2007) applied a combined GIS and water balance based model to estimate the shift in water balance at a watershed level due to the change in land use and implementation of MAR structures in the Kutch district of Gujarat. They estimated a decrease in the runoff of approximately 60% and an increase in recharge of 5%. The amount of actual recharge is limited by the increase of actual evapotranspiration and irrigation demand by a change in land use.

Glendenning and Vervoort (2010) applied a water balance method supported by data collected in a two-year field study in the Arvari hard-rock river basin in Rajasthan, India. They estimated potential recharge as 7% of annual rainfall.

3. Study Area

The study area is the Bhadar basin, located in Saurashtra peninsula (Figure 2). This area lies between 57°9’ and 73°56’E longitude and between 23°44’ and 24°33’N latitude. The area is 6 596 km^2, elevation ranges from 35m to 240m AMSL. Geomorphologically, the area is characterized by hilly terrain and low-lying areas (25% of the area lays below 100m AMSL). The basin falls within the boundary of five Gujarat’s districts: Rajkot (72% of Bhadar area), Jamnagar (16%), Amreli (8%), Junagadh (3%) and Surendragar (1%). Climate is semi-arid and is characterised by three seasons: summer - from April to June, monsoon - from July to September, and winter - from October to March. Average annual rainfall is 625 mm with more than 90% of the precipitation occurring between June and September during the monsoon season.

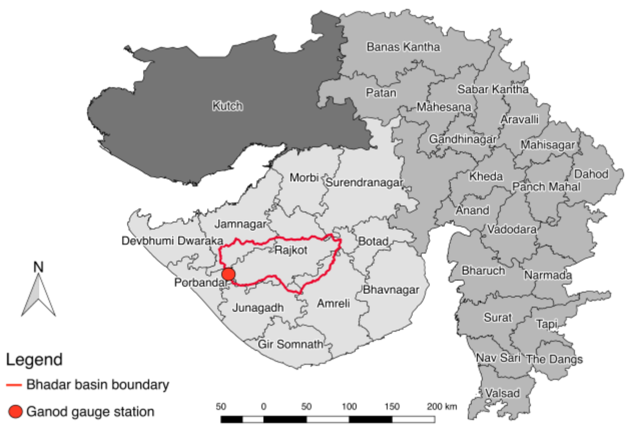

Figure 2: Districts of Gujarat and location of Bhadar basin

Agriculture witnessed a great development following the Green Revolution in the 1960s and currently around 85% of the total area is used for agriculture (Roy et al., 2016). The main crops in the area are cotton and groundnut followed by wheat and other minor crops (DAG, 2017). Cotton is the most water demanding crop and 70% of irrigation is supplied by groundwater (mainly from dug wells) (NWRWS, 2010).

Regarding hydrogeology, the predominant geological formation in the Bhadar basin is the Deccan trap. This setting is a hard-rock formation made by multiple lava flows. The thickness of each layer sequence represents a single flow event, and it ranges between a few meters to more than 30 m. These flows can be either massive (highly compacted core) or vesicular (characterised by many cavities or “vesicles”, resulting from the escape of gas bubbles during the cooling of the lava) (Singhal, 1997).

These lava flows are generally intruded by different acidic and basic dykes of 2 to 5 m thickness. These features are highly relevant for groundwater movement: in some parts, these dykes are highly weathered and form aquifers themselves; in other places, the dykes are so compacted (non-weathered) that they form a barrier for groundwater movement. Because of the presence of these dykes, hydrogeological conditions for groundwater flow and abstractions can be highly variable within short distances (Kulkarni et al., 2000). The weathered upper layer forms a good aquifer of varying thickness, which in some areas reaches 20 m (Singhal, 1997).

The groundwater levels follow the seasonal behaviour of the monsoon. From the CGWB (2015), it is reported that groundwater levels in the pre-monsoon period (April) can go as low as 40m BGL. Abstraction yields in this period are minimal and most of the dug wells during the summer season are dry.

4. Field visit

The field visit was carried out between the 14th and 16th of May 2019. Based on the time availability, four MAR sites in the basin were visited. The selection of the sites was based on the location of the 31 observation wells from the CGWB (Central Ground Water Board) located in the basin. The criteria for selecting the locations to visit considered the geographical location within the basin, the order of the river, elevation, dimensions of the structures and the distance from the observation well.

Overall, the basin is highly developed in terms of MAR. A large number of check dams could be noticed in every stream encountered during the drive. Being summer, the structures were found empty and the maximum temperature reached peaks of 47°C. The activities carried out on the field involved direct check dam measurements as well as surveys with farmers.

In terms of direct measurements, the geometry of the structure and river bed was assessed together with the current conditions in terms of silting. It was found that width of the check dams ranges between 15 and 50m, height between 1 and 2m. Years of construction are variable as well as the parties involved in the constructions (government, local NGOs and initiatives from local farmers). The check dams are highly variable in terms of maintenance. Desilting is occurring sporadically, and in some locations, material is removed for construction purposes. In others, silt is taken by farmers and mixed with cow manure as soil for the fields. Many check dams are either broken or fully covered with silt.

To cope with the lack of data and feasible measurements, local farmers were interviewed regarding the performance of the check dams. Farmers owning land in the vicinity of the check dams were interviewed. A standardised questionnaire was developed with questions dealing with check dam hydrological behaviour, abstractions, irrigation practices and calendars.

Farmers reported that in summer the dug wells completely dry out, while in wet years during the monsoon season, the aquifer gets almost saturated, with groundwater levels reaching less than 1m BGL. This phenomenon can be explained by the small storage capacity of the upper aquifer (Kumar and Perry, 2018; Verma and Krishnan, 2011). In dry years, it can happen that wells do not get substantially recharged.

