MANAGED AQUIFER RECHARGE FOR SUSTAINING GROUNDWATER SUPPLIES FOR SMALLHOLDER COFFEE PRODUCTION IN THE CENTRAL HIGHLANDS OF VIETNAM:

REPORT ON PILOT TRIAL DESIGN AND RESULTS FROM TWO HYDROLOGICAL YEARS (MAY 2017 TO APRIL 2019)

October 2019

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EXECUTIVE SUMMARY

Widespread increase in the use of groundwater for intensive commercial agriculture across the Central Highlands has resulted in clear signs of seasonal groundwater stress. Deficits in the availability of irrigation water may trigger pronounced impacts on agriculture as evidenced from recent droughts in the region. The impacts are expected to worsen due to climate change. Enhancing resilience to climate variability is dependent upon achieving sustainable groundwater use and management. Climate change adaptation measures are needed to buffer against climate variability and thereby stabilize water resource availability.

Water resource challenges may be approached in two ways: improved management of water demand and/or augmenting groundwater supplies. This study examines the latter option through the testing of Managed Aquifer Recharge (MAR). A related study by Viossanges *et al.* (2019) considers the former by examining the impacts of demand management related interventions intended to improve water use efficiency. In this study, MAR has been proposed as a means by which farmers in the Central Highlands can be pro-active in overcoming seasonal water shortages by converting their irrigation wells for both recharge and pumping and making use of available seasonal runoff to boost local groundwater storage. However, unlike many other countries with high dependence on groundwater resources, this form of intervention has yet to be proven in Vietnam.

The aim of this research is to develop and pilot test pragmatic, low-cost, farm-level approaches to MAR to establish whether it offers scope for farmers to intervene to enhance climate resilience by improving local groundwater resource conditions.

Following a rigorous site selection process prior to the 2017 wet season, 5 sites were selected along with paired sites (i.e. nearby irrigation wells not equipped for MAR) that are used for reference purposes. The 5 MAR pilot trials were set up in close collaboration with the local farmers as the primary beneficiaries of the intervention. The MAR systems collects runoff over collection areas ranging from around 150 to 3,000 m^2 made up of a mix of local fields, rooftops and unpaved roads. This water is drained via gravity through a sand filter chamber and finally into the farmer's well. Since May 2017, each site has been carefully monitored and evaluated in terms of the volumes of water stored and recovered, groundwater level response, water quality impacts, site maintenance, financial costs and farmer attitudes/perceptions. This report covers the two year period from the start of piloting up until April 2019. The trial remains ongoing at the time of writing.

The results for the two hydrological years reveal that the average volumes of runoff water stored in the aquifer was 115 m^3 over the monsoon season across the sites with maximum values of 300 m^3 for highest performing sites. Sites with clean water

from roof runoff recharged most, whilst highly turbid runoff water from unpaved roads recharged least. Low recharge efficiency relative to the rainfall yield over the runoff collection area in many cases suggest scope to enhance the system performance.

Detailed water quality sampling was carried out during both the wet and dry seasons for a comprehensive suite of physico-chemical and microbiological parameters. This reveals that there was no water quality parameter measured of serious concern from human health, irrigation or environmental view-points with the exception of *E. coli* which was also elevated in the reference wells. Several of the parameters measured entering the MAR wells such as total dissolved solids, nitrate and turbidity were elevated compared to the reference wells, but were either short lived peaks, or at levels generally not of concern relative to the national water quality standards.

Based on numerical modelling and water quality tracer analyses, it would appear that most of the water stored in the aquifer was likely unrecoverable from the recharge well owing to groundwater velocities up to around 100 metres per year that were surprisingly higher than that previously reported in the shallow basaltic aquifer targeted for storage. Whilst the opportunity for farmers to recover the actual body of water recharged from the wells used for recharge appears to be unlikely, the MAR process does serve to slow down the water flows considerably by aquifer transport as compared to the surface drainage system. This makes the water available in the local area over the dry season if picked up from downstream wells and/or from surface water courses which are understood to be largely fed largely by groundwater discharge in the drier months (Viossanges *et al.* 2019). Institutionalizing MAR under this scenario may require new models of governance, perhaps with a need for some emphasis on community level water management, enabled through institution building and awareness raising.

Estimates of the costs for establishing MAR systems appears to be relatively attractive. This needs to be verified through further engagement with a broader range of farmers. Tentative estimates suggest that the capital costs if implemented by farmers are around VND 10 million (USD 440) and annual running costs are around VND 0.34 million (USD 15). The principles for determining the benefits of MAR are clear, however data limitations preclude quantification at this stage.

Baseline and follow up interviews with the farmers participating in the trial show that they have good practical understanding of how the MAR system functions and have been observing its performance closely. Not all of the farmers are yet ready to operate and maintain the MAR systems and their commitment to supporting further adoption would need to be established. An ongoing process of engagement would be helpful to track their attitudes over time.

There is some scope for farmers and rural communities more generally to gain benefits if the MAR approach can be verified so that appropriate policies and plans can be developed to enable upscaling. There are also risks that the higher than anticipated groundwater velocities will diminish the direct benefits expected of the participating farmers and bring about unexpected indirect benefits to downstream farmers able to capture the water through wells or from surface water courses.

This is believed to be the first time that MAR has been implemented in Vietnam. The trial indicates great scope for farmers to gain from the MAR approach. The Krong Buk pilots have made firm inroads towards gaining a sound technical, social and economic proof of concept for MAR. These results are sufficiently promising to support broader piloting in contrasting hydrogeological conditions across the Highlands. A wider range of pilots would help make a stronger case for policies and strategies that support more widespread MAR adoption and thus enhance the resilience of smallholder coffee farmers in the Central Highlands.

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List of Acronyms and Abbreviations

MAR: Managed Aquifer Recharge
MPN Most Probable Number
NTU: Nephelometric Turbidity Units
O&M: Operations and Maintenance
TDS: Total Dissolved Solids
USD: United States Dollar
VND: Vietnamese Dong

1. INTRODUCTION

1.1 Background and Local Context

The Central Highlands of Vietnam is a prized region for Robusta coffee production. Areas under coffee cultivation have grown more than 20-fold since the early 1980's owing to a suitable climate, rich soils and abundant water resources, harnessed effectively through supportive government policies and programmes (Marsh 2007). Water management is an important element of Vietnamese Robusta coffee production (Amarasinghe *et al.* 2015; D'haeze 2019). The input of irrigation water improves crop yields and quality, thereby making farming economically viable.

Across large parts of the Central Highlands the predominant source of irrigation water for coffee is considered to be groundwater (Viossanges *et al.* 2019; Milnes *et al.* 2015). The region is largely made up of hardrock aquifers characterized by low storage capacity and high sensitivity to increased demand as compared to alluvial aquifers that tend to be more widespread in lowland and coastal areas (Shah, 2012).

An escalation in groundwater use over the past four decades has brought about detrimental impacts evidenced by reduced availability of groundwater at the end of each dry season in the shallow, unconfined aquifers, along with systematic declines in groundwater levels in deeper aquifers and associated diminishment of groundwater discharge to rivers and streams (Milnes *et al.* 2015; Cheesman and Bennett 2005; D'haeze *et al.* 2005). In Dak Lak and Dak Nong provinces for example, average groundwater levels are reported to be 4 to 5 meters lower than in the 1980s, leaving farmers and even domestic users with inadequate water supply (2030 Water Resources Group 2017; MK17 Project Team 2013). In the absence of adequate legal and regulatory framework to support groundwater management in the country, pumping has expanded leading to the depletion of groundwater resources. The Government of Vietnam firmly recognizes sustainable management of groundwater resources in the Central Highlands to be of strategic importance to the socioeconomic development region (MONRE 2006). In addition, increasing attention is being given to water scarcity and drought management in the Highlands, as the frequency and severity of droughts has been increasing in recent years, likely due to a combination pressures from growing demand and climate change (CCAFS-SEA 2016; MONRE 2006).

Managed aquifer recharge (MAR) has been proposed as a means by which groundwater storage can be enhanced and groundwater depletion reversed (Gale 2005). MAR focuses on the intentional recharge of surface water to suitable aquifers to boost groundwater supplies that allows for subsequent recovery for productive uses or to achieve a range of possible social, economic and environmental benefits.

Practiced in no fewer than 62 countries worldwide (Stefan and Ansems 2018), MAR is a commonly applied tool in countries and regions where groundwater dependence is high. The simplicity of MAR concepts tend to understate the depth of knowledge, capacity and experience needed to make implement and manage MAR successfully. Without such pre-requisites the underlying risks may lead to the situation where MAR may fail to meet its intended goals (Rodríguez-Escales *et al.* 2018).

A number of studies have drawn attention to the need for Vietnam to develop new capability in MAR to address water supply shortfalls (2030 Water Resources Group 2017; CCAFS-SEA 2016). However practical experience remains very limited, although interest is growing. The potential role and value of MAR has been recognized (e.g. *Bui et al.* 2015), and previous investigations carried out to examine the opportunities for introducing MAR carried out (Stefan 2014; Thoa *et al.* 2008). Field-based trials had yet to be conducted at the time of commencement of this study.

1.2 Study Aims

This study broadly aims to establish, test and evaluate the scope for managed aquifer recharge (MAR) as a technique for improving groundwater availability and resilience to drought for the benefit of rural communities in the Central Highlands. It sets out to achieve this by designing and introducing forms of MAR in ways that are locally tailored and meet the needs of the primary beneficiaries of the intervention – the local farmers themselves. In this sense, MAR would be implemented by the farmers themselves at a small (pilot) scale and positioned on-farm. This would be in keeping with the principles of simplicity and low-cost (Figure 1.2.1). Under these arrangements, it is hoped that the likelihood of take-up by other farmers in the region would be improved, assuming the pilots are shown to be successful.

Piloting to achieve proof of concept for locally appropriate MAR presents a number of challenges that need to be addressed.

From a biophysical perspective the key considerations include:

- i) Ensuring that the design, operation and maintenance of MAR interventions are appropriate for farmers to manage;
- ii) Storing sufficient volumes in the aquifer and, ideally, building up the groundwater levels to provide more reliable groundwater availability in the later stages of the dry season for irrigation rounds when water availability is typically most critically limited; and
- iii) Safeguarding the groundwater quality through the MAR activities, cognisant that source water for MAR is generated from intensively utilized agricultural landscapes.

From a governance perspective they include:

iv) Ensuring that the capital, operating and maintenance costs of MAR are acceptably low to farmers to ensure active participation;
v) Providing benefits from MAR (both direct and indirect) sufficient to stimulate a sense of ownership and ongoing commitment to MAR from the participating farmers; and
vi) Overcoming attitude/perception related issues or knowledge gaps of farmers and the wider stakeholder groups through targeted outreach efforts.

This report describes the process of implementing the pilot trial and results from the first and second hydrological years of operation covering the 2017/18 and 2018/19. It builds on a progress report that provided initial results from the first year and outlined a set of recommendations to improve system performance in subsequent years (Pavelic *et al.* 2018 and summarized by Pavelic *et al.* 2019). The research design and findings presented in the report takes the above listed points into consideration to the extent possible.

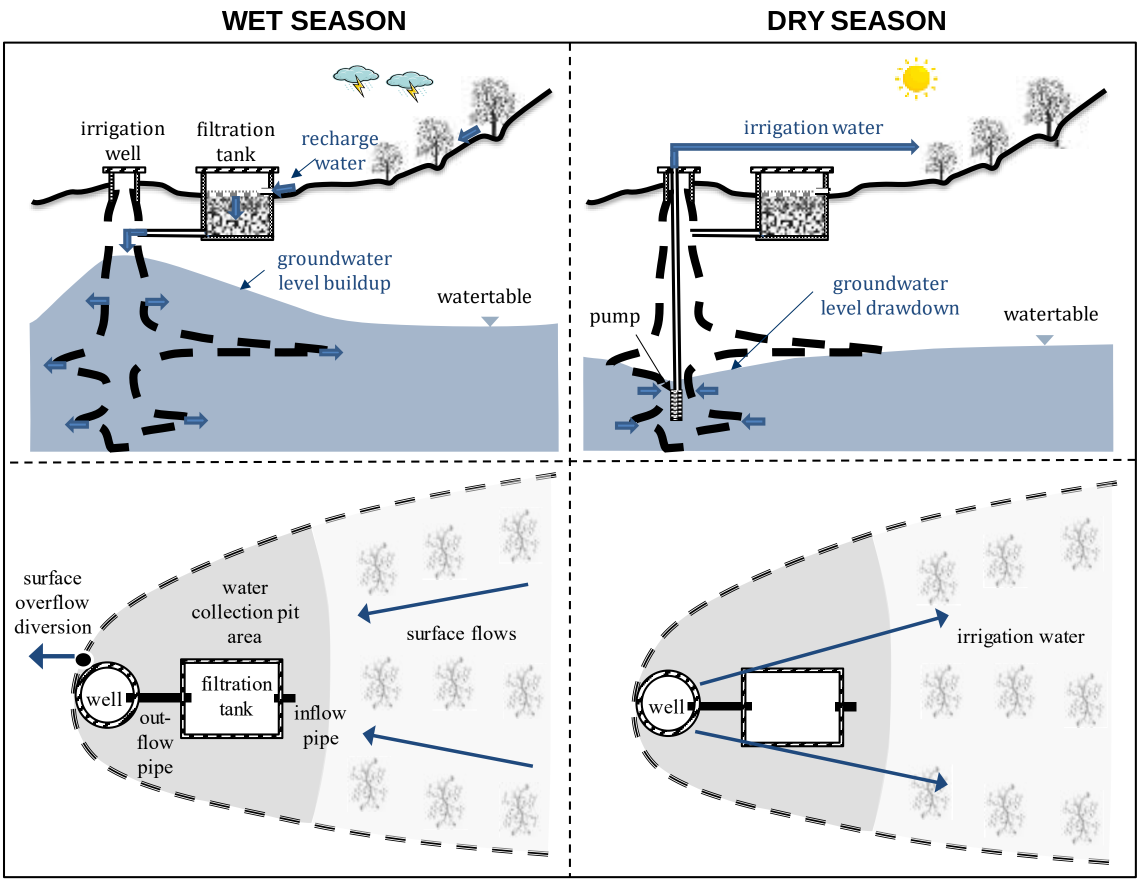


Figure 1.2.1. Generalized schematics showing the main features of the MAR design and operation in cross-sectional view (top) and plan view (bottom). *Information provided in Section 2 gives the site specific design details. Note that collection areas may also include rooftops, roads and other runoff generating surfaces (not shown in the figure).*

2. MAR PILOTING APPROACH

2.1 Site Selection Criteria

The project team adopted the view that multiple MAR sites should be selected, set-up and evaluated, thereby laying the ground for a more diverse and robust evaluation of MAR on the Dak Lak plateau. Findings from earlier research identified areas of highest groundwater scarcity where MAR piloting would add most value. These water scarce hotspots are situated on locally elevated parts of the basaltic plateau where shallow wells are most prone to drying-out (Milnes *et al.* 2015). Sites for MAR piloting were sought that met the following criteria:

1) presence of a shallow irrigation well (<30 metres deep) where there are routinely water shortages during the dry season (as confirmed by the well owner);
2) suitable collection area and slope to harvest local runoff water for recharge
3) small area (i.e. few m^2) of unused land in the vicinity of the well to install runoff water collection and pre-treatment infrastructure;
4) latent storage capacity in the aquifer to store recharge water – i.e. depth to water table at the end of the wet season of at least 5 metres;
5) a receptive farmer/well owner willing to convert his/her irrigation well to MAR for the dual purpose of recharge and pumping; and
6) absence of groundwater use for domestic purposes (as the suitability of the pumped our recharge water for household purposes needed to be confirmed through the trial).

Furthermore, the project team jointly decided together in joint discussions with representatives from Nestle, the Swiss Agency for Development and Cooperation (SDC) and the Centre for Hydrogeology and Geothermics (CHYN), that MAR sites should be situated within the general area of, but strictly outside of the physical boundaries of the nearby experimental micro-watershed where work was underway to establish the impacts of improved irrigation practices on surface water and groundwater resources availability (Viossanges *et al.* 2019). This avoided the risk of interference between the two approaches being tested (i.e. interventions based on water supply and water demand).

2.2 Site Selection Process and Site Characterization

A detailed site selection procedure was followed to identify MAR sites along with corresponding nearby sites that would serve as suitable references for the situation without MAR. Surveys were carried out in February and March 2017 to assess prospective sites within four specific areas of the Cư Né commune. Each of the 25 sites inspected were rated according to the criteria listed in Section 2.1 and highest ranking sites were revisited and sites jointly agreed upon. This procedure yielded 5

MAR sites (identified as M1 to M5), along with 7 reference sites (identified in relation to the corresponding MAR site, e.g. M1-R1).

The MAR sites are distributed in two broad clusters. One cluster for M1 to M3 is situated within Ea Krom village and a second cluster for M4 to M5 in Kmu village located 2-3 kilometres to the west (Figure 2.2.1). The two clusters of MAR sites (and their associated reference sites) are distributed across four watersheds. Sites M1 through to M3 lie within discrete watersheds, whereas M4 and M5 lie within the same watershed. The nearest reference sites to their respective MAR site were situated at distances ranging from 70 to 210 metres away, and located within the same watershed. The experimental micro-watershed lies within an upstream portion of the watershed for M3. The entire study area for MAR is distributed across an area of approximately 50 km^2.

At each of the selected MAR sites, the farmers confirmed their interest in MAR and willingness and take part in the trial. They agreed to the retrofitting of their irrigation wells with pre-treatment, pipework, flow controls and downhole monitoring equipment. Farmers at the reference sites also confirmed their commitment to participation.

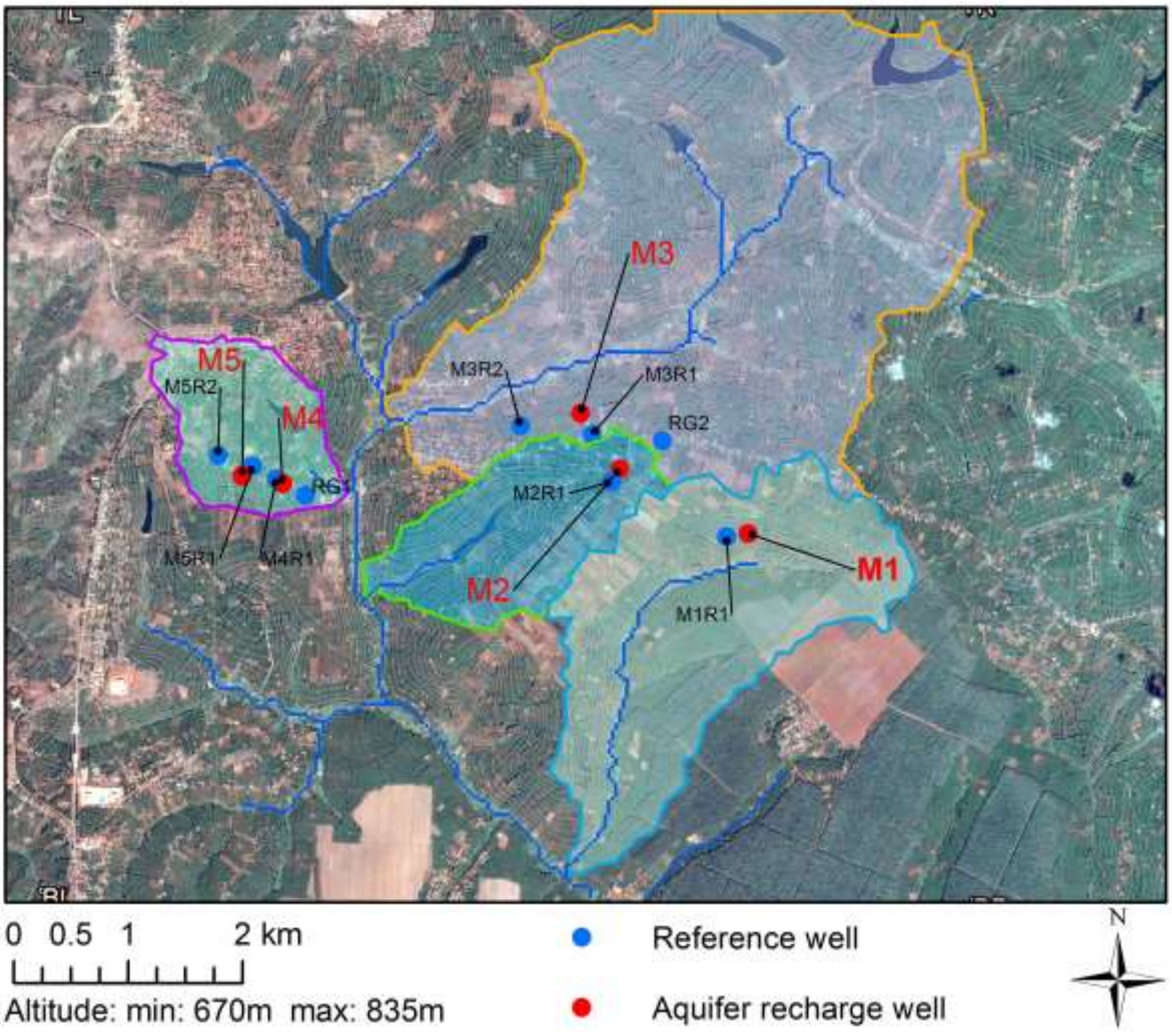


Figure 2.2.1. Site map indicating location of MAR and reference sites and their associated watersheds

2.3 MAR Design and Subsequent Improvements

The MAR system involves the diversion and drainage of local rainfall runoff and infiltration into existing open hole (unlined) irrigation wells after undergoing simple pre-treatment through a filtration tank sometimes preceded by a sedimentation tank. Pre-treatment serves to ensure the suspended solids content of the water entering the aquifer is reduced to lessen undue clogging that would otherwise compromise the hydraulic performance of the system. Some of the wells were equipped with a pump such that during the dry season, groundwater is pumped out according to the crop water demands. The finer suspended solids that pass through the filter would be expected to be deposited within the well and therefore recovered during pumping, thereby ensuring sustainable operations over the long term.

