LINKAGES BETWEEN IRRIGATION PRACTICES AND GROUNDWATER AVAILABILITY

EVIDENCE FROM THE KRONG BUK MICRO-CATCHMENT DAK LAK - VIETNAM

Final Technical Report

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Executive Summary

Groundwater plays a major role in Dak Lak province as it is vital for domestic water supply, supports coffee production through irrigation and maintains dry season flow in rivers. Dak Lak province regularly experiences periods of droughts with associated localized water scarcity due to falling water tables that impact water availability for irrigation (MK17 Project Team, 2013; CCAFS, 2016). Confronted with the need to provide sufficient water for irrigation while maintaining groundwater availability for other sectors, improving the irrigation practices of coffee farmers is the key to a sustainable water management in Dak Lak and more broadly across the Central Highlands.

Understanding the linkages between improved irrigation practices and groundwater resources requires an in-depth understanding that can be achieved through a small-scale, highly monitored catchment. Earlier work at the regional scale (Milnes et al., 2015) selected a suitable experimental catchment to be instrumented, within an identified water scarcity hotspot.

This small (≈1km^2) catchment was equipped in 2016 with a dense monitoring system of 9 groundwater level loggers, along with 1 weather station, 1 soil moisture station and 1 V-notch gauging station. In addition, extensive field visits were carried out between 2017 and 2019 to understand the irrigation practices and their changes over time. Data acquired included land use, direct measurement of abstraction and interviews of 56 farmers (out of ≈100 farmers in the catchment). This study site provides a pilot facility that is unique to the Central Highlands to examine the links between irrigation practices and the water resources.

Main results:

An appraisal of these linkages has been carried out in this experimental catchment and the main findings are as follows:

Irrigation practices:

1) Groundwater is by far the most important source for irrigation in the catchment; 65 % of the farmers use it, with the other 35 % use ponds. Further, for the 35 % using ponds, direct rainfall/run-off storage is limited compared to irrigation requirements supporting only 25 % of annual amount. The other 75 % of 'pond water' used for irrigation is groundwater baseflow 'captured' from springs and subsurface seepage used to refill the ponds and in turn used for irrigation instead of flowing downstream.
2) In addition to shallow wells which are extensively developed in the catchment, deep boreholes (typically ≈100 m deep) have started to be drilled in the last few years. Currently only 8 % of farmers own a borehole for irrigation in the catchment, but 37 % of farmers using other sources consider investing in a borehole in future. However, drilling success rates in this area seem low at 25 % according to local drillers. High initial cost and high risk has so constrained the development of deep boreholes.
3) Two irrigation methods are used in the catchment: basin and sprinkler. Other methods such as drip or mini-sprinkler have not been observed. Consumption for the two methods was directly measured on-site.

4) The average value for the basin method is 400 L/tree/round [*45 measurements, standard dev. = 145*] and for sprinkler: 700 L/tree/round [*55 measurements, standard dev. = 304*]. These values are similar to measurement carried out across the region as part of the project.

5) Since its introduction in the 2000's, the sprinkler is gaining quickly in popularity, particularly since 2012. According to farmers, this is mostly due to increased labor cost and labor shortages, and improved cost-efficiency. Today the large majority of farmers (65 %) in the catchment are irrigating with sprinkler; while they were only 35 % in 2010.

6) Despite farmer's perception of sprinkler as an "efficient" practice from a practical perspective, this study shows that sprinkler use in the catchment seem highly inefficient in terms of water. Field analysis showed that uniformity in application is a major issue, with only 40% of trees receiving a correct amount of water, the majority of trees being either under or over irrigated. Expansion in sprinkler use poses a serious threat in areas with similar conditions to Krong Buk district.

7) At present, sprinkler irrigation is not widely adopted. It is used by only 20% of farmers at the project scale. Since adoption has been regularly increasing since 2000's, its further expansion should be closely monitored due to the implication on water consumption.

Groundwater resources:

8) Based on literature review, recharge of aquifers from rainfall is high in the region, usually above 30% of rainfall. While it could be slightly over-estimated due to methods limitations, in the catchment, baseflow and water budget analysis showed recharge rates at ≈ 45% of rainfall.

9) Water level monitoring in the catchment confirms the hypothesis of previous research showing a greater seasonal variation in water levels at higher relative elevation (MK17 Project Team 2013; Milnes et al., 2015). This was also observed in MAR wells nearby (Pavelic et al. 2019).

10) Relatively high permeability of the weathered basalts ($K = 4.8 \times 10^{-05}\ m.s^{-1}$) and high gradients of 0.05 $m.m^{-1}$ are observed. Resulting velocities of groundwater in the catchment are expected to range from approximately 35 to 120 $m.year^{-1}$ and suggest water transit through the system in less than 10 years (a relatively short residence time for groundwater). These a values are in line with values estimated at MAR sites by Pavelic et al. (2019) of up to 95 $m.year^{-1}$.

11) Continuous monitoring of groundwater levels showed that:

    a. The delay between the on-set of the rainy season and significant recharge of the aquifer is approximately 60 days, confirming earlier observations in the region (Milnes et al., 2015) and highlighting the importance of the unsaturated zone properties (especially thickness) in water transfers.

b. In the weathered aquifer, 15-minute frequency monitoring shows that during irrigation events dug wells in the higher elevation can be depleted. However, water levels recover to pre-irrigation level within less than a half day following the end of pumping. This shows that such drying-up of wells in monitored locations are linked to over-pumping and the associated cone of depression rather than larger-scale water table lowering. Horizontal drilling to enhance the well capacity is one of the strategies employed by farmers to increase well capacity. The efficiency of such method should be further investigated.

c. In contrast to the upper weathered basalt, it is believed the lower fractured aquifer cannot support widespread development in the catchment, although it can support local irrigation with some degree of success. In this lower fractured aquifer, current monitoring in 1 borehole shows that irrigation abstraction affects levels in this aquifer at the end of dry season, and impacts of pumping can be observed several hundred meters away. The fundamental difference between the two aquifers should be highlighted, particularly as boreholes are often seen by farmers as a solution to water scarcity in the longer term.

12) Streamflow analysis showed that a large portion of the flow has been transiting through sub-surface, including groundwater. It showed that the onset of the irrigation season appears to dramatically accelerate the reduction of flow as baseflow in the catchment is diverted to ponds to be supplied to the fields. Based on these observation, it could be argued that improved basin irrigation farmers located on the higher elevation might result in higher baseflow, in turn, diverted to ponds to be used by sprinkler users. However, testing this hypothesis is beyond the scope of this study, but could be evaluated in future modelling.

13) Estimation of abstraction made based on both irrigation method and source of water shows that current extraction rate is in the order of 20 % of annual average recharge. This implies current use is largely within the boundaries of the available groundwater resources. However, sustainable development in the Dak Lak plateau implies avoiding negative consequences for downstream users and ecosystems. Although a degree of development of groundwater of 20% of recharge appears reasonable, at the seasonal scale, acceleration of baseflow recession has been observed in the critically driest month. Thus, the sustainability of current irrigation practices may be questionable.

14) *Whatif* scenario analysis showed that improvement in water usage could led to important saving in both groundwater storage and increased stream flow. It also showed that increased sprinkler adoption would have a negative impact if it is not done in conjunction with better practices. Wider scale study seem to show that farmer are moving to optimized use of water. This improvement in practice will lead to further water savings, even if sprinkler irrigation is increasingly adopted.

This assessment has provided a valuable first step that contributes towards a more holistic understanding of groundwater use for coffee irrigation. Flaws in the current understanding have to be addressed. Direct associations between the impact of training on streamflow and water levels could not be identified as changes in practices do not happen simultaneously but rather in a progressive way, making their quantification over a 3 year monitoring timeframe difficult. Other changes in the catchment (e.g. change in irrigation methods, change in land use etc.) also need to be accounted for as they might offset or enhance the gain from improved practices. Further research emphasis should also be put on re-designing soil moisture monitoring to better evaluate the fate of excess irrigation applications.

This assessment focused on the hydrogeological context and the ‘demand side’ of abstraction. In parallel, some research is also exploring on how to enhance the ‘supply side’. Increasing the available water through MAR systems is currently being trialed (Pavelic et al., 2019) as an option to boost the annual supply in groundwater.

Improved groundwater management in the Dak Lak region requires evidence-based policies and action. This experimental catchment and these initial results represent a valuable step forward to evaluate, document and analyze changes. This will eventually support a necessary coupling of understanding the on-farm practices along with hydrological changes.

Contents

List of Acronyms and Abbreviations

a.s.l:	above sea level
BFI:	Base Flow Index
b.g.s.:	below ground surface
CCAFS:	Climate Change, Agriculture and Food Security
CGIAR:	Consultative Group for International Agricultural Research
CHYN:	Centre d'hydrogéologie et de géothermie
DGoM:	General Department of Geology and Mines
CU	Christiansen Coefficient of Uniformity
ET:	Evapotranspiration
HRNS:	Hanns R. Neumann Stiftung
JICA:	Japan International Cooperation Agency
K:	Permeability
LULC:	Land-use Land-cover
MAR:	managed aquifer recharge
SDC:	Swiss Agency for Development and Cooperation
T:	Transmissivity
US$:	US dollars
VND:	Vietnam Dong
WASI:	Western Highlands Agro-Forestry Sciences and Technical Institute

Introduction

Located in the central highlands of Vietnam, Dak Lak province is one of the major coffee production areas (circa 40% of Vietnam's production). Irrigation is used to boost production and is mainly sourced from groundwater. Increased coffee production in the past decades went hand in hand with higher water demand for irrigation.

Regular droughts and lowering water tables in the end of dry season - leading in some locations to drying-up of shallow wells - are a major constraint to coffee production and securing incomes of small-scale farmers of the Dak Lak plateau (CCAFS, 2016). In parallel, studies (D'Haeze et al., 2003, 2005) have shown that farmers currently tend to over irrigate up to twice the optimal amount. Thus significant water savings could be made using optimal practices resulting in multiple benefits both for farmers, downstream users and the environment.

These findings provided ground for the Nestle-SDC[1] funded project "*Vietnam to produce more coffee with less water – towards a reduction of the blue water foot print in coffee production*. Through this project, knowledge and optimal practices for optimal irrigation have been disseminated to coffee farmers (Amarasinghe et al., 2015). In order to assess to which extent improved irrigation practices can translate into improved groundwater supply reliability and more sustainable groundwater use, an experimental micro-catchment has been set-up as a collaboration between CHYN[2] and HRNS[3] in 2016 with high-resolution monitoring of groundwater levels, a climate and a stream-flow gauging station.

This instrumented site aims to provide a useful tool to understand groundwater dynamics at the local scale and its linkages to change in irrigation practices. Ultimately research in the experimental catchment aims at (i) tracking changes in irrigation practices and (ii) assessing the impact of improved coffee irrigation practices on the groundwater availability at the farm level during critical late stages of the dry season and on maintenance of dry season river flows; (iii) provide science-based evidence for improved planning and management of groundwater use in Dak Lak region.

This technical report will be focusing on:

- *Evaluating current irrigation setting in the catchment in order to highlight trends in practices and provide measured, irrigation method specific, abstraction rates.*
- *Describing the groundwater resources dynamics of the basaltic aquifers, a prerequisite to address several practical questions (fluctuation of the water levels, response to rainfall and pumping).*
- *Establishment of a water budget analysis to provide a holistic understanding of the groundwater cycle components and a first-pass estimate of the current sustainability of the practices in the watershed.*
- *Providing a set of key messages for practitioners along with recommendations*

[1] Swiss Agency for Development and Cooperation
[2] *Centre d'hydrogéologie et de géothermie (CHYN) - Université de Neuchâtel - Suisse*
[3] *Hanns R. Neumann Stiftung (HRNS), previously E.D.E Consulting*

1. Study area

The Experimental micro-catchment site has been selected as a result of a first regional hydrogeological assessment (Milnes et al., 2015) on the Dak Lak basaltic plateau. This large scale assessment resulted in the hypothesis that that improved irrigation was more likely to have an impact in higher elevation areas due to:

-higher water-level fluctuations at higher altitudes due to topography-driven groundwater flow with higher water level fluctuation amplitudes at higher altitudes (leading to drying up of wells)

- thicker unsaturated zones at higher altitudes leading to higher buffer zones for intermittent water storage of excess-irrigation water

-longer distance to groundwater discharge areas (located at low altitudes)

Based on these findings, this micro-catchment has been selected as a suitable site for testing these hypotheses, as it is located at the highest elevation of the plateau and wells reportedly drying up at end of dry season.

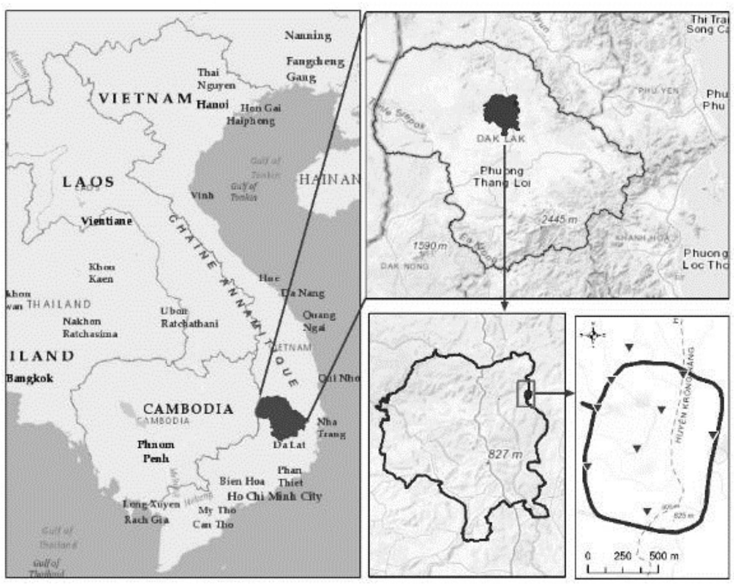


Figure 1 Location of the instrumented micro-catchment in the Central Highlands of Vietnam

The micro-catchment is located in the center of Dak Lak province (Figure 1) and has an area of circa 1 km^2 (0.91 km^2). It comprises of a central Y-shape drainage network, surrounded by higher elevation fields (Δh: 740 m to 800 m a.s.l). It is representative of the landscapes found in the Basaltic plateau. The upper profile consists of Rhodic Ferralsols, supporting today's coffee production. Annual precipitation in the area is 1,548 mm in average for the 2000 - 2010 period in Buon Ho station located 20 km south of the catchment. Most of the precipitation occurs during the 8-month wet season extending from May to December, followed by the dry season in January to April. The small-scale of the study site allowed in 2016 the deployment of a dense monitoring system of 9 groundwater level loggers, along with 1 weather station, 1 soil moisture station and 1 V-notch gauging station (Milnes et al., 2015). Figure 2 describes the monitoring network while the details of the equipment can be found in Appendix A.

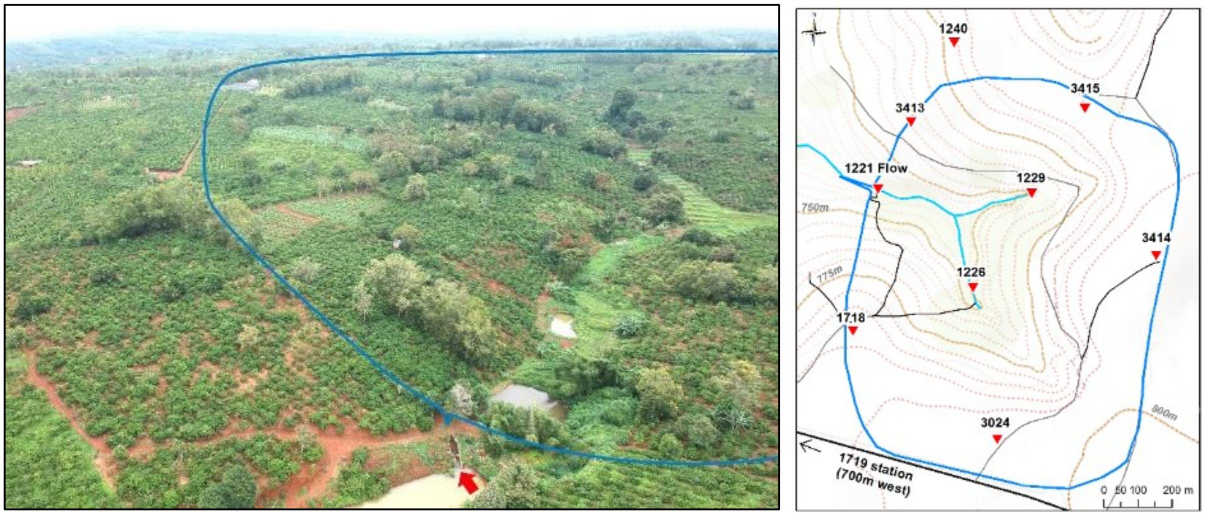


Figure 2 *Left*: photograph of the catchment, including partial contour of the catchment (blue line) and location of the catchment and gauging station (red arrow). *Right*: map of the experimental micro-catchment topography, main access tracks and monitoring network location.

2. Farming & irrigation practices

2.1. Farming and land-use

2.1.1. Farm size and number of farmers

Cadastral data were used to estimate the average farm size. Although bias exists (e.g. case of an owner of multiple farms) the average cadastral block in the study area was 9,200 m^2 a value consistent with the 1.13 ha average farm size observed in the project area (cf. Appendix B) and in the region (Rios et al., 2005; Ringler et al. 2017).A total of 118 cadastral blocks where identified, smaller blocks represented house and yards and field blocks confirmed that the average farm size is 1ha. This value is used as a proxy to estimate the number of farms in the catchment at approximately 100. An important specificity of these coffee farms is that often owners do not live on the farm but instead in nearby villages or further cities. They come to the site only during key periods (irrigation, harvesting etc.).