As a common practice, water is never directly abstracted from the check dams. In all sites it was reported that in case the check dam has reasonable storage, it stays full throughout all the rainy season. Depending on the rainfall spells, it gets fully recharged multiple times in a year. The period in which the structures empty is dependent on the location and the check dam dimensions. Farmers reported that the wells influenced by the structures are only the ones in close proximity. However, no radius of influence could specifically be quantified from the information gathered during the field visits.

Generally, every farmer has at least a dug well and a borewell tapping the deeper confined aquifer. Dug wells analysed have an average diameter of 3,5m and their depth varies between 10 and 30m. Depending on the season and the amount of water in the check dam, if water gets abstracted from the wells, the recovery time can vary between few hours to some days, depending on the local aquifer transmissivity.

One important finding is that as common practice, water is often transferred from the borewells to the dug wells when the last ones get dry. Dug wells are used in this case as small reservoirs for short irrigations or drinking source for the cattle. As a result, water levels measurements performed from dug wells are not completely representative of the actual water table conditions in the area.

All farmers interviewed reported that dug wells have water until the nearby check dam is full. This suggests a hydraulic connection between the two structures. Without the refill from the deeper borewells, dug wells get dry or retain small amounts of ponding water during summer.

In accordance with the literature, the main crops are cotton, groundnut and wheat. In Kharif season, generally farmers divide the cropping area between cotton and groundnut simultaneously in order to increase income security. The distribution of the two crops varies according to the market and water availability. This is because cotton is more water demanding then groundnut.

Most of the irrigation is done through flooding. Some farmers use sprinkler irrigation in the early stage of the crops. It is reported a small percentage of drip irrigation. Cotton requires between 10 to 15 irrigations depending on the type. Groundnut does not require irrigation in wet years, otherwise it might require one to three irrigation spells. Wheat is highly water demanding, with 10 to 12 irrigations during the growing season. Typical abstraction values for an irrigation event range between 100 and 200m^3/day for a cropping area of 6ha.

5. Conceptual model

A daily water balance approach is used to study the hydrological dynamics of the check dam. Figure 3 below shows the volumes considered in the water balance: runoff R, precipitation P, evaporation E, infiltration I, general losses G, and outflow Out.

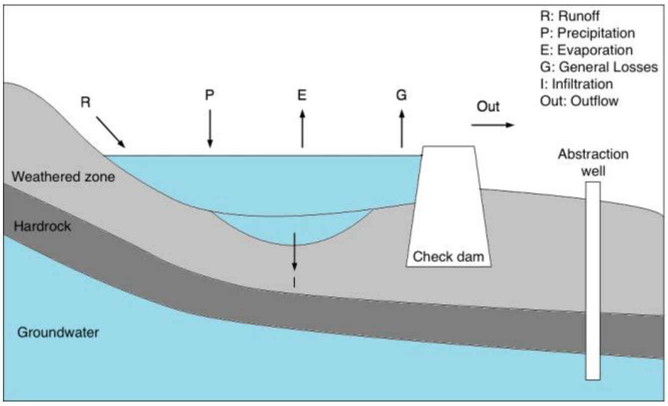

Figure 3: Water balance of the check dam

The change in storage of check dam can be computed as the difference between inputs and outputs:

$$\Delta V = R + P - E - I - G \qquad [1]$$

The water volume stored in the structure at the time step t is therefore:

$$V(t) = \min[V(t-1) + \Delta V(t); V_{MAX}] \qquad [2]$$

If the structure has reached its capacity, the outflow is:

$$Out(t) = V(t-1) + \Delta V(t) - V_{MAX} \qquad [3]$$

Check dam geometry

Most of the check dams found in the basin are reservoirs that form a tale along the river. Because of this particular shape, the volume can be estimated from the stream gradient and the river cross-section (Figure 4). In this study, the topographic slope calculated from Digital Elevation Model with a resolution of 1 arc-second is taken as an estimate for the stream gradient α. However, this approximation might lead to some errors since stream gradient might differ from the topographic slope, as affirmed by Strahler (1952).

The storage capacity V_{MAX} of the structure can be then approximated with a quadratic relationship with structure's height H_S:

$$V_{MAX} = \frac{W_s \cdot {H_S}^2}{2 \tan \alpha} \qquad [4]$$

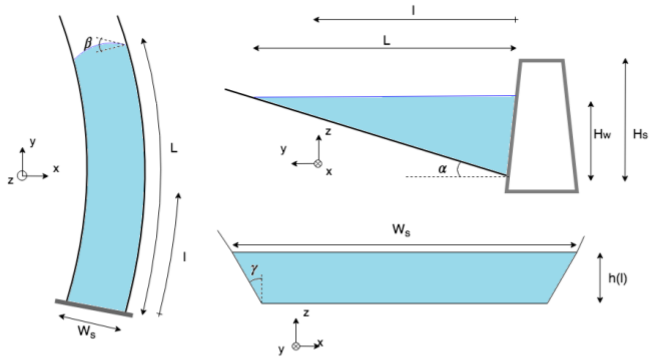

Figure 4: Cross-sections of a check dam and stored water volume

Precipitation, Evaporation, Runoff

Volumes of precipitation and evaporation can be calculated from the surface area of the impounded water. Rainfall data were requested to the State Water Data Centre (SWDC), which provided daily measurements from three meteorological stations located in the Bhadar basin between 1961 and 2017.

Regarding evaporation, Penman equation for evaporation from a free water surface is used as an estimate (Penman, 1948). Daily values of incoming net solar radiation, wind speed, temperature, surface pressure, relative humidity are all taken from NASA POWER project Data sets (grid resolution of 0.5°).