Runoff water is collected from areas immediately upslope of the well from a mix of land surface types according to the local conditions (Table 2.3.1). Those sources include local fields, unpaved roads and tracks, rooftops and paved residential compounds.

The collection area for each site was estimated from detailed site inspections taking account of local micro-topographic variations that may have a strong influence on local flows. The slope of the collection areas varied from 0.9 percent around M2 through to 11.8 percent at M5.

Based on the results of the first year and field inspections in January 2018, areas of improvement were identified for most sites to help increase the volume and efficiency of recharge in the second hydrologic year. The design enhancements implemented in April 2018 are given in Table 2.3.2.

The filtration tank was installed in a suitable location of available land upslope of the well. It consisted of a one metre diameter polyethylene plastic water tank that was sawn in half and installed below ground with above-ground protrusion to height comparable to that of the well-head. A pre-filter layer consisting of non-woven geotextile fabric material was sourced and added to the top of the sand to screen out course debris (leaves, branches etc.). Mesh sheeting was placed over the tank to keep out large debris.

In the case of sites M1 to M3 the collection areas were in an undeveloped state and so a flow diversion channel had to be constructed to convey water from to the nearest point of natural drainage towards the filtration tank in each case. A 400 litre (100×100×40 cm) sediment trap of masonry construction was also installed prior to the filtration tank to stop course debris from silting-up the tank. In the case of sites M4 and M5 the collection areas had previously been terraced and concrete lined channels constructed to convey water offsite by the land owners. Sediment traps were therefore not required. At M5 the large collection area motivated the installation of two parallel filtration tanks.

The filtration tanks were filled with a 30 cm layer of gravel underlying a 30 cm layer of sand. The tests carried to select the appropriate combination of sand and gravel are detailed in Appendix 1. Tanks were covered with mesh to stop the entry of leaf and other debris.

Pipework and fittings - inflow and outflow pipes are composed of 2-inch diameter or wider PVC pipe. Valves are installed above and below the tank. PVC pipe was used to transport water from the filtration tank to enter the well. A plastic elbow was added to direct water down vertically to the well and an endcap nozzle fitted to dissipate the water energy and avoid erosion of the walls of the well.

Site specific design characteristics are summarized in Table 2.3.1. Photographs of sites M1 and M4 are given in Figure 2.3.1.

Table 2.3.1. Design details for each MAR site

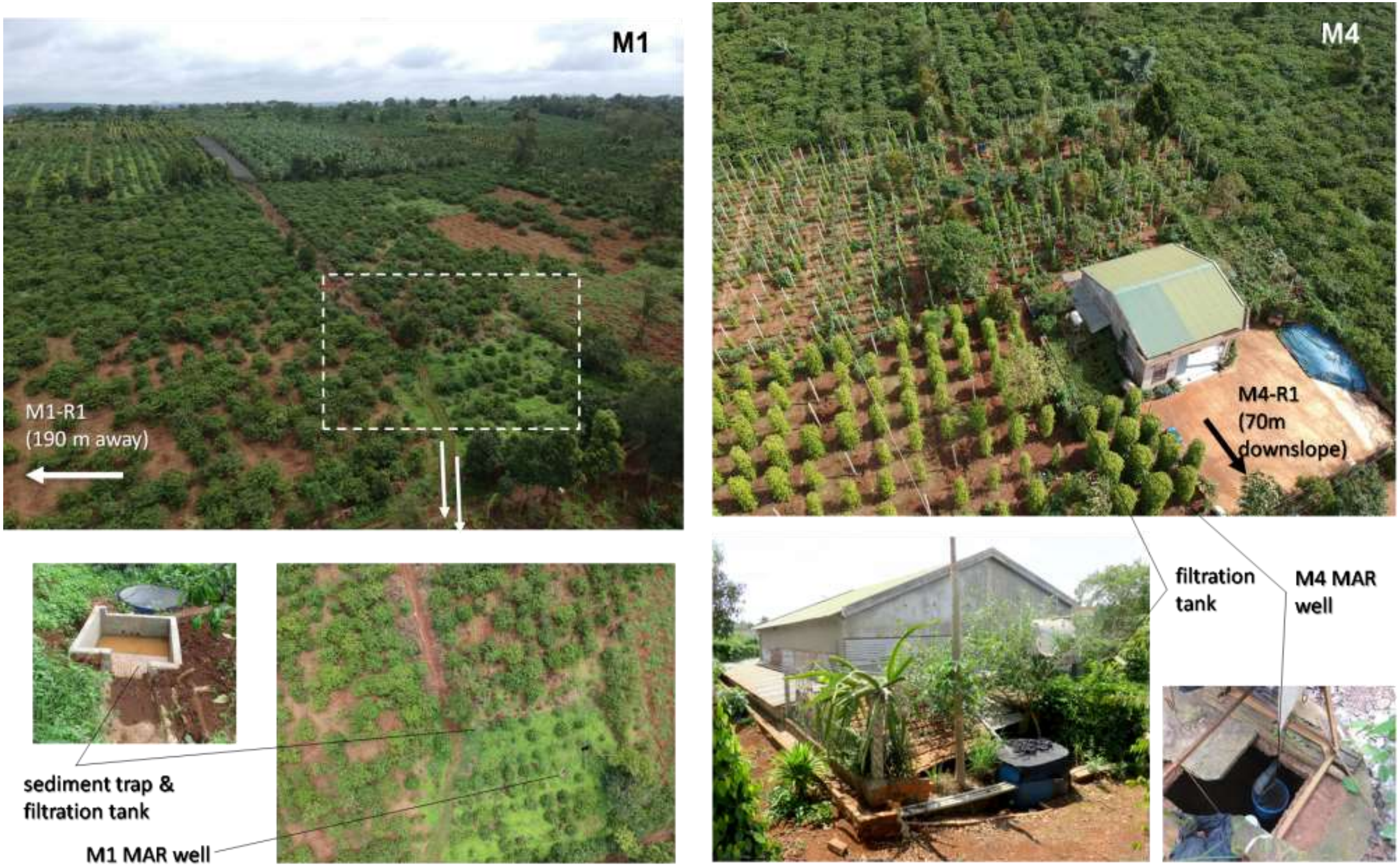
Site	No. Filt. Tanks	Sed. Trap	No. Ref. Wells	Collection Area (m^2)	Landuse of Collection Area
M1	1	Yes	1	2,700	Field
M2	1	Yes	1	634	Unpaved road
M3	1	Yes	2	1,670	Rooftop + yard + field + track
M4	1	No	1	154 (year 1)[1] 188.6 (year 2)[1]	Rooftop + field
M5	2	No	2	3,022 (year 1) 3,104.2 (year 2)	Field (year 1) Field + rooftop (year 2)

[1] Fields situated upslope of the roof assumed to collect limited water and so not included

Table 2.3.2. Site upgrades undertaken in April 2018 to help improve recharge performance in the second year of the trial

Site	Upgrade
M1	Constructed minor bund across the unpaved track as main conduit for flow to intercept more of the runoff water
M2	Constructed minor bund across the unpaved road to enhance water capture Construction of a new masonry tank to replace plastic tank not well suited to the site
M3	No significant change
M4	Harvest additional roof runoff from front of the residence by installation of additional rainwater downpipe.
M5	Harvest additional water by diverting roof runoff water from nearby residence to the site

Figure 2.3.1. Photographic images of sites M1 (left) and M4 (right)



2.4 Regulatory Arrangements and Approvals

The Ministry of Natural Resources and Environment (MONRE) holds outright responsibility for the implementation of measures to protect all water resources, including groundwater (Hoanh *et al.* 2013). That mandate includes responsibility for the prevention of degradation and depletion of water resources and the issuing (and withdrawal) of licenses to abstract water. The most recent Government of Vietnam Decree No. 38/2011/ND-CP on water resource exploitation or wastewater discharge into water sources came into effect in 2011 but makes no provision for the issuing of licenses or permits in relation to emerging technologies such as MAR.

Discussions were held with the Department of Natural Resources and Environment (DONRE) and the Department of Agriculture and Rural Development (DARD) of Dak Lak Province to bring the proposed MAR trial to their notice and to ensure the trial would be conforming with existing laws and rules. This interaction indicated that formal permission to conduct the MAR trial would not be required as the proposal involved the recharge of runoff from an agricultural catchment, unlike had the case involved the discharge of industrial waste underground which certainly would have required permitting. The monitoring program prepared for trial was considered sufficient to ensure adequate protection from potential adverse impacts on groundwater resources of the Dak Lak plateau. Monitoring was undertaken in collaboration with the Sub-Division of Water Resources in the Central Highlands, (former name: Hydro-geological Unit 704), based in Buon Ma Thuot of the National Center for Water Resources Planning and Investigation (NAWAPI) of MONRE.

3. INSTRUMENTATION AND MONITORING

Each of the MAR sites are monitored to establish the functioning, performance and beneficial impacts associated with MAR. This is achieved through comparable monitoring between the MAR and the reference sites, with the latter reflective of the baseline conditions. Specific hydrologic parameters that are examined at either or both the MAR and reference sites include groundwater levels, volumes of water recharged and recovered, and the quality of the recharge water and groundwater. The rainfall received across the area is also monitored. In addition, the operational functioning of the MAR system is established through indicators such as the frequency of site maintenance and community perceptions.

3.1 Hydro-climatic Monitoring

3.1.1 Rainfall

Two tipping bucket rain gauges produced by Davis Instruments fitted with Odyssey data recording system were acquired from Dataflow Systems Ltd., New Zealand (http://www.odysseydatarecording.com/). One rain gauge was positioned within the vicinity of the M4 to M5 cluster (RG-1 in Kmu village) and the other within the vicinity of the M1 to M3 cluster (RG-2 in Ea Krom village).

3.1.2 Groundwater levels

Twelve water depth and temperature recorders were acquired from Dataflow Systems to enable monitoring of all MAR and reference wells. Water level recorders feature a 20 metre depth range and vented cable to compensate for atmospheric pressure variations. The instruments were fitted in each well within a slotted PVC pipe housing for security and to avoid possible interference with downhole pumps.

Over the course of the first year of the trial systematic failures of the groundwater loggers was experienced due to water entry brought about by loss of casing integrity for seven of the twelve recorders over the period from August 2017 to January 2018. The entire set of recorders was replaced in March 2018 with an improved design provided by Dataflow Systems. Two of the original recorders still functioning were transferred to the filtration tanks at site M5 and M5 to provide backup measurements of recharge events.

A topographic survey was carried out by a local private contractor to get a fix on the altitude of the casing tops of all wells used in the study. The survey was conducted using a LEICA NA-720 Theodolite and levelling staff gauges. Values are given according to the WGS-1984 coordinate system.

3.1.3 Recharge rate estimation

A pragmatic approach was applied to estimate recharge rates at each of the MAR sites. This relied on the combined use of three sets of data including rainfall, groundwater level and filter tank flow rates. The start and end of each discrete recharge event was determined through careful visual interpretation of the rainfall and groundwater level data, recognizing that each recharge event was associated with a rapid build-up in the groundwater level in the well, which quickly decayed after cessation. Groundwater level loggers were set to record at 5 minutely intervals to enable recharge events to be identified to a degree considered satisfactory without requiring prohibitively high site visits to download data. Clearly identifying the water level signatures associated with MAR-derived recharge (as distinct from broader recharge processes) is essential. This was done by comparing the groundwater level response at the MAR well with the appropriate reference well.

The discharge rate from the filtration tank was measured periodically in dry periods when the sites could be more easily accessed. The discharge rate was determined from the measured rate of decline in water level within the tank after filling the tank and opening the valves to enable drainage into the well. For MAR sites not equipped with pumps water was transported by tractor from a nearby well. The volumetric characteristics for the interval above the media layers was determined for each tank to convert changes in levels to volumetric storage.

Thus, having established the timing and duration each individual recharge event and the rate of recharge (by interpolation), the volume of recharge was determined by multiplying the duration of any given recharge event by the estimated recharge rate at the time of that event. The total recharge over a given period were aggregated from individual event-wise recharge volumes.

It may be worthwhile to note that the more convenient option to deploy *in-situ* flow recording instrumentation was discounted due to the prohibitively high cost of equipment under the prevailing field conditions, characterized by low and highly variable flow under low hydraulic gradients.

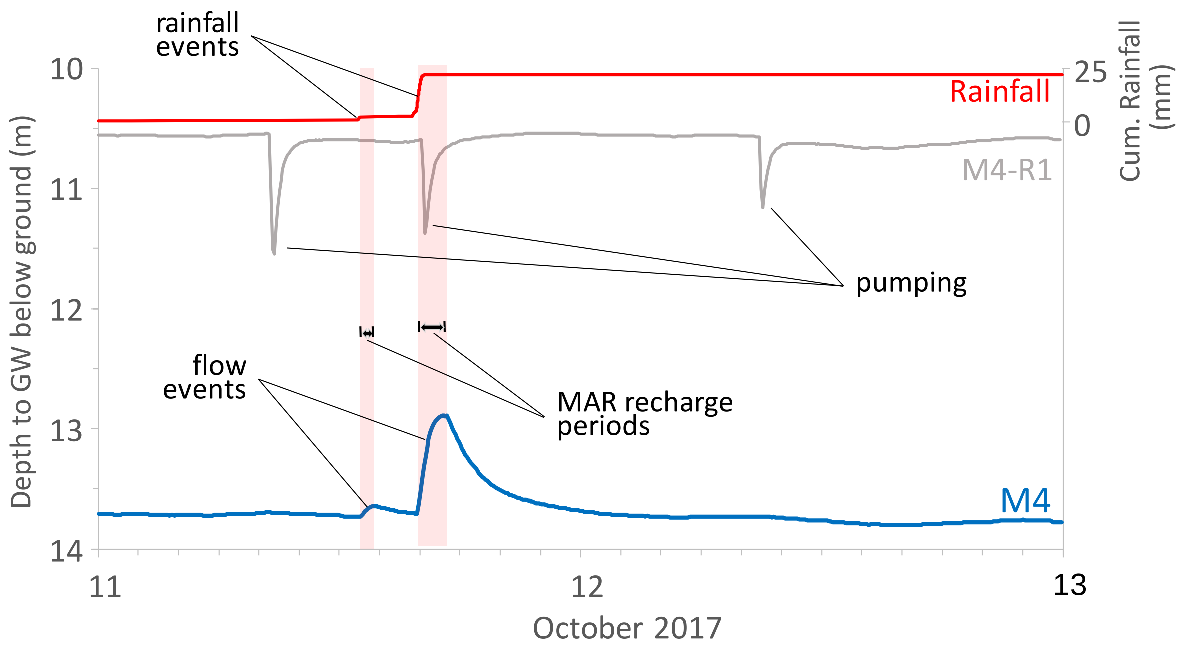


Figure 3.1.1. Groundwater level and rainfall data used to estimate the timing and duration of recharge events. The case of the M4 site over a 2 day period in October 2017 is shown for illustrative purposes. Corresponding data for M4-R1 is also given to illustrate the absence of a major response to rain, however three short pumping events are evident.

3.1.4 Pumping rates and volumes

Surveys were carried out to establish whether the MAR wells were pumped for irrigation. Groundwater level observations in these wells were used for verification purposes and to identify specific times of pumping. In some cases, the estimated volumes withdrawn were estimated by a combination of direct measurement of the discharge rates from the pumped well and interviews with the well owners to establish the area irrigated and number of rounds.

3.2 Water Quality Monitoring

Water quality testing was carried out periodically over the course of the trial. In the first year the MAR wells were sampled on five occasions (three times over the wet season and two during the dry season), whilst reference wells were sampled only one time during each season. In the second year monitoring was restricted to three MAR wells (M1, M4 and M5), along with their associated reference well.

The sampling suite throughout included parameters for physical, general inorganics, metals, nutrients, microbial pathogens and pesticides. Samples were dispatched to SGS laboratories in Ho Chi Minh city for analysis. Samples for *E.coli* were analysed at the Dak Lak Health Department, Provincial Preventative Medicine Center in Buon Ma Thuot due to the analytical requirement for receipt of samples within 12 hours of collection.

During the wet season a 6 litre collection bucket was placed within the well directly beneath the water entry pipe to collect representative samples of the recharge water as the sites were not accessible during wet weather conditions. During the dry season all samples were collected by pumping the wells continuously for at least 30 minutes before taking the sample to flush the well. The pump inlet was lowered as far as possible to collect water from these layers. Prior to collecting the sample the flow rate was measured with a calibrated bucket to estimate the volume of water pumped.

Samples were collected and handled using standard methods, kept under refrigerated conditions and transported to the laboratories in polystyrene cooler boxes packed with ice.

3.3 Estimation of MAR costs and benefits

3.3.1 Costs

The financial and economic performance of MAR is a key determinant of its acceptance and uptake (Ross and Hasnain 2018). In the analysis of 21 MAR schemes largely from developed countries (but not including Vietnam), Ross and Hasnain (2018) concluded that the costs vary substantially. Schemes using recharge wells, bores and expensive infrastructure are more costly than those based on infiltration basins using untreated water. When advanced water treatment is needed, this involves significant additional costs. These conclusions have been confirmed by a subsequent analysis of 28 schemes from over 20 countries including several in developing countries[1]. However, in the Dak Lak case, existing irrigation wells dug by farmers are used for MAR and forms of treatment are basic, and therefore it is expected that the costs would be reduced significantly.

Ross and Hasnain (2018) also offered four alternative metrics for comparing the costs of MAR schemes: [1] levelized cost of water supply; [2] water supply security insurance cost; [3] water recharge cost; and [4] water recovery cost. Levelized cost is a widely accepted method of costing infrastructure projects, defined as the constant level of revenue necessary each year to recover all the capital, operating and maintenance expenses over the life of the project divided by the annual volume of water supply. Water supply security insurance costs can be calculated by dividing the capital cost of the project by the daily supply capacity (USD/m^3/day). Capital cost and operating cost per cubic metre of water recharged and water recovered adjusted for inflation provide alternative metrics.