2.1.2. Land-use

The general land use consists mainly of coffee trees, with some larger trees kept for wind protection and shade (cf. photograph in Figure 2 above). Housing areas are mainly found near the main road. Pepper is also grown, usually close to the households. In the lowest parts of the catchment, the small valleys are mainly used for paddy rice cultivation (in the wet season) and as water storage ponds.

Imagery was used to map the land use in further detail. Aerial imagery allows capturing details of crops grown, size of trees, plantation densities, location of all ponds and in some cases dug wells and borehole drilling locations (Figure 3) cross-verification during field work was also carried-out.

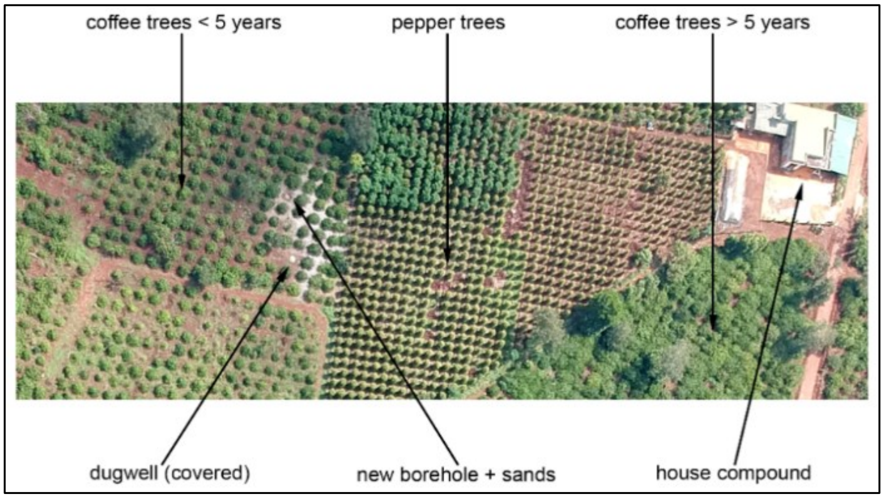
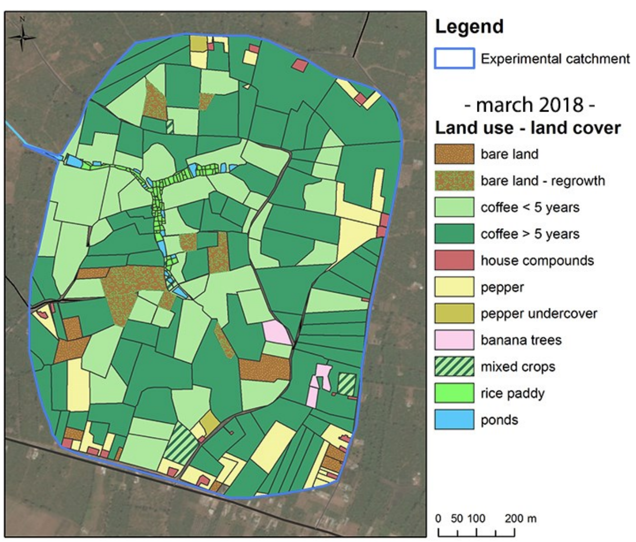


Figure 3 Features observed from sample image

Fully grown coffee trees represent by far the most important crop. In several fields younger trees are in place, with soil exposed in-between the trees. In total coffee production represents more than 80 % of the total area (75 ha). Pepper represent the second most important crop (6.5 ha) and is sometimes grown under a large plastic mesh to avoid direct sun exposure (cf. photograph in Appendix I). In some locations, coffee trees have been removed, and bare soil is exposed, with in some cases seasonal rain fed crops grown during the wet season. Paddy rice area is limited in extent with only small plots cumulating to 1 ha in total. Different from coffee and pepper, paddy is mostly rainfed. It is grown mainly during the wet season and left as fallow rest of the year. 26 house compounds are located in the catchment usually in the higher areas near roads. It should be noted that several other houses are located just outside of catchment, south and east near the main road. The *Figure 4* gives an overview of the land use – land cover (LULC) in the catchment.



Land use - land cover	Total area (ha)	Field size avg. (ha)
bare land	2.16	0.24
bare land - regrowth	3.02	0.38
coffee < 5 years	24.87	0.47
coffee > 5 years	50.19	0.60
pepper	6.08	0.20
pepper (plastic shading)	0.40	0.20
rice paddy	0.99	0.01
mixed crops	1.05	0.18
banana trees	0.72	0.24
ponds	0.48	0.03
house compounds	0.68	0.03
Total area	90.64	

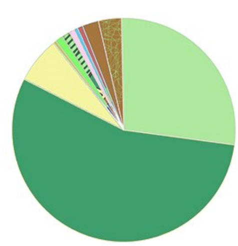


Figure 4 LULC in the experimental catchment in March 2018 and table of total area and average field size for each typology identified.

2.2. Irrigation practices

2.2.1. Brief methodology

In order to understand the actual irrigation practices in the catchment, field visits and measurements where complemented by short interviews of 56 farmers. The interviewees were selected in a random way (as being present on their farms) and attempting to capture the whole catchment (lower and higher areas). With approximately 50 % of the estimated total number of farmers being interviewed, it can be assumed that this is highly representative of the catchment practices.

Interviews were designed to be short and comprehensive. The set of questions, spanning from water source to changes in irrigation practices, can be found in Appendix C.

In parallel, during the irrigation period, the effective abstraction was measured directly on-farm using discharge measurement, irrigation duration per tree and in the case of sprinkler irrigation complementary questions. The measurement sheet developed by HRNS technicians can be found in Appendix D. In the catchment direct measurements were done in 25 farms. These data were supplemented by another set of 75 measurements done outside the catchment but in the same region (HRNS data collection, 2018)

2.2.2. Sources of water for irrigation

Interviews with farmers showed that aside from water accessed through wells, surface water storage also plays a significant role. Up to 35 % of water currently comes from surface water storage, with the other 65% from wells and boreholes. These usage patterns are in line with earlier observations in the region (D'haeze et al., 2005).

In the past only dug wells and ponds were used to access groundwater. The last decades have witnessed a steady increase in water access infrastructure. Development of irrigated coffee accelerated in the 2000's and it is assumed that from 2010, the catchment was fully developed. The *Figure 5* describes the evolution of water source in the last decade.

Since 2014, boreholes are drilled in the catchment for irrigation and farmers seem to favor this technology in future years. During interviews, 37 % of the farmers are considering using a borehole in the future. At regional scale, deep borehole drilling is developing quickly and in an uncontrolled way (MK17 Project Team, 2013). Currently the main driver of change towards borehole drilling is water availability: 68 % mention "*not enough water*" as a main reason for changing or considering change in water source. As of 2018, according to interviewees, the cost of investment is usually the main factor hindering borehole drilling. Locally, prices of borehole are in the order of 300,000 VND [4] per meter (local drilling company, 2018. *Pers.com.*). If the borehole does not yield water (i.e. does not encounter water-bearing fractures) there is a 50% reduction of the price. Thus a 100 m deep borehole will cost circa 1,300 US$, with a risk of a net loss of 650 US$ if the borehole does not yield water. The risks seem particularly

[4] Equivalent to 13 US$ in 2018

high in the vicinity of the catchment with a success rate[5] as low as 25%, while this rate increases up to circa 100 % one kilometer West onwards from the catchment (local drilling company, 2018. *Pers.com.*). Thus, although often considered by farmers, it does not necessarily means that deep boreholes will eventually become a major source of water supply in future in this area, and the common belief that drilling a deep well will solve the water scarcity issue might not be true in this case.

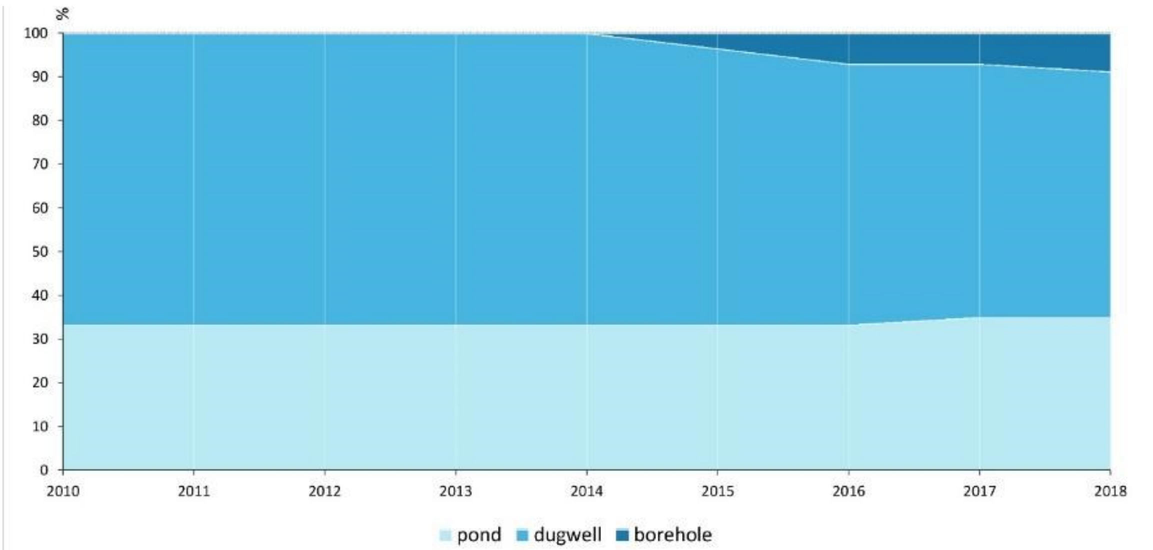


Figure 5 Percentage share of water source for irrigation in the experimental catchment, based on interviews of 50 % of catchment's farmers.

Aside from farmer-build small ponds, at the regional scale the government has been building dams for surface water storage. More dams for surface water storage are planned to be built in the future (Ringler et al., 2017; Unit 704, *2018 pers. comm.)*. Therefore it is likely that surface water storage will play an important role in future irrigation strategies. Recent studies showed that for irrigation of coffee using surface storage, water is usually transferred to a maximum of 2km away (Ringler et al., 2017). Thus increased surface water might ease pressure on the groundwater system in the vicinity of the system, but not in the upper parts of catchments, were water scarce hotspots are usually found (Milnes et al., 2015). At catchment scale intensification of such water source might lead to baseflow reduction for downstream users and increase sensibility to drought as surface storage has a lower buffer capacity than groundwater. A conjunctive use of surface and ground water might offer an alternative scenario. Based on limited observations, such conjunctive use (using both a surface water storage and groundwater) has been observed in the experimental catchment (this study) but not near larger reservoirs (Ringler et al., 2017).

[5] *Success rates gives the chances of a borehole to yield water. It is used mainly in heterogeneous aquifers such as hard rocks. Here 25% means that only 1 in every 4 borehole would provide sufficient water. It should be noted here that it is based on driller's experience and not statistics.*

2.2.3. Irrigation techniques

A recent study (Seelmann, L., 2018) showed that there are several irrigation methods used in Dak Lak province ranging from 'traditional' (Basin or Sprinkler) to more 'modern' ones such as drip irrigation. A comparison matrix of these methods (Seelmann, L., 2018) is provided in Appendix E. In the experimental catchment, only 'traditional' methods are found:

- **Basin irrigation**, where water is applied through a pipe directly to a dug basin around the tree of 2.5 m x 2.5 m. After a certain time, the farmers move the pipe to the next tree until the whole field is covered. This technique presents the advantages of (i) being of low investment costs, (ii) targeted watering to roots, (iii) easy maintenance. However, it is strongly constraint by labor availability, cost and time required to cover all coffee trees.
- **Sprinkler irrigation**, where a line of sprinkler heads is installed (1 to 3 heads) each covering 40 to 50 trees. This method simulates rain and cools down the atmosphere at the farm level. It is flexible in terms of soils and locations, removes dust from the leaves and prevents some pest infestations. A major point of this method is that it is much less labor intensive. The main constraint is the initial investment cost which is higher than basin. Several constraints might hinder sprinkler efficiency (uniformity of distribution, losses) as detailed in the next section 2.2.4.

The discussions with farmers seem to indicate a strong shift towards wide-spread sprinkler use in the experimental catchment (cf. Figure 6). According to interviews, sprinkler irrigation started in this area in the early 2000's. Until 2013, basin irrigation was the main method. From then, there has been a steady change, with more and more farmers switching to sprinkler. Today, sprinkler is the most common method, used by up to 65% of farmers as of 2018. Basin irrigation is still used by one third of the farmers in the catchment (35%).

The majority (58%) of farmers thinks that the sprinkler irrigation is "more efficient" as it "*does not require as much labor"* and is considered as "economical" in that it provides cost-efficiency. There are several drivers of change that can be considered:

- After a stagnation in the early 2000s, coffee prices increased, providing opportunities for farmers to save money to be re-invested in improved irrigation equipment
- In 2012, the government started to support 'High Efficiency Irrigation' through various decisions and decrees, with the Central Highlands of Vietnam as an important target (Ringer C., 2016)
- In parallel, labor costs have been increasing. Seasonal migration of laborers has been reduced due to overall development of Vietnam, thus finding labor forces becomes more difficult, making sprinkler an attractive option if investment funds are sufficient.
- 3-phase electricity is being deployed rapidly over the Dak Lak plateau and the area was likely connected to that grid in 2013 (Unit-704, 2018, pers. comm.)
- Sprinkler equipment's ubiquitous availability and lowering cost may be another driver of change.

There are strong indicators that this trend is likely to continue, as the large majority (75%) of farmers are considering this irrigation technique in the future suggesting more conversion from basin to sprinkler will occur. Although the catchment is located in an area identified as water scarce and thus possibly not representative of the Dak Lak province as a whole (as seen in Section 6 on up-scaling), this shift in irrigation method could be of prime importance for future management of the water resources.

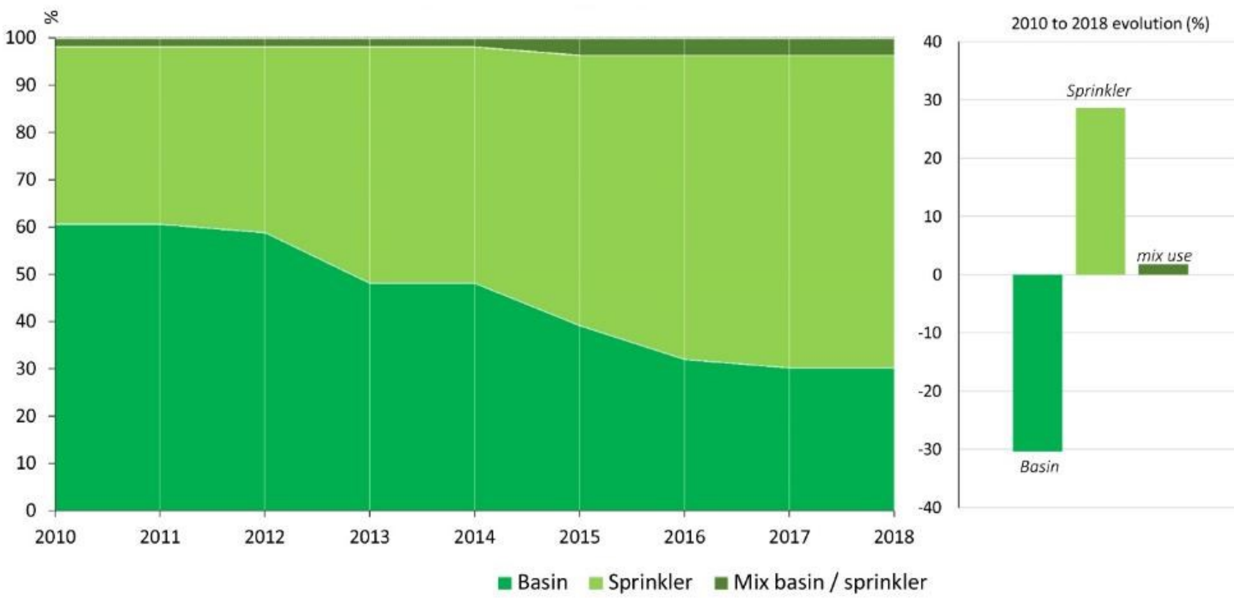


Figure 6 Percentage share of irrigation method in the experimental catchment, based on interviews of 50 % of catchment's farmers.

2.2.4. Sprinkler irrigation efficiency

2.2.4.1. Uniformity of distribution

As sprinkler irrigation seems to be increasingly adopted, its efficiency in delivering water to trees was assessed. Sprinkler seeks to provide a consistent spray of water across the field thereby providing a uniform soil moisture. In case of non-uniform distribution of water, there is a high risk of having under- or over-irrigated trees leading to either lower yield or wastage of water.

The efficiency of a sprinkler system is linked to two factors: (i) the uniformity of application; and (ii) the application losses (Keller and Bliesner, 1990). As pumping and piping setup are mostly similar between basin and sprinkler irrigation, here specific attention was given to the uniformity issue.

Uniformity can be estimated using the Coefficient of Uniformity (CU) developed by Christiansen (1942) as:

$CU = 100\ (1.0 - \frac{\sum|z-m|}{\sum z})$Where:

CU = coefficient of uniformity, in %

z = individual observations at each sample point from uniformity test, in mm

m = ($\sum z$) / n = mean depth of observations, in mm

n = number of observations

The observations have been carried out using ‘catch cans’ that were made using locally available material (cf. figure in Appendix I). Testing the uniformity using such locally made material, would allow, if distribution is uniform, to use these as simple and affordable indicators for farmers of when optimal irrigation has been reached using a single catch-can place in the field. 20 catch-cans were distributed across the planned irrigated area of a single sprinkler head. Catch-cans were placed in ‘pairs’ to test if coffee tree foliage led to variability in uniformity between root zone and inter-tree spacing. The sprinkler system was then switched on and water collected. A field sheet containing information on farmer practices and a map of the location of the catch-cans and associated results was collected for further analysis. A total of 6 locations were tested using this approach.