The volume of runoff entering in the check dam is computed from daily runoff depth and the catchment area of the structure. The catchment area is computed in QGIS using the Digital Elevation Model of the area and the location of the structure. The Upslope area command was used to contour the catchments from the check dams selected for the field visit. Runoff depth is estimated with the SCS - Curve Number Method developed by the Soil Conservation Service (SCS, 1972).

Infiltration

In order to estimate infiltration rate, it is important to consider and understand the factors that affect this process. According to Bouwer (2002), the mechanism of infiltration from a structure depends on *i)* the presence of a clogging layer and *ii)* the depth to the water table.

Figure 5 shows the two types of mechanisms: infiltration controlled by the hydraulic gradient (Figure 5a), and infiltration controlled by gravity (Figure 5b).

Hydraulically controlled infiltration occurs in the absence of a clogging layer, and when the depth to the water table $D_W$is less than twice the structure width W_S. If the aquifer is relatively deep ($D_W > W_S$) or a layer of low permeability is clogging the basin, the infiltration is controlled by gravity.

Because of the hydrogeological characteristics of the area, both of the aforementioned mechanisms can occur in the basin: at the beginning of the rainy season, when the aquifer is dry and water table is deep, infiltration is controlled by gravity; when the groundwater level rises during monsoon season, infiltration is controlled by hydraulic gradient.

As a result, a function relating infiltration with water table depth needs to be applied to evaluate infiltration volumes correctly. Moreover, with this relation it is possible to take into account induced recharge by abstractions.

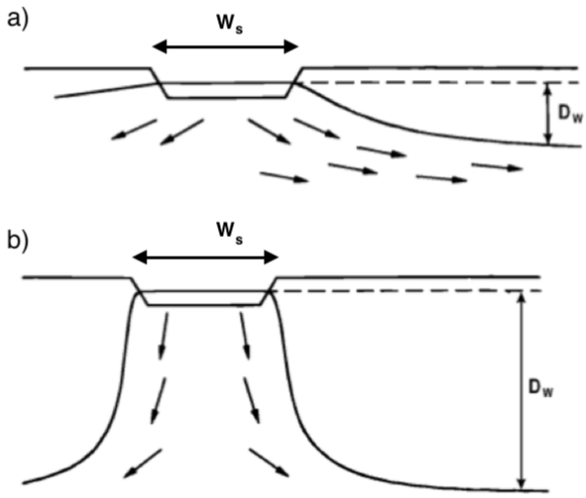

Figure 5: Mechanisms of infiltration (Bouwer, 2002)

The general assumptions for this model can be summarised as:

1. Infiltrated water seeps only in lateral and vertical directions, and not in the direction of the stream flow;
2. The soil where infiltration occurs is homogeneous with a uniform hydraulic conductivity;
3. The flow of water infiltrating through the vadose zone is completely saturated (except when a clogging layer is present);
4. The system is considered to be in steady-state;
5. The water table is sufficiently below the surface so that evaporation and water uptake from roots can be neglected;
6. The effect of infiltration from the single check dam on the water table is negligible.

If Assumption 1 is counted, the check dam basin can be modelled as an open channel. The relation between infiltration and aquifer properties has been studied by many researchers since the 1930s (Dachler, 1936). Bouwer (1969) summarised most of the research on leakage from open channels and his study is taken here as primary reference for modelling infiltration.

According to Bouwer, there are three main conditions of leakage from an open channel (Figure 6):

Condition A: Channel embedded in uniform soil underlined by a more permeable material;
Condition B: Channel embedded in uniform soil underlined by a less permeable material;
Condition C: The soil in which the channel is embedded is of much lower hydraulic conductivity than the original soil for a relatively short distance (clogging layer).

As previously explained, the area is highly heterogeneous and hydrogeological conditions can change within small distances. As a result, it is not possible to generalise which of the three conditions is the most representative. In case of a check dam located on top of a high-permeable dyke, condition A could be the most representative; if the structure is overlaying a highly impermeable layer, condition B might occur; if the bottom of the check dam basin is covered by compacted silt, condition C can be the most representative. All three Bouwer conditions are then simulated and analysed as three case scenarios. Analytical equations for the three conditions are taken from Bouwer (1969).

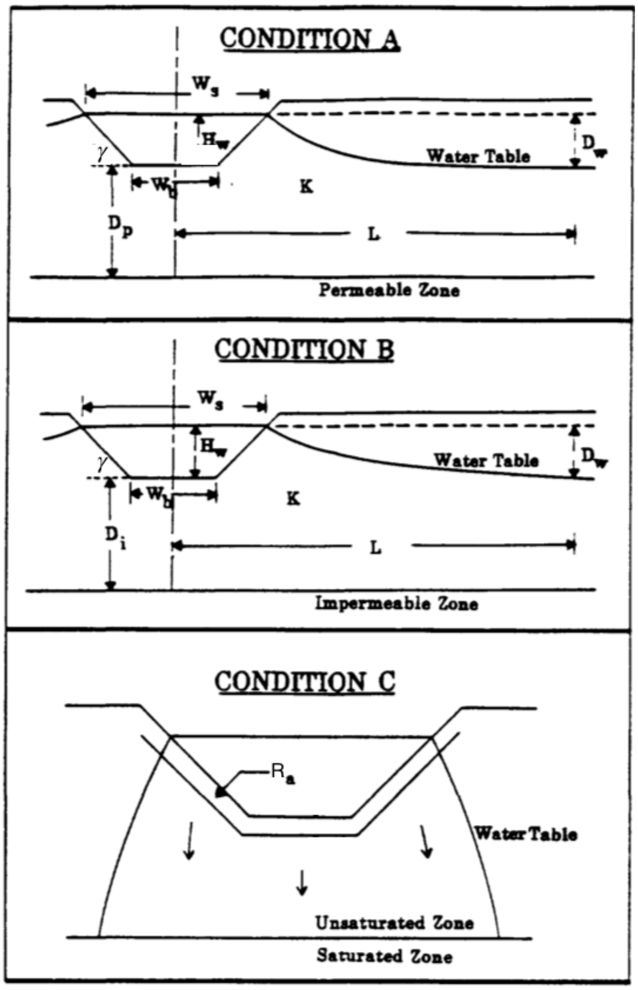

Figure 6: Bouwer's infiltration conditions (Chin, 1990)