Maliva (2014) suggested that the costs of MAR projects include both capital (fixed) costs and operation and maintenance (O&M) costs. Capital costs include, but are not limited to: land, feasibility and design, construction, supervision and regulatory

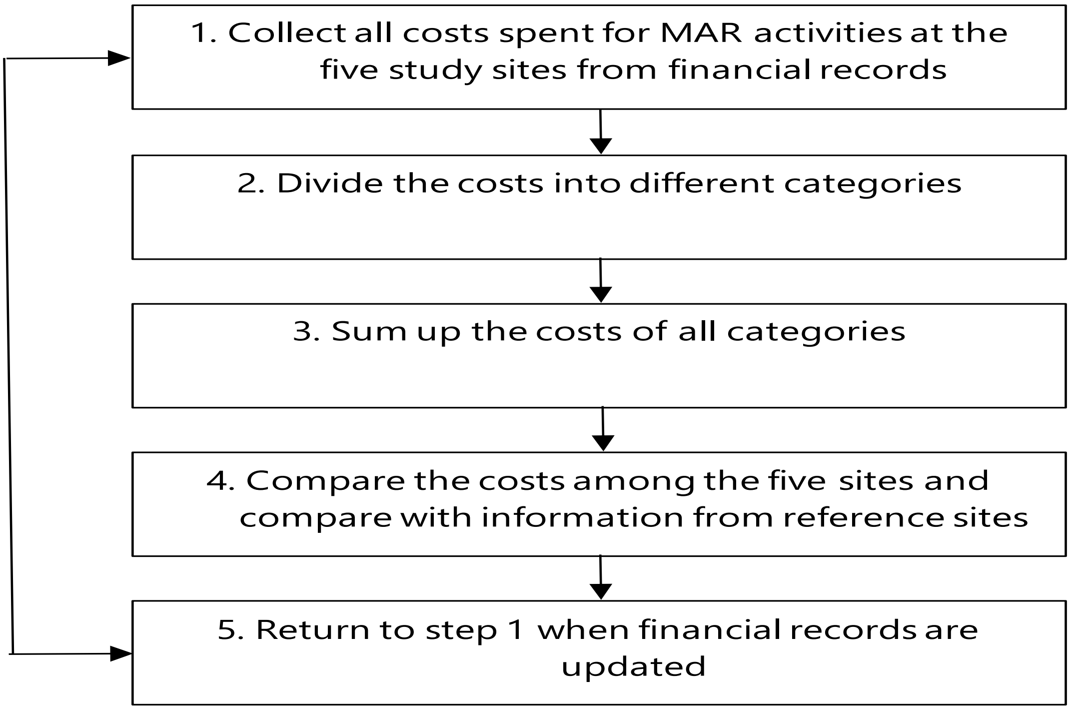
[1] Results are expected to be published in 2020 in a UNESCO publication on exemplary cases of MAR

testing. (O&M) costs include labour, power supply, regulatory monitoring, pre-treatment, and post-treatment (where necessary).

At this early stage of this study, it is not yet possible to calculate the actual levelized costs or other alternative metrics for the MAR pilot sites because the annual volume of water supply is still being collected and the time series of operating costs is limited. Therefore, herein only the method used on how costs are calculated is introduced, following the approach of Maliva (2014) as much as possible, then present the initial results and initial discussions.

The cost estimates in this study include four steps as shown in Figure 3.3.1.

Figure 3.3.1 Process used to estimate costs for the MAR pilot experiments



Step 1: In this step all costs related to MAR experiments in 2017 and 2018 recorded by the financial unit of the organization are collected and compiled into an Excel worksheet by chronological order. Each cost is attached with a brief description on its purpose.

Step 2: Each cost is assigned to a specific category. The categories include capital and operating costs divided into items for non-research purposes, and those for research. Non-research items are essential to the functioning of the MAR system and represent the costs that would be applied during routine implementation by farmers. Costs comprise of material and labour costs for each MAR site: establishment costs to survey the MAR sites, payments for installation of MAR structure, miscellaneous materials and tools required for this installation and modifications of MAR structure to improve water flow. O&M costs include materials such as sand, gravel and geo-textile and labour costs to clean the filtration tanks and sediment traps. Some labour was provided voluntarily by farmers who own the well but was not recorded. Scientific research items include the materials for monitoring water quantity and quality, water sampling and testing and labour used to collect monitoring data. Such costs would not be paid for by farmers if they were to apply MAR at these or other sites.

Step 3: Costs of all categories of each site are summed into two groups: materials and labour. Revision of category costs to provide remarks is implemented in this step.

Step 4: Costs of materials and labour for all sites are compiled and tabulated and percentages of each item in the total cost are calculated. Five site averages of each item are also calculated for analysis.

Step 5: Whenever the updated financial records for new costs of MAR pilots are available, e.g. at the end of each season or year. Step 1 is repeated to include new records into the cost estimates and analysis. Costs in 2017 and 2018 are used for calculated costs for year 1 and year 2 of MAR trials.

3.3.2 Benefits

Besides the cost estimate, economic appraisal of MAR often entails using cost benefit analysis to monetize the benefits. Maliva (2014) suggested eight methods for monetizing benefits as presented in Table 3.3.1. The value of water stored in the aquifer by MAR systems can be evaluated by direct and indirect measures of willingness to pay including value marginal product, alternative cost, contingent valuation and various other methods. MAR systems used for lesser value uses such as irrigation need to have low construction and operational costs.

In a developing country context, apart from economic viability, the capacity to pay also needs to be factored in. In cases of high economic viability but low capacity to pay due to limited local financial resources, external support may be required.

In the case of 5 MAR trials in Dak Lak province, data is available to estimate the extra net value of output that can be obtained from additional applications of water owing to the project. Analysis of water market price, large survey on willingness to pay and alternative costs, damage costs and in situ values cannot be estimated during this stage of the project. Therefore, simple methods for benefit estimation with basic information from interviews such as in-situ groundwater value can be applied.

Table 3.3.1. Methods to monetize benefits of managed aquifer recharge systems (Maliva, 2014)

No.	Method	Description
1	Market prices	Value of water determined by actual prices set by willing buyers and sellers in a competitive market.
2	Alternative cost	Value of water storage or treatment is determined from the cost of the least expensive alternative that provides comparable benefits.
3	Value marginal product	The value of water is quantified from the marginal productivity of water, i.e., the extra value of output that can be obtained from additional applications of water.
4	Contingent value	Survey-based methods to determine an individual's willingness to pay or willingness to accept compensation for a good or service.
5	Hedonic property value	Value of water is inferred from market transactions (e.g., real estate sales) that are linked to the value of water.
6	Defensive behaviour	Value of a safe and reliable water supply can be estimated from expenditures to avoid exposure to unsafe water.
7	Damage cost	Value of water is estimated from damage costs avoided, such as health impacts or drought damage.
8	In-situ groundwater value	MAR system value is estimated from costs avoided resulting from groundwater being in place, such as pumping and land subsidence costs.

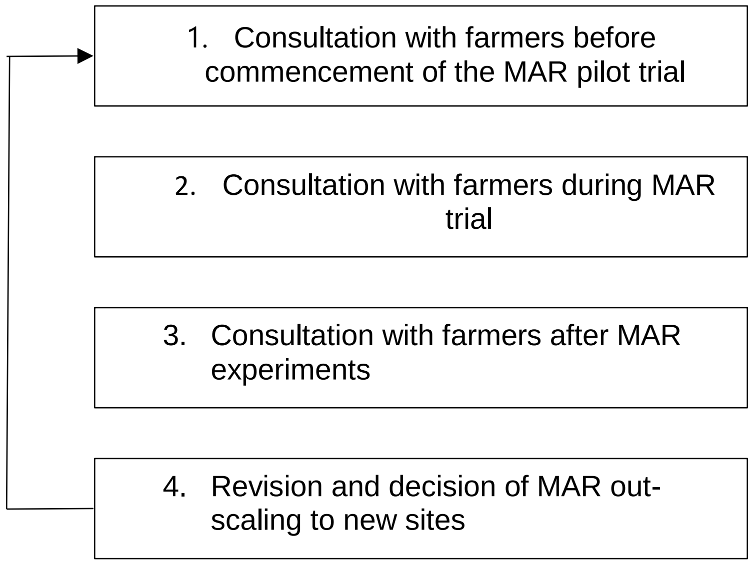
3.4 Farmer Attitudes to MAR

Attitude is a powerful determinant of behaviour and actions of farmers in relation to engagement with new technologies (Chi and Yamada 2002). Ascertaining the attitudes of the participating farmers towards the MAR pilots is a necessary step in assessing the potential for successful up-scaling and out-scaling of this technology.

At this stage of the study farmer attitudes are investigated using a pragmatic approach based on four steps as illustrated in Figure 3.4.1. It relies on a process of consultation with the farmers before the commencement of the MAR pilot trial; during the trial and at the most recent stage of the trial. Whilst more advanced methods could have been used; for example the Likert-type scale survey[2] (Croasmun *et al.* 2011) or the Q-Methodology[3] (Leviston *et al.* 2013), the time-frames and resources needed to generate the datasets that have sufficient statistical power would have been beyond the scope of the project.

[2] Likert Scale is a psychological measurement approach based on a rating scale that measures levels of agreement or disagreement. It makes the assumption that the attitude of the respondent can be measured.
[3] Q-Methodology is used to study people's 'subjectivity', otherwise thought of as their particular viewpoint

Figure 3.4.1 Process of analysis of farmer attitude to MAR



Step 1: The consultation with farmers before MAR was implemented during the pre-survey and survey to select suitable locations for the trial. Individual farmers were consulted at various locations, in particular where their wells are potentially suitable for MAR or suitable for using as reference wells for monitoring MAR impacts.

Step 2: The consultation with farmers during MAR involves regularly consulting with farmers who own the MAR wells to receive their comments and advice on improvement of the performance of the system. Individual farmers are interviewed and group discussions are organized during this step.

Step 3: Consultation with farmers at the conclusion of MAR experiences. In this step besides consultation with individual farmers, as per Step 2, group discussions are more important to learn how farmers evaluate the pros and cons of MAR, and establish how to improve and their attitude to continuation of MAR operations beyond the trial and to gain insights for out-scaling. A Likert-type scale survey could be carried out in this step that employs questionnaires to derived responses according to a preassigned rating scale (e.g. from strongly disagree through to strongly agree).

Step 4: This involves the revision of the MAR design and O&M system as deemed necessary from earlier steps to assist in out-scaling to new sites. Wider focus group discussions with stakeholders including farmers, local authorities and the private sector is organized. Decision on MAR out-scaling to new sites will be made, and the process will return to Step 1 for new sites if and where trials are deemed necessary.

Step 1 has been completed, and the study is in the middle of interviews associated with Step 2. A group discussion was organized in November 2018 after the end rainy season and near the start for the first round of irrigation for the season.

4. RESULTS

4.1 Hydrology and Climate

4.1.1 Rainfall patterns

The rainfall at Kmu village for the period from 1 June to 31 December was 1,399 mm in 2017 and 1,227 mm in 2018 (Table 4.1.1). Average annual rainfall for the study area is estimated to be 1,674 mm/year based on rainfall records from 2001 to 2012 for four measurement stations situated within a 51 km radius of the study area (Buon Ho, Ea Kmat, Buon Ma Thuot and Ea Hleo). Rainfall during 2017 was approximately average or marginally higher, whereas in 2018 it was around 27 percent below average.

Table 4.1.1. Rainfall values for 2017 and 2018

Year	1 Jun to 31 Dec (mm)	Annual (mm)
2017	1,398.8	1,600.2 [1]
2018	1,227.4	1,462.2

[1] Annual figure in 2017 is underestimated as rainfall collection commenced on 9 May 2017 with the installation of the rain gauges

4.1.2 Groundwater level behaviour at MAR and reference sites

Observed groundwater levels are indicated for two pairs of wells as shown in Figure 4.1.1; one set from Kmu village (M4/M4-R1) and another from Ea Krom village (M1/M1-R1). The M1 pair is situated in the upper reaches of its watershed (EL = 762.3 - 762.7 metres asl); whilst the M4 pair are situated in lower reaches of its watershed (EL = 725.7-727.1 metres asl).

At all of the wells a steady rise in levels is clearly observed during each wet season due to natural recharge processes. Levels typically peak during August to September. In addition, the intense rainfall from Typhoon Damrey in November 2017 when 102 mm of rainfall was recorded led to a major peak that eclipsed the season peak several months prior.

Comparing both pairs of wells shows a consistency in the broad trends, although short term trends are substantially different. Both reference wells show the characteristic signals of daily pumping for domestic supply from nearby shallow wells.

Both M1 and M4 wells show the tell-tale patterns associated with MAR recharge events. These are substantially more pronounced at M4 than M1 as the major recharge contribution came from the residential roof with high runoff coefficient.

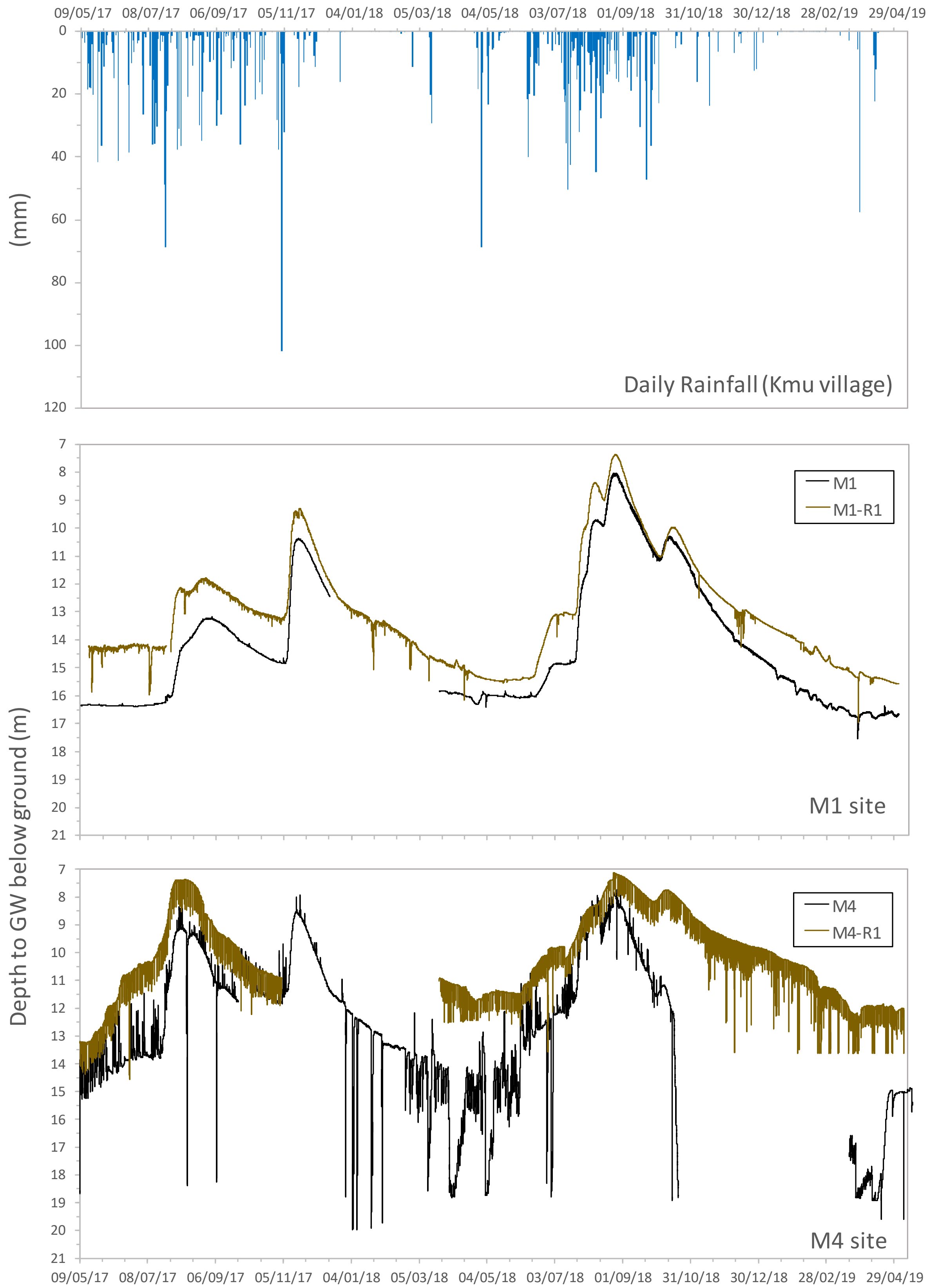


Figure 4.1.1. Groundwater level and rainfall at two pilot sites

4.1.3 Filtration tank flow rates and performance

Despite the large variations in discharge rates evident across the sites (Figure 4.1.2), the majority of observed flow rates range from around 10 to 30 m^3/day. During 2017 and during parts of 2018, site M2 had distinctly lower values, often <10 m^3/day. This site collects runoff from a public road (Table 2.3.1), and contains the most turbid water – values of water inflowing to tanks ranging from 160 to 550 NTU (as presented later). The sand layer at this site had to be replaced on two occasions over the year; whereas at other sites only routine maintenance was carried out during each visit to measure flow rates. Filter tank maintenance in September 2018 involving changing of the sand and gravel layers proved only partly successful with flow rates gradually returning to previous levels within 1-2 months. At M1 and M3, which collect runoff from fields, flowrates also dipped below 10 m^3/day during periods of the trial.