A typical map of results can be seen in Appendix F. For each site, first the CU was calculated (Table 1) then the amount collected was plotted against the distance from the sprinkler and the average irrigation. In ideal conditions of uniformity, most of the results should be along the average, regardless of the distance from the sprinkler head.

The results show that, for all sites, the CU values are very low, varying between 29% and 69%. There does not appear to be much literature on sprinkler irrigation specifically for coffee crops, but for general field and forage crops, values below 75% are considered very low, and for high value crops, a CU >84% is recommended (Keller and Bliesner, 1990).

Table 1 - Values of Coefficient of Uniformity (CU) estimated from field experiments close to the experimental catchment

Field site	Site D1	Site D2	Site D3	Site 13	Site 14	Site 15
CU (in %)	47	52	47	29	69	39

The CU results show that none of the sites follow ideal conditions and distribution of water is generally non uniform (cf. Figure 7 below).Windy conditions are a regular occurrence in the Dak Lak plateau but was not problematic on the testing days. However, light wind conditions (>10km/h) occurs very often during irrigation season.

Several explanations can be given for such low performance of sprinklers:

- Non-optimal pressure and sprinkler head often of low quality with damaged or eroded nozzle
- Most fields are on gentle slopes that lead to non-uniform application of water
- Windy conditions, although limited on the testing days, might affect the overall functioning in general as windy conditions occur very regularly on the Dak Lak plateau. This could further affect the CU measured and lead to even more reduced efficiency.

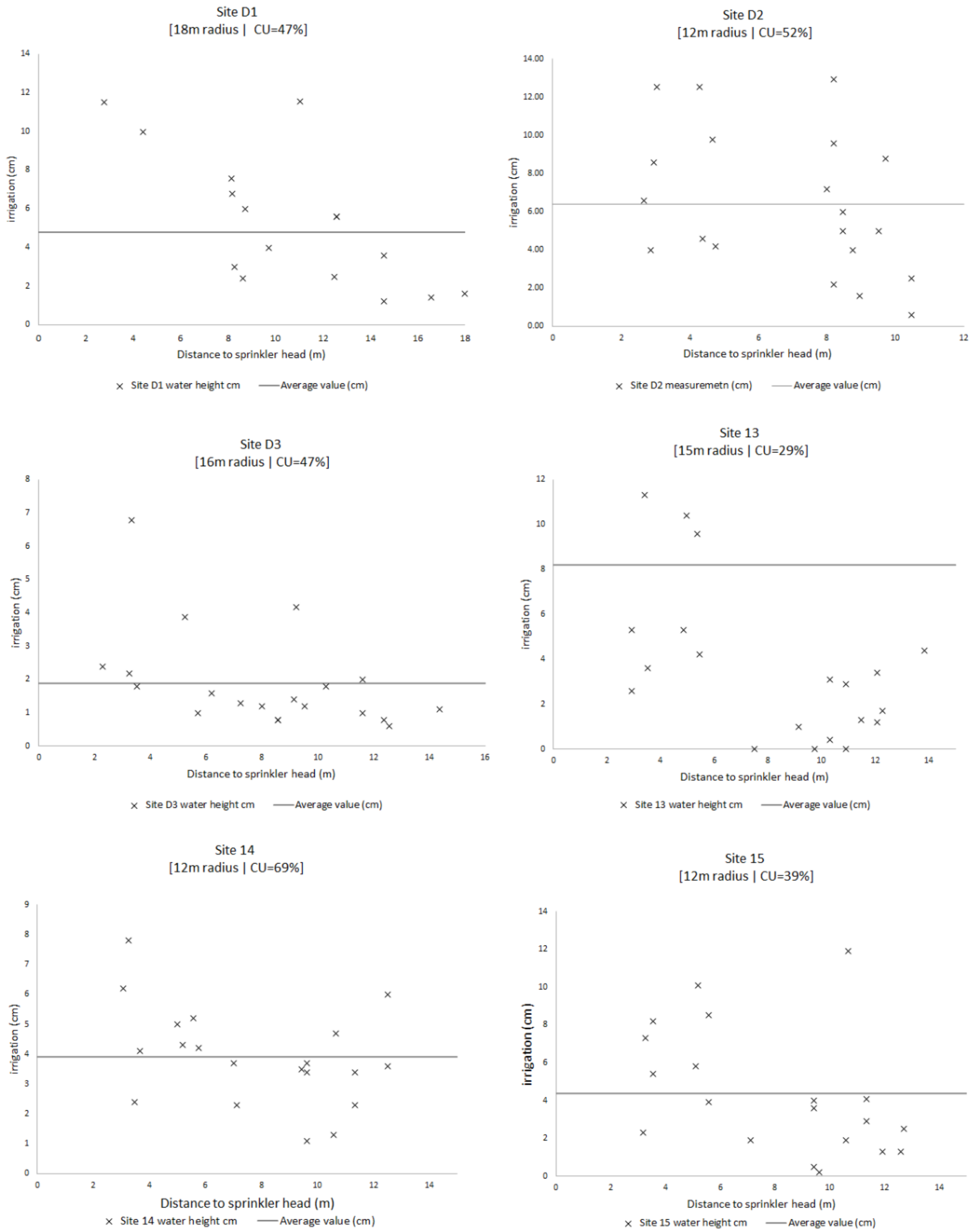


Figure 7 - Results of uniformity test for each sprinkler irrigation tested (6 sites, 20 samples per site). In a uniform system, the amount of water should be close to average value regardless of the distance from sprinkler head.

2.2.4.2. *Impact of low uniformity*

The low uniformity naturally leads to over- irrigation of some trees and under-irrigation of others. To represent the impact of low uniformity at the field scale, a first-pass estimate of water distribution (Figure 8) is based upon a total of 120 samples (20 at each site). For each sample, the difference relative to the average value of the site was calculated in percentage terms. Then across the 120 samples, the frequency distribution (number of occurrences) of the ranges of variability ranging from - 100% through to + 275% was calculated. Based on this calculated frequencies, it is possible to derive the corresponding frequency of water application for an assumed area of 1 hectare supporting 1,000 trees. Although the method lacks strong rigor, it at least gives a basic indication of the variability in irrigation rates under sprinkler.

The results (Figure 8) suggest that 29% of coffee trees are under-irrigated and another 28% are over-irrigated, with only 43% of trees receiving the an amount close to recommended values (400 L for basin and 600L for sprinkler.

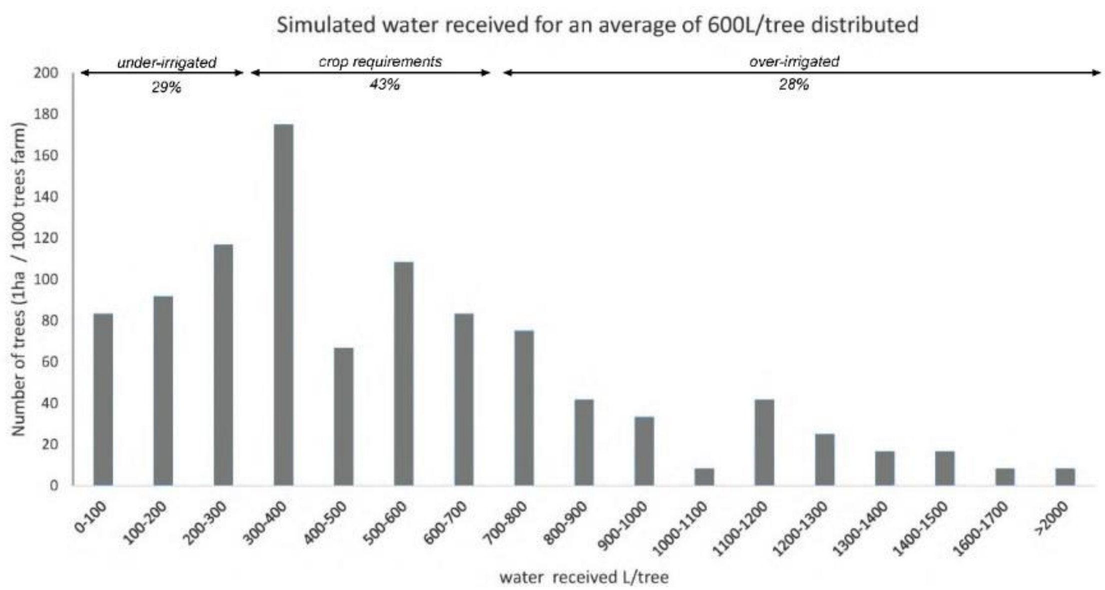


Figure 8 - simulated water distribution across a 1ha farm, with an average distribution of 600L/tree.

2.2.5. Spatial patterns of irrigation

During field visits and interviews, specific attention has been given in recording coordinates of both pumping and irrigation locations. This gives the opportunity to map spatial trends in the irrigation practices. Figure 9 synthetizes the practices. It shows that pipes for distribution of water from source to field are in average 250 m, and in some cases up to more than 500 m.

These values are in line with another study in Dak Lak province (Rios et al. 2005) that found an average value of 220 m.

In the lower elevation areas, a wide area extending from the drainage system is irrigated mainly by surface storage water. Average pipe length to irrigation point was calculated at 130 m.

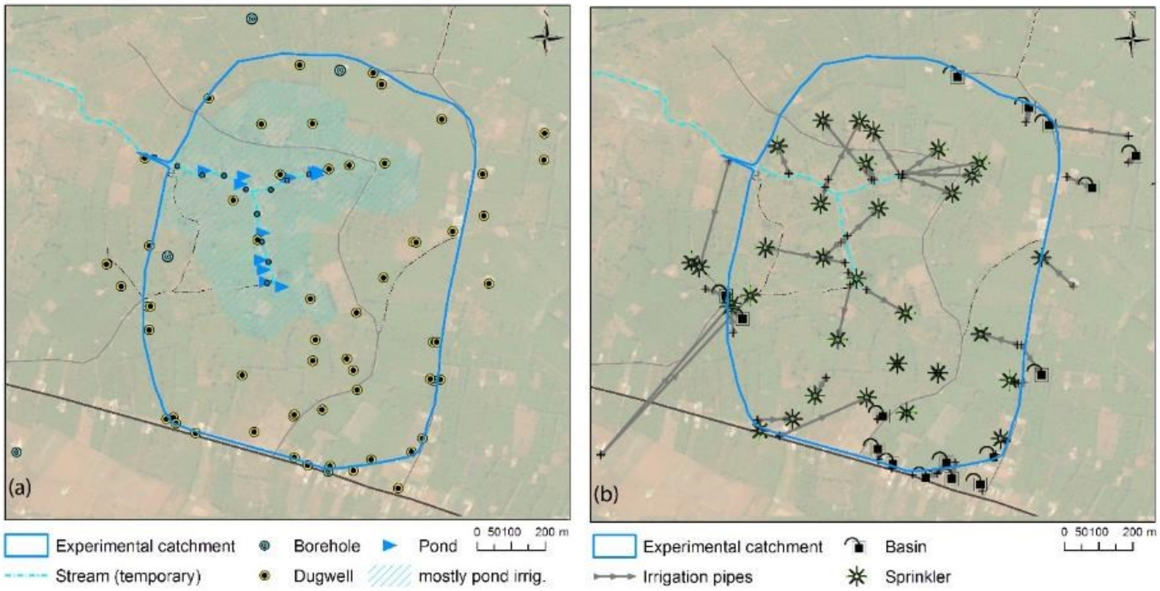


Figure 9 Map of irrigation practices in the experimental catchment

2.2.6. Water abstraction in the experimental catchment

Direct water use measurements in the experimental catchment (25) and outside the experimental catchment (75) shows a consistent difference depending on the irrigation technique. Water usage with sprinkler is nearly double at around 700 L/tree/round compared to 400 L/tree/round with basin irrigation.

The *Table 2* shows the measurement in the area and how they compared to recommended values

Table 2 - Commonly found water usage recommendations in Dak Lak province

Source	Irrigation	Recommended		Measured	
		L/tree/round	mm/year [a b]	L/tree/round	mm/year [a b]
HRNS (> 4years trees)	Sprinkler / basin	375	125		
HRNS (< 4years trees)	Sprinkler /basin	250	83		
WASI	unknown	500	165		
This study measured on-site	basin			411	135
This study measured on-site	sprinkler			732	241

[a] *considered 1,100 trees/ha*
[b] *mm calc. with similar amount at each round. In practice it is recommended (WASI) to apply more water during the first round and then reduce volumes in following rounds.*

These values show that basin users seems to have fairly good water saving practices, while sprinkler usage is far less effective in that regard. Such difference was expected given that the sprinklers cover also the canopy and space in-between trees while basin provides water directly close to the root system.

Frequency distribution analysis of water consumption allows to evaluate the variability in water usage for each irrigation technique (Figure 10). Basin irrigation usage displays a typical 'bell shape' distribution, with most of farmers using 300 to 600 L/tree/round. However sprinkler usage is much more variable with a skewed distribution and an average of ≈700 L/tree/round. This might be a sign that sprinkler irrigation is not managed in an accurate way leading to some 'randomness' in volume applied.

On-site, it could be true given the nature of the system, which has to be turn on and left running, with farmers moving to other locations and not strictly controlling the distribution time. However, this might also come from a bias in the measurement process, which differed from basin method as duration of distribution had to be asked to farmer rather than directly measured (cf. Appendix D). This might have introduced a bias in the results.

Thus in the future, particular attention should be given not only to evaluate management of sprinkler irrigation equipment, but also to improve the measurement protocol.

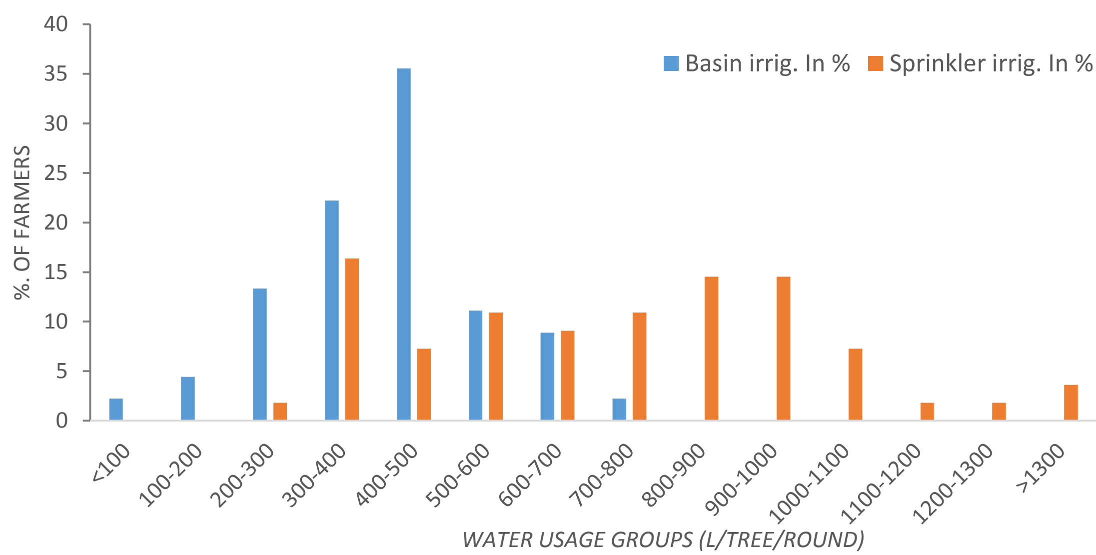


Figure 10 - Frequency distribution of water usage for coffee irrigation for each irrigation technique

In addition, it should be noted that using a much larger sample across the study area, recent results (D'haeze, 2019) confirms that sprinkler users consume more water. Results of statistical analysis showed trained farmers now use 400L/tree/round and 600 L/tree/round for basin and sprinkler users respectively.

3. Groundwater resources assessment

3.1. Conceptual understanding

The study area is centrally located within the plateau. This plateau consists of tholeitic basalts and subalkaline olivine basalts - also referred as *Tuc Trung formation* (ßN_2-Q_I*tt*) (General Department of Geology and Mines - DGoM, 1972). The thickness of this formation is estimated to be up to 243 meters.

The GDoGM published a regional 1:200.000 scale hydrogeological map (2003). Basalts in this case are described as having a "*relatively rich*" water storage capacity and associated yields of Q=1.5 L/sec. The thickness of the aquifer is estimated at 10 to 243 m. Based on an earlier set of data (*undated*) from GDoGM, JICA (2002) described the basalt having a thickness of 80 to 150 m, a predicted yield of 0.16 to 10.47 L/sec and a well specific capacity[6] of 0.01 to 3.59 l/sec/m.

The aquifer structure underlying the catchment is typical of the central plateau, described in several reports and derived from lithology available (JICA, 2002; D'Haeze 2005; DGoGM 2013; Milnes et al., 2015). The aquifer consists of a two layered system with:

- An upper unconfined aquifer, constituted of intensely weathered basalts. The rock structure is mostly lost and led to usually unconsolidated reddish soils of clays, silts and laterite (cf. typical lithography in Co4 borehole as recorded by unit 704 – Appendix G). In some cases, boulders are also observed (JICA, 2002). The lower boundary of the weathered aquifer is where hard and nearly un-weathered basalt is found.
- Below, a second layer consists of a confined to un-confined lower aquifer, formed by a series of slightly weathered, often fractured basalt, alternating with fresh basalt and thick clayey lenses, constraining the flow. Although there is no wide-scale study on depth of fractures and weathered layers, a reference borehole log (Co4 Borehole, Appendix G) suggests that productive fractures can occur at great depth, with productive horizons of variable thickness (0.5 to 7.5m) found at variable depths between 60 and 145 m b.g.s.[7]

The following Figure 11 displays rock samples for a borehole drilled near the catchment, the upper weathered section can be differentiated from the lower section composed of vacuolar basalt and massive basalt.