Abstractions

Water withdrawals from wells in the proximity of check dams can influence the infiltration rate. This phenomenon is called induced recharge and have been reported by different studies (Chaturvedi and Srivastava, 1979; Butler Jr et al., 2007; Shen and Xu, 2011). Induced recharge by abstractions can be included in the model with the drawdown in the water table D_w that occurs below the structure (Figure 7).

For this purpose, Thiem equation is used to estimate the decrease in water level D_a at the structure (Thiem, 1906).

$$D_a = -\frac{A}{2\pi T}\ln\left(\frac{r_s}{r_{well}}\right) + D_{well} \qquad [5]$$

Where T is the transmissivity of the aquifer (m^2/day), A is the abstraction rate (m^3/day), r_s is the distance between the check dam and the well, r_{well} is the radius of the well and D_{well} is the decrease in water level in the well (all in m).

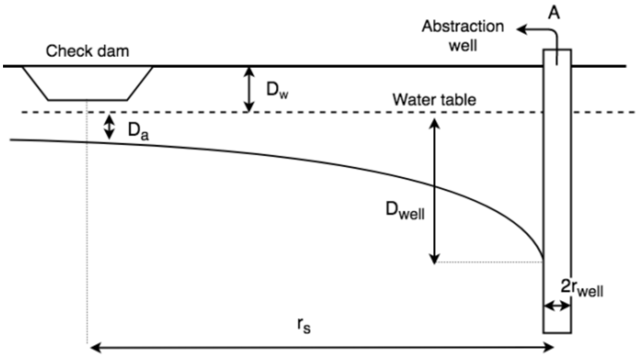

Figure 7: Drawdown from pumping

Note that Thiem equation is valid for porous confined aquifer in steady-state, and it can lead to some inaccuracy if applied to hard-rock aquifers. Another aspect to consider is that abstractions affect infiltration rate only if the water mound and the water table are hydraulically connected. In case of presence of a clogging layer, water withdrawals will not affect the storage in the structure.

This procedure considers a steady-state system. In fact, it is assumed that abstractions that occur in one day have an effect on the water table only on that particular day. The drawdown is assumed to be completely recovered on the following day. This aspect adds further uncertainty and might enhance the inaccuracy of the model.

It is assumed that water withdrawals from dug wells are due only to irrigation demand. Abstraction volumes, rates and irrigation calendars are estimated from the surveys carried out during field visit.

Water table input function

In order to analyse the water table behaviour in the basin, groundwater level data from the CGWB are used. For each year four groundwater level measurements are available: post-Rabi (January), pre-monsoon (April), Monsoon (August) and post-Kharif (November). Because water level fluctuation is dependent on precipitation, years are classified based on annual rainfall *(dry*, *normal* and *wet*).

The water table in the area is characterised by an oscillating and periodic behaviour throughout the year, following the seasonal variation of rainfall. A sinusoid is therefore used as an estimation for water level based on the day of the year. Three functions are therefore developed in order to best fit the sets of measurements available for four months of the year The function coefficients are found by graphical qualitative adjustment; the function interpolating the *normal* years is shown in Figure 8 as example.

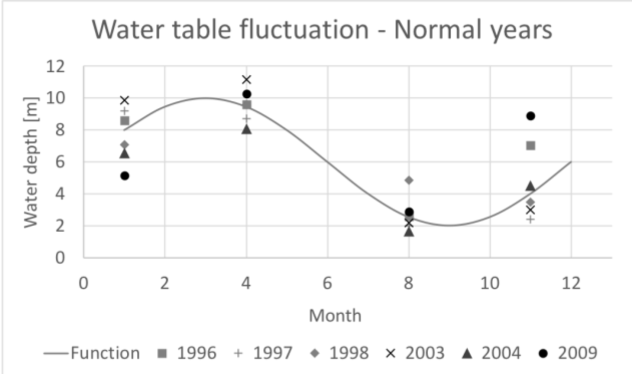

Figure 8: Water table for *normal* years (Annual precipitation between 400 and 800 mm)

Simulation in R

The conceptual model presented in previous sections is implemented as code in the R environment (R Core Team, 2017). R is a programming language and free software to perform statistical computing. The criteria for which this software was chosen is based on its widespread implementation.

Check dam's water balance is simulated for eleven years (2000 to 2010). Precipitation, evaporation, runoff and drawdown from abstractions are imported as CSV files. The code computed infiltration volumes for the three different Bouwer conditions.

Model validation

In order to validate the model presented, measurements of daily water level would be needed for all the period in which water is present in the check dam. Time constraints did not allow the recording of these measurements for the check dam assessed in the Bhadar basin. Hence, data were requested to Dr Yogita Dashora from the study of Dashora et al. (2017).

This study focused on the estimation groundwater recharge from check dams in Rajasthan. Four different check dams were analysed in the Dharta watershed for the years 2014 and 2015. Measurements involved daily rainfall and water level in the structure for all the monsoon season and the period in which water remained in the check dams. Water level measurements were taken by farmers from a gauge board painted on the upstream side of the structures.