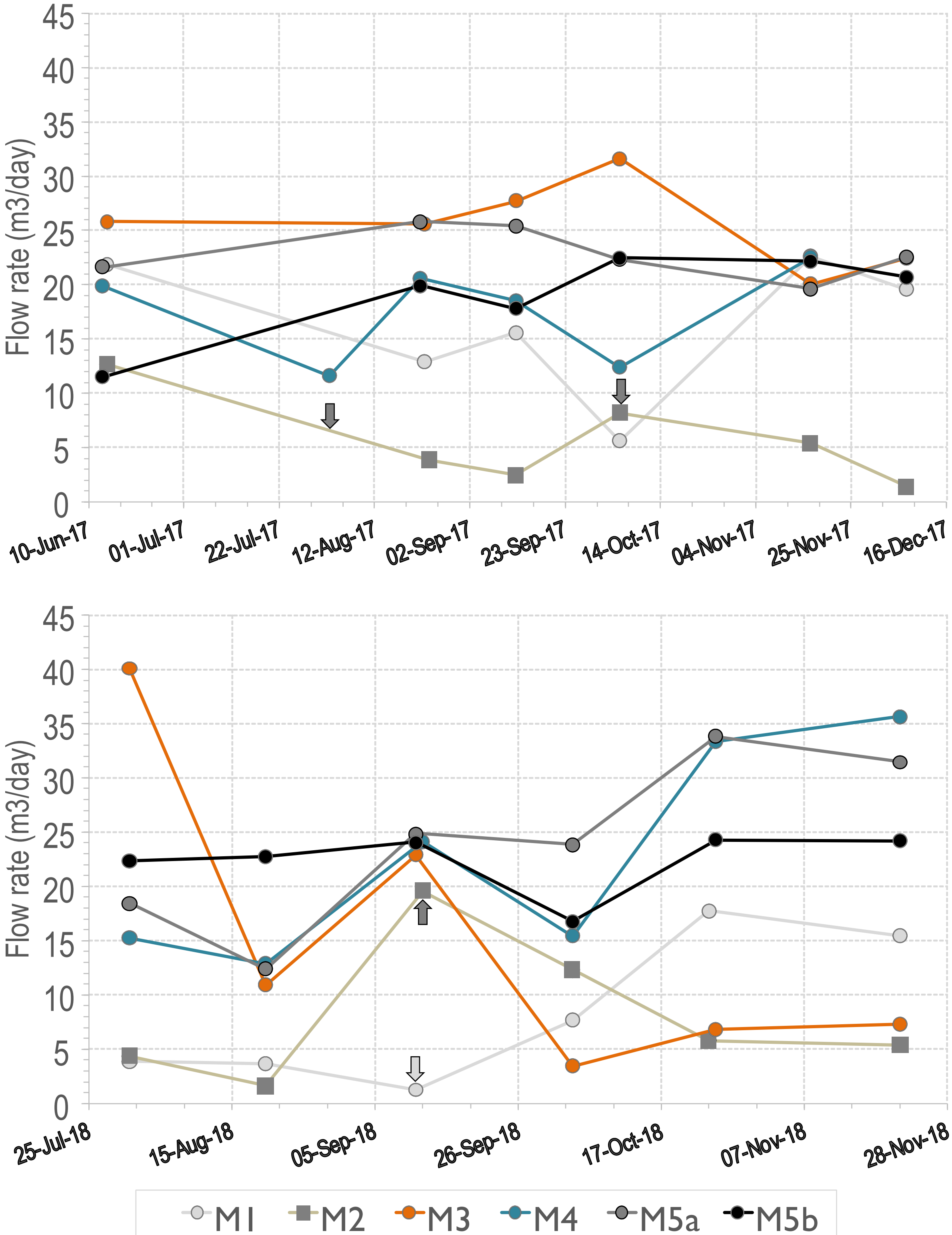


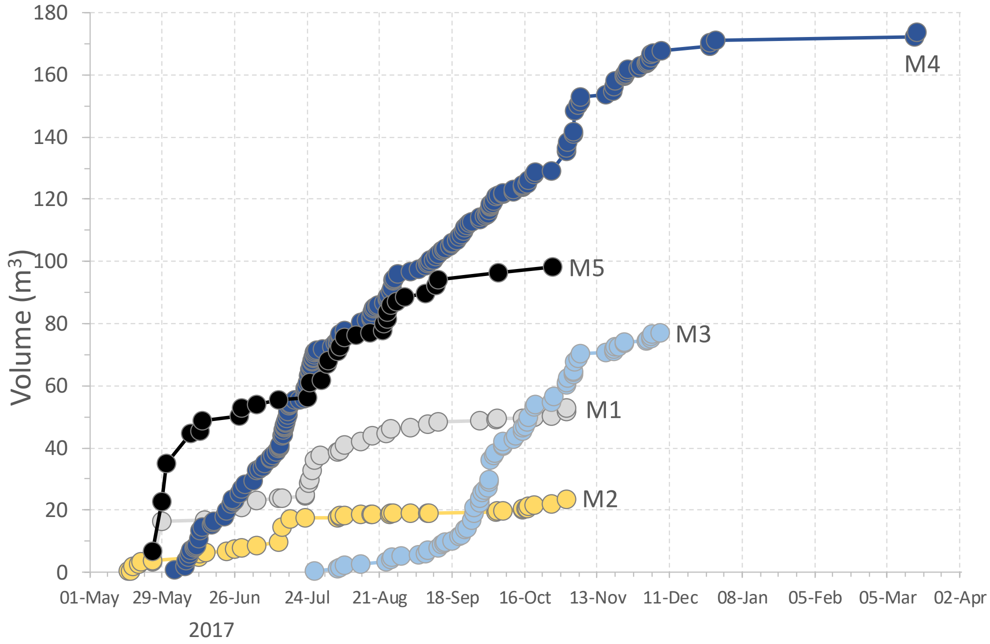
Figure 4.1.2. Changes in flow rates through the filtration tanks over the trial period. *Major maintenance events involving sand replacement at sites M1 and M2 are indicated by the vertical arrows.*

4.1.4 Estimation of MAR recharge

Plots of the cumulative volume of water recharged at each site are given in Figure 4.1.3. Calculated volumes in 2017 range from a minimum of 23 m^3 from 42 rainfall recharge events at M2 through to a maximum of 174 m^3 from 188 events for M4. Corresponding values for 2018 range from 5 m^3 from 24 events at M1 through to 303 m^3 from 136 events at M5. Values in 2017 are limited to periods when the groundwater level loggers were operational and hence likely underestimated actual values to some degree.

Despite the lower rainfall in 2018 compared to the previous year, the design modifications led to substantial improvements at M5 and M3, with minor improvements at M4. Declines were observed at the poorer-performing M1 and M2 sites (Table 4.1.1). The average event-based duration of recharge ranged from 1.0 to 2.5 hours per event across the sites.

The recharge efficiencies, determined as the proportion of rainfall yield captured through recharge ranged from <1 to 77 percent (Table 4.1.1). Highest values of recharge and the largest number of recharge events over the season were associated with sites utilizing roofs where runoff coefficients were highest. Runoff coefficients for different types and slopes of roof differ but can be as high as 0.9 for galvanized iron sheet roofs (Kumar 2004). Milnes *et al.* (2015) estimated the average surface runoff in Krong Buk catchment to be 166 mm/year (around 10 percent of rainfall). This value is within the range of runoff harvested at most MAR sites.



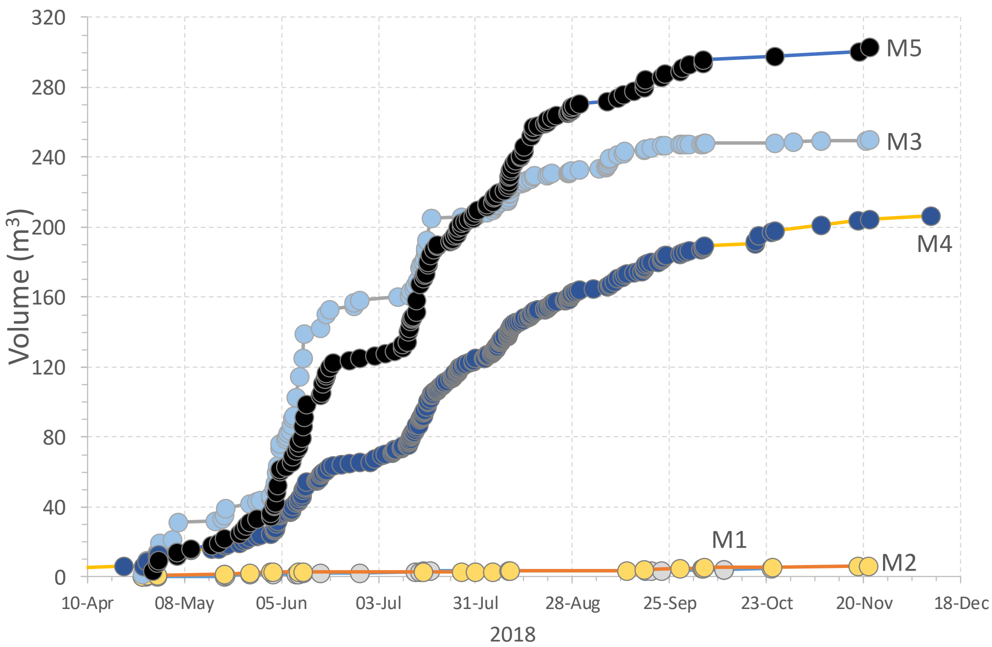


Figure 4.1.3. Cumulative volumes of water recharged at all MAR sites in 2017 (top) and 2018 (bottom)

Table 4.1.1. Summary of recharge performance at the pilot sites for the two hydrologic years

Site	Analysis Period	No. Events	Total Volume Recharged (m^3)	Rainfall Yield (m^3) [3]	Recharge Efficiency (%) [4]
First hydrological year					
M1	9 May – 1 November 2017	39	53	3688	1.4
M2	10 May – 1 November 2017	42	23	866	2.7
M3	20 July – 7 December 2017 [1]	70	77	2637	2.9
M4	8 May 2017– 22 March 2018 [2]	188	174	257	67.6
M5	8 May – 1 Nov 2017	32	49	4128	1.2
Second hydrological year					
M1	25 April – 24 October 2018	24	5	3507	0.1
M2	25 April – 24 October 2018	25	6.1	824	0.7
M3	25 April – 21 November 2018	118	250	2245	11.1
M4	28 February – 9 December 2018	300	206.4	269	76.8
M5	28 April – 21 November 2018	136	303	4097	7.4

[1] adjustments to design delayed starting date for analysis to July
[2] effectively started in early June after domestic pumping from the M4 well had ceased
[3] derived from the rainfall and total runoff collection area
[4] derived from the total recharge value relative to the rainfall yield

4.1.5 Pumped volumes

During the first irrigation season (2018) only two of the five MAR wells (M2 and M4) were used for pumping (Table 4.1.2). Sites M1, M3 and M5 were not utilized, with the availability of other wells nearby cited as the reason. The socioeconomic survey shows that each of the farmers has between 2 and 3 wells equipped for pumping. Pumping estimates for M2 are estimated to be 840 m^3 in the first round. The unfortunate failure of the groundwater level loggers meant that reliable whole-of-season estimates could not be determined this season. In the second season three of the wells were used for pumping (M2, M4, M5). Reliable estimates of pumped volume are not available.

Table 4.1.2. Summary of information on dry season pumping

Site	Well Pumped	Details
M1	Year 1 – No	Well owner uses another well nearby
	Year 2 – No	As above
M2	Year 1 – Yes	842 m^3 pumped in first and only round based on 1 ha of coffee at 757 litres/tree (1,110 trees).
	Year 2 –Yes	Intermittent pumping from 26 to 28 February 2019
M3	Year 1 – No	Well owner uses a borehole about 200 m away
	Year 2 – No	As above
M4	Year 1 – Yes	Well pumped intermittently from 20 February until 30 June 2018
	Year 2 – Yes	Daily use for domestic supply of about 1 m^3/day but not irrigation
M5	Year 1 – No	Well owner uses a borehole about 100 m away
	Year 2 – Yes	Occasional pumping for vegetable production (e.g. 16 to 17 February 2019)

4.2 Water Quality

Directly recharging surface runoff into aquifers through MAR changes the pre-existing hydrologic cycle on a localized scale and potentially short-cuts the natural biophysical processes that would otherwise allow pollutants that may be present in the water to be attenuated within the landscape over longer time scales (Dillon *et al.* 2010). For the intensively used agricultural watersheds of the study area, the primary risks are associated with residues derived from agricultural inputs; from sediment washed-off from cultivated fields and from microbial risks originating from livestock and other farm animals. Further, the storage of surface water with geochemical characteristics that contrast with the ambient groundwater may trigger reactions that could leach minerals from the aquifer matrix. The monitoring program took these threats as fully into account as possible (i.e. cognisant of the limits in terms of analytical capability and resourcing).

The water quality data for the MAR and reference wells on a season-wise and annual basis are provided in summarised form in Table 4.2.1. Complete tabulations of the data are provided in Appendix 2.

The suite of general inorganic parameters where national standards for drinking and irrigation water have been established (i.e. sodium, chloride, sulphate, TDS) were all well below both sets of standards. Recharge waters are fresh in nature, with highest seasonally averaged TDS value of 144 mg/L for M5 during the 2017 wet season and the lowest of 27 mg/L at M1 during the 2018 wet season. TDS values in the reference wells range from 5 to 22 mg/L and are thus consistency lower than the recharge waters.

pH values of the reference wells are weakly acidic and consistently below the recommended standard value for irrigation of 5.5. The MAR wells too were below standards during the dry season, when not strongly influenced by the often mildly alkaline runoff water. The recharge water after storage and ambient groundwater are generally too acidic for drinking without pH adjustment. There are no direct human health implications associated with acid water, however its aggressive nature can corrode pipes and introduce dissolved metals into the water.

Turbidity levels for the reference wells were below the drinking water standard of 2 NTU in most cases, but did occasionally exceed the threshold. For the MAR wells turbidity values were typically higher than the standard during the wet season (2 to 327 NTU). Dry season values were lower than in the wet season, but remained above the standard. Turbidity, is an easily measured indicator of the content of organic and inorganic particles, and does not directly affect human health but affects the aesthetic condition of the water and can interfere with the processes used to disinfect water in water treatment. Elevated turbidity has no major negative consequences for agricultural use.

Nitrate (and nitrite) levels were all well below the drinking standards in all samples. Relative to the reference wells, concentrations of all detected nitrogenous compounds were more elevated in recharge water but not at levels considered of concern for drinking purposes.

Levels of copper, arsenic, or manganese measured at both the MAR and reference wells were also not of concern. Iron on the other hand, was commonly detected above the drinking limit of 0.3 mg/L at the MAR wells during both seasons (measured as the total concentration on filtered samples). The reference wells also occasionally exceeded the standard. The major soil type of the area are Ferralsols, originating from basalt weathering and are rich in iron (and aluminium) oxides (D'haeze *et al.* 2003). These soils can be mobilized by runoff as reflected the high turbidity of the recharge water. Iron is essential element for good human nutrition, but high levels can affect the taste and appearance of water and limits on the concentration permitted are thus mainly for aesthetic reasons.

E. coli levels were well above standards for drinking for all MAR wells during the wet season. For the dry season values were considerably lower, although only on limited occasions were values below detection at the MAR wells. The presence of *E. coli* in the dry season is a reflection of rainfall recharge in the days prior to sampling. Reference wells were generally below detection, however detections were also observed. The presence of *E. coli* is a commonly used indication of impacts from human or animal wastes. Bacterial contamination is short-lived as *E. coli* is rapidly attenuated outside of the host within time-scales of days to tens of days (Dillon *et al.* 2009). The analytical limits of detection were insufficient to absolutely confirm an absence of *E. coli* bacteria, but were sufficiently low (<3 MPN/100 mL) to suggest low microbial risk.

Pesticides were not detected on any occasion in any of the MAR or reference well samples. The monitored suite included persistent organic pesticides (POPs) banned since 1992. All other remaining constituents were banned only very recently (February 2018)[4]. Monitoring was deemed generally necessary as POPs may remain present within the environment as a legacy or remain in use as a result of poor compliance of government regulations (Nguyen, 2017). Six of the eleven compounds measured below detection levels have drinking water standards above the detection limits (aldrin, chlordane, DDT, dieldrin, lindane and heptachlor).

The landuse characteristics of the collection area had a bearing on the water quality composition, as would be expected. In general terms, lowest TDS, nitrate and metal concentrations were evident where the roof runoff was the major collection area. *E. coli* was however not lower for roof runoff collection areas than for fields.

[4] Implemented through Circular No. 03/2018/TT-BNNPTNT dated February 9, 2018 as issued by the Minister of Agriculture and Rural Development (MARD)

Interestingly, it was noted that the concentrations of major inorganic parameters (and thus also TDS values) were higher in the wet season surface water runoff than the ambient groundwater at the reference wells. Net removal of ions is believed to be taking place within the subsurface system. As the geochemical state (redox conditions) of the recharge and ambient waters differ, it is likely that this triggers a series of reactions leading to the loss of some ions due to transformation or sorption onto the aquifer surfaces. It is well known, for example, that elevated concentrations of bicarbonate (and hence calcium as well) due to high dissolved carbon dioxide in rainwater would be neutralized by aquifer passage (Herczeg *et al.* 2004). More detailed geochemical analysis would be useful to verify the geochemical transformations taking place as the recharge water is stored and transported through the aquifer.

Table 4.2.1. Summary of water quality data for MAR and Reference wells for each hydrologic year. *National standards for irrigation and drinking are also indicated. Measurements that exceed either of the national standards are highlighted in red text.*

Year 1

Parameter	Unit	National Standards		MAR Well (Wet Season / Dry Season)					Reference Wells (Wet & Dry Seasons)
		Irrigation[1]	Drinking[2]	M1	M2	M3	M4	M5	
pH	-	5.5-9	6.5-8.5	7.5 / 5.8	7.7 / 5.3	7.4 / 5.7	7.4 / 5.7	8.0 / 6.2	5.0 - 5.8
Turbidity	NTU		2	127 / 14	327 / 7	70 / 58	17 / 4	102 / 32	0.2 - 11
Total Dissolved Solids (TDS)	mg/L	2,000		98 / 14	89 / 7	133 / 10	35 / 13	144 / 20	5 - 22
Calcium (Ca)	mg/L			3.7 / 1.1	2.9 / 0.5	4.1 / 0.5	1.3 / 0.7	3.0 / 0.8	0.5 - 2.0
Magnesium (Mg)	mg/L			1.1 / 0.3	0.9 / 0.1	1.2 / 0.1	0.4 / 0.2	0.9 / 0.2	0.1 - 0.6
Sodium (Na)	mg/L		200	19.5 / 1.8	19.6 / 1.0	26.6 / 1.7	7.1 / 2.0	40.4 / 4.1	0.3 - 2.7
Potassium (K)	mg/L			3.8 / 0.5	1.3 / 0.1	7.1 / 0.4	0.5 / 0.7	1.6 / 0.4	0.3 - 1.1
Chloride (as Cl^-)	mg/L	350	250	3.7 / 0.7	3.7 / 0.7	3.7 / 0.7	3.7 / 0.7	3.7 / 0.7	1 - 5
Sulfate (as SO_4^{2-})	mg/L	600	250	9.9 / 0.9	7.2 / 0.9	7.4 / 0.9	7.0 / 0.9	11.1 / 0.9	1 - 10
Bicarbonate (HCO_3^-)	mg/L			51.3 / 8.9	44.4 / 4.2	84.1 / 5.8	17.8 / 6.2	81.9 / 11.2	2.8 - 9
Ammonium (NH_4^+) (as N)	mg/L			0.9 / 0.8	0.7 / 0.8	0.9 / 0.8	0.7 / 0.8	0.7 / 0.8	0.1
Nitrate (as NO_3^-)	mg/L		50	8.9 / 0.2	13.9 / 0.3	4.2 / 1.0	2.3 / 1.9	5.3 / 2.0	0.05 - 4.5
Nitrite (as NO_2^-)	mg/L		3	0.1 / 0.02	0.04 / 0.02	0.1 / 0.02	0.02 / 0.02	0.1 / 0.02	0.02 - 0.03
Phosphorus (as PO_4^{3-})	mg/L			0.4 / 0.1	0.2 / 0.04	0.7 / 0.1	0.1 / 0.1	0.6 / 0.2	0.01 - 0.4
Copper (Cu)	mg/L	0.5	1	0.032 / 0.013	0.033 / 0.033	0.022 / 0.012	0.014 / 0.011	0.022 / 0.017	0.004 - 0.063
Iron (Fe)	mg/L		0.3	0.28 / 0.13	1.6 / 0.21	0.41 / 0.05	0.09 / 0.05	0.35 / 0.44	0.03 - 0.37
Arsenic (As)	mg/L	0.05	0.01	0.008 / 0.008	0.008 / 0.008	0.008 / 0.008	0.008 / 0.008	0.008 / 0.008	0.008
Manganese (Mn)	mg/L		0.3	0.015 / 0.172	0.011 / 0.008	0.029 / 0.006	0.008 / 0.036	0.015 / 0.006	0.001 - 0.003
E coli	MPN/100mL		0	75 / 48	240 / 217	460 / 165	930 / 37	460 / 572	3 - 1100
Pesticides	µg/L			- / -	- / -	- / -	- / -	- / -	- / -

Year 2

Parameter	Unit	National Standards		MAR Well (Wet Season / Dry Season)			Reference Wells (Wet & Dry Seasons)
		Irrigation[1]	Drinking[2]	M1	M4	M5	
pH	-	5.5-9	6.5-8.5	6.4 / 5.7	6.5 / 5.4	7.4 / 6.4	4.9 - 6.4
Turbidity	NTU		2	55 / 19	2 / 23	24 / 14	0.1 - 17
Total Dissolved Solids (TDS)	mg/L	2,000		27 / 79	34 / 10	110 / 26	5 - 18
Calcium (Ca)	mg/L			0.8 / 10.4	0.7 / 1.7	0.9 / 1.3	0.2 - 2.3
Magnesium (Mg)	mg/L			0.2 / 1.6	0.2 / 0.3	0.3 / 0.3	0.1 - 1.7
Sodium (Na)	mg/L		200	5.3 / 1.7	7.1 / 1.1	26.6 / 4.7	0.2 - 1.3
Potassium (K)	mg/L			0.8 / 15.3	0.9 / 0.4	1.3 / 0.3	0.2 - 1.0
Chloride (as Cl^-)	mg/L	350	250	2.0 / 2.1	1.6 / 1.3	1.8 / 2.0	0.7 - 3.6
Sulfate (as SO_4^{2-})	mg/L	600	250	0.9 / 2.5	1.6 / 1.2	1.0 / 1.5	1.2 - 2.4
Bicarbonate (HCO_3^-)	mg/L			16.7 / 53.3	14.2 / 3.8	76.6 / 13.7	1.6 - 9.3
Ammonium (NH_4^+) (as N)	mg/L			0.2 / 1.0	<0.06 / <0.06	<0.06 / <0.06	<0.05
Nitrate (as NO_3^-)	mg/L		50	1.8 / 0.1	9.1 / 1.2	2.8 / 2.5	0.11 - 5.5
Nitrite (as NO_2^-)	mg/L		3	0.04 / <0.01	0.01 / <0.01	0.01 / <0.01	<0.01 - 0.10
Phosphorus (as PO_4^{3-})	mg/L			0.3 / 0.1	0.05 / 0.2	0.5 / 0.3	0.02 - 0.18
Copper (Cu)	mg/L	0.5	1	0.003 / 0.003	0.004 / 0.005	0.003 / 0.003	0.0007 - 0.0058
Iron (Fe)	mg/L		0.3	0.69 / 7.0	0.06 / 0.09	0.35 / 0.33	0.05 - 0.77
Arsenic (As)	mg/L	0.05	0.01	<0.0002 / <0.0002	<0.0002 / <0.0002	0.0002 / 0.0006	<0.0002
Manganese (Mn)	mg/L		0.3	0.08 / 1.9	0.07 / 0.04	<0.01 / 0.04	0.013 - 0.04
E coli	MPN/100mL		0	93 / 13200	2400 / 1950	90 / 8050	4 - 2400
Pesticides	µg/L			- / -	- / -	- / -	- / -

[1] Government of Vietnam 2011. National technical regulation on water quality for irrigated agriculture (QCVN 39:2011/BTNMT)
[2] Government of Vietnam 2009. National technical regulation on drinking water quality (QCVN 01:2009/BYT)

4.3 Groundwater Modelling

4.3.1 Modelling approach

Simple modelling was carried out at the early stages of the trial to gain a clearer understanding on how the surface water recharged in the shallow basaltic aquifer through MAR pilot trials was likely to behave under the influence of different sets of biophysical conditions. This assessment considers two key indicators that may influence MAR performance, namely:

(i) the residual effect of MAR on groundwater levels during the critical dry season period; and
(ii) the extent to which the stored recharge water may be recaptured from the well that it was recharged.