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[6] *The specific capacity refers to the quantity of water produced in a well per unit drawdown. (Poehls et al. 2011)*

[7] *b.g.s. refers to "below ground surface" and represent the depth from ground level.*

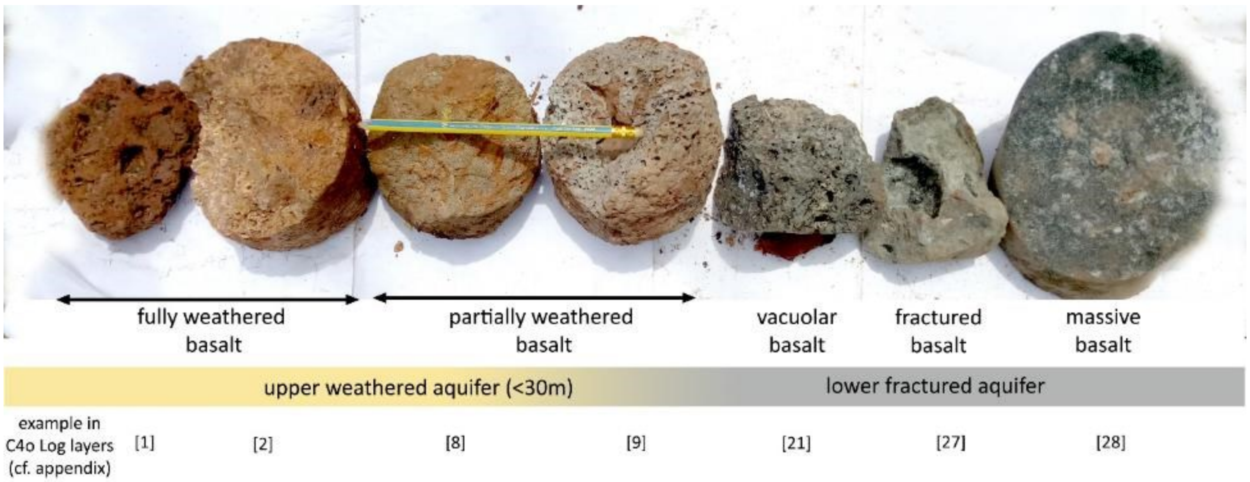

Figure 11 Sample rocks from a borehole drilled near the experimental catchment

3.2. Aquifer properties

Precise aquifer property data are scarce in the plateau, as it usually requires extensive pumping tests. JICA (2002) provides pumping test data for up to 18 locations. However, associated lithology (borehole log) necessary to associate the properties to an aquifer unit is only available for a few points. It still represents a useful proxy to understand the aquifer properties. A recent regional study (Milnes et al., 2015) also included pumping tests for selected monitoring boreholes representing each aquifer typology of the plateau. Test results in boreholes *C4o* and CB1-II specifically described the deep fractured aquifer and the upper unconfined weathered basalt respectively. The following Table 3 gives an overview of aquifer parameters:

Table 3 Summary table of basaltic aquifer properties in Dak Lak plateau

Well ID	Source	X UTM 49N	Y UTM 49N	Aquifer	Alt. (m)	depth (m)	T ($m^2.day^{-1}$)	K ($m.s^{-1}$)
D1	JICA, 2002	212271	1432676	Fractured basalt	714	140	47.0	1.39E-05
D2	JICA, 2002	196617	1461593	Fractured basalt	644	180	2.3	5.56E-07
D3	JICA, 2002	217070	1412609	Fractured basalt	484	140	26.0	9.95E-06
D4	JICA, 2002	209295	1427255	Fractured basalt	615	180	19.0	3.82E-06
C4o	Milnes et al., 2015	200339	1414808	Deep fractured basalt	645	170	0.6	1.00E-08
CB1-II	Milnes et al., 2015	190996	1414173	Weathered basalt	596	50	146.9	4.80E-05

T: Transmissivity; K: Permeability

As part of regional assessment, a first conceptual model of groundwater flow in the area was presented (Milnes et al., 2015). Assuming a regionally constant thickness of the upper weathered layer of circa 30 m, the authors showed that there are higher groundwater-level fluctuation in higher altitudes, in relation to distance to discharge areas. Similarly, the unsaturated zone is thicker in higher areas. The groundwater is flowing locally through the un-confined aquifer and often discharges into springs and streams. Underneath, the confined fractured aquifer supports some regional flows, as observed through artesian flow near the Srepok river.

3.3. Recharge estimates

Groundwater recharge is a useful indicator in terms of groundwater management. It allows quantification of the annual replenishment of a given aquifer and thus provides a useful proxy towards assessing the sustainability of the groundwater use in a defined area.

There are a limited number of studies in the Dak Lak plateau that included recharge estimates. Most estimations were made over large areas, often using a basin water balance approach (COWI-Kruger Konsult, 1996; JICA, 2002), water table fluctuation (D'haeze, 2005) or in some cases a spatialized water balance using remote sensing data (Milnes et al., 2015). Usually, variability in methods, scales and accuracy often leads to widely variable results in recharge estimates over a given area.

Interestingly, in the case of the Dak Lak plateau, there seems to be a strong consensus over the order of magnitude of recharge at circa 30 % of recharge (cf. Table 4 hereafter). However, these estimates tend to hide local variability, that has been highlighted by the regional GIS and remote sensing based analysis of CHYN (Milnes et al., 2015). The authors showed that there is an important variability of recharge over the 450 km^2 Krong Buk basin. Based on Milnes et al. (2015) results, the recharge-rainfall ratio (in %) has been mapped and its distribution estimated in order to highlight such variability across small distances, independently from rainfall (Figure 12). Recharge –Rainfall ratios ranged from 3% in urbanized areas up to 47% in the most favorable conditions

In this study, as part of the groundwater-budget analysis described in detail hereafter in section 4.2 p.30, the recharge has been estimated at 643 mm in 2017, or 49% of rainfall. It might be slightly over-estimated due to the method used in assessing the budget components, but the value remains in the order of magnitude of values found at the larger scale.

Table 4 Summary table of recharge estimates from literature in Dak Lak plateau

Data source	Secondary source	Method	Aquifer	Scale	recharge (mm)	Rech Avg (mm)	rain (mm)	R/R ratio **
Cheesman et al., 2005	COWI-Kruger Konsult (1996)	*unknown*	*weathered basalt*	Dak Lak plateau	480 to 500	490	1,580	31.01 %
JICA, 2002	-	WB-STM[1]	*weathered basalt*	Srepok basin 10,700 km^2	535	535	1,658	32.3 %
JICA, 2002	Srepok (DANIDA)	Spring baseflow	*weathered basalt*	Ea Co Tam spring (A=7 km^2)	510	510	-	-
D'haeze et al., 2005	-	WB, WTF[2], Baseflow	*weathered basalt*	Ea Tul watershed	W:743, A: 517, D:361*	517	1,845	28.02 %
D'haeze et al., 2005	Fortunel (2000)	*unknown*	*weathered basalt*	Dak Lak plateau	400	400	-	-
CHYN, 2015	-	WB-GIS[3]	*weathered basalt*	Krong Buk (458 km$^{2)}$- extracted for catchment	509	509	1,572	32.38 %
Cheesman et al., 2005	*unknown*	*unknown*	*Deep fractured*	Dak Lak plateau	10-20% of total rech.	73.5	-	-

**W: wet year; A: average year; D:dry year*

**: R/R ratio: Recharge rainfall ratio (in %)

[1] WB-STM: Water Balance - Sugawara's tank model

[2] WTF: Water Table Fluctuation

[3] WB-GIS: spatialized GIS analysis (rainfall-runoff-ET)

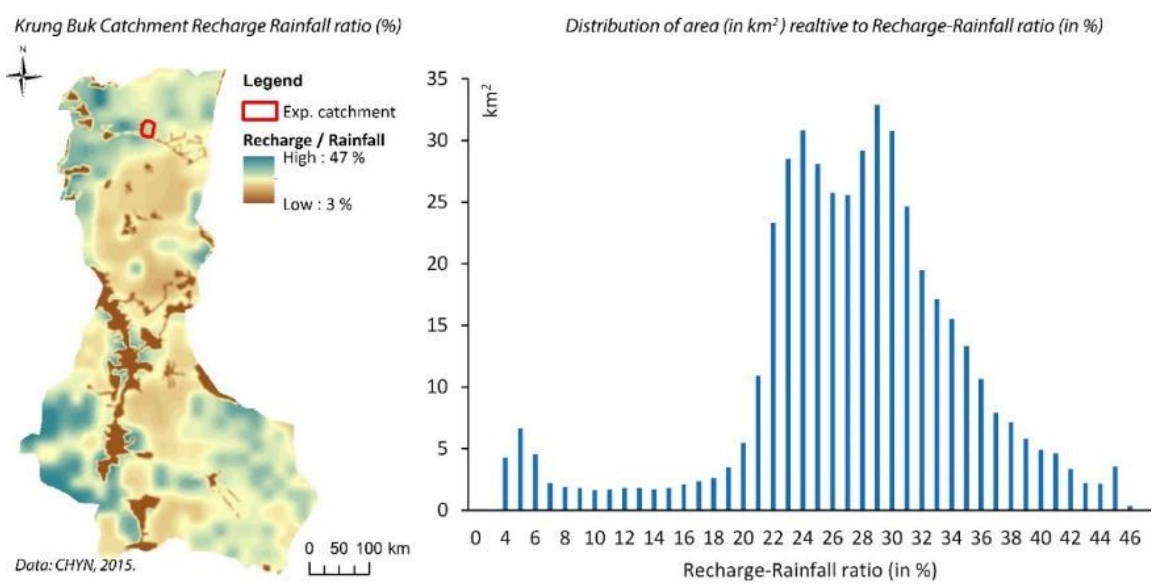

Figure 12 - Map of recharge-rainfall ratio in the Krong Buk catchment and aerial distribution of ratios.

3.4. Groundwater table, flow direction and speed and gradients

Field investigation allowed to identify 32 locations in the catchment were the groundwater level could be measured. **Error! Reference source not found.** describes the water table elevation both during the dry season (May 2018) and after the rainy season (October 2018), along with an estimated depth to the hard rock based on depth of dug wells.

The groundwater table is following to some extent the topography, and a sample groundwater flow line shows the convergence of groundwater flow towards the catchment outlet where the 1221 gauging station is located. Springs were observed along the streamlines and have been used to improve the interpolation.

The interpolated map can also be used to extract data to compare the unsaturated thickness, water level fluctuation and flow gradient during both seasons along the example of flow line A-B (Figure 14).

The measured groundwater levels and associated 2D profile confirms some of the hypothesis proposed by CHYN (Milnes et al., 2015) as it shows based on field evidence that in the catchment:

- Unsaturated thickness increases with elevation
- Water level fluctuation between seasons is greater at higher elevation and reducing closer to the lower areas
- Gradients vary from 0.02 $m.m^{-1}$ to fairly steep values of 0.08 $m.m^{-1}$

The typical velocities (or specific discharge) of groundwater in the aquifer can be estimated based on gradients and using Darcy's law.

Darcy law:

$$Q = -KA\left(\frac{dh}{dL}\right)$$

And Specific discharge as

$$v = -K\left(\frac{dh}{dL}\right)$$

Where

Q is the flow rate ($m^3.s^{-1}$)
K is the hydraulic conductivity of the aquifer formation ($m.s^{-1}$)
A the area normal to the direction of flow (m^2)
$\left(\frac{dh}{dL}\right)$ is the hydraulic gradient between two points ($m.m^{-1}$)

Typical hydraulic conductivity (K values) from literature in Dak Lak province have been reviewed in section 3.2 above Table 3). However, most of the pumping test seems to encompass both fractured and weathered components of the aquifer systems. Here in order to measure velocities through the upper weathered layer, the permeability value estimated by CHYN (Milnes et al., 2015) specifically for this layer of K = 4.80 x 10^{-05} $m.s^{-1}$ was used. Two typical gradients observed in the experimental catchment (i.e. $\left(\frac{dh}{dL}\right)$ min = -0.0230 $m.m^{-1}$ and $\left(\frac{dh}{dL}\right)$ max = -0.0785 $m.m^{-1}$) were used (see A-B section on Figure 14). Resulting velocities of groundwater in the catchment are expected to range from approximately 35 to 120 $m.year^{-1}$.

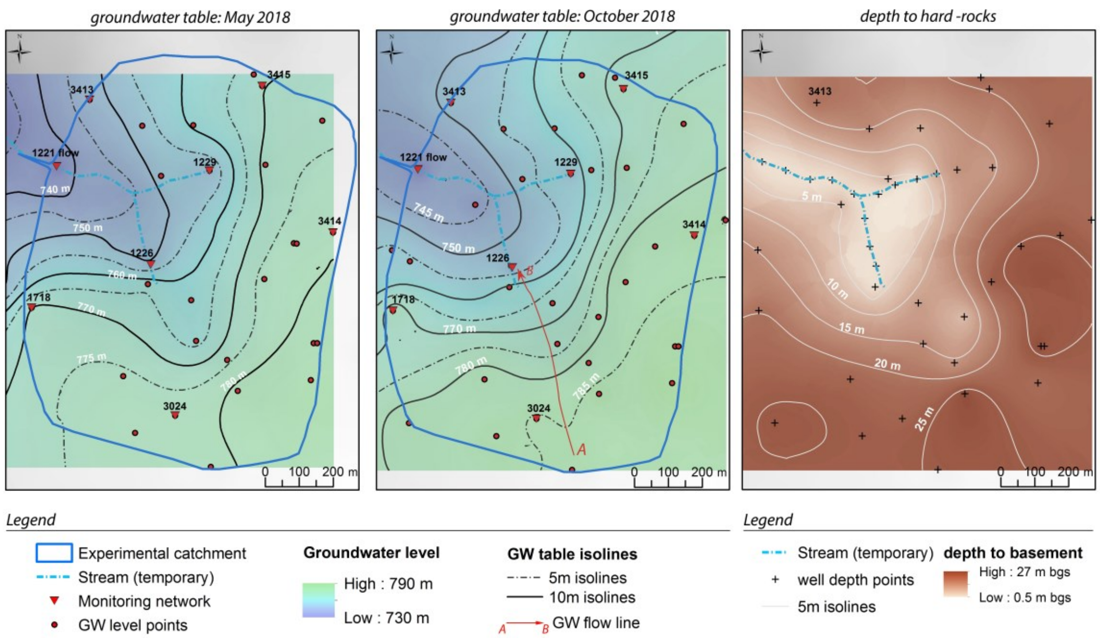

Figure 13- From left to right: Map of end of dry season and post wet season water table including an example of a groundwater flow line. Note: based on evidences of groundwater resurgences along the streams, interpolation was constrained with additional simulated points along stream lines. Right side: map of depth to hard rocks in the catchment.

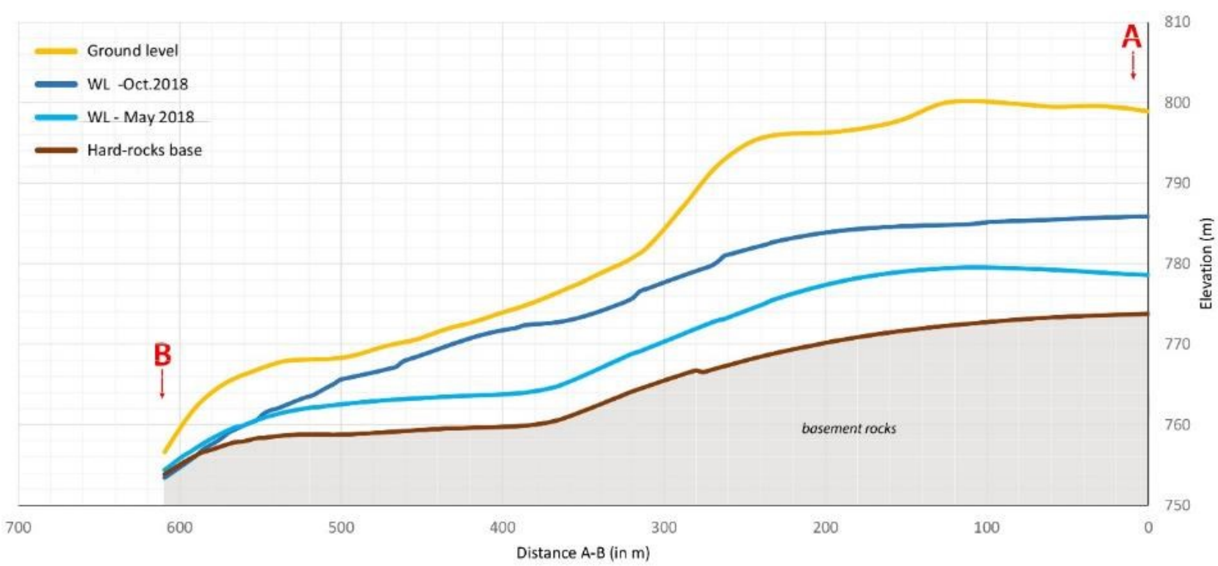

Figure 14 - 2D model of water table fluctuation and depth to hard rock based on interpolated field data

3.5. Groundwater level dynamics

3.5.1. Irrigation impact on soil moisture and recharge

One of the issues highlighted earlier by CHYN (Milnes et al., 2015) was that the important thickness of unsaturated soil (in some cases >10 m) might lead to excess irrigation not reaching the water table during the same dry season. Instead it would be stored in the unsaturated zone and cause lowered water tables in the end of the dry season. Eventually, this 'trapped' water would enhance recharge during next rainy season.