Based on the storage capacity, Badgaon check dam was chosen to perform model validation (average storage capacity 42 000m^3). Data of daily rainfall, evaporation, and water level in Badgaon check dam were provided. Runoff coefficients were also given. A simulation with the geometry of the Badgaon check dam is run for the years 2014 and 2015.

6. *Results and discussion*

Based on the check dam assessment from the field visit, it is considered an average check dam of 30m width and 2m height, located on a stream with a gradient of 0.1° and a river bank slope of 20°. The resulting storage volume is 34 400m^3. This value falls within the storage volumes of the check dams reported in different studies in similar areas (Dashora et al., 2017; Glendenning and Vervoort, 2010; Patel, 2002). The catchment area is assumed to be 15km^2, as an average area from the sites selected from the field. As assessed from the field visit, direct withdrawals from check dams are not common. Hence, general losses G from the water balance (Equation [1]) can be neglected, as no other relevant outputs could be identified.

A simulation without abstraction is first run for 11 years (2000-2010) for the three Bouwer conditions. The stored water volumes are shown in Figure 9 below and the overall results are summarised in

Table 1 below.

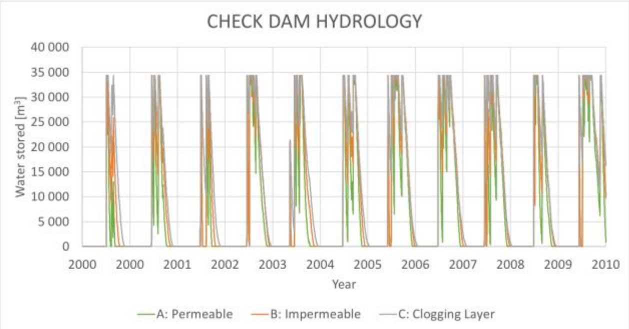

Figure 9: Water volume stored in the check dam, 2000-2010

Table 1: Average values for simulation without groundwater abstraction (years 2000-2010)

	Condition A	Condition B	Condition C
Infiltration rates	41.1 mm/day	23.1 mm/day	7.8 mm/day
Infiltrated volume	160 000 m^3	108 000 m^3	39 000 m^3
Infiltrated volume*	2.9 %	2.0%	1.1%
Evaporated volume	26 000 m^3	33 000 m^3	60 000 m^3
Annual storage days	142	164	195

*% of runoff

From the storage volumes shown in Figure 9, it can be seen that the check dam gets periodically full and empty every year, as a result of the monsoon season. Water storage varies depending on the Bouwer condition considered, and the difference between the three varies depending on the year.

From the results displayed in

Table 1, the influence of the hydrogeological setting is evident. It can be seen that in sites over a permeable layer (condition A), water infiltrates more quickly compared to sites on an impermeable bedrock. This can be explained by the fact that water stacks more easily over a layer with low permeability. In this case, the water mound forms an obstruction that prevents water to infiltrate. In case of a permeable layer instead, water seeps into the deeper hard-rock, and the flow from the check dam is faster.

Values of infiltration rates match with the ones observed by Patel (2002), which reported an average infiltration rate from Arni check dam of 30.05 mm/day between 1996 and 1999. Infiltration rates are also compatible with the study done by Glendenning and Vervoort (2010) in Rajasthan, where infiltration rates ranged between 12.3 and 55.6 mm/day.

Regarding the presence of a clogging layer, a hydraulic impendence of 200 days is considered. This value corresponds to a 20cm thick layer of silt of hydraulic conductivity of 0.001m/day. From the results, it is demonstrated that the presence of this layer is a great limit for infiltration. In fact, the clogging layer reduces infiltration by almost 70% if compared to condition A and by 55% for condition B. The effect of desilting has also been studied by Patel (2002), where he compared normal and desilted structures in Saurashtra. He found that for percolation tanks, infiltration rates differ of 61% in normal and desilted structures. This value supports the results from the simulation of condition C with clogging layer. However, it is important to note that the amount of clogging depends on the thickness and the hydraulic conductivity of the silt layer.

Looking at the infiltrated volumes, it can be seen that the average proportion of infiltration compared to runoff is below 3%. In 2001, condition A records the maximum infiltration with 6.6% of runoff water infiltrated. This suggests that small-size check dams have a low impact in capturing surface runoff. However, it is presumable that many structures in series would have a considerable effect on river flow.

In fact, the catchment area considered is the one enclosed by the check dam location without considering other structures upstream. This procedure is chosen because the objective of the study is to assess the effects of a single check dam in all the enclosed catchment. The combined effect of multiple check dam in series should be analysed in the catchment-scale part of this project. As discussed previously, the Bhadar basin has a high-density implementation of MAR. Hence, the effective catchment area should take the effective check dam density into account.

The values of relative infiltration are particularly low, especially if compared to results by Dashora et al. (2017). The comparison is made with one of the check dams assessed in Rajasthan, which has a similar geometry with the simulated one (storage capacity of 42 000m^3). They found that recharge amounted as 32 and 27% of runoff in 2014 and 2015 respectively.

However, it is important to consider that the relative value of infiltrated water depends on check dam storage capacity, catchment characteristics (like rainfall, slope, land use and so forth), but also on the catchment area. In fact, in the study by Dashora et al. the check dam catchment area is only 3.38km^2, while the one simulated in the present study is 15km^2. This means that the runoff flowing in their check dam is considerably lower, as annual rainfall are similar to the ones typical for the Bhadar basin (505 and 614mm for 2014 and 2015 respectively). If comparing instead the absolute volumes of infiltration, the simulated ones are in accordance with the measurements from Dashora et al., who recorded in 2014 and 2015 annual infiltration volumes of 113 000m^3 and 56 000m^3 respectively.