Knowledge of the underlying conditions that are affecting these indicators could help improve the way MAR systems are designed and operated in future. The focus of this modelling investigation is the groundwater system around an individual farmers' MAR well. Within this physical domain it examines the behaviour of the recharge water plume in response to seasonal hydraulic stresses under a range of potential hydrogeological conditions that are likely to apply to the MAR pilots (based on the available information). Details of the model design and implementation are provided in Appendix 3.

These modelling results are conceptual in nature and informed by local data to the extent possible, but are not directly representative of the field situation. Hence direct comparisons between field and model results are not made, however, the insights from the model are brought out and discussed to support the interpretation of the pilot trial data.

4.3.3 Model results

The groundwater level changes at the MAR well over the course of the simulation period of one hydrological year are shown in Figure 4.3.1. The plots for each scenario indicate that groundwater level rises (mounding) occur as a result of the recharge process. Peak mound heights – over and above the more gradual seasonal rises due to natural recharge - range from 0.2 metres relative to the baseline groundwater levels for the majority of scenarios but can be up to 0.6 metres for two scenarios including the lower bound aquifer hydraulic conductivity. In all cases the groundwater level mounding simulated during recharge dissipates rapidly after the cessation of recharge, with all traces of the residual mound decayed within around 20 days or less. The mounding induced by diffuse (broadscale) natural recharge is clearly evident over the recharge phase. Simulated diffuse recharge mound heights vary from 0.3 up to 1.2 metres.

Figure 4.3.2 shows the radial extent of mounding during three critical periods over the hydrological cycle, namely prior to recharge under ambient groundwater flow along with the advanced stages of recharge and pumping periods. Mounding heights of up to 0.4 metres or more extend up to a distance of about 10 metres radially around the MAR well, and a cone of depression of up to 1.5 metre depth extends radially out to a distance of around 30 metres during the pumping phase.

The proportion of recharge water that can be recovered during the pumping period offers a clear indicator of the dynamics of the recharge plume in the aquifer. A recovery figure of 100 percent indicates all of the recharge water was pumped out from the MAR well, whereas at the other extreme, a value of 0 percent indicates none of the recharge water was recovered (i.e. only the ambient groundwater is pumped out). The percent recovery was determined from mass balance calculations as described by Pavelic *et al.* (2002) based upon the concentration data derived from the solute transport component of the numerical model.

The percentage recoveries vary from a peak of 39 percent for scenario 1 down to 0 percent for scenarios 3, 6, 7 and 8 (scenario descriptions are given in Table A3.2). The scenario data were grouped to indicate the relative importance of the various factors (Table 4.3.1). They show that the factor of overriding importance is the background velocity of the groundwater. Higher velocities lead to more pronounced movement of the plume downstream of the MAR well and make capture in the dry season increasingly difficult.

The volume of water recharge has some influence, where velocities were sufficiently low to ensure recoverability. Higher porosity was associated with slightly higher recoverability, due to physical containment of the dimensions of the recharge water body. When the distribution of recharge and pumping periods was varied during the wet and dry seasons respectively, this led to improved recoverability relative to the fixed scheduling. The variable schedule is likely to more closely reflect actual field practices according to the rainfall patterns and crop water requirements.

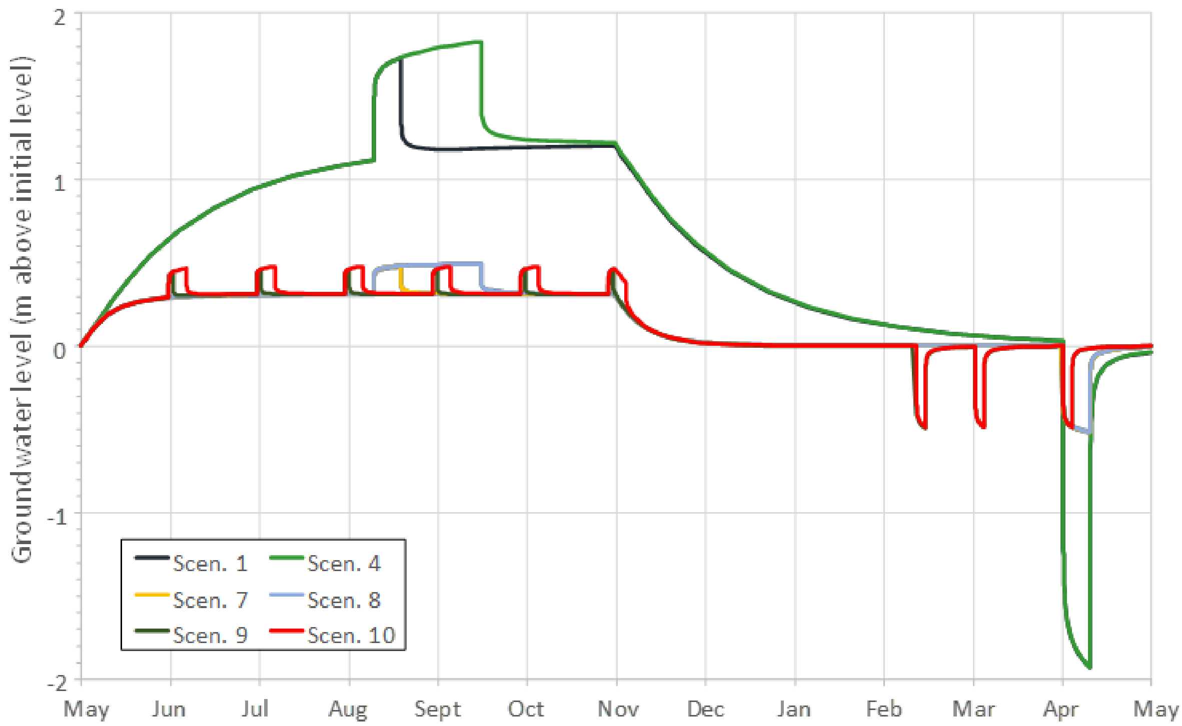


Figure 4.3.1. Simulated groundwater levels at the MAR well over the hydrologic year for the 6 of the 11 scenarios that capture the full range of modelled responses. *Levels are presented as the change in level relative to the ambient flow conditions set at 0.0 m. Periods when recharge and pumping takes place are not conveniently indicated but can be inferred for each scenario from the observed hydraulic behaviour.*

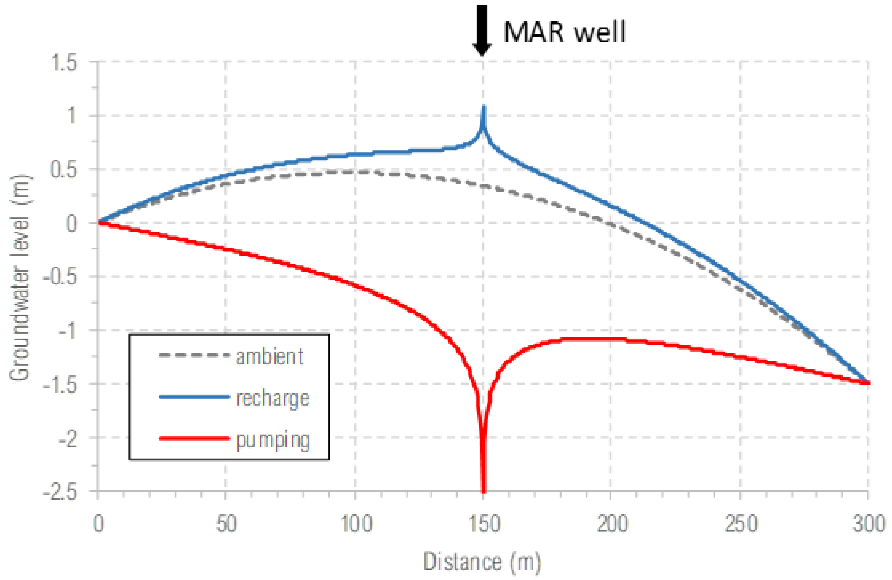


Figure 4.3.2. Simulated groundwater levels along a north-south transect of the model area for scenario 4 at two key stages of the simulation plus the ambient conditions. *The 'reduced' (i.e. differential) groundwater levels are presented in the graph such that the upstream boundary (distance = 0 m) is set at 0.0 m.*

Table 4.3.1 Simulated percent recovery of recharge water comparing scenarios with respect to four key factors: groundwater velocity, recharge volume, aquifer porosity, and scheduling of recharge and pumping. *The simulation number is indicated in italics in brackets alongside recovery values. Further details on the simulations are given in Table A3.2.*

Low	High	Status of Other Factors
Varying groundwater velocity		
39.1 [*1*]	0.0 [*3*]	high porosity, low volume
30.6 [*4*]	0.0 [*6*]	high porosity, high volume
Varying recharge volume		
39.1 [*1*]	30.6 [*4*]	high porosity, low velocity
1.4 [*2*]	1.7 [*5*]	high porosity, medium velocity
Varying aquifer porosity		
1.4 [*2*]	0.0 [*7*]	medium velocity, low volume
1.7 [*5*]	0.0 [*8*]	med velocity, high volume
Variability in recharge and pumping schedules		
1.4 [*2*]	4.3 [*9*]	fixed schedule, high porosity, medium velocity, high volume
1.7 [*5*]	3.8 [*10*]	varying schedule, high porosity, medium velocity, high volume

4.4 Movement of the Recharge Water within the Aquifer

This modelling analyses suggest that the recharge water added to the aquifer at the individual pilot scale will lead to a modest degree of hydraulic mounding, but that this mounding will rapidly diminish and be absent during dry season months when groundwater pumping is of highest value. This is in general agreement with the field observations.

The potential hydrologic impacts of MAR implemented at a pilot scale are limited. Recharge from one MAR well is minor compared to an estimated average annual diffuse recharge. In the case of M4, it likely amounts to ~0.01 percent of the total recharge within its corresponding watershed. Thus, it is likely that hundreds of wells would need to be converted to MAR for the volumes of additional recharge to have a significant contribution on the groundwater balance.

Furthermore, the modelling suggests that the physical limits of migration of recharge water will likely be 150 metres or less within a hydrological year, but that the ability for farmers to physically recover that water from the MAR well will likely be low, and largely dependent on the background velocity of the aquifer. If hydraulic gradients and/or hydraulic conductivity of the aquifer is high, recoverability will be low.

The lateral groundwater flow gradients are estimated from the hydraulic data for the well pairs (Figure 4.4.1). Gradients between the pairs are typically within the range from 0.02 to 0.08. Groundwater flows are from the MAR well towards the Reference Well in all cases except M3. Groundwater flow in the shallow aquifer is influenced by the steep local topography. Ground slopes between well pairs range from 1 to 12 percent. The groundwater gradients observed in the pilot areas are high and are 3 to 10 times higher than the regional gradient calculated by Milnes *et al.* (2015) of 0.006. Hence the lateral groundwater velocities could be as high as 95 metres per year; or approximately from the 60 metres from the middle of the wet season say in August to the latter stage of the dry season in March when water is required.

The water quality monitoring data is useful to make a broad assessment on actual recoverability. The total dissolved solids (TDS) and nitrate (NO_3) data were used for this assessment as distinct contrasts were apparent between the recharged and ambient waters. As Figure 4.4.2 shows clearly, both TDS and NO_3 levels were elevated for the recharge water during the wet season at all of the MAR sites except M4 where the recharge primarily of roof was difficult to differentiate from the ambient groundwater. At the remaining four MAR sites, the signatures evident in the wet season are entirely diminished by the dry season, with values comparable to that of the reference wells. This is reasonably firm evidence taken from the field that supports the findings from the numerical model that the recharge water is migrating downstream before the water can be recovered. More recent data available for three of the MAR sites show that the same trend was repeated in the second hydrologic year.

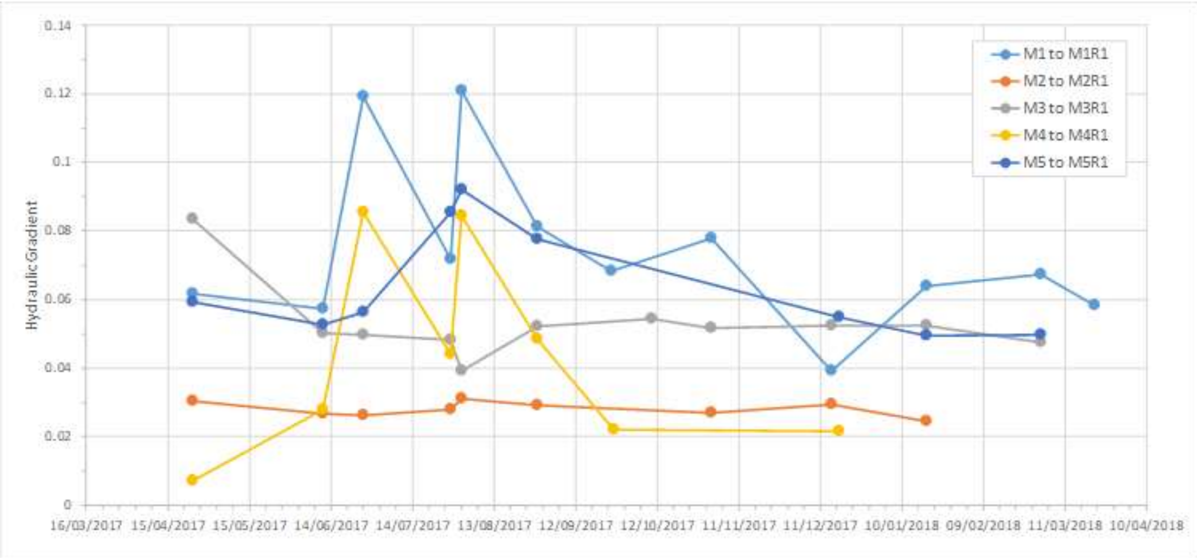


Figure 4.4.1. Changes in hydraulic gradients between MAR and Reference Wells over time.

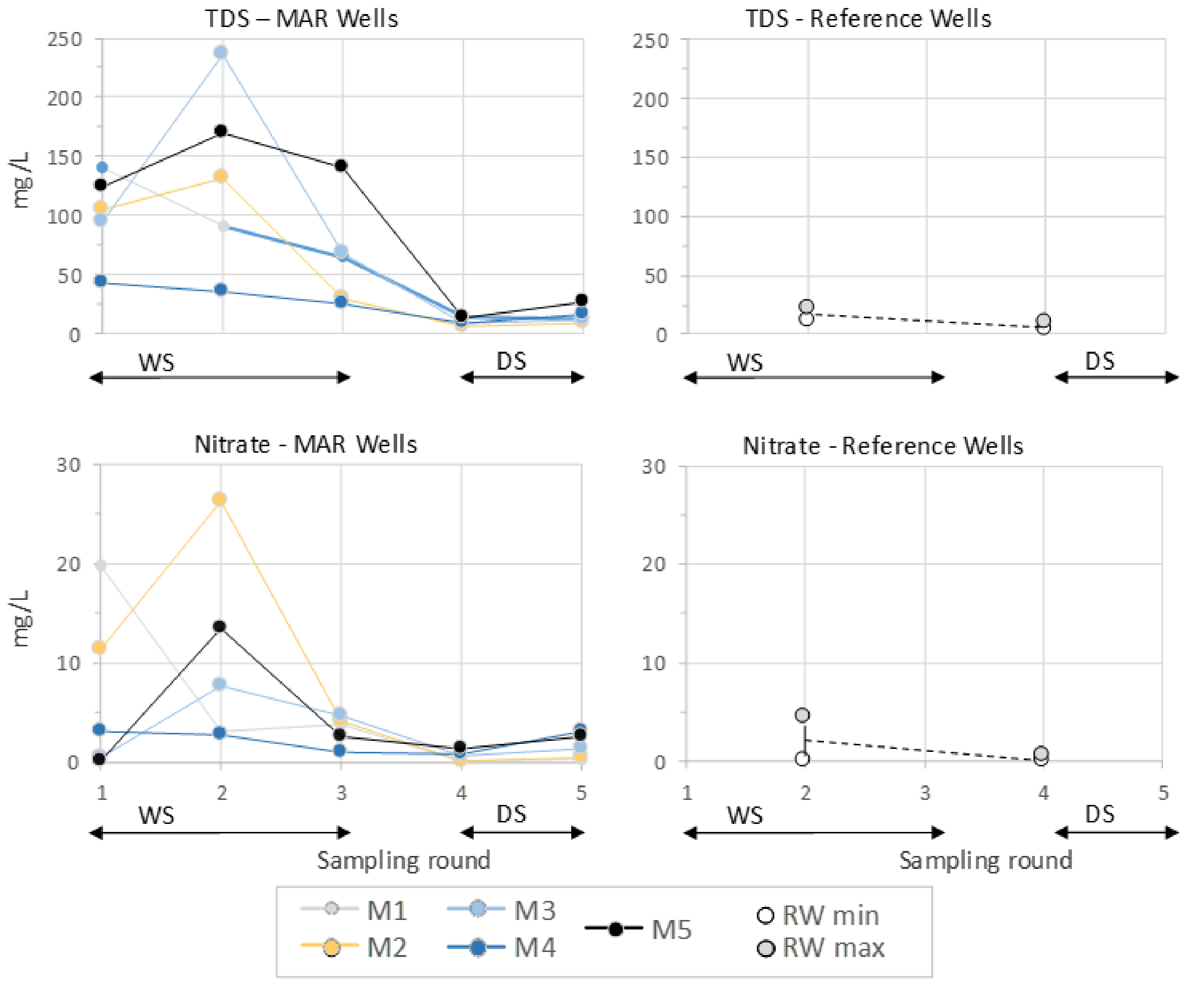


Figure 4.4.2. Changes in TDS and nitrate at MAR and Reference Wells over the first hydrological year

4.5 Costs and benefits of MAR

4.5.1 MAR costs in the first hydrological year

By following the above process of cost estimates, the average costs for the 5 MAR sites are compiled from 91 cost items in year 1 (2017) and presented in Table 4.5.1. More detailed cost breakdown data for non-research and research related costs are given in Appendix 4. Remarks on the tabulated data follow.