In consequence, in order to assess the impact of irrigation on recharge, a soil-moisture probe has been installed in 2016, originally coupled with water level measurements at station 1718. Several issues with the equipment had hindered the data collection. Some data has been retrieved and is used here. According to field visits, probe depth was set at 1m, below the root zone of coffee trees. Records of soil moisture (Figure 15) shows that during the 2017 and 2018 dry seasons, the soil moisture decreased steadily after December (approximately -2 % per month) until onset of irrigation season. In march-april, the soil moisture seems to raise, probably due to irrigation events, the signal is weak and much lower than expected in such context, particularly given the position of the probe supposedly located just below the root zone (≈60 cm). It is highly probable that the probe has not been placed in an appropriate location as it is located on the edge of a field near a house yard rather than within the coffee plantation. The coffee plantation owner is using sprinkler irrigation, which in practice will be installed in a way to avoid wetting the house yard. Thus it is believed that the recording location received much less water than the rest of the plantation and is not representative of the actual infiltration.

Given the importance of understanding the dynamics of excess irrigation, it is highly recommended in future studies to: (i) switch to install affordable, simple, multi depth soil moisture loggers[8] (ii) reconsider location of monitoring station and adaptation of the network to cover both irrigation practices.

[8] As example of supplier, see: Odyssey *Multi-Profile Soil Moisture Sensor Probe*: *http://odysseydatarecording.com/index.php?route=product/product&product_id=72&search=multi-Profile*

Figure 15 Soil moisture - showing a weak signal - and graphical estimate of natural recession without irrigation excess water infiltration (blue arrows)

3.5.2. Water level fluctuations

The data collected in the catchment were synthesized in Figure 16**Error! Reference source not found.**. It shows that the groundwater level fluctuation varies greatly across monitoring stations. This confirms calculations based on groundwater mapping (cf. section 3.4). Stations located on higher elevations (3414, 1719, 3415) display a much higher fluctuation between seasons (Δh > 4 m) than stations located very close to discharge points (1229) showing nearly no annual variation (Δh < 2 m). This confirms one of the hypotheses postulated by Milnes et al. (2015) in a regional study.

Regarding groundwater recharge, although the rainy season usually starts in April or May, significant recharge can only be observed in the end of August (2016, 2019) and July (2017, 2018). This delay of up to 60 days is due to (i) water moisture deficit during early rains and (ii) time needed for percolation to the groundwater table. It confirms other delays in response already observed in similar context (MK17 Project Team, 2013; Milnes et al., 2015).

4 years of observation in the experimental shows that there is no evidence of groundwater depletion. At all monitoring stations, the groundwater level decreases during the dry months but recovers to its highest elevation during the rainy season. Although the period of monitoring is limited to 4 years, it confirms observation over longer datasets in other locations in the Dak Lak plateau (Milnes et al., 2015).

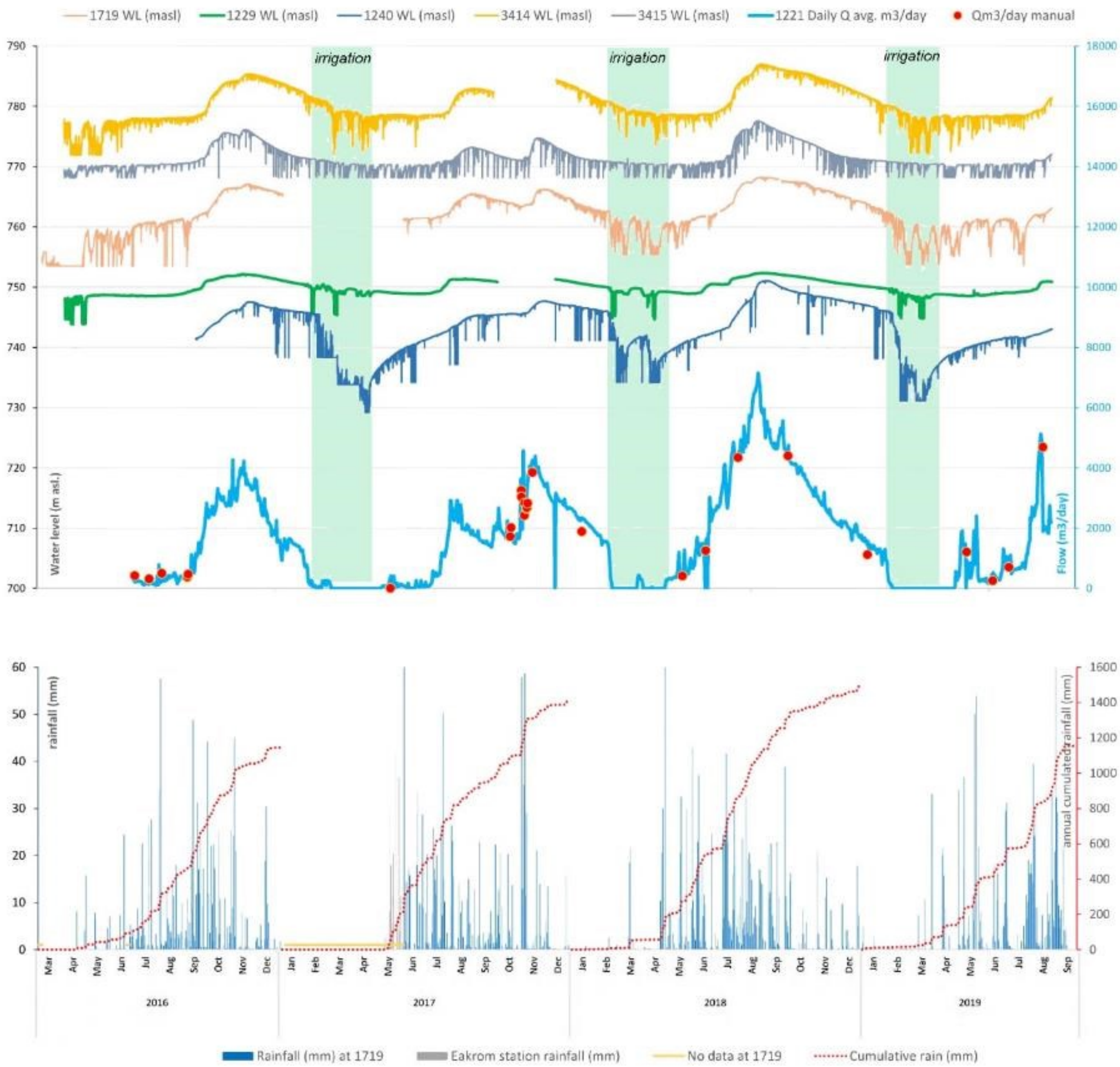

Figure 16 Synthesis chart of monitoring network data collected between April 2016 and October 2018, including water level elevation in monitoring wells (top), annual cumulated flow at gauging station (middle) and daily and cumulated precipitation at 1719 weather station. Note: in May 2017 the rainfall data was not available and instead retrieved from Eakrom station.

3.5.3. Impact of pumping on water level

High frequency monitoring allows to assess in detail the aquifer behavior during the irrigation season. For the 2018 hydrological year, 3 selected sites located (i) in the weathered aquifer in upper elevation (3414), (ii) in a deep borehole in the underlying hard rocks (1240) and (iii) in the weathered aquifer near a spring at lower elevation (Figure 17) are described in detail along with individual pumping events (Figure 18).

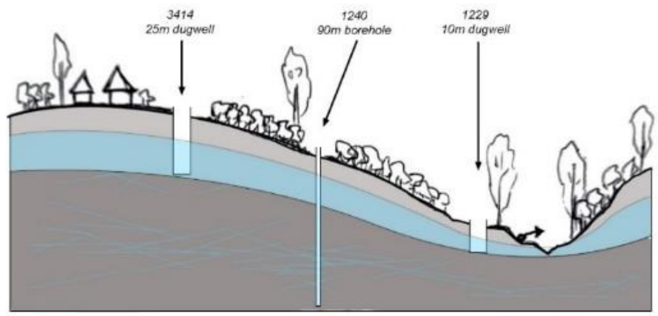

Figure 17 - location of selected monitoring points in various contexts

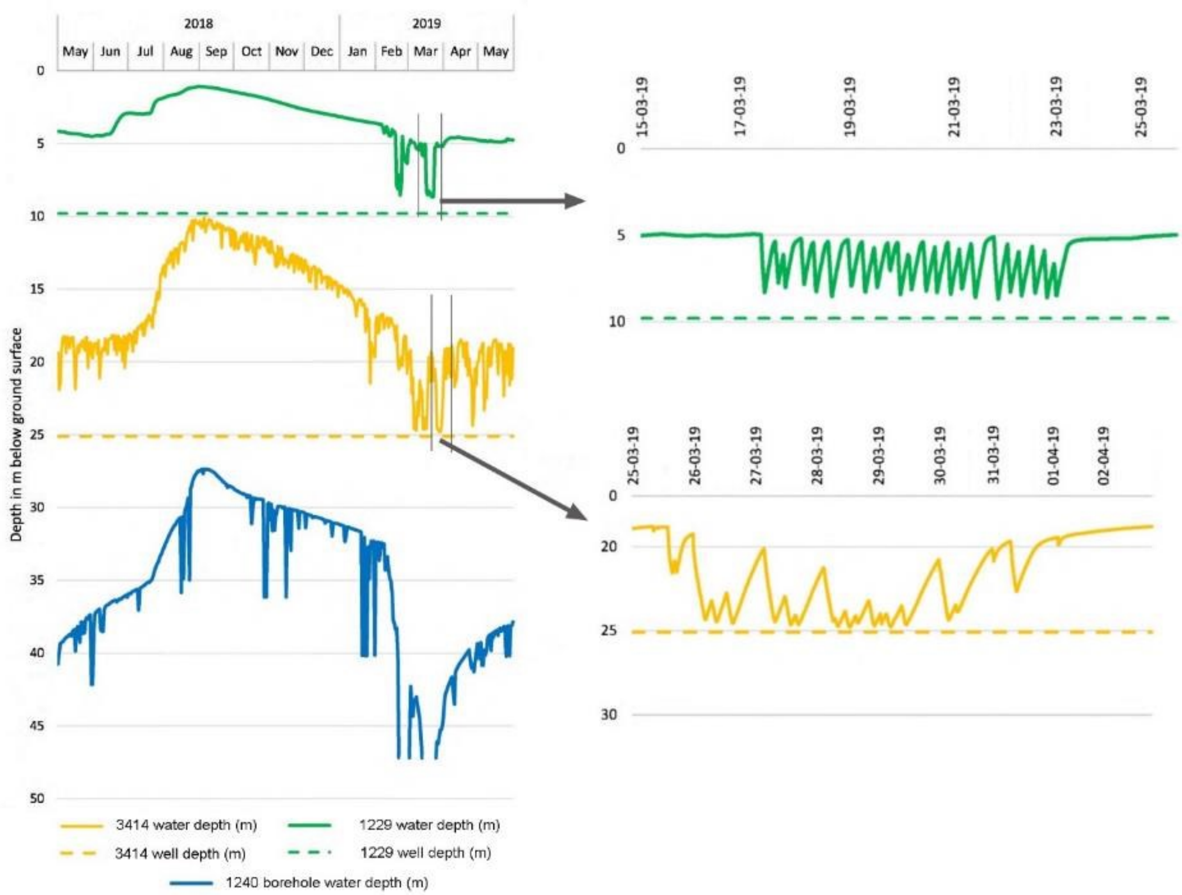

Figure 18- details of water level during irrigation events for 3 selected monitoring stations

3.5.3.1. Water table dynamics in the upper weathered aquifer

In the weathered aquifer (dug wells 3414 and 1229, yellow and green color in Figure 18 respectively) the impact of the irrigation seems limited in time. As 15 minutes frequency data shows, in 1229 dug well, located in lower elevation, the water level is close to the surface at 5m. Between 17th and 23rd of march 2018, the owner pumps regularly, but does not dry up the well (of 10 m depth) and water rises quickly when the pump is stopped. At higher elevation (station 3414), the owner dries up the well within two hours, then the pump has to be switched off to allow water level to rise a few meters before the pump is started again and quickly drains the well. It is interesting to note that in both cases (well dried up or not) the water level in the wells recovers within half-day to pre-irrigation event conditions. This shows that the well seems to be drying up not because the overall aquifer water table drops. Instead the pump capacity seems too high compared to the capacity of the well to provide water. As a consequence, the cone of depression when pumping induces depletion of the water in the well.

Field surveys of water abstraction in the catchment showed that farmers often pump in rates in the order of 2.5 L/sec. Such a rate is coherent with transmissivity <100 m^2/day (Krásný, 1993) that are found in the region (cf. *Table 3*). However, the limited thickness of saturated aquifer of only 5 m is constraining the capacity of wells. This problem is partially overcome by farmers through drilling horizontal drainage perpendicular to the well to maximize the flow.

Additionally, the total amount of groundwater abstracted during a year has been estimated (cf. 4.2.4 below) at 90mm across the catchment. Using a Specific Yield value (as representing the volume of water contained in rocks that can be extracted by gravity) of 0.12 (as in section 4.2.6 below), it can be roughly assumed that the total amount extracted corresponds to a desaturation of the aquifer of a thickness of 75cm only.

3.5.3.2. Water table dynamics in lower fractured aquifer

The monitoring station 1240 data, located in a deep borehole tapping the lower fractured aquifer shows a very different pattern: important pumping (3 farmers share the borehole, using a submersible pump) induces a significant drop in water table (> 15 m) that takes several month to recover and does impact significantly the water level at the end of the dry season. This slow recovery tends to indicate that the lower fractured aquifer presents a much lower transmissivity than the upper weathered aquifer, as described elsewhere in the literature (cf. 3.2, *Table 3*).

The high resolution of the monitoring (i.e. 15 minutes interval) enables to witness pumping events occurring outside of the irrigation period (e.g. during August 2017). This may indicate pumping for domestic water use, however the 1240 station is located in a field, away from houses and is locked. The nearest household is located 190 m away in SSE direction; the owner of this house confirmed the existence of a borehole in their house compound. Finally, daily analysis of the logger data shows that the water level is impacted in the early morning hours (between 5 am and 7am), a typical time of pumping for household needs. This observation supports that in the lower fractured basalt, water level can be impacted across long distances through connected fractured networks. This difference between the two aquifer dynamics is important to take into consideration in planning as different impacts of groundwater development have to be considered.

3.6. Stream flow analysis

A gauging station was installed in June 2016 and upgraded with a high-precision V-notch in September 2017. Stream flow is usually composed of three components: (i) direct run-off (water flowing at the surface without infiltrating in the soil), (ii) interflow (water infiltrating in the soil and moving laterally), and (iii) groundwater flow transiting through the aquifer. In practice, in streamflow hydrographs it can be impossible to distinguish between the 3 components separately (Bosch et al., 2017). Instead two components are considered: (i) *runoff*, composed of 'true' runoff and the fast moving portion of interflow and (ii) *baseflow*, consisting of the slower portion of interflow and groundwater flow transiting through the aquifer (Bosch et al., 2017).

The hydrograph separation (Figure 19) was carried out using Eckhartdt algorithm (Eckhartdt, 2005). Best calibration fitting in *BFI*[9]*+ software* (Gregor, 2014) was found with using parameters of α = 0.97 and BFI_{max} = 0.90. BFI*max* was estimated both using literature and graphic calibration fitting. The soil profile was considered as fairly permeable and the upper weathered aquifer considered as a porous media. Eckhartdt, 2005 recommends a BFImax value of circa 0.80 in this case and further research over 15 catchments in Brazil (Collischonn et al., 2013) showed that this value must be adapted to the context of the catchment and can vary significantly (0.95 to 0.52 in porous aquifers). The α parameter was estimated using recession analysis method from Eckhartdt (2008). Recession analysis was done for the month January 2018 (Appendix H). During this recession period, (i) the updated V-notch station was in function, (ii) no recharge occurred and (iii) no irrigation occurred yet.

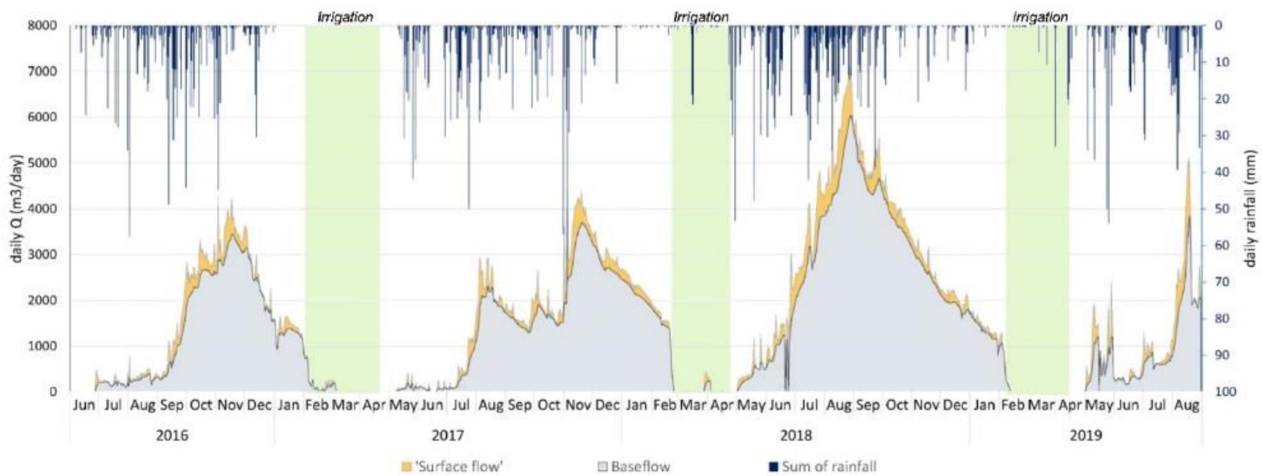

Figure 19 Streamflow recorded at gauging station. Lower graph presents the daily flow (m^3/day) with baseflow (grey) and run-off (yellow) separated. The upper histogram displays daily rainfall (mm) and irrigation periods (green) are represented to support interpretation.