With regards to the days of storage, there is concurrence with both literature and field visit findings. The days of storage in the check dams assessed by Glendenning and Vervoort (2010) range between 138 and 382 days. Dashora et al. (2017) reported that four different check dams emptied between middle August and middle January. The dates in which the simulated check dam gets empty vary according to the rainfall and the Bouwer condition, but overall they match with what reported by local farmers during the field visit (late September until early January).

Water storage

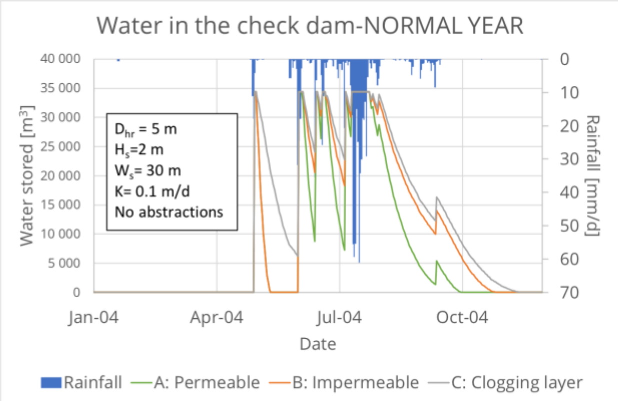

Figure 10: Water volume stored in the check dam – *normal* year (2004)

Figure 10 above shows the water storage in the check dam for the three Bouwer conditions in 2004, which is taken as a representative year (*normal* year with annual precipitation of 784 mm). The graph shows that as soon as runoff starts in middle May, the structure gets at its full capacity. The amount of runoff depends on rainfall intensity as well as the antecedent moisture conditions (SCS, 1972). Hence, small rainfall events during dry periods are not sufficient to produce surface runoff, which is the main input in the check dam's water balance.

When the structure gets full, infiltration and evaporation start, and the volumes decrease. In condition A and B, the structure gets empty in 13 days, for getting at full capacity again in middle June. It can be seen that the structure gets full multiple times in the year based on rainfall spells.

Condition A with a permeable layer underneath the weathered zone is the one in which the volume decreases the fastest, and the structure gets entirely empty after 173 days (on 31st of October). Condition B and C follow with 197 and 217 days of storage respectively. This is because, as already explained, the permeable layer allows water to infiltrate more compared to a site over an impermeable hard-rock, where water has to flow horizontally.

The case in which a clogging layer covers the storage basin is the one that takes longest to empty. Because of the silt cover, infiltration occurs at the lowest rate.

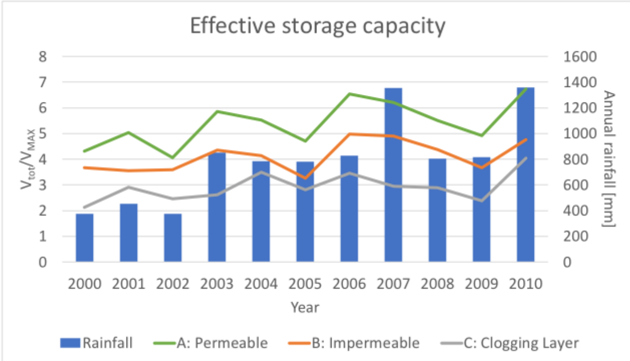

Figure 11: Effective storage capacity of the check dam

Figure 11 above shows the effective capacity of the check dam, together with annual rainfall throughout the simulation period. It is calculated dividing the total volume stored V_{tot} in a year ($V_{tot} = Q + P - Out$), by check dam storage capacity V_{MAX}. This value represents the number of fillings in a year and the effective amount of water stored in the structure.

It can be seen that behaviours of condition A and B fluctuate in similar ways, being condition A generally higher of 1 unit. The case of a clogging layer covering the basin shows a lower and more constant value of this parameter. During the 11 years of simulation, the average effective storage capacity is 4.8, 4.1 and 2.8 for condition A, B and C respectively. These values are in accordance with what found in literature. In fact, results by Kamboj et al. (2011) showed that in Bhadar basin, check dams are able to store more than five times their storage capacity.

The fact that condition A has overall the highest storage efficiency is related to the higher infiltration rate. In fact, check dam in condition A gets empty faster, and this gives a chance to more water to be stored. On the contrary, water in condition C infiltrates slowly, and when surface runoff water enters the structure, more outflow is produced.

Infiltration

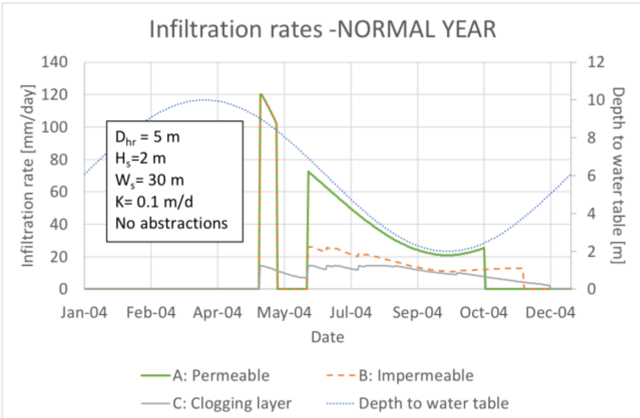

Figure 12: Infiltration rates from check dam – *normal* year (2004)

In Figure 12 shows the infiltration rates for the three Bouwer conditions for the year 2004 (*normal* year). The graph shows condition A and B having an initial infiltration rate of almost 120mm/day in the first phase of filling in the second half of May. Because of this high infiltration rates, the structure gets empty in 13 days for these two settings.