The average capital costs for the 5 sites was about VND 18 million (equivalent to USD 800). All research-related items are not included in this section but have been itemized in Appendix 4. Among 5 sites the highest and lowest are about VND 24 million (about USD 1,000) and VND 12 million (USD 500) for sites M3 and M4, respectively. The reasons of this difference are that at M3 a long channel was strengthened (about 150 metre long, including a 20 metre concrete bank to divert water from the top to the middle of the hill where the MAR well is located), while at M5 two filtration tanks were installed to collect more water from the existing wall below a large sloping field rather than only one as at other sites.

Harvested water at these two sites (M4 and M5) is rather clean, therefore a sediment trap is not needed as for the other sites (M1, M2 and M3). However, with the benefit of hindsight, it is clear that the labour cost for re-installation of the tank could have been avoided if done properly at the beginning.

The average total cost is composed of about 54 percent for materials and 46 percent for labour. This implies that if farmers would like to construct a MAR system, the cost to them for materials would be only about VND 10 million (USD 440) on average. If they can make use of existing water harvesting facilities such as the house roof (as for M4), they would have to pay only about VND 6 million (USD 270) for materials, but if they want to divert more water into their wells by doubling the tank capacity (as for M5), they would have to pay about VND 12 million (USD 540). The costs for the filtration tanks at M5 are exceptionally high at about 40 percent of the total cost (as two tanks were installed). There is less variation amongst the other sites.

Among non-research items, the highest average is the labour to establish the MAR structure (46 percent of total cost). These average O&M costs are VND 0.34 million (USD 15) per year. The O&M costs are just a few percent of the capital costs.

For a proper comparison with other MAR systems we should have the capital and O&M costs per unit volume of water recharged and discharged. Levelized cost analysis can be carried out once data for two complete hydrological years has been attained.

Table **4.5.1**. Capital and operating costs for the MAR sites and cost of recharge water in the first year

Site	Capital Costs[1] (×10³ VND / USD)	O&M Costs[1] (×10³ VND / USD)	Volume of Recharge Water (m³/year)	Capital Cost of Recharge Water per m³ (×10³ VND / USD)	O&M Cost of Recharge Water per m³ (×10³ VND / USD)
M1	16,408 / 731	175 / 8	53	310 / 14	3.30 / 0.15
M2	17,152 / 764	960 / 43	23	757 / 34	41.74 / 1.86
M3	24,495 / 1,091	175 / 8	77	318 / 14	2.27 / 0.1
M4	11,791 / 525	175 / 8	174	68 / 3	1.01 / 0.04
M5	19,701 / 878	225 / 10	49	402 / 18	4.59 / 0.2
Avg.	17,909 / 798	342 / 15	75	239 / 11	4.55 / 0.2

[1] Based on an exchange rate of VND 22,446.9 in mid- 2017

4.5.2 MAR costs in the second hydrological year

The average costs for the 5 MAR sites are compiled from 40 cost items in year 2 (2018) and presented in Table 4.5.2. More detailed cost breakdown data for non-research and research related costs are also given the second table in Appendix 4. Capital costs in year 2 are mainly for improvement of water collection systems, with highest values of VND 5.2 million (USD 229) for new pipeline system to collect water from a roof at M5 site and VND 2.6 million (USD 115) for concrete structure at M2 site. O&M costs in year 2 are similar to those in year 1, from VND 0.2 to 0.6 million (USD 9 to 30). These O&M costs increased at M1, M3, M4 sites but decreased at M2 and M5, and caused an average increase of USD 3 for the 5 sites. However, O&M costs per m^3 at the M1 and M2 sites were much higher in year 1 due to very low recharge volumes, whereas costs at M3 and M5 were much lower due to the higher recharge volumes.

Table **4.5.2**. Capital and operating costs for the MAR sites and cost of recharge water in the second year

Site	Capital Costs[1] (×10³ VND / USD)	O&M Costs[1] (×10³ VND / USD)	Volume of Recharge Water (m³/year)	Capital Cost of Recharge Water per m³ (×10³ VND / USD)	O&M Cost of Recharge Water per m³ (×10³ VND / USD)
M1	560 / 24	682 / 30	5	112 / 4.9	136.33 / 5.96
M2	2,633 / 115	682 / 30	6	432 / 18.87	111.75 / 4.88
M3	360 / 16	267 / 12	250	1 / 0.06	1.07 / 0.05
M4	850 / 37	217 / 9	206	4 / 0.18	1.05 / 0.05
M5	5,244 / 229	217 / 9	303	17 / 0.76	0.72 / 0.03
Avg.	1,929 / 84	413 / 18	154	13 / 0.55	2.68 / 0.12

[1] Based on an exchange rate of VND 22,877.5 in mid- 2018

4.5.3 MAR costs over the two years

The average costs for the 5 MAR sites in two years (2017-2018) are compiled in Table 4.5.3. Since capital costs in year 2 are much lower than in year 1, capital costs are mainly spent in year 1. For 2-year capital costs, the highest and lowest are for M5 and M4 sites, approximately VND 25 million (USD 1,100) and VND 12.6 (USD 562), respectively. For 2 year O&M costs, the values are similar to those in year 1 or year 2, with highest at M2 site due to high sedimentation that required high labor costs for regular cleaning (in year 3 this site will be stopped and replaced by a new site - M6). Due to the improvement of water collection at the M3 and M5 sites the recharge volume in year 2 increased significantly and lead to an average of 229 m^3 in these 2 year-trial of 5 sites with over 200 m^3 recharged at M3, M4 and M5 sites. The O&M costs for these 3 sites were also low, at approximately USD 0.05 per m^3.

Table **4.5.3**. Capital and operating costs for the MAR sites and cost of recharge water during both years (2017-2018)

Site	Capital Costs[1] ($\times10^3$ VND / USD)	O&M Costs[1] ($\times10^3$ VND / USD)	Total Volume of Recharge Water (m^3)	Capital Cost of Recharge Water per m^3 ($\times10^3$ VND / USD)	O&M Cost of Recharge Water per m^3 ($\times10^3$ VND / USD)
M1	16,968 / 755	857 / 38	58	293 / 13.02	14.77 / 0.65
M2	20,041 / 891	1,642 / 73	29	689 / 30.6	56.42 / 2.49
M3	24,855 / 1,107	442 / 19	327	76 / 3.39	1.35 / 0.06
M4	12,640 / 562	392 / 17	380	33 / 1.48	1.03 / 0.05
M5	24,946 / 1,107	442 / 19	352	71 / 3.14	1.26 / 0.06
Avg.	19,890 / 884	755 / 33	229	87 / 3.86	3.29 / 0.15

[1] Based on exchange rates of VND 22,446.9 in mid- 2017 and VND 22,877.5 in mid- 2018

Although MAR trials in Dak Lak have different purpose and scale compared with MAR cases in other countries, data in Table 4.5.4 can provide a tentative comparison of capital and O&M costs of broadly comparable projects. Capital costs per m^3 as well as O&M costs per m^3 in Dak Lak fall within a similar range to those from other countries.

Table 4.5.4. Capital and operating costs for the MAR sites and cost of recharge water in other countries (from Ross and Hasnain 2018)

Site	Capital Costs ($\times10^3$ USD)	O&M Costs ($\times10^3$ USD)	Volume of Recharge Water ($\times10^3$ m^3/year)	Capital Cost of Recharge Water per m^3 (USD)	O&M Cost of Recharge Water per m^3 (USD)
Khulna Bangladesh[5]	12.37	0.38	0.68	18.27	0.56
Uttar Pradesh, India[6]	12.28	1.49	45.00	0.27	0.03
Dharta, India[7]	60.63	18.59	779.00	0.08	0.02
Baramati India	87.80[8]	0	78.00	1.13	0

4.5.4 Benefits of MAR

The main benefit of MAR is likely to be improved water security owing to stabilisation of water supplies in years of high and low rainfall. MAR, when water supplies are good, provides additional groundwater storage, enabling farmers to maintain optimum watering and preserving coffee yields in exceptionally dry years. Estimation of the so-called 'stabilisation value' of MAR requires further information about:

• What climatic/rainfall scenarios trigger a shortage of water and a requirement for additional groundwater irrigation supply, i.e. what is the definition of an exceptionally dry year?

• How much aquifer recharge and storage would be required to provide for this additional supply while maintaining pumping yields and avoiding excessive aquifer depletion, potentially making a distinction between the upper weathered and lower aquifers?

4.6 Farmer Attitudes to MAR

In the first step, 17 wells were identified that were either suitable for MAR trialling or MAR references to monitor impacts. The first visit to the study area involved a pre-survey of a long list by the national team members with the assistance of local authorities and leaders of farmer groups. The watersheds for these sites and their elevation were established to assist in the selection process. A follow-up survey was carried out by both international and national teams to revisit the sites and compare the characteristics of each in light of the criteria for MAR site suitability.

[5] Project includes infiltration of water freshwater pond through 4 large diameter gravel filled wells to a brackish aquifer. This forms a freshwater bubble from which water can be recovered during the dry season
[6] Project includes 10 recharge wells drilled into the base of one village pond
[7] Project includes 5 check dams, costs are converted to USD at 2014 exchange rate
[8] Project includes desiltation of 7 check dams. Desiltation is required every 10 years. The original capital cost of building these very old infiltration tanks is written off

Consultation with farmers was done during the pre-survey and survey in Step 1. At all the sites, farmers were interested and engaging upon hearing about the MAR concept for the first time, because up to that time, the idea that their wells could be used for recharge as well as extraction was unknown. Some farmers even tried to convince the team to implement MAR at their sites. Some farmers also expressed concerns as to whether the recharged water would stays in the vicinity of their wells or flow to other places. However, they all agreed that the opportunity for increasing the groundwater storage was better with MAR than without MAR and they would be happy if the recharged water could increase water availability in the wells of their neighbours or in the community. However, at that time they did not have any idea as to how to implement the MAR and just assumed that it was simply a matter of leading the flow of water into the wells as they saw occur in an unmanaged way at many places where the wells do not have the cap and its wall height is only just above the ground surface elevation.

Initial opinions on MAR could be changed during Step 2 after farmers saw how the MAR trials are implemented, since we cannot simply direct surface water into the well because sediment may gradually fill up and clog the well, and according to groundwater regulations, draining water containing polluting substances into aquifers is prohibited (MONRE 2017). Therefore filtration tanks, as well as sediment traps at some sites, are required for MAR. Farmers are also aware that water sampling and testing is being carried out during implementation.

The more recent opinion of the farmers was gauged from a small interview-based survey. The entire set of results from this survey are provided Appendix 5. The following remarks can be deduced from this dataset:

4.6.1 Household heads and details of households (items 1 to 8)

- All household (HH) heads of 5 MAR sites are male, aged between 37 and 48 years old
- Only one at M2 site is an Ede minority who was born and lives in Dak Lak for 48 years, the four others are Kinh people who migrated from North Central Vietnam (M1 and M3) and North Vietnam (M4 and M5) between 19 to 34 years ago.
- Four Kinh HH heads have higher education level (secondary or graduation from high school) than the Ede HH head M2 (primary school).
- Number of members in the HHs are from 4 to 8 with 2 to 7 in the working ages for farming (15 to 60 years old)
- Besides coffee, pepper is another source of income for HHs M1, M3 and M4.

4.6.2 Farming information (items 9 to 15)

- Farming area of HHs vary from 1.6 ha to 2.5 ha and comprises of 2 to 3 parcels, except M1 with just 1 parcel.
- Most of HHs use groundwater as the main irrigation water source, except M5 uses more surface water than groundwater. Rainfed farming without supplementary irrigation is not applied in these five HHs.
- In the total of 11 parcels of land that belong to these five HHs, 6 are coffee monoculture, 4 are intercropped with coffee and pepper, and only 1 is pepper monoculture.
- Sprinkler irrigation is used in all 11 parcels, but basin irrigation is also combined in 5 parcels, depending on the topography and water sources.
- In these 11 parcels, only M2 and M4 are irrigated with groundwater from the wells with MAR trials.

4.6.3 Water facilities (items 16 to 23)

- All HHs have dug wells; numbers range from 1 to 4 wells. Only M3, M4 and M5 HHs have boreholes.
- Diesel pump is not used by these five HHs. Only electric pumps are used, but not all wells and boreholes are equipped with pump.
- Only M5 uses water from boreholes for domestic and drinking purposes. The other four use water from wells for these purposes. Everyone in the HH, except children, is responsible for domestic and drinking water supply.
- Irrigation water is needed for the dry season. In particular, during March irrigation water is not sufficient.
- Only M2 HH head noticed that groundwater level is lower than in the past. M1 and M3 HH heads noticed that it does not change and M4 and M5 HH head did not observe any variation.

4.6.4 Opinions about MAR (items 24 to 32)

- All five HH heads understand well the objective of MAR as to increase groundwater resource by direct surface runoff into existing dug wells. They can describe well how the MAR process functions, including the role of the sediment trap and filtration tank.
- M1 and M2 HH heads considered the MAR experiments as project funded by foreign organizations and M1 HH head even expects some financial support to him when we use his well for the trial. This is a problem of participatory-based research that is common in many developing countries.
- To respond to the question if they are willing to take over the O&M of MAR in the future, M1 and M3 HH heads answered "No" because they have sufficient water source for irrigation. Even M1 does not believe that MAR can help to increase groundwater resource after observing how the system works.

- On the other hand, HH heads for M2, M4 and M5 answered "Yes" to this question with conditions. All of them request financial support to continue the O&M, including labour costs. HH head M2 also mentioned the need for out-scaling MAR in the village because he realized that MAR applied for only his single well may not bring significant positive impacts.
- For improvement, the main concern of these HH heads are the high sediment content in runoff water that blocks the filtration and does not leave much opportunity for water to flow into the well. They also realized that using larger tanks for more water collection would be costly. However, the M1 HH head proposed that we should disseminate the techniques to local people so that they can consider how to apply them.
- At present, all five HH heads could not see the effects of MAR yet. HH head M4, even also observed the variation in the well of his neighbour, but could not see the effect yet. Thus, no answer is provided for the question to explain the change.
- Therefore responses by HH heads M1 and M3 to the question if they will recommend MAR to other farmers are "No", because they don't see any positive effect as yet. The answer from HH heads M4 and M5 is "Yes", with the conditions that investment and O&M costs, including the labour cost, will be supported. The M2 HH head considered the recommendation to apply MAR is the responsibility of local authorities and the project, therefore he would not do it.

4.6.5 Consultation with farmers during the MAR trial

In Step 2 of the process of analysis of farmer attitude to MAR consultation with farmers during MAR trials involves regularly consulting with farmers who own the MAR wells and group discussions to receive their comments and advice on improvement of the performance of the system. At the group discussion we also learn how farmers evaluate the pros and cons of MAR, and establish how to improve and their attitude to continuation of MAR operations beyond the trial and to gain insights for out-scaling.

One activity in this Step 2 was a consultation meeting for group discussion organized at Mr. Nam house (M4 site owner) on 30th November, 2018, with the presence of 4 MAR owners M1, M2, M4 and M5, and 6 reference well owners M1-R1, M2-R1, M3-R1, M3-R2, M5-R1 and M5-R2 plus a hamlet head together with 7 project team members.

The following points were mentioned by farmers at the meeting:

a. The M5-R1 owner said that weather in 2018 was favourable for coffee crop, therefore water for irrigation was not an issue and was not paid much attention. This notice was confirmed by several other farmers. Therefore the M2 well owner mentioned that he saw no negative or positive effects of MAR in his well. The M3-R2 owner also said the same. However, the M5-R2 owner thought that water in his well had improved recently because of the MAR at M5.

b. The M5-R1 owner also mentioned that he does not have any experience in MAR trial how to measure the effect of MAR. The reason is because the project team only installed a water level logger in his well and collected data for scientific analysis at the office and did not show him anything yet.

c. Therefore the M1-R1 owner suggested that the project provided him data on the groundwater level at his site immediately after measurement as he had given his well for monitoring freely. He prefers to monitor/check groundwater levels by himself in the dry season. However we replied that we replied it takes time to process and analyze the data before we can provide to him.

d. The M2-R1 owner concerned about pesticide and weedicide impacts, because farmers are using these chemicals in the province. Therefore he did not agree to use his well for MAR because he was considering to use the well for drinking water in the future.

e. The M4 owner said that in the past he only pumped out water from the well and recharge was never done. Now his well is used for both pumping and recharge. He thought that MAR was a significant development and a lot of water had been recharged down into his well to enhance the groundwater resource. He also said that the filtration tank capacity was now undersized and that it should be increased as a lot of water overflowing out of the tank during heavy rains. He and other well owners said that if roof runoff is used for recharge then no filtration system is needed. The systems should be operated such that the first few flushes at the start of the rainy season are allowed to bypass the well, and then the runoff for rest of the year enters the well directly, without going through a filtration system.

f. Other well owners thought that if the filtration system is to be used, improvement is needed. The plastic tanks used in the MAR trial likely last only 3-5 years which is too short, therefore more solid masonry systems with large volume would be better.

g. The M5 owner with the roof used to supply water to M5 site said that if we used all the roofs in the area for recharge, we will create major improvements in the groundwater resource in the region. Many other well owners support this idea. They thought that harvesting roof runoff had good potential, therefore we should tailor the design to the different MAR typologies to provide guidelines on how to do this in practice in a simple way at low costs. The hamlet head, not a MAR/Ref well owner, said that if we wanted to have significant impacts on the groundwater resources then a pilot of 5 sites was insufficient, we needed to do this at some hundreds to thousand sites. Therefore he thought that with simple and low cost MAR system to collect water from house roofs he can encourage farmers to out-scaling in the hamlet.

h. In general, famers were quite positive about MAR. Some mentioned that implementing MAR is better than doing nothing. However, when they were asked whether they or other farmers have or will apply MAR at other sites, their answer was 'not yet' because they still wait to see the clear effects and also to receive guidelines from the authorities. To answer the question whether they will continue the MAR trial after the research project finishes, most of them expected to continue with support for O&M costs from other sources such as from local authorities or other organizations, or we can justify the benefits to value and recognize their contribution.

A Likert-type scale survey could be carried out in Step 3 (Figure 3.4.1) after farmers clearly see how MAR works and its effects after a few irrigation seasons.

In the meantime, as a part of Step 4: 'Revision and decision of MAR out-scaling to new sites' two related reviews on MAR trial by external reviewers were implemented in 2019. The first was carried out by Assoc. Prof. Dr. Le Thi Kim Cuc - Directorate for Water Resources, Ministry of Agriculture and Rural Development and Assoc. Prof. Dr. Doan Van Canh - Chairman of Vietnam Association of Hydrogeology to evaluate the performance efficiency of the MAR trial in the field and collect local feedback on the results of the MAR pilot trial to assess the effect and to recommend the replication of the trial, and the second by Dr. Nguyen Quoc Manh, policy expert- Department of Crop Production, MARD to provide policy recommendations related to Farmer Coaching Visit (FCV) and MAR.

4.6.6 Major outstanding challenges

The major challenges at present associated with the MAR trial are:

- Farmers do not see the effects yet, therefore they do not consider that MAR is a result of their actions for their own benefits but to some degree, as activities of a foreign-funded project.
- Moreover, when MAR structures are constructed for research purposes, it appears much more complex than farmers would expect from the beginning.
- In future, the project will need to implement Steps 3 and 4 of the process to study if the farmer attitudes to MAR have changed. This process will help to prepare appropriate guidelines how to do MAR under different situations, and the strategy as to how to disseminate the findings to large groups of farmers with the help of local authorities and policy makers.