Over nearly three hydrological years (2016-2018), hydrograph separation shows that stream flow is predominantly baseflow, with circa 90% of flow transiting through the groundwater component or as subsurface flow (Table 5). The rate of recharge is compared with rainfall for each year. R-R ratios are varying between 30.9% and 52.6% of rainfall. The lower bound of 30.9% is in line with recharge estimates in the region (cf. *Table 4*) while the upper bound corresponds to recharge estimates as part of the water balance in this study (cf. section 4.2.6). Those high estimates might be explained also by the

[9] BFI: Base Flow Index. Defined as the ratio of annual baseflow in a river to the total annual run-off.

difficulty to separate the actual baseflow (i.e. water flowing into the aquifer) and sub-surface flow that is accounted.

The impact of soil moisture will have implication on conversion of rainfall into storm flow and baseflow. Early rainfall does not induce much flow while rainfall on saturated soils will result in a peak of baseflow and storm flow. For example, 2017 rainfall was marked by an unusual high rainfall event during November – a time where the soil column is highly saturated in water content and led to a flow of up to 290 m3/h constituted of both groundwater and runoff.

Another important observation is the natural recession of the flow observed in the December –January period followed by a sudden drop in February corresponding to the onset of the irrigation season as observed in the monitoring network. Based on field evidence, this can be explained by a 'capture' of the baseflow through collection of flow in several ponds. This 'capture' occurs through a small stream that mainly conveys spring water (baseflow) after the end of rainy season. These are located mainly in the headwaters of the Y-shape drainage network (cf. study site map in *Figure 2*) and in some locations at the foothills along the stream. When the irrigation season starts, the farmers will divert the water from the small stream to ponds through temporary bunds and a piping system. Diversion starts in limited quantities to compensate loss through evaporation of run-off stored during the last rainy season and then at large scale to support irrigation after ponds have been emptied quickly during initial phase of sprinkler irrigation. Further estimates are given as part of groundwater-budget analysis (cf. section 4.2.3 hereafter)

Table 5- Quantitative results of baseflow separation.

	2016 (hydrologic year: April 2016 to April 2017)		**2017** (hydrologic year: April 2017 to April 2018)		**2018** (hydrologic year: April 2018 to April 2018 [incomplete])	
	m^3	mm	m^3	mm	m^3	mm
Total flow	364,991	401	505,356	555	808,258	888
Run-off	42,608	47	56,071	62	86,986	96
Baseflow	322,383	354	449,285	494	72,1272	793
Rainfall	1,043,826	1147	118,3831	1,301	1,371,799	1,507
	Run-off	Baseflow	Run-off	Baseflow	Run-off	Baseflow
Proportion	11,7%	88,3%	11,1%	88,9%	*10,8%*	*89,2%*
Baseflow / rainfall ratio	30,9%		38,0%		52,6%	

4. Transient water balance & groundwater budget

The water balance provides a useful tool to assess the relative importance of each component of the water cycle in the catchment. First, a conceptual model of the catchment has been developed to understand the water flow components and their linkages, as described in the Figure 20.

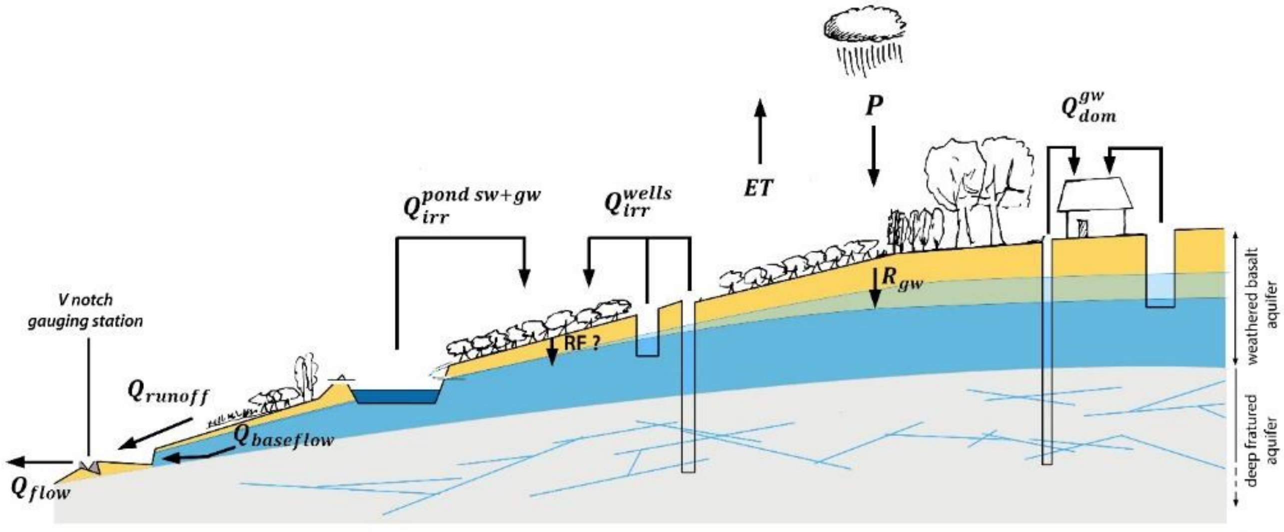

Figure 20 Conceptual model of the water cycle in the experimental catchment

The conceptual model can be described as:

$$\boldsymbol{P} = \boldsymbol{ET_{nat}} + \boldsymbol{Q_{flow}} + \boldsymbol{Q_{irr}^{pond\ sw+gw}} + \boldsymbol{Q_{irr}^{wells}} + \boldsymbol{Q_{dom}^{gw}} + \mathbf{RF} \quad \text{(equ.1)}$$

With:

$\boldsymbol{Q_{flow}} = \boldsymbol{Q_{baseflow}} + \boldsymbol{Q_{runoff}}$ and

$\boldsymbol{R_{gw}}$ the groundwater recharge component of the rainfall as:

$$\boldsymbol{R_{gw}} = \boldsymbol{Q_{baseflow}} + \boldsymbol{Q_{irr}^{pond\ gw}} + \boldsymbol{Q_{irr}^{wells}} + \boldsymbol{Q_{dom}^{gw}}$$

Where:

$\boldsymbol{P}$ is the precipitation in the experimental catchment

$\boldsymbol{ET_{nat}}$ is the total evapotranspiration

$\boldsymbol{Q_{flow}}$ is the flow recorded at the catchment outlet V-notch gauging station, and is a function of $\boldsymbol{Q_{baseflow}}$ and $\boldsymbol{Q_{runoff}}$ as the groundwater and storm flow respectively. These two components have been separated in previous section 3.6.

$\boldsymbol{Q_{irr}^{pond\ sw+gw}}$ represents the water stored in ponds and consists of the surface run-off captured during the rainy season (sw) and the additional baseflow captured from springs during the dry-season irrigation period.

$\boldsymbol{Q_{irr}^{wells}}$ is the groundwater abstracted from wells and boreholes for irrigation purposes.

$\boldsymbol{Q_{dom}^{gw}}$ is the groundwater abstracted for domestic water consumption of households located in the catchment

$\boldsymbol{RF}$? is the return flow from excessive irrigation percolating back to the aquifer, currently difficult to estimate due to limited instrumentation (cf. section 3.5.1) .

The model is based on a series of assumptions:

- Only the upper weathered aquifer is considered, flow of groundwater between this aquifer and the lower fractured basalt aquifer are considered negligible.
- There is no inflow of groundwater and all groundwater exits through the gauging station or through pumping.
- Groundwater pumped from boreholes is included in the balance, as often these boreholes tap from both aquifers.
- As observed in monitoring borehole trends, there is no observable increasing or decreasing trend in water levels on an annual basis and it can be considered that there is no change in water storage (Δh = 0).

Based on this conceptual model, two first-pass assessments have been carried out: a *transient water balance* will represent the temporal variability in inflows and outflows of the entire catchment (including the monthly Δh. Then a *groundwater budget* over a complete hydrological year will focus on the groundwater reservoir in particular and focus on assessing the sustainability of the current irrigation practices.

4.1. Transient water balance 2016-2018

Monitoring has started in the catchment in March 2016. Based on the conceptual model equation (equ.1), it was assumed that the transient water balance could be approached through a simplified version of (equ.1) as:

$\boldsymbol{P = ET_{tot} + Q_{flow}}$ **(equ.2)**

where:

$\boldsymbol{P}$ is the monthly rainfall in the catchment

$\boldsymbol{ET_{tot}}$ is the total evapotranspiration of the catchment, encompassing the 'natural' ($\boldsymbol{ET_{nat}}$) and 'irrigation induced' evapotranspiraiton from pumping.

$\boldsymbol{Q_{flow}}$ is the total discharge at the V-notch gaugin station, broken down as $\boldsymbol{Q_{baseflow}}$ and $\boldsymbol{Q_{runoff}}$

The variation in groundwater storage either positive or negative, is not represented here. It can be simulated as the closing component of the monthly balance.

Precipitation (P) data were obtained from the installed weather station 1719, and for short periods where data was missing, completed with nearby station of EaKrom (<50km). The 1719 station is located 900 m from the catchment (Figure 2). For evapotranspiration (ET_{tot}), estimation the evapotranspiration estimation was based on remote sensing products. Evapotransiration based on local climate was not used for this transient analysis as the weather station installed in 2016 had issues on some climate parameters (wind, humidity etc.) in limited periods of time. In remote sensing, several products are available and the *SSEBop v.4,* a sub-product of *MODIS data* was selected, as recent data was readily available for download. In terms of accuracy, annual totals for 2016 and 2017 were compared with previous estimates in the area (Milnes et al., 2015). Previous studies (Milnes et al., 2015) showed that MOD16 product annual ET was circa 1,200 mm and needed a correction factor to reach the estimated real ET of circa 850 mm per year. Here annual aggregations of *SSEBop v.4* monthly data showed values in the order of 850mm, demonstrating its relative accuracy. The monthly outflow $\boldsymbol{Q_{baseflow}}$ and $\boldsymbol{Q_{runoff}}$ of the catchment was derived from the flow analysis carried out in section 3.6.

Figure 21 presents the transient water balance for the April 2016 to October 2018. At the end of dry season (April-May), a delay of two month is observed every year between the beginning of precipitation and generation of baseflow and run-off similar to other regional studies (MK17 Project Team, 2013; Milnes et al., 2015). Subsequently, when IN-flow of precipitation ceases, the OUT-Flow through baseflow continues for at least a month before disappearing in February-March, due to both recession of the water table (natural and enhanced by pumping) and capture of baseflow in ponds for irrigation, as described in section 3.6. Figure 21 highlights the dry season periods with no or limited in-flow in the catchment and all out-flow sourced from either groundwater and soil moisture. A parallel study investigates how Managed Aquifer Recharge (MAR) could be used to store groundwater during the highest IN-Flow months and make it available during the driest months (Pavelic et al., 2019)

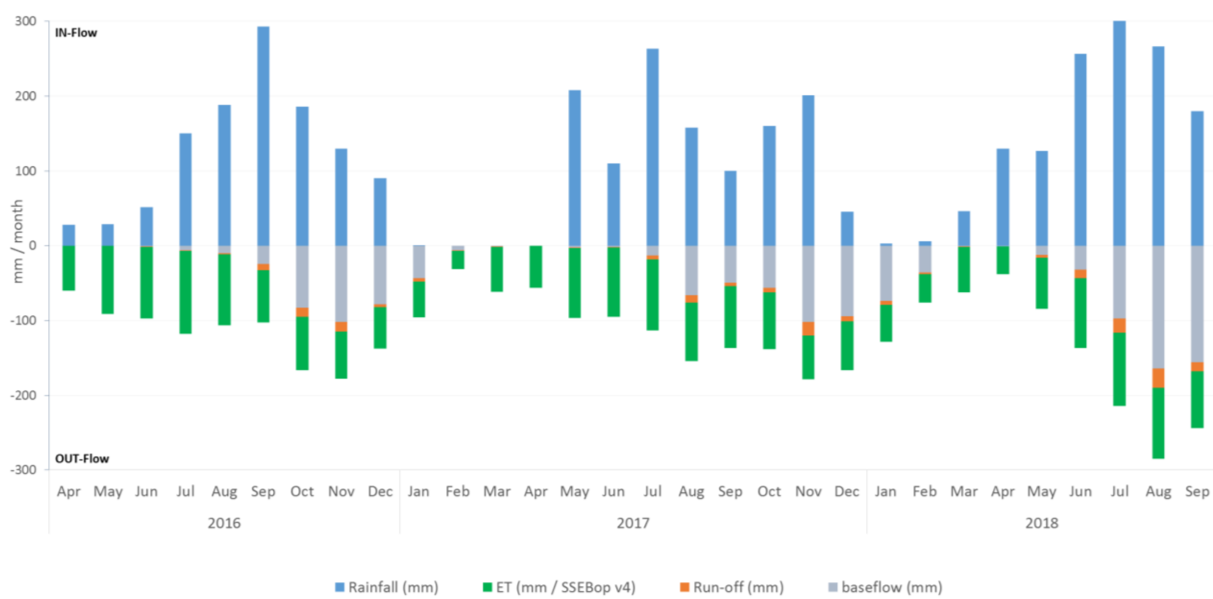

Figure 21 Transient water balance for the experimental catchment

The evapotranspiration presents a slight variability but is significant through every month, as expected given the perennial crops grown in the catchment (more than 80% coffee trees (c.f. section 2.1.2). The evapotranspiration from coffee irrigation can be observed particularly in March and April 2017, where after constantly decreasing in the previous month, the values are increasing without any rainfall. Although this signal demonstrates that the irrigation water used by the coffee trees is observable through remote sensing, it is difficult to separate the natural ET from the irrigation induced ET.

4.2. Groundwater budget

For the groundwater budget, the focus is to estimate as accurately as possible the in-flows and out-flows of the aquifer system. The assumptions used to build the conceptual model (Figure 20 above) are still valid. Recharge from rainfall and return-flow from irrigation can be considered as the only in-flows. Outflow is made of 3 components: the baseflow exiting the aquifer at the outlet, the baseflow captured in ponds during the irrigation period and the groundwater extracted through pumping in dug wells and boreholes, both for irrigation and domestic purposes. The groundwater budget on an annual basis can be expressed as:

$$\boldsymbol{R_{gw} + RF = Q_{baseflow} + Q_{irr}^{pond\ gw} + Q_{irr}^{wells} + Q_{dom}^{gw}}$$

The groundwater budget has been established for the hydrologic year 2017, spanning from 1st of April 2017 up to 31 march 2018 as it provides complete records of all budget variables, including on-site measurements of groundwater abstraction.

4.2.1. Return flow from irrigation

The significance of return flow from excess irrigation (RF) is not quantifiable with the current understanding of the unsaturated zone dynamics (cf. section 3.5.1). Previous research from CHYN (Milnes et al., 2015) pointed out that irrigation on soils with a moisture deficit is not likely to result directly in return flow to the aquifer in the same dry season. However, this is highly dependent on the unsaturated zone thickness, which in lower elevations is reduced to a few meters. Further, it is possible that the excess irrigation water stored in the soil enhances recharge later in the season. Thus return flow has been kept in the budget but not accounted for pending further research on the topic is carried out.

4.2.2. Baseflow at catchment outlet

The baseflow has been estimated using flow data from gauging station data and separation of surface run –off and baseflow contribution. Using 2017 data (Table 5) a value of $\boldsymbol{Q_{baseflow}}$ **= 494 mm** was used.

Table 6 Baseflow data for 2017 hydrological year

	2017 (hydrologic year: April 2017 to March 2018)	
	m^3	mm
Total flow	505,356	555
Run-off	56,071	62
Baseflow	449,285	494
Rainfall	1,183,831	1,301

4.2.3. Baseflow captured in ponds during irrigation

Diversion of baseflow into ponds was highlighted as an explanation of accelerated recession of baseflow at the onset of the irrigation seasons and described in section 3.6. Based on field-based records, it is possible to provide volumetric estimates of this baseflow capture, at more than 40,000 m^3 or 48 mm at catchment scale.

Table 7 First-pass estimate of baseflow capture through diversion to ponds for irrigation

Volume of run-off stored in ponds (m^3)	Total volume used from ponds* (m^3)	Baseflow diverted to ponds for irrigation (m^3)	Baseflow reduction at catchment scale (in mm)
14,441	57,780	43,339	48

***** *estimated based on pond area, tree densities, irrigation method, land use and field data.*

4.2.4. Groundwater extraction for irrigation

Aside from the area irrigated by ponds identified in section 2.2.5, groundwater is extracted mostly from open dug wells and in some case boreholes. Estimation of the volumes pumped over this area was estimated using:

- The high-resolution land-use map, allowing to map coffee field areas, both young and older and estimate tree densities in the catchment.
- Statistics of sprinkler and basin proportion within this zone, from interviews of 50% of farmers in the catchment that showed that 60% of farmer use sprinkler and 40% basin method.
- Water use based on measurements in the area (basin: 410L/tree/round and sprinkler 730L/tree/round). A constant 3 rounds of irrigation was assumed.
- Applying -20% usage for areas identified as young trees
- Accounting for limited irrigation for pepper fields.

Table 8 presents the result for each irrigated crop, a value of 90.8 mm at catchment scale is abstracted from the aquifer.

Table 8 Groundwater abstraction in the area irrigated with wells

Land-use - march 2018	Irrig. Method	Total area (ha)	Irrig. Use / year (mm)	Irrig. Use /year (m^3)
coffee < 5 years	basin irrig.	3.82	98	3,777
	sprinkler irrig.	5.74	175	10,091
coffee > 5 years	basin irrig.	14.46	123	17,835
	sprinkler irrig.	21.69	220	47,647
pepper	n.a.	6.06	50	3,035
pepper undercover	n.a.	0.39	50	199
			Total (m3)	82,585
			Total (mm in catchment)	91

4.2.5. Domestic groundwater abstraction

There are 26 households located in the catchment. Aside from bottled water that is used for drinking purposes, groundwater is the only source of water supply for domestic use and small livestock. Detailed monitoring data shows that this use is limited. Interviews with owners showed that usage is often around 500 l/day/household. The highest value found was 1,000 l/day/household. For using a groundwater budget, it is recommended to use a 'risk-averse approach', i.e. overestimating the domestic abstraction given its importance for livelihoods. Here this value of 1,000 l/day/household has been applied to all 26 households as a conservative approach. This represents 9,490 m^3 per year or 10 mm per year over the catchment.