These high infiltration rates are due to the fact that in that period of the year, the water table is below the interface between the weathered zone and the permeable layer. This is visible from the water table function represented in Figure 12. In this case, infiltrated water and water table are hydraulically disconnected. In this phase, infiltration is entirely controlled by gravity and is dependent on the geometry of the check dam as well as the water level in the structure. In this case, the ratio between infiltration rate and hydraulic conductivity (I/K) is slightly higher than 1. This is in accordance with what was shown by Bouwer (2002), who studied the model by Dillon and Liggett (1983) regarding the transition between disconnected water table conditions and hydraulic connections for infiltration.

In the second phase of the filling, a difference in infiltration rate between permeable and impermeable layers can be seen. Infiltration rates are much lower than the initial phase (less than 60mm/day for condition A and less than 30mm/day for condition B). It can be seen that infiltration condition A decreases until middle September, where it reaches the minimum of 20mm/day. After this date, infiltration increases again until the structure gets empty.

In contrast with what happened in the first filling stage, in this period the water table is hydraulically connected with the check dam. In fact, the infiltration rate of condition A resembles the water table fluctuation. For condition B, similar considerations can be made. As already explained, infiltration rate is generally lower in case of an impermeable layer.

If the check dam is covered with a clogging layer, infiltration rate stays below 20mm/day and stays roughly constant until it gets empty (14th December). This Bouwer condition considers the hydraulic disconnection between the water mound and the water table. As a result, infiltration rate does not depend on the fluctuation of the water table, as it is for condition A and B. This mechanism of infiltration is only dependent on the water level in the structure. This explains the decrease in infiltration rate in the last stage of the storage: when the water level in the check dam decreases, the hydraulic pressure reduces, and infiltration becomes slower (October-December in Figure 12).

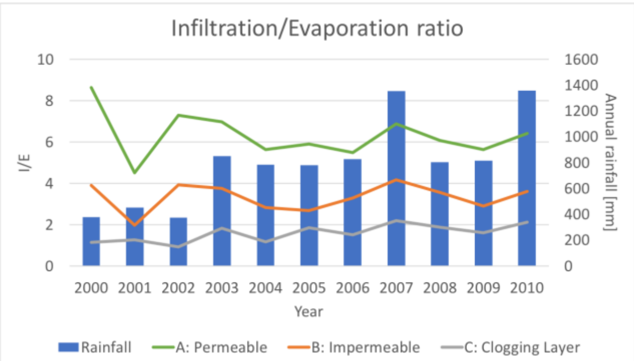

Figure 13: Infiltration-Evaporation ratio

Figure 13 shows the ratio between infiltration and evaporation occurring in the check dam. For dams located in semi-arid areas, losses by evaporation can be a severe limitation in their ability to store and infiltrate water. This value is therefore one of the indicators used to assess the efficiency of the structure (Neumann et al., 2004).

Depending on the year, this ratio ranges between 3.9 and 5.9 for a permeable layer (condition A); between 7.3 and 3.5 for condition B and between 0.9 and 2.2 for condition C. Average values are 5.3, 3.4 and 1.6, which means that 14%, 24% and 40% of the total stored volume V_{tot} is lost by evaporation for A, B and C respectively. These outcomes are in line with the results previously explained: as condition A is the one that infiltrates the most, it is also the more efficient in terms of losses by evaporation. Condition C instead, is the one that implies more loss due to evaporation, which confirms the deterioration that a clogging layer brings to the performances of check dams.

These values are similar to the ones found in the study of Patel (2002) in the Bhadar basin. He estimated infiltration/evaporation ratios occurring in percolation tanks and check dams to range between 1.83 and 8.94 depending on the structure, the maintenance and the hydrogeology of the site. These numbers are also verified by comparing the simulation results with the study done by Dashora et al. (2017). They found a ratio between infiltration and evaporation from four check dams to be comprised between 3.6 and 5.9.

Influence of groundwater abstractions

A simulation is run to model the influence of induced recharge from abstractions from nearby wells. It is considered a well located 100m from the check dam from which water is abstracted for irrigation purposes. It is assumed a rate of 100m^3/day for irrigating the total cropping area. Table 2 below summarises the average values of results from this simulation, together with the increase/decrease with respect to the simulation without abstractions.

Table 2: Average values for simulation with abstractions (years 2000-2010)*

	Condition A	Condition B
Infiltration rates [mm/day]	47.9 (+6.8)	31.8 (+8.7)
Infiltrated volume [m^3]	172 000 (+12 000)	129 000 (+21 000)
Infiltrated volume [% of Runoff]	3.1 (+0.2)	2.4 (+0.4)
Evaporated volume [m^3]	23 000 (-3 000)	27 500 (-5 500)
Average annual days of storage	133 (-10)	147 (-18)

*Numbers in brackets indicate the net difference between the condition with abstractions and the one without abstractions (+ increase, - decrease)

During the 11 years of simulation, the average increase of infiltrated volume is of 7.4% (more than 12 000m^3 per year) for condition A, and of 20.6% (more than 21 000m^3 per year) for condition B. These values confirm the well-known effect of induced recharge by abstraction wells nearby check dams (Moore and Jenkins, 1966). Overall, infiltration increases and evaporation decreases.

This difference is due to the induced recharge by abstractions. In fact, the drawdown caused by the pumping decreases the water table at the structure site. As a result, the drop in the water table increases the infiltration rate for the day in which abstractions occurred.

Model validation

A simulation for the three Bouwer condition is run with meteorological data and geometry of Badgaon check dam for the years 2014-2015. Figure 14 shows the water level observed in the check dam together with the ones simulated by the model.