5. CONCLUSIONS

Pragmatic, farm-scale MAR pilots have been implemented for the first time in Krong Buk district to establish the performance of the interventions and the impacts on the groundwater resources. Following a rigorous site selection process in early 2017, a total of 5 MAR trial sites were selected along with paired sites that are used for reference purposes. These sites were set up in close collaboration with the local farmers and primary beneficiaries of the intervention. The MAR systems collect runoff over collection areas ranging from around 150 to 3,100 m^2 made up of a mix of local fields, rooftops and unpaved roads and allows this water to drain via gravity through a sand filter chamber and finally into the farmer's well. Since May 2017, each site has been carefully monitored and evaluated in terms of the volumes of water stored and recovered, groundwater level response, water quality impacts, site maintenance, financial costs and farmer attitudes/perceptions. This report covers the first two years of piloting from May 2017 until April 2019.

The results for the first hydrological year reveal that the volumes of runoff water stored in the aquifer varied between 23 and 174 m^3 across the sites. In the second year average recharge volumes have increased, with measured values of up to 303 m^3 due to modification to system design, despite the lower rainfall. Sites with clean water from roof runoff performed best, whilst highly turbid runoff water from unpaved roads performed worst.

Detailed water quality sampling during the wet and dry seasons for a comprehensive suite of physico-chemical and microbiological parameters, reveals that there was no water quality parameter measured of serious concern from human health, irrigation or environmental view-points. Several of the parameters measured entering the MAR wells such as total dissolved solids, nitrate and turbidity were elevated compared to the reference wells, but were either short lived peaks, or at levels generally not of concern relative to the national water quality standards.

Most of the water stored in the aquifer was likely unrecoverable from the recharge well during the dry season owing to the high groundwater velocities brought about by steep groundwater gradients.

An important point to note is that the process of MAR changes the way water moves within the hydrologic system. Runoff water that would otherwise move swiftly through the surface drainage system is transferred to the aquifer by MAR where its velocity is greatly slowed down. By reducing the velocity, there is greater availability of water for the local community. Recharge water may be picked up from downstream wells and/or from surface water courses which are reportedly fed largely by groundwater discharge in the drier months (Viossanges *et al.* 2019). Not all of the MAR wells were used for dry season pumping; with farmers opting in some cases to use alternative wells for irrigation. This shows the possibility to capture the recharge water not only from the MAR well, but also from other wells in the local area.

Initial estimates of the costs for establishing MAR systems appear to be relatively attractive. This needs to be verified with further engagement with a broader range of farmers. Tentative estimates suggest that the capital costs if implemented by farmers are around VND 10 million (USD 440) and annual running costs are around VND 0.34 million (USD 15).

Baseline and follow up interviews with the farmers participating in the trial show that they have good practical understanding of how the MAR system functions and have been observing its performance closely. Not all of the farmers are as yet ready to operate and maintain the MAR systems nor necessarily support further adoption. An ongoing process of engagement is needed to track their attitudes over time as incremental improvements are made to the MAR pilot systems.

The trial indicates great scope for farmers to gain benefits from the MAR approach. The Krong Buk pilots have made firm inroads towards gaining a sound technical, social and economic proof of concept for MAR. These results are sufficiently promising to support broader piloting in other agro-ecological and hydrogeological conditions across the Highlands. A wider range of pilots would help make a stronger case for policies and strategies that would enable more widespread MAR adoption and thus enhance the resilience of smallholder coffee farmers in the Central Highlands to growing demand and climate change.

6. ACKNOWLEDGEMENTS

This ongoing research is made possible through the support provided by Nestlé/Nescafe, the Swiss Agency for Development and Cooperation (SDC) and the CGIAR Research Program on Water, Land and Ecosystems (WLE). Through the implementation of the joint Nestlé-SDC supported project "*More coffee with less water - towards a reduction of the blue water footprint in coffee production*", the proposal to examine Managed Aquifer Recharge was raised and jointly agreed upon. The involvement of IWMI members of the team was made possible through the support of WLE.

The project team would like to thanks the following individuals for their various contributions to date:

- Mr Mai Xuan Thong and Mr Y Hue Ksor based in Krong Buk (HRNS) and Ms Phan Thị Xuân Thắm (Vietnam National University, HCM) for assistance in site establishment and field support;
- Mr Carlo Galli (Nestlé), Eileen Hofstetter (SDC), Mr Wouter De Smet (Nescafé) and - two reviewers of the Nestlé-SDC supported project - Grit Techel (UNIQUE Forestry and Land Use, Germany) and Bui Hai Nam (National Institute of Agricultural Planning and Projection, Vietnam) - for providing useful advice on the technical design;
- Mr Alisher Sharypau (HRNS) for some of the photographic work.

Finally, Dr C.T. Hoanh is acknowledged for first visioning the scope for MAR in the coffee growing areas and beginning the discussion with the stakeholders that initiated this pioneering trial.

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APPENDIX 1. Filter stability tests

The 2-layer filter installed at each MAR site consisted of a gravel layer overlain by sand. Given that a range of grades of sand and gravel are readily available from local supply outlets for construction purposes, short duration flow tests were carried out to determine a stable combination through testing different combinations of media types under flow conditions. The aim of these tests was to identify a stable combination based on short-terms flow tests with visual checks on the clarity of the outflow water.

To do the experiments, materials were first washed with fresh water and placed in transparent buckets with a capacity of approximately 4 litres in the order of very approximately, one-third gravel followed by one-third sand and one-third water column. Three different types of bottom gravel layer were tested: large gravel (5-40mm), medium gravel (5-10mm) and fine gravel (<5mm). The sand layer was maintained as medium sand (<5mm) in each case. The direction of water flow was vertically downwards.

For the test with large gravel the sand had moderately penetrated the gravel layer to a distance of 5 centimetres after 20 litres had passed (5 bucket volumes). The average infiltration velocity with clear well water was 3.3 mm/sec. For the test with medium gravel the depth of penetration after 5 bucket volumes was 2 centimetres and the infiltration rate was 1.7 mm/sec. For the fine gravel there was no discernible sand penetration into the gravel and the infiltration rate was 0.8 mm/sec. These tests demonstrated the tradeoff between filter pack stability and infiltration rates. Based on these results the finest (pea) gravel was selected as the larger gravels are likely to be unstable over the longer term and the flow rate with the fine gravel was likely to be satisfactory.

Figure A1.1. Photos showing the filtration test apparatus with large gravel (left) and fine gravel (right) at the base

APPENDIX 2. Water quality data

Year 1

Parameter	Unit	National Standards		MAR Well (Wet Season)					MAR Well (Dry Season)					Reference Wells (Wet & Dry Seasons)						
		Irrigation[1]	Drinking[2]	M1	M2	M3	M4	M5	M1	M2	M3	M4	M5	M1R1	M2R1	M3R1	M3R2	M4R1	M5R1	M5R2
Physical Properties																				
Electrical conductivity	µS/cm			85.67-157.05	34.56-186.4	86.05-306.9	29.76-43.17	159.4-208.55	16.5-16.92	7.85-9.75	10.08-14.01	9.34-23.4	14.68-34.9	9.46-10.4	7.04-10.13	12.67-20.98	11.72-21.49	7.19-19.85	12.07-24.72	10.23-15.01
pH	-	5.5-9	6.5-8.5	7.05-7.69	7.48-7.96	6.7-7.82	7.09-7.66	7.56-8.47	5.58-6.02	4.98-5.66	5.11-6.22	5.52-5.87	5.56-6.81	5.11-5.24	5.16-5.25	5.4-5.8	5.37-5.53	4.95-5.73	5.15-5.38	5.19-5.48
Turbidity	NTU		2	32-220	160-550	5.4-150	3.3-39	55-190	8.9-20	0.5-14	0.72-115	3.8-4.6	6.8-57	0.3-2.9	0.57-0.9	0.51-0.85	1.2-1.8	1-11	0.35-0.84	0.2-0.6
General Inorganic																				
Total Dissolved Solids (TDS)	mg/L	2,000		64.639-139.5812	30.098-131.73	68.368-236.52	25.651-43.2588	124.3716-169.18	13.05-14.43	6.18-8.17	8.66-12.15	9.24-16.17	12.67-26.41	7.7-12.885	6.26-15.595	9.5-19.41	10.65-22.23	5.31-21.79	9.39-21.64	8.69-18.48
Calcium (Ca)	mg/L			2.77-5.49	2.02-3.78	2.869-5.2	1.08-1.37	2.755-3.13	0.86-1.31	0.24-0.67	0.27-0.77	0.65-0.72	0.4-1.11	0.53-0.88	0.6-2.04	1.07-1.53	1.18-1.66	0.58-1.08	1.11-1.89	0.89-1.08
Magnesium (Mg)	mg/L			0.82-1.71	0.637-1.24	0.81-1.5	0.325-0.45	0.799-1.01	0.15-0.39	0.03-0.17	0.03-0.2	0.19-0.19	0.08-0.31	0.18-0.24	0.14-0.64	0.31-0.5	0.35-0.56	0.14-0.35	0.31-0.55	0.25-0.36
Sodium (Na)	mg/L		200	11.789-30.36	5.231-33.75	10.429-54.34	4.947-8.19	35.424-43.31	1.83-1.85	0.51-1.5	0.76-2.63	1.09-2.95	1.3-6.8	0.57-1.29	0.88-1.83	0.69-1.73	0.52-2.54	0.27-2.71	0.9-1.62	0.56-2.4
Potassium (K)	mg/L			2.978-4.3	0.26-2.36	4-12	0.4-0.57	1.123-2.03	0.4-0.52	0-0.28	0.4-0.4	0.34-1.14	0.28-0.5	0.3-0.3	0.3-0.35	0.4-0.5	0.4-0.41	0.3-0.3	0.4-1.1	0.3-0.3
Chloride (as Cl^-)	mg/L	350	250	1-5	1-5	1-5	1-5	1-5	0.3-1	0.3-1	0.3-1	0.3-1	0.3-1	1-5	1-5	1-5	1-5	1-5	1-5	1-5
Sulfate (as SO_4^{2-})	mg/L	600	250	5-14.6	1.6-10	2.16-10	1-10	4.37-18.9	0.74-1	0.72-1	0.7-1	0.76-1	0.71-1	1-10	1-10	1-10	1-10	1.48-10	1-10	1-10
Bicarbonate Alkalinity (HCO_3^-)	mg/L			49.96-49.96	47.9-47.9	48.93-48.93	18.54-18.54	43.78-43.78	8.52-9.32	3.73-4.76	4.99-6.56	5.15-7.21	7.04-15.42	3.21-4.54	3.15-3.21	5.53-7.06	7.12-8.99	2.84-8.36	4.5-5.21	5.53-6.75
Carbonate Alkalinity (CO_3^{2-})	mg/L			0-0	0-0	0-0	0-0	0-0	0-0	0-0	0-0	0-0	0-0	0-0	0-0	0-0	0-0	0-0	0-0	0-0
Hydroxide Alkalinity (OH^-)	mg/L			0-0	0-0	0-0	0-0	0-0	0-0	0-0	0-0	0-0	0-0	0-0	0-0	0-0	0-0	0-0	0-0	0-0
Nutrients																				
Ammonia (NH_3) (as N)	mg/L			0.01-0.17	0.01-0.1	0.01-0.16	0.01-0.1	0.01-0.1	0.06-0.1	0.06-0.1	0.06-0.1	0.06-0.1	0.06-0.1	0.1-0.1	0.1-0.1	0.1-0.1	0.1-0.1	0.1-0.1	0.1-0.1	0.1-0.1
Ammonium (NH_4^+) (as N)	mg/L			0.01-0.17	0.01-0.1	0.01-0.17	0.01-0.1	0.01-0.1	0.06-0.1	0.06-0.1	0.06-0.1	0.06-0.1	0.06-0.1	0.1-0.1	0.1-0.1	0.1-0.1	0.1-0.1	0.1-0.1	0.1-0.1	0.1-0.1
Nitrate (as NO_3^-)	mg/L		50	3.12-19.76	4.21-26.24	0.42-7.64	1.04-3.01	0.08-13.43	0.16-0.28	0.1-0.49	0.54-1.41	0.75-3.12	1.41-2.57	0.05-0.17	0.05-0.19	0.4-0.69	0.08-0.57	0.18-1.64	0.46-4.48	0.16-0.24
Nitrite (as NO_2^-)	mg/L		3	0.02-0.31	0.02-0.07	0.02-0.3	0.02-0.02	0.02-0.13	0.02-0.02	0.01-0.02	0.012-0.02	0.02-0.02	0.02-0.02	0.02-0.025	0.02-0.02	0.02-0.02	0.02-0.02	0.02-0.02	0.02-0.02	0.02-0.02
Total Nitrogen (as N)	mg/L			1.6-2.89	1.4-2.34	1.39-2.53	1.09-2.83	1.39-2.58	0.35-0.68	0.19-0.35	0.02-0.39	0.16-0.7	0.06-0.7	0.43-0.97	0.6-1	0.67-0.97	0.43-1.14	0.57-1.18	0.58-3.85	0.59-1.46
Phosphorus (as PO_4^{3-})	mg/L			0.01-0.89	0.01-0.48	0.18-1.4	0.01-0.24	0.13-1.11	0.13-0.14	0.01-0.06	0.02-0.09	0.05-0.07	0.01-0.48	0.02-0.1	0.01-0.1	0.01-0.31	0.04-0.1	0.11-0.4	0.04-0.1	0.02-0.1
Metals																				
Copper (Cu)	mg/L	0.5	1	0.009-0.049	0.007-0.063	0.016-0.03	0.006-0.019	0.007-0.03	0.003-0.022	0.003-0.063	0.003-0.021	0.003-0.019	0.003-0.03	0.004-0.049	0.004-0.063	0.005-0.021	0.019-0.03	0.03-0.03	0.019-0.03	0.03-0.03
Iron (Fe)	mg/L		0.3	0.19-0.37	0.24-3.98	0.03-0.85	0.03-0.21	0.08-0.75	0.02-0.23	0.17-0.24	0.03-0.06	0.03-0.06	0.23-0.64	0.03-0.37	0.03-0.24	0.03-0.03	0.03-0.03	0.03-0.23	0.03-0.03	0.03-0.23
Arsenic (As)	mg/L	0.05	0.01	0.008-0.008	0.008-0.008	0.008-0.008	0.008-0.008	0.008-0.008	0.008-0.008	0.008-0.008	0.008-0.008	0.008-0.008	0.008-0.008	0.008-0.008	0.008-0.008	0.008-0.008	0.008-0.008	0.008-0.008	0.008-0.008	0.008-0.008
Manganese (Mn)	mg/L		0.3	0.001-0.042	0.001-0.029	0.001-0.086	0.001-0.022	0.001-0.044	0.14-0.203	0.003-0.013	0.001-0.01	0.001-0.07	0.001-0.01	0.001-0.003	0.001-0.003	0.001-0.001	0.001-0.001	0.001-0.001	0.001-0.001	0.001-0.001
Bacteria																				
E coli	MPN/100mL		0	3-4600	43-2400	280-1100	460-1100	3-2400	3-93	3-430	90-240	3-70	43-1100	3-150	3-240	3-4	3-43	3-1100	3-3	3-3
Pesticides																				
Pesticides	µg/L			ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

ND = not detected

[1] Government of Vietnam, 2011. National technical regulation on water quality (QCVN 39:2011/BTNMT) for irrigated agriculture

[2] Government of Vietnam, 2009. National technical regulation on drinking water quality (QCVN01:2009/BYT)

Year 2

Parameter	Unit	National Standards		MAR Wells (Wet Season)			MAR Wells (Dry Season)			Reference Wells (Wet & Dry Seasons)		
		Irrigation[1]	Drinking[2]	M1	M4	M5	M1	M4	M5	M1R1	M4R1	M5R1
Physical Properties												
Electrical conductivity	µS/cm			16.92-50.31	23.4-61.36	34.9-204.3	11.18-225.75	7.28-14.63	15.18-42.79	6.63-17.56	5.05-7.4	11.59-20.8
pH	-	5.5-9	6.5-8.5	6.02-6.85	5.87-7.12	6.81-7.8	5.1-6.37	5.17-5.57	6.1-6.76	4.85-6.42	4.99-6.41	4.87-6.32
Turbidity	NTU		2	20-93	0.75-3.8	5.7-57	6.5-32	5-41	13-15	0.47-17	0.11-0.25	0.27-6.4
General Inorganic												
Total Dissolved Solids (TDS)	mg/L	2,000		13.05-38.1	16.17-45	26.41-177.67	14.445-144.29	8.655-11.04	21.8-30.54	4.83-14.05	4.545-8.265	10.19-18.18
Calcium (Ca)	mg/L			0.4-1	0.6-0.7	0.4-1.6	2.3-18.5	0.6-2.7	0.5-2	0.3-1.9	0.2-1.8	0.27-2.3
Magnesium (Mg)	mg/L			0.09-0.41	0.19-0.29	0.08-0.59	0.44-2.68	0.06-0.55	0.06-0.44	0.17-0.63	0.08-0.36	0.24-1.7
Sodium (Na)	mg/L		200	1.83-7.7	2.95-9.4	6.8-44.3	0.4-2.9	0.5-1.7	2.1-7.2	0.4-1.2	0.2-0.8	0.7-1.3
Potassium (K)	mg/L			0.52-1.05	0.78-1.14	0.28-1.95	15.3-15.3	0.43-0.43	0.09-0.45	0.21-0.78	0.3-0.35	0.42-0.96
Chloride (as Cl^-)	mg/L	350	250	1.96-1.96	1.62-1.62	1.84-1.84	1.96-2.32	1.28-1.28	1.46-2.51	0.68-2.4	1.5-2.02	0.9-3.61
Sulfate (as SO_4^{2-})	mg/L	600	250	0.74-1.03	0.76-2.06	0.71-1.29	1.51-3.47	1.22-1.22	1.46-1.6	1.31-2.38	1.35-1.35	1.21-1.27
Bicarbonate Alkalinity (HCO_3^-)	mg/L			0.000	0.000	0.000	7.32-99.31	3.78-3.9	12.57-14.88	2.2-8.78	1.59-3.54	2.93-9.27
Carbonate Alkalinity (CO_3^{2-})	mg/L			0.000	0.000	0.000	0.000	0.000	0.000	0-0	0-0	0-0
Hydroxide Alkalinity (OH^-)	mg/L			0.000	0.000	0.000	0.000	0.000	0.000	0-0	0-0	0-0
Nutrients												
Ammonia (NH_3) (as N)	mg/L			0.51-0.51	0-0	0-0	2.81-2.81	0.000	0.000	0-0	0-0	0-0
Ammonium (NH_4^+) (as N)	mg/L			0.51-0.51	0-0	0-0	2.81-2.81	0.000	0.000	0-0	0-0	0-0
Nitrate (as NO_3^-)	mg/L		50	0.28-3.42	3.12-15.25	1.63-4.19	0.12-0.17	0.52-1.97	0.49-4.53	0.21-0.47	0.11-0.53	0.31-5.5
Nitrite (as NO_2^-)	mg/L		3	0.02-0.059	0.02-0.02	0.02-0.02	0.000	0.000	0.000	0.000	0.000	0.103-0.103
Total Nitrogen (as N)	mg/L			0.35-1.63	0.7-1.13	0.06-1.13	5-5	0.000	0.000	0.96-3.02	0.88-3.19	0.85-1.39
Phosphorus (as PO_4^{3-})	mg/L			0.02-0.65	0.02-0.08	0.37-0.51	0.08-0.08	0.2-0.2	0.28-0.28	0.02-0.04	0.02-0.02	0.02-0.18
Metals												
Copper (Cu)	mg/L	0.5	1	0.003-0.003	0.004-0.004	0.003-0.003	0.0021-0.004	0.0048-0.0048	0.0023-0.0035	0.0007-0.0032	0.002-0.0058	0.001-0.0035
Iron (Fe)	mg/L		0.3	0.6-0.77	0.06-0.06	0.06-0.64	0.12-13.78	0.04-0.14	0.13-0.52	0.49-0.77	0.05-0.05	0.42-0.52
Arsenic (As)	mg/L	0.05	0.01	0-0	0.0003-0.0003	0.0005-0.0005	0.000	0.000	0.0006-0.0006	0-0	0-0	0-0
Manganese (Mn)	mg/L		0.3	0.02-0.14	0.07-0.07	0-0	0.16-3.62	0.03-0.04	0.04-0.04	0.013-0.02	0.013-0.013	0.03-0.04
Bacteria												
E coli	MPN/100mL		0	11-1100	700-11000	15-240	2400-24000	1500-2400	1100-15000	4-2400	40-43	7-43
Pesticides												
Pesticides	µg/L			ND	ND	ND	ND	ND	ND	ND	ND	ND

Summary of all pesticide results

Parameter	Unit	National Standards		Year 1	Year 2
		Irrigation[1]	Drinking[2]		
Aldrin	µg/L	-	0.030	<0.03	<0.03
Chlordane [3]	µg/L	-	0.200	<0.1	<0.1
Chlorpyrifos	µg/L	-	-	<0.1	<0.1
DDD	µg/L	-	-	<0.1	<0.1
DDE	µg/L	-	-	<0.1	<0.1
DDT [4]	µg/L	-	2.000	<0.1	<0.1
Diazinon	µg/L	-	-	<0.1	<0.1
Dieldrin	µg/L	-	0.030	<0.03	<0.03
Endosulfan [5]	µg/L	-	-	<0.1	<0.1
Lindane	µg/L	-	2.000	<0.1	<0.1
Heptachlor [6]	µg/L	-	0.030	<0.03	<0.03

Notes

[1] Government of Vietnam, 2011. National technical regulation on water quality (QCVN39:2011/BTNMT) for irrigated agriculture
[2] Government of Vietnam, 2009. National technical regulation on drinking water quality (QCVN01:2009/BYT)
[3] includes cis- oxy- and trans- isomers of chlordane
[4] sum of p,p-DDT, o,p-DDT, p,p-DDE and p,p-TDE
[5] sum of endosulfan I, endosulfate II and endosulfan sulfate
[6] includes heptachlor epoxide, heptachlor endo-epoxide and heptachlor exo-opoxide

APPENDIX 3. Description of the groundwater model

The modelled aquifer system is represented by the uppermost weathered (vacuolar) basalt aquifer layer that is ubiquitous to the Dak Lak basaltic plateau. The more extensive but less permeable lower aquifer comprised of massive basalt (sometimes fractured) is not considered as MAR focusses on the shallow dug wells less than 30 metres deep that represent by far the major form of groundwater infrastructure.