4.2.6. Groundwater recharge

Groundwater recharge is often difficult to estimate. As described in section 3.3, there is relative consensus in the basaltic plateau of Dak Lak that recharge rates are high, often above 400 mm (circa 30% of the annual rainfall). Here, as based on the assumptions of the conceptual model established earlier, the recharge has been defined as closing the balance after all out-flow components have been estimated. Recharge is estimated at 643 mm, representing 49% of rainfall. This value seems high, but is supported by measured baseflow values representing most of the out-flow. One explanation would be that the baseflow separation has overestimated the recharge through consideration of inter-flow as baseflow (cf. section 3.6).

As a quick cross-check, a simulated recharge using the 30 % of the rainfall ratio found in the literature would yield a recharge of 390 mm. further, the water table fluctuation method can be used to estimate the recharge. The water table fluctuation method is based on the assumption that recharge can be estimated in unconfined aquifers as the change in water level multiplied by the available storage within the aquifer, expressed as specific yield. Here GIS analysis shows that average water table fluctuation is 4.1 m in the catchment. Specific yield (Sy) values of weathered aquifers in the literature vary, but based on studies in weathered basalts in India (Varade et al., 2014) a value of Sy = 0.12 (dimensionless) has been used. In this case a broad estimate of the recharge would be 490 mm.

The estimates in the literature are made upon much larger scale and calculations in section 3.3 showed that on smaller catchments with suitable conditions, recharge values are higher. Also, estimates based on water-table-fluctuation might not be appropriate in the catchment as it presents a wide variability in level variation. Thus although indicating that recharge estimate from baseflow might be overestimated, should be taken with caution and requires further research; it does not discard its validity for the groundwater budget analysis as a first-pass estimate.

4.2.7. Groundwater budget results

The groundwater budget (Figure 22) shows that the current abstraction from groundwater is 21.6 % of recharge, showing that on an annual basis, the current abstraction seems to be within the boundaries of available annual resources. Less than 2% of the annual recharge is consumed for domestic purposes and 75 % of the recharge leaves the catchment as baseflow. It should be noted that this annual balance might hide seasonal issues such as streamflow reduction observed during onset of irrigation season. In consequence, although appearing positive in terms of availability, it is possible that the current situation is not within sustainable boundaries.

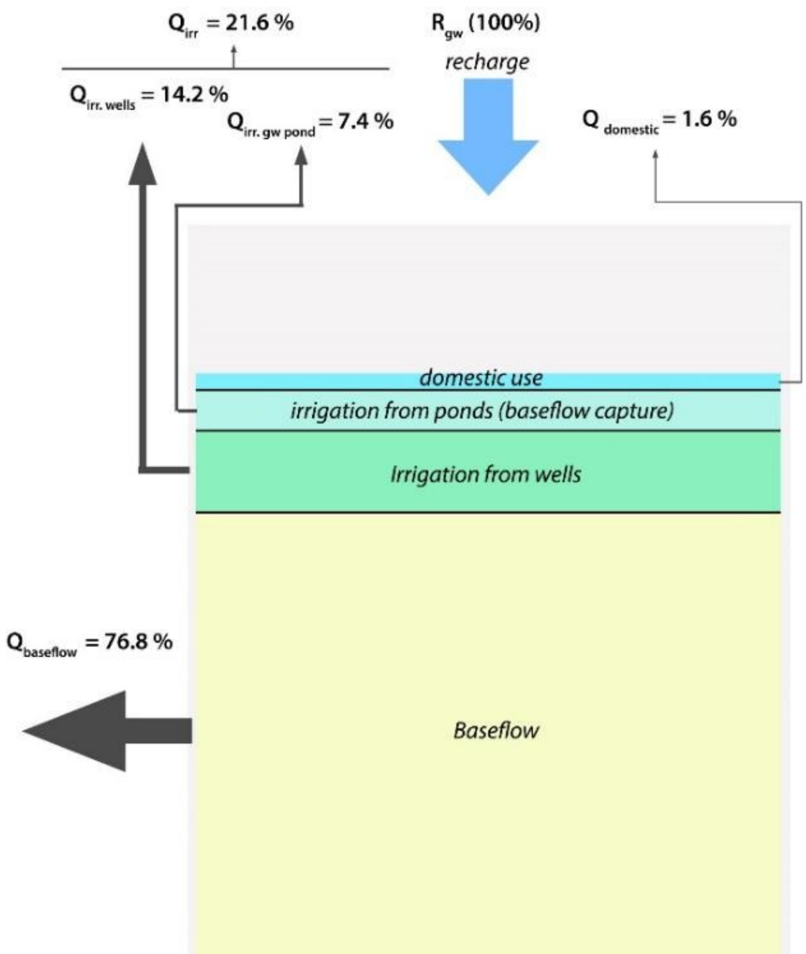

Figure 22 Summary figure of relative importance of groundwater budget components

5. Forecasting impacts of changes in practices in the catchment

Based on the understanding of the hydrogeological conditions, the irrigation practices and description of a typical annual ‘groundwater budget’ as determined from this study; it is possible to do an initial forecast of the likely consequences of changes in irrigation practices on water resources in the catchment.

5.1. Methods

Based on field observations, discussions with farmers and trends in irrigation practices (cf. D'haeze, 2019), a set of ‘what if’ scenarios have been established and the groundwater abstraction budget recalculated accordingly. As detailed previously, the water source in the catchment varies between storage ponds and groundwater. As pumping happens at a stage when the stream flow is limited or non-existent, a change in the amount of groundwater usage will most likely directly affect the aquifer storage. Conversely, change in the amount of water needed from ponds will affect the discharge of the stream from which it is diverted from. Thus gains and losses of water are presented depending on where they are impacting. The following table shows the 5 scenarios tested.

Table 9 - Scenarios used to assess impact of changes in practices on water resources

Scenario	Description	Water use (Litres/tree/round)	Irrigation methods
Sc1A past	Before project: farmers are not trained on water savings. Ratio of irrigation method is considered the same as 2018.	Basin: 571 L/t/r Sprinkler: 1038L/t/r *Data : D’haeze, 2019*	Basin: 34% Sprinkler: 66%
Sc1 BaU	Business as Usual: There is no evolution compared as the situation is this study (2018-19). C.f. to section 4.2 for detailed situation.	Basin: 412 L/t/r Sprinkler: 730L/t/r	Basin: 34% Sprinkler: 66%
Sc2 Sp+	Sprinkler adoptions keeps increasing. Phasing out of the basin irrigation due to increased cost of labor and lowering sprinkler costs	Basin: 412 L/t/r Sprinkler: 730L/t/r	Basin: 0% Sprinkler:100%
Sc3 Sp+Op+	Sprinkler adoptions keeps increasing. Phasing out of the basin irrigation due to increased cost of labor and lowering sprinkler costs. In parallel training and spill-over effects from project recommendations and inter-farmer discussions leads to optimal use of water	Basin: 400 L/t/r Sprinkler: 600 L/t/r	Basin: 0% Sprinkler:100%
Sc4 Op+	adoption of sprinkler method stabilizes at current level. In parallel training and spill-over effects from project recommendations and inter-farmer discussions leads to optimal use of water	Basin: 400 L/t/r Sprinkler: 600 L/t/r	Basin: 324% Sprinkler: 66%

5.2. Results

The table below summarizes the results of running the various scenarios.

Table 10 - Summary of scenario results compared to Business as Usual

	Sc-1A past	*Sc-1 BaU*	*Sc-2 Sp+*	*Sc-3 Sp+Op+*	*Sc 4 Op+*
Consumption (mm)	200.53	137.7	172.2	126.3	114.8
Consumption compared to GW recharge*	31%	22%	27%	20%	18%
Total gain/loss in mm	62.8	*No change*	-18.6	11.4	22.9
gain / loss in aquifer volume (m3)	82585	*No change*	-16937.7	473	71594
gain / loss in aquifer volume height (cm)	30		-15.5	0.4	10.06
gain/l loss in stream flow (m3)	24618		*No change*	9894	9894
gain / loss in equivalent of low flow (days)	21		*No change*	8	8

**ref. recharge 640mm(1500mm rainfall in 2018)*

Assuming the methods of irrigation have not changed in the catchment since the start of the project, the **Scenario 1A** shows that the training led to a significant improvement and water-savings. This annual water savings represents 82,585 m^3 of groundwater that is not withdrawn from the aquifer. Based on assumptions on aquifer properties used in section 4.2 (specific yield Sy=0.12), this volume has in theory led to an increase of the water table of 30cm in average over the entire catchment and particularly at higher elevations. Following this scenario, the improvement of sprinkler users also has a strong impact on the amount of water needed from ponds. A gain of 24,618 m^3 of pond water has been estimated. This represents a significant amount of water that is not captured and flows downstream. It is equivalent to the stream discharge of February during 21 days (1,200m^3/day). It is difficult to link these simulated gains with monitoring data as there is a whole range of factors affecting the variables (water table elevation and stream flow).

Looking ahead future impacts allows to assess where future efforts might be focusing. The **scenario 1** results shows that a wider adoption of sprinkler without continuous improvement of water use practices would have deteriorating effects on water savings and would lead to decline in water table of possibly 15cm. Further, the current capacity of ponds might be increased. This scenario was not modelled here but would have a strong impact on stream flow.

However the **scenario 2** shows that water savings can be further improved, even if sprinkler is widely adopted, if farmers are continuously moving towards using optimal water volumes. The latter seems to be occurring according to recent positive observations at the wider project scale and water measurements in 2019 (D'haeze, 2019).

Scenario 3 simulates that farmers using basin do not switch to sprinkler, and all farmers continue moving towards optimal practices due to lasting effects of training and discussions among farmers (D'haeze, 2019). It shows significant gains can be expected with an extra saving of 71,000 m^3 per year in the aquifer reservoir and nearly 10,000 m^3 of water that would not need to be diverted into ponds but instead available for downstream users. **The scenario 4** shows that if the sprinkler adoption stabilized (due to investment, field context etc.), greater gains can be foreseen if optimal practices are used by all farmers, with a ratio of usage of recharge below 20%. (c.f. Figure 23)

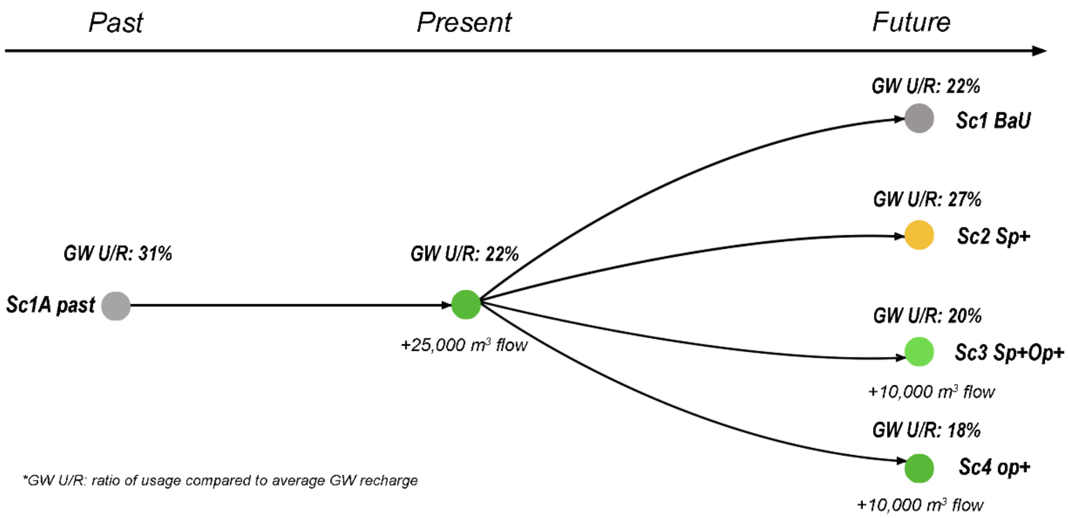

Figure 23 - Main results from scenario analysis

The results show that training has a significant impact on the water resources saving. However, in the case of areas with an increasing number of farmers replacing basin irrigation with sprinkler, a particular effort should be pointed at optimizing the use of these new technologies to ensure continuous water savings.

The future of the water usage in the experimental catchment will be affected by several factors, from water use practices, irrigation method adoption but also changes in the land use and cropping patterns, rejuvenation of trees etc. The latter are not included in the current scenarios and might have a significant impact water consumption.

6. Discussion on up-scaling findings of the micro-catchment

This study is based on a small-scale ($1km^2$) highly instrumented catchment. This catchment was selected as representing a typical setting of a water stressed area, located at higher elevation in the Plateau, in the province of Dak Lak. This section reframes the findings and their applicability in the broader context of the project.

6.1. Groundwater resources assessment up-scaling

The geological context is fairly homogenous at large scale across the basaltic plateau. Rhodic Ferralsols covering a sequence of first weathered basalt then hard fractured basalt is found over most of the project areas. The aquifer system studied here is considered to be representative of the plateau.

In consequence, it can be assumed that findings can be transferred to the Basalt plateau of central highlands, pending sufficient caution is taken in comparing the contexts of both farming practices and local hydrogeology.

6.2. Irrigation practices up-scaling

For farming and irrigation practices however, it is important to check the situation at the project scale as it varies significantly.

In terms of water use, the initial measurements in the catchment, although based on a limited number of samples do align with larger scale measurements over more than 400 farmers in the project area (D'haeze, 2019).

A database of 15,000 farmers was collected by HRNS as part of the project and included information on the source of water and method of irrigation. This allows to compare the situation in the district of the micro-catchment (Krong Buk) compared to districts in other provinces (Figure 24).

It shows that the irrigation practices observed in the catchment (cf. section 2 above) might not be representative of other districts and provinces. For example, groundwater is largely the main source of water in the catchment, while in lower areas such as Gia Lai or Lam Dong, surface water is mostly used. This is partly due to the higher occurrence of reservoirs in these provinces. Similarly, the trends in method used vary significantly across the landscape.

The results from the micro-catchment shows that since their introduction in early 2000's, sprinklers, which consumes more water, have become by far the main method used in the district of the catchment (Krong Buk). However, although sprinkler is also used in 1/4th of the farms in Gia Lai and Dak Nong, it is not used in Lam Dong.

This shows the impact of sprinkler adoption might at first be limited only to areas sharing the specificities of Krong Buk where farmers can invest in time-saving technologies. In consequence, the applicability of results of the micro catchment at wider scale are strongly constrained.

Nevertheless, the timeline of sprinkler adoption shows that although it is now only 20% of farmer using this technology in the region, it has been constantly increasing since its introduction in 2000's. As price of labor increases and sprinkler becomes more affordable, the rate of adoption of sprinkler should be monitored as it might have a significant impact on water resources.

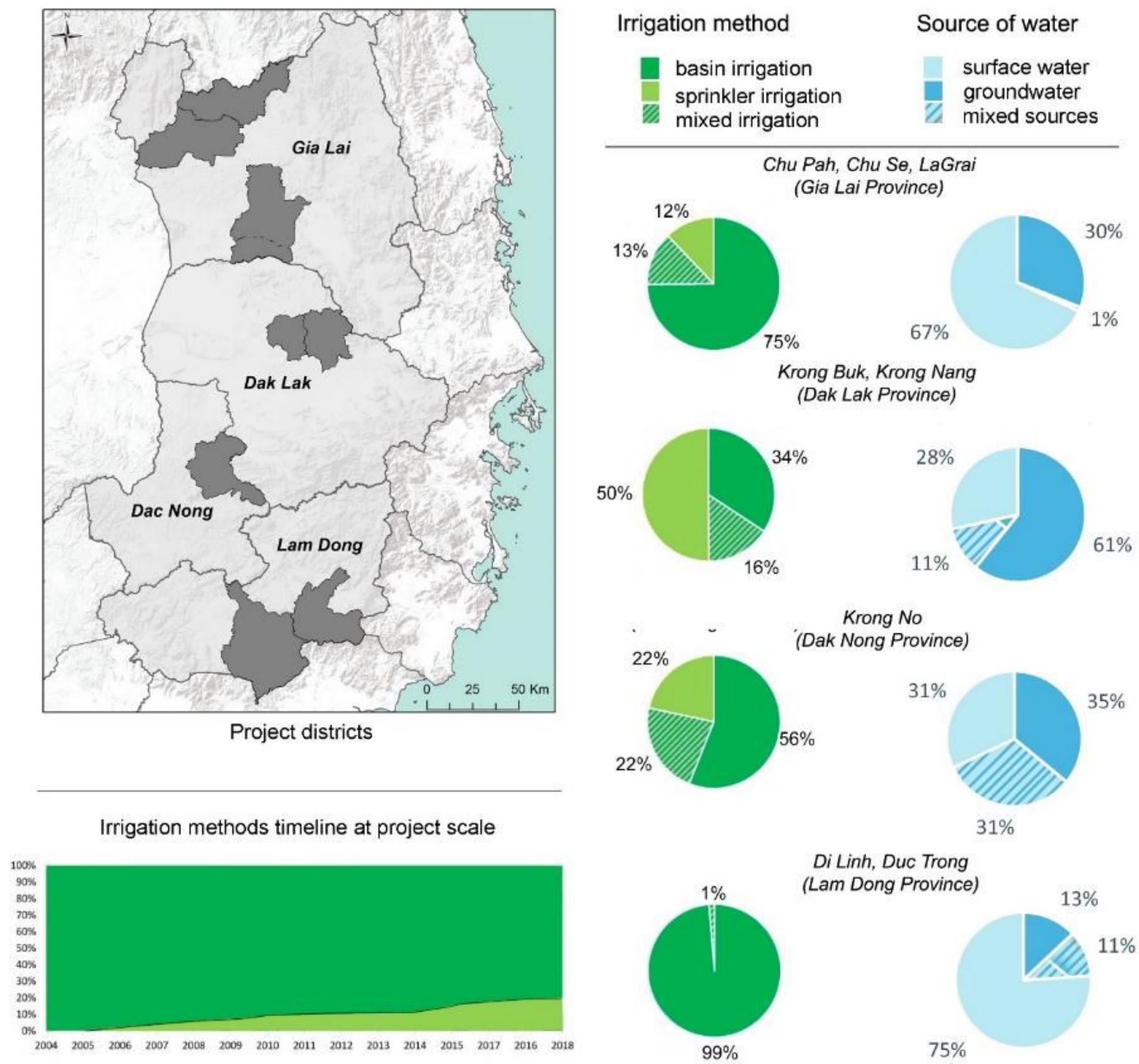

Figure 24 - Synthesis on irrigation methods and source of water for irrigation at District level for Project Areas

7. Conclusions and recommendations

Groundwater plays a major role in Dak Lak province as it is vital for domestic water supply, supports the coffee production through irrigation and maintains dry season flow in rivers. The latter, often overlooked, is essential to riparian communities, river ecosystems functioning and hydropower generation. Dak Lak province regularly experiences periods of droughts and localized water scarcity, as seasonally falling water tables impact water availability for irrigation. Confronted with the need to provide sufficient water for irrigation while maintaining groundwater regional role, improved irrigation practices are a key to a sustainable development of farmers across the Central Highlands.

Understanding the linkages between improved irrigation practices and groundwater resources to provide evidence-based policy support requires an in-depth understanding that can be achieved through a small-scale, highly monitored catchment. In this study, an initial appraisal of these linkages has been carried out, based on earlier work at regional scale (Milnes et al., 2015) and three years of data monitoring. The following points have been demonstrated:

In terms of irrigation practices:

1) Groundwater is not the only source for irrigation in the catchment but by far the most important; 65 % of the farmers are using it, with the other 35 % using ponds. Further, for the 35 % using ponds, rainfall run-off storage is limited compared to irrigation requirements supporting only 25 % of annual amount. The rest being 'captured' baseflow from springs used to refill the ponds and used for irrigation instead of being allowed to flow downstream.
2) Deep boreholes (circa 100 m deep) started to be drilled in the last few years, now only 8% of farmers own a borehole for irrigation in the catchment, but 37 % of the farmers using other sources consider investing in a borehole in future. High cost and high risk of failure are major constraints.
3) Two irrigation methods are used in the catchment: basin and sprinkler. Other methods such as drip or mini-sprinkler have not been observed. Consumption for the two methods was directly measured on-site. Average value for the basin method is 400 L/tree/round [*45 measurements, standard dev. = 145*] and for sprinkler 700 L/tree/round [*55 measurements, standard dev. = 304*]. This lines up with wider scale measurement across the region.
4) Since its introduction in the 2000's, the sprinkler is gaining popularity, particularly since 2012, according to farmers this is mostly due to increased labor cost and labor shortages, and improved cost-efficiency. Some national level policy changes might also be a trigger. Today a large majority of farmers (65 %) in the catchment are irrigating with sprinkler.
5) Despite farmers' opinion, sprinklers used in the catchment have showed to be highly inefficient. The uniformity test shows that:
    a. Sprinkler currently use have very low uniformity and are inefficient regarding water use. Only 40% of trees receive a correct amount of water, the majority being either under or over irrigated
    b. Due to non-uniformity, farmers cannot use a single catch-can to assess the amount of water distributed to their field.
6) Looking at the wider scale however, the sprinkler is not widely adopted. It is used by only 20% of farmers at the project scale. However adoption has been regularly increasing since 2000's and should be monitored due to the implication it has on water consumption.

In terms of linkages with groundwater resources:

7) Recharge of aquifers from rainfall is high, usually above 30% of rainfall and in this case possibly above 45% of rainfall.
8) Water level monitoring confirms the earlier hypothesis (Milnes et al., 2015), showing a greater variation at higher relative elevation (Δh > 4 m), where some wells become dry. Similar observations were made in nearby MAR sites (Pavelic et al. 2019)
9) Relatively high permeability of the weathered basalts ($K = 4.80 \times 10^{-05}$ $m.s^{-1}$) and high gradients of 0.05 $m.m^{-1}$. Resulting velocities of groundwater in the catchment are expected to range from approximately 35 to 120 $m.year^{-1}$) suggest water transits through the system in less than 10 years. These values are in line with values estimated at MAR stations by Pavelic et al. (2019) of up to 95 $m.year^{-1}$.

10) High frequency monitoring of groundwater levels showed that:

    a. The delay between on-set of the rainy season and significant recharge of the aquifer is approximately 60 days, confirming earlier observations in the region (Milnes et al., 2015) and highlighting the importance of the thickness of the unsaturated zone.

    b. In the weathered aquifer 15-minute frequency monitoring shows that during irrigation events, wells in the higher elevation can be depleted, however, water level recovers to pre-irrigation level within less than a half day following end of pumping. This shows that such drying-up of wells are linked to over-pumping and associated cone of depression rather than global water table lowering. Horizontal drilling to enhance the well capacity is one of the strategies to increase water availability.
    c. In opposition to the upper weathered basalt, it is believed the lower fractured aquifer cannot support widespread development although it can locally successfully support irrigation. In this lower fractured aquifer, current monitoring shows that irrigation abstraction affects levels in the end of the dry season, and impacts of pumping on water table can be observed several hundred meters away. The fundamental difference between the two aquifers should be highlighted, particularly as boreholes are often seen by farmers as a solution for the future.

11) Streamflow analysis showed that a large portion of the flow (90 %) has been transiting through groundwater. It highlighted that the onset of the irrigation season appears to dramatically accelerate the reduction of flow as baseflow in the catchment is diverted to ponds to be supplied to the fields. Based on these observation, it could be argued that that improved irrigation from basin users located on the higher elevation might result in higher baseflow, in turn diverted to ponds to be used by sprinkler users.

12) Estimation of abstraction made based on both irrigation method and source of water shows that current extraction rate is in the order of 20 % of annual recharge. This implies current use is largely within the boundaries of availability of groundwater. However, a sustainable development in the Dak Lak plateau includes avoiding creating negative consequences for downstream users and ecosystems. Although a degree of development of groundwater of 20% of recharge appears reasonable, at seasonal scale, acceleration of baseflow recession has been observed in the critical

driest months. Thus it is then questionable whether the level of sustainable use has already been reached

13) *What if* scenarios showed that improvement in water usage could led to important saving in both groundwater storage and increased stream flow. It also showed that increased sprinkler adoption would have a negative impact if it is not done in conjunction of better practices. Wider scale study seem to show that farmers are moving to optimized use of water. This improvement in practice will lead to further water savings, even if sprinkler is increasingly adopted.

This assessment has provided a valuable first step that contributes towards a more holistic understanding of groundwater use for coffee irrigation. Flaws in the current understanding have to be addressed. Direct impact of training on streamflow and water levels could not be carried out as changes in practices do not happen simultaneously but rather in a progressive way, making their quantification over a 3 year monitoring timeframe difficult. Other changes in the catchment (e.g. change in irrigation methods, change in land use etc.) also need to be accounted for as they might enhance or offset the gain from improved practices. Further research emphasis should also be put on re-designing soil moisture monitoring to better evaluate excess irrigation transfers.

Improved groundwater management in the Dak Lak region requires evidence-based policies and action. This experimental catchment and these initial results represent a step forward in providing a unique opportunity to evaluate, document and analyze changes. This will eventually support a necessary coupling of understanding the on-farm practices along with hydrological changes.

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Appendix

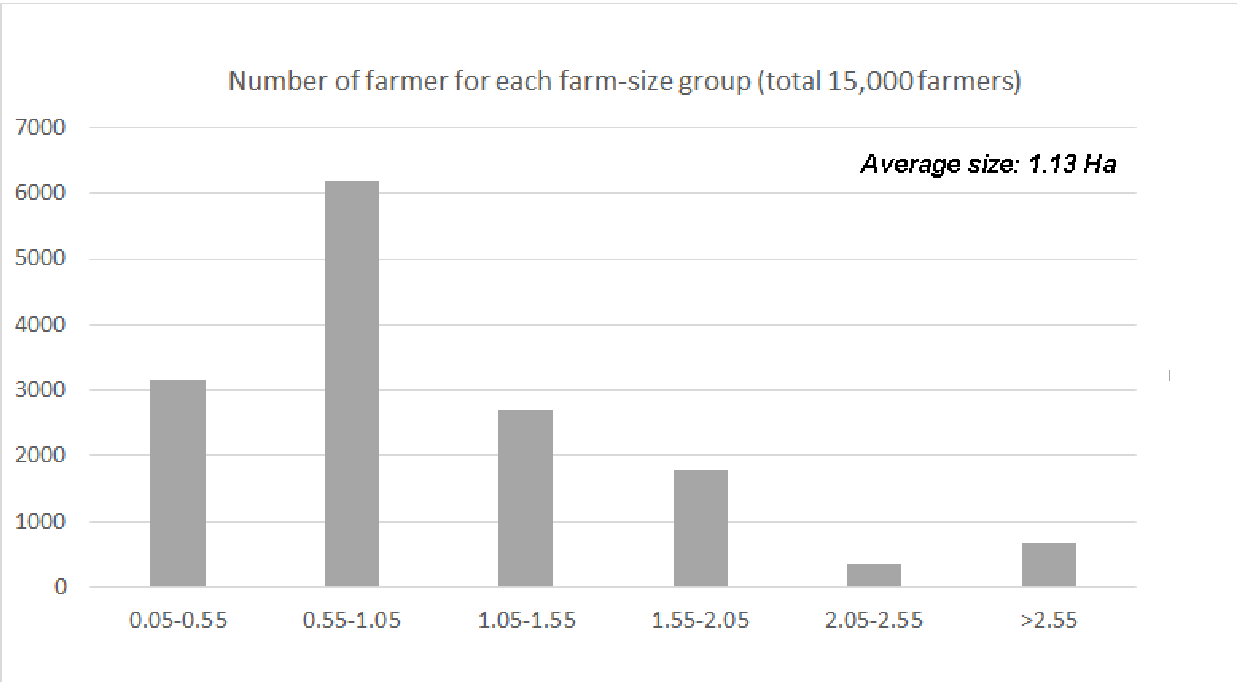
A. Appendix – monitoring instruments details

Name	1719_Sscope-Meteo	3024_KellerGSM_1	1718_SScope-wl-soil-moisture	3414_KellerGSM_2	3415_KellerGSM_3	3413_KellerGSM_4	1240_KellerP_1		1229_KellerP_2	1226_KellerP_3	1221_KellerP_4
Monitoring	Wind-Rain-Water level	Water level	Soil moisture - Water level [FAILED repetively / then completely July 2018]	Water level	Water level	Water level	Water level		Water level	Water level	Water level-> Flow rate
Box ID	1719	3024	1718	3414	3415	3413					
Simcard_no.	0944 863 704 replaced with 01666 159 715	0127 343 5457	0941 453 752	0944 935 164	0945 362 903	0944 890 510					
Rain	Yes										
Wind	Yes										
WL.Probe	Yes	Yes	Yes	Yes	Yes	Yes	Yes		Yes	Yes	Yes
Soil moisture			Yes								
Probe ID		244653	Soil:923303012	481876	481877	481875	1240		1229	1226	1221
Well type	Shallow well	Shallow well	Shallow well	Shallow well	Shallow well	Shallow well	Borehole		Spring - Shallow well	Shallow well next to spring	gauging station
Water level	22.00	20.35	19.26	18.96	18.28	12.66	40.72	37.5	5.7	5.38	
Well.Dept	27.00	23.18	21.00	25.10	19.75	20.26	90		9.8	7.35	
Tube length	26.61	22.99	20.94	25.12	19.72	20.24	59.60		9.69	7.30	
Probe_dept	26.41	22.90	20.85	25.02	19.65	20.19	58.63	#####	9.59	7.25	1.27
Lat	13.071022	13.070068	13.072926	13.074912	13.07879	13.078428	13.08052		13.07655	13.074068	13.076663
Long	108.264373	108.275499	108.271699	108.279684	108.277806	108.273234	108.274367		108.27641	108.27486	108.272361
Elevation - Well head [masl]	779.88	798.17	786.87	796.90	787.77	761.03	778.35		753.41	748.04	730.37

RefElev.	772										
ProbeElev.	745.59	-22.90	-20.85	-25.02	-19.65						
Household	Hoàng Mạnh Thu	Trần Anh Tuấn	Hoàng Văn Việt(wl) & Lương Công Hiên (Moisure)	Trần Văn Tám	Nguyễn Văn Sơn Nguyễn Văn Thắng	Nguyễn Nhất	Nguyễn Duy Lượng	Lê Đình Dương	Ama Phân	Ama Ngoa (Y Ben)	Ama Phôn
Use of shallow well	Irrigation+Domestic	Irrigation+Domestic	Irrigation+Domestic	Pepper irrigation + Domestic	Domestic	Domestic	Irrigation		Irrigation+Domestic	Irrigation	
HouseholdPhone	0979230205	01652816073	Việt:01654183403 &Hiên: 0935091177	0935546910	Sơn:01686770761 Thắng: 0978137183	01685567414	0974779916	0935 691 808	01668134049	01652836662	01663209863
Address	Ea Krom - Cư Né	Ea Krom - Cư Né	Ea Krom - Cư Né	Tân Tiến - Ea Toh	Cư trú: Bình Thuận. Tạm trú:Tân Tiến - Ea Toh	Quảng Ngãi	Ea Krom - Cư Né		Buôn Kai - Pơng Drang	Buôn Drah - Cư Né	Buôn Drah - Cư Né
Instal.time	07-Mar-16 13:00	07-Mar-16 15:10	07-Mar-16 17:00	04-Apr-16 12:00	04-Apr-16 15:20	04-Apr-16 17:00	07/Aug/16 14:45	17/Sep/16 9:24	05-Apr-16 11:30	27-Apr-16 10:50	28-Jun-16 9:10
Comment				Yêu cầu hỗ trọ xét nghiệm nước						đang đào gần điểm lộ. Nếu được hỗ trợ vật liệu thì sẽ xây bảo vệ đỉnh giếng năm nay. Nếu không sang năm mới xây	
Đồng ý lắp				OK	OK	OK			OK	OK	OK
Lắp đồng hồ				OK		OK			Do nhiều nhà sử dụng nên không thể lắp đồng hồ		

B. Appendix – Farm size across the project area

Based on a database of 15000 farmers collected as part of the study, the following repartition of of farm size can be found across project's area:



C. Appendix interviews irrigation

GENERAL INFO

Nr	
Male / Female + Full name	
Address	
Telephone number	
Plot number (check on Map)	
GPS XY coordinate of irrigation place (if known)	
GPS XY coordinate of pumping point (if known)	

FARM CROPS

Irrigated Farm crops (coffee, pepper etc etc…)	
Area Irrigation Farm crops 1: Coffee (ha)	
Area Irrigation Farm crops 1: Pepper (ha)	
Area Irrigation Farm crops 3: other (ha)	
TOTAL IRRIGATED AREA (ha)	
Number of trees crops 1: coffee	
Number of trees crops 2: pepper	
Number of trees crops 3: other	
MIXING TREES ? Yes [ ] No [ ]	
Expected total irrigation rounds in 2018	

SOURCE OF WATER

Source of water in 2018 Dugwell [ ] Borehole [ ] Pond [ ]	
when did you start using this source of water ? (year)	
what did you use before ? Dugwell [ ] Borehole [ ] Pond [ ]	
If you changed, what is the main reason of changing source of water ?	
If you have not changed do you think about changing source of water ?	
If you change, what source of water would you use in future ? Dugwell [ ] Borehole [ ] Pond [ ]	

IRRIGATION

Irrigation method in 2018 Sprinkler [ ] Basin [ ]	
when did you start using this irrigation technique ? (year)	
what did you use before ? Sprinkler [ ] Basin [ ]	
If you changed, what is the main reason of changing irrigation method ?	
If you have not changed do you think about changing source of water ?	
If yes, what source of water would you consider using in future ? Sprinkler [ ] Basin [ ]	

TRAINING AND WATER SAVINGS

Did one of your wells run dry at end of season ?	
If yes, what is the type and depth of the well ?	
Did you participate any water saving training (yes / no)	
If yes (water use training), when ? (year)	
If yes (water use training), by whom ?	
Any other training (not water) ? Yes /no	
If YES ? Details: what topic, year	
If NO, do you know about water saving practices ? (yes / no)	
If yes, from where / whom ?	

D. Appendix irrigation measurement

IRRIGATION MEASUREMENT Sheet	
	Measurements / calculations
IRRIGATION OF COFFEE by SPRINKLER	Number of Sprinkler Heads in set Number of trees/sprinkler head Number of irrigated trees by set Number of irrigating hours before moving set (h) Equivalent to minutes (min) Volume of the measurement recipient (in L) Measurement time (sec) 1 Measurement time (sec) 2 Measurement time (sec) 3 Measurement time (sec) AVERAGE Water pump discharge in L /sec Water pump discharge in L /min Water amount (l)/tree
IRRIGATION OF COFFEE by BASIN Watering	Volume of the pump measurement recipient (in L) recipient Measurement time (sec) 1 recipient Measurement time (sec) 2 recipient Measurement time (sec) 3 Measurement time (sec) AVERAGE Water pump discharge in L /sec Water pump discharge in L /min BASIN watering time (Seconds per basin): Measure 1 (seconds) Measure 2 (seconds) Measure 3 (seconds) AVERAGE Time for 1 basin (seconds) Number of litters/tree