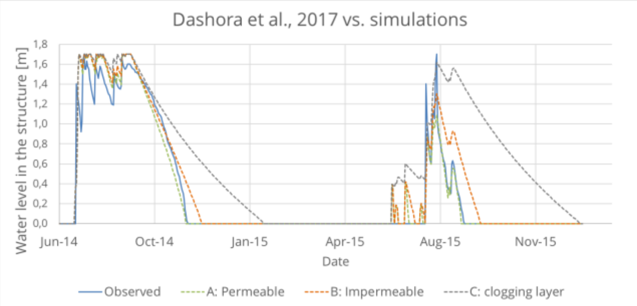

Figure 14: Water levels - simulation and measurements from Dashora et al. (2017)

Figure 14 displays the water levels for the simulation together with the field measurements. In the year 2014, all Bouwer condition follow relatively close to the measurements. There is a general overestimation of the water level from the model, but the difference is generally lower than 0.2m. When the structure starts to get empty, it can be seen that condition A follow closely the measurements recorded by farmers.

In 2015, it can be seen that in June the model simulates some water in the check dam while no recording of this occurred. This discrepancy can be explained by the fact that during this period, there were few days of precipitation with around 30mm/day falling upon the catchment. These days of precipitation were not enough to produce surface runoff because of the dry conditions of the basin before the monsoon season. The model, however, computes runoff by multiplying the precipitation depth by a runoff coefficient (0.02 in 2015) and does not take into consideration the antecedent moisture condition of the basin.

After the structure gets full and water is measured in the check dam at the end of July, condition A fairly replicates the observations, and it predicts the day of empty with only three days discrepancy.

Table 3: Validation results

R^2 of water levels	**2014**	**2015**
Condition A	0.939	0.867
Condition B	0.934	0.731
Condition C	0.885	0.331

Table 3 above displays the coefficient of determination R^2 between the model and the observed water depth values for the years 2014 and 2015. This coefficient is an indication of the goodness-of-fit measure for linear regression models (Cameron and Windmeijer, 1997). Note that the days in which both the model and the observations are zero are excluded.

In concordance with the previous results, it can be seen that condition A is the most representative for the Badgaon check dam for both years 2014 and 2015, with an R^2 of 0.939 and 0.867 respectively. Condition B has a lower fitness with the observations, with R^2 of 0.934 in 2014 and of 0.731 in 2015. The case of clogging layer (condition C), is the least representative of the three Bouwer conditions, with a coefficient of determination of 0.885 in 2014 and 0.331 2015. These results can be explained by the fact that the Badgaon check dam did not have a thick layer of silt; especially in 2015, when the surface was manually scraped. The fact that R^2 is generally lower for all Bouwer conditions in 2015 can be explained by the discrepancy in surface runoff previously illustrated.

The validation of the model using the measurements from Dashora et al. (2017) indicates that the tool developed in this work can be successfully applied to check dams in other semi-arid areas. However, the performance of the model is directly linked with the method used to estimate surface runoff and its accuracy compared to measurement data.

7. Conclusions

In this study, a tool is developed in R to analyse and simulate the water balance of check dams to understand the impact on local hydrology in hard-rock region of Gujarat. The tool is used to simulate the check dam behaviour under different hydrogeological settings and parameters.

The model was validated by implementing measurements from a check dam studied by Dashora et al. (2017) in Rajasthan in 2014-2015. The coefficient of determination R^r from the validation was found to be 0.939 in 2014 and 0.867 in 2015.

The main factors influencing check dam behaviour are structure geometry, characteristics of the setting, catchment area and depth to the water table. Hydrogeological setting is an essential parameter for the amount of water infiltrated from the structure. Moreover, the presence of a clogging layer can reduce infiltration volumes up to 70%, depending on the impendence of the silt cover.

It is demonstrated that check dams get full multiple times per year, being able to store up to six times their storage capacity. The fraction of water volume stored by the check dam and lost by evaporation ranges between 10 and 50%.

The impact of a single structure on surface runoff is relatively low: on average the volume stored is less than 4% of runoff. However, it is presumable that the cumulative effect of multiple structures would lead to a significant impact on river flow for downstream areas.

It is also found that induced recharge from nearby abstraction wells can increase the recharge volumes up to 20%, but only if the basin is not covered with a clogging layer.

Recommendations and future development

As previously explained, check dam geometry has a significant influence on their hydrological behaviour. In order to improve the accuracy of the model in predicting water budgets, it is suggested to measure area-volume-elevation curves on the field. This should be done during the summer season, when the structures are dry, with the use of dumpy levels or theodolites. Infiltration tests are also suggested to estimate hydraulic conductivity in the weathered upper zone. Geophysical surveys - like Vertical Electrical Sounding (VES) or Electrical Resistivity Tomography (ERT) - could be performed to understand the hydrogeological setting underneath the weathered upper layer. Because the model is dependent on the water table dynamics, it is also suggested to measure groundwater depth at different distances from the structure. By doing so, it is possible to determine a more accurate and site-specific water table functions over time.

In the presence of measurements from the field, the developed model has great potential to predict check dam behaviour. Complete calibration and validation would require measurements of precipitation, evaporation, and runoff. The daily water level in the structure should also be measured with a high temporal resolution water level data logger (e.g. diver) or with daily measurements performed by locals.

The study of individual structures can be incorporated into a catchment-scale model, as is the intention of the larger project that enables this study. This would allow studying the cumulative impact of small-scale decentralised MAR implementation, on both groundwater resources and surface runoff.

Finally, it is remarked that this tool has the potential to be used in different semi-arid locations. Because it is based on analytical equations, it can be applied in different hydrogeological settings (also on alluvial aquifers) with adequate site-specific data.

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