The FEFLOW model, Version 6.1 (Diersch 2014) was employed to simulate groundwater flow and solute transport processes that would be representative of the most water-stressed areas of the basaltic plateau represented by topographic highs. A 2D plan view model was constructed with a domain size of 300 by 300 metres. This notionally represents an area of farmland situated on the side of a hill. A single MAR well is positioned at the centre of this domain. The aquifer is assumed to be homogeneous with a total potential thickness of 30 metres and saturated thickness of 25 metres at the MAR well under ambient conditions. The top boundary represents the upside of the hill and the lower boundary the downside. The left and right edges of the model parallel to flow direction represent no flow boundaries. The characteristics of the model are summarized in Table A3.1.

Simulations were carried out to test the influence of what was considered the most important factors that influence the key indicators listed above and ultimately affect MAR feasibility. Those factors included:

- the volume of water stored during the recharge phase
- the background flow velocity of the groundwater (determined by the aquifer hydraulic conductivity and hydraulic gradient)
- the porosity of the aquifer
- the timing/scheduling of recharge and pumping events

In total there were 11 numerical scenarios to account fully for the aforementioned factors as detailed in Table A3.2.

Table A3.1. Summary of constant and adjusted variables used in the model

Parameter	**Description**
Constant variables	
Model domain	90,000 m^2 (300 m x 300 m)
Mesh	5,888 elements (triangular)
Aquifer thickness and elevations	30 m total thickness; base of aquifer = 0 m; top of aquifer = 30 m
Hydraulic head at upper and lower boundaries	Upper: 29.5 m (high gradient case); 25.75 m (low gradient case) Lower: 20.5 m (high gradient case); 24.25 m (low gradient case)
Specific storage coefficient	0.0003 /m
Natural recharge	500 mm/year (uniformly distributed over 6 months)
Pumped volume	396 m^3/season (equivalent to 400 L/tree/round for 3 rounds over area of 0.3 ha planted at 1,100 trees/ha)
Aquifer dispersivity	1 m (horizontal direction)
MAR wells	1 (fully penetrating the aquifer)
Time scale and	One hydrological year (1 May to 30 April)
MAR schedule	Recharge period: from 100 – 109.1 / 136.5 days (for low / high volume respectively); Pumping period: from 335 – 344.2 days (fixed)
Relative concentration of solutes	1 for recharge water; 0 for ambient groundwater
Adjusted variables	
Recharge volume (Q_r)	131.5 – 525.6 m^3/year (low and high volumes)
Hydraulic conductivity (K)	1 – 4 m/day
Hydraulic gradient (*i*)	0.005 – 0.030
Total aquifer porosity (n)	0.1 – 0.3

Table **A3.2**. Overview of the 11 numerical scenarios carried out

Scen. No.	**MAR**	**MAR Recharge Volume**	**Velocity**	**Porosity**
1	Yes	Low (a)	Low (c)	High (f)
2	Yes	Low (a)	Medium (d)	High (f)
3	Yes	Low (a)	High (e)	High (f)
4	Yes	High (b)	Low (c)	High (f)
5	Yes	High (b)	Medium (d)	High (f)
6	Yes	High (b)	High (e)	High (f)
7	Yes	Low (a)	Medium (d)	Low (g)
8	Yes	High (b)	Medium (d)	Low (g)
9	Yes	Low (a) + variability (h)	Medium (d)	High (f)
10	Yes	High (b) & variability (h)	Medium (d)	High (f)
11	No	-	Medium (d)	High (f)

(a) Q_r = 131.5 m^3/d; (b) Q_r = 525.6 m^3/d; (c) K = 1 and *I* = 0.005; (d) K = 4 and *i* = 0.005; (e) K = 4 and *i* = 0.03; (f) n = 0.3; (g) n = 0.1; (h) Q_i distributed into six monthly recharge events and Q_r distributed into three monthly pumping events. Symbols used here are defined in Table A3.1.

APPENDIX 4. Breakdown of costs of MAR for the Dak Lak pilot study

Year 1 (2017)

Cost Items	Category	M1		M2		M3		M4		M5		Average of 5 sites			Notes
		Cost ($\times 10^3$ VND)	% of Total	Cost ($\times 10^3$ VND)	% of Total	Cost ($\times 10^3$ VND)	% of Total	Cost ($\times 10^3$ VND)	% of Total	Cost ($\times 10^3$ VND)	% of Total	Cost ($\times 10^3$ VND)	Cost[1] (USD)	% of Total	
MAR establishment	Materials	2,261	13.6	2,261	12.5	2,261	9.2	2,571	21.5	4,704	25.8	2,812	125.3	15.4	
	Labor	6,498	39.2	6,242	34.5	6,498	26.3	4,503	37.6	6,164	33.8	5,981	266.4	32.8	
Filtration tank	Materials	3,350	20.2	3,350	18.5	3,350	13.6	3,350	28.0	6,700	36.7	4,020	179.1	22.0	
	Labor	-	-	-	-	-	-	900	7.5	1,200	6.6	420	18.7	2.3	For re-installing tanks
Filter material	Materials	467	2.8	467	2.6	467	1.9	467	3.9	933	5.1	560	24.9	3.1	
	Labor	-	-	-	-	-	-	-	-	-	-	-	-	-	Labor cost is minor
Sediment trap and diversion improvement	Materials	3,832	23.1	3,832	21.2	3,832	15.5	-	-	-	-	2,299	102.4	12.6	
	Labor	-	-	1,000	5.5	8,087	32.8	-	-	-	-	1,817	81.0	10.0	
Operation & Maintenance	Materials	25	0.2	560	3.1	25	0.1	25	0.2	25	0.1	132	5.9	0.7	
	Labor	150	0.9	400	2.2	150	0.6	150	1.3	200	1.1	210	9.4	1.2	
Sub-total	***Materials***	***9,935***	***59.9***	***10,470***	***57.8***	***9,935***	***40.3***	***6,413***	***53.6***	***12,363***	***67.7***	***9,823***	***438***	***53.8***	For non-research items
	Labor	***6,648***	***40.1***	***7,642***	***42.2***	***14,735***	***59.7***	***5,553***	***46.4***	***7,564***	***41.4***	***8,428***	***375***	***46.2***	
Total		**16,583**	**100.0**	**18,112**	**100.0**	**24,670**	**100.0**	**11,965**	**100.0**	**19,927**	**109.2**	**18,251**	**813**	**100.0**	
Costs for research purposes	*Materials*[2]	*23,496*	*55.2*	*23,496*	*53.3*	*23,496*	*46.2*	*23,496*	*61.8*	*23,496*	*53.0*	*23,496*	*1,047*	*53.0*	
	Labor[3]	*2,481*	*5.8*	*2,481*	*5.6*	*2,681*	*5.3*	*2,548*	*6.7*	*2,614*	*5.9*	*2,561*	*114*	*5.8*	
Sub-Grand Total	***Materials***	***33,431***	***78.6***	***33,966***	***77.0***	***33,431***	***65.7***	***29,909***	***78.7***	***35,859***	***80.9***	***33,319***	***1,484***	***75.2***	Including items for research
	Labor	***9,129***	***21.4***	***10,123***	***23.0***	***17,416***	***34.3***	***8,100***	***21.3***	***10,179***	***23.0***	***10,989***	***490***	***24.8***	
Grand Total		**42,560**	**100.0**	**44,089**	**100.0**	**50,847**	**100.0**	**38,009**	**100.0**	**46,037**	**103.9**	**44,308**	**1,974**	**100.0**	

[1] Based on an exchange rate of VND 22,446.9 in mid-2017

[2] Materials for scientific research purposes, including collecting water monitoring data and samples, transporting samples to laboratories

[3] Labour for scientific research purposes, including collecting water monitoring data and samples, transporting samples to laboratories

Year 2 (2018)

Cost Items	Category	M1		M2		M3		M4		M5		Average of 5 sites			Notes
		Cost ($\times 10^3$ VND)	% of Total	Cost ($\times 10^3$ VND)	% of Total	Cost ($\times 10^3$ VND)	% of Total	Cost ($\times 10^3$ VND)	% of Total	Cost ($\times 10^3$ VND)	% of Total	Cost ($\times 10^3$ VND)	Cost[1] (USD)	% of Total	
MAR establishment	Materials			1,033	31.2	-	-	345	32.3	3,146	134.3	905	39.6	38.6	
	Labor	560	45.1	1,600	48.3	360	57.4	505	47.3	2,098	89.6	1,025	44.8	43.7	
Filtration tank	Materials	-	-	-	-	-	-	-	-	-	-	-	-	-	
	Labor	-	-	-	-	-	-	-	-	-	-	-	-	-	
Filter material	Materials	-	-	-	-	-	-	-	-	-	-	-	-	-	
	Labor	-	-	-	-	-	-	-	-	-	-	-	-	-	
Sediment trap and diversion improvement	Materials	-	-	-	-	-	-	-	-	-	-	-	-	-	
	Labor	-	-	-	-	-	-	-	-	-	-	-	-	-	
Operation & Maintenance	Materials	-	-	-	-	-	-	-	-	-	-	-	-	-	
	Labor	682	54.9	682	20.6	267	42.6	217	20.3	217	9.3	413	18.0	17.6	
Sub-total	***Materials***	***-***	***-***	***1,033***	***31.2***	***-***	***-***	***345***	***32.3***	***3,146***	***134.3***	***905***	***40***	***38.6***	For non-research items
	Labor	***1,242***	***100.0***	***2,282***	***68.8***	***627***	***100.0***	***722***	***67.7***	***2,314***	***98.8***	***1,437***	***63***	***61.4***	
Total		**1,242**	**100.0**	**3,315**	**100.0**	**627**	**100.0**	**1,067**	**100.0**	**5,461**	**233.2**	**2,342**	**102**	**100.0**	
Costs for research purposes	*Materials*[2]	20,706	93.4	13,623	79.6	13,623	94.4	20,706	94.2	20,706	101.4	17,873	781	87.5	
	Labor[3]	215	1.0	181	1.1	181	1.3	215	1.0	215	1.1	201	9	1.0	
Sub-Grand Total	***Materials***	***20,706***	***93.4***	***14,656***	***85.6***	***13,623***	***94.4***	***21,051***	***95.7***	***23,853***	***116.8***	***18,778***	***821***	***92.0***	Including items for research
	Labor	***1,456***	***6.6***	***2,463***	***14.4***	***808***	***5.6***	***936***	***4.3***	***2,529***	***12.4***	***1,638***	***72***	***8.0***	
Grand Total		**22,163**	**100.0**	**17,119**	**100.0**	**14,431**	**100.0**	**21,988**	**100.0**	**26,382**	**129.2**	**20,416**	**892**	**100.0**	

[1] Based on an exchange rate of VND 22,877.5 in mid-2018

[2] Materials for scientific research purposes, including collecting water monitoring data and samples, transporting samples to laboratories

[3] Labour for scientific research purposes, including collecting water monitoring data and samples, transporting samples to laboratories

APPENDIX 5. Results from survey of the five households with MAR infrastructure

No.	Items	M1			M2			M3			M4			M5		
	1. Information about Household Head															
1	Name of household head	Tu Minh Hao			Y Khiem Nie			Ta Dinh Cong			Nguyen Hoai Nam			Ngo Minh Loi		
2	Sex	Male			Male			Male			Male			Male		
3	Age / Years in Farming	37 / 16			48 / 32			45 / 10			43 / 19			42 / 23		
4	Education level of the HH Head	9/12			5/12			12/12			8/12			12/12		
5	Ethnicity of the HH Head	Kinh			E De			Kinh			Kinh			Kinh		
6	Origin / No. of years in Dak Lak	Quang Binh / 34			Dak Lak / 48			Nghe An / 22			Phu Tho / 19			Phu Tho / 32		
	2. Details about the Household															
	Age class	< 15	15-60	> 60	< 15	15-60	> 60	< 15	15-60	> 60	< 15	15-60	> 60	< 15	15-60	> 60
7	No. members by age/No of female	1	3/1			7/4	1	3/2	4/1		2	2/1		2	2/1	
8	Other sources of HH income beside coffee	Pepper						Pepper, lemon			Pepper, durian, avocado					
	3. Farming information															
	Parcel	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*
9	Area of each parcel (Ha)	1.60			1.00	0.60	0.40	0.50	2.00	-	1.30	0.60	-	1.20	0.35	0.40
10	Area irrigated by ground water (Ha)	1.60			1.00			0.50	2.00		1.30	0.60				0.40
11	Area irrigated by surface water (Ha)					0.60	0.40							1.20	0.35	
12	Area not irrigated (i.e. rain fed)															
13	Crop types grown on each parcel (C; coffee, P: pepper)	C+P			C	C	C	C	C+P		C+P	C+P		C	C	P
14	Watering system on each parcel (S: sprinkler, B: basin)	S+B			S+B	S+B	S+B	S	S		S	S		S	S+B	S
15	Which parcel listed above is irrigated by the MAR well	No			No. 1	None	None	No. 1	None		None	None		None	None	None
	4. Water facilities															
16	Number of dug wells/boreholes	4/0			2/0			3/1			1/1			2		
18	Wells / boreholes equipped with electric (E) or diesel (D) pump	2E / 0			2E / 0			2E / 1E			1E / 1E			2E / 1E		

No.	Items	M1	M2	M3	M4	M5
19	Domestic water supply source	Well	Well	Well	Well	Borehole
20	Drinking water source	Well	Well	Well	Well with a filter	Borehole
21	Who is responsible for domestic water	Everyone, except kids	Everyone except kids	Everyone except kids	Everyone except kids	Everyone except kids
22	When irrigation is needed? In which months irrigation water is not sufficient?	Dry season / 3	Dry season / 3	Dry season / 3	Dry season / 3	Dry season / 3
23	Groundwater levels in wells compared to the past (1,5, 10 years…)	No change	Lower	No change	Unknown	Unknown
	5. Opinion about MAR					
24	Do you understand why the MAR system has been installed on your farm?	- Raising groundwater table in the area - But this water project does not have money to lease land and hire dug wells from local residents	- Raising groundwater table in the area - But this water project is financed by foreign organization	Improving - Increasing groundwater source for coffee irrigation in the dry season	Leading runoff from rainfall into the dug well to raising groundwater table in the area	The water project is implementing a pilot model that can improve the water availability and raise groundwater table in the area to cope with the fact that dug wells run dry in the dry season
25	Can you briefly explain how you think the system works	Runoff from rainfall → filtered out of mud and sediment → runs into the dug well → Raising groundwater level in the dug well	Water from rainfall filtered out of mud and sediment → runs into the dug well → Raising groundwater level in the dug well	Water from rainfall filtered out of mud and sediment → runs into the dug well → Raising groundwater level in the dug well	Water collected from rainfall → filtered out of mud and sediment → runs into the dug well → Raising groundwater level in the dug well	Water collected from rainfall → filtered out of mud and sediment → runs into the dug well → Raising groundwater level in the dug well

No.	Items	M1	M2	M3	M4	M5
26	Would you be willing to take over the MAR O&M in the future?	No	Yes	No	Yes	Yes
27	If Yes: Do you need any support to do it?		If: - Many other villagers join me for establishing similar MAR systems - I can get some financial support to cover investment and O&M including labor costs		If investment and O&M costs (including labor cost) are supported	If investment and O&M costs (including labor cost) are supported
28	If No: What is the main reason for declining?	I have sufficient water for irrigation. I do not believe in the benefits which the MAR system can bring		I have a drilled well, which can provide enough water for irrigation. I have sufficient water for coffee irrigation.		
29	Are their improvements that can be made to improve how the MAR system works? If so, please describe briefly.	The results of MAR implementation in the pilot area should be widely disseminated so that local people know and follow	- It is necessary to prevent the sediment from running into the well. - Rainwater cannot run into the well due to a lot of mud and sediment in the filtration tank →obstructions happen frequently → the filtration tank overflows	The filtration tank is small + Filtering velocity is slow + a lot of mud and sediment going to the filtration tank → the filtration tank overflows frequently	- The effect and benefit from MAR will be lost since the MAR systems established in a small scale + small filtration tank → the volume of water flowing into the well is small. - If MAR system is established in a large scale → big land area for MAR is needed and investment and O&M costs will be high	MAR systems can bring more effects and benefits if: - The filtration tank is larger and more rainwater flows into the well - Many other households in the area establish MAR structures together with me

No.	Items	M1	M2	M3	M4	M5
30	Have you noticed any differences in your water supply because of the MAR?	I cannot see any difference in the water supply between the times before and after MAR established.	I cannot see any difference in the water supply between the times before and after MAR established.	I cannot see any difference in the water supply between the times before and after MAR established.	- There is no difference in the water supply situation between the times before and after the MAR system has been established. - For neighbouring households, the situation of water supply is not getting better after the MAR system has been established	There is no difference in water supply between the times before and after the MAR system has been established.
31	If yes please explain briefly about changes in water quantity/quality					
32	Would you recommend the MAR system to other farmers in your area?	No, because I do not see any effects and benefits from the MAR system.	No, because this is the business of local authorities and the 'water project'	No, because I do not see any effects and benefits from the MAR system.	Yes. If costs of investment and operation - maintenance (including labor cost) are supported.	Yes. If costs of investment and operation - maintenance (including labor cost) are supported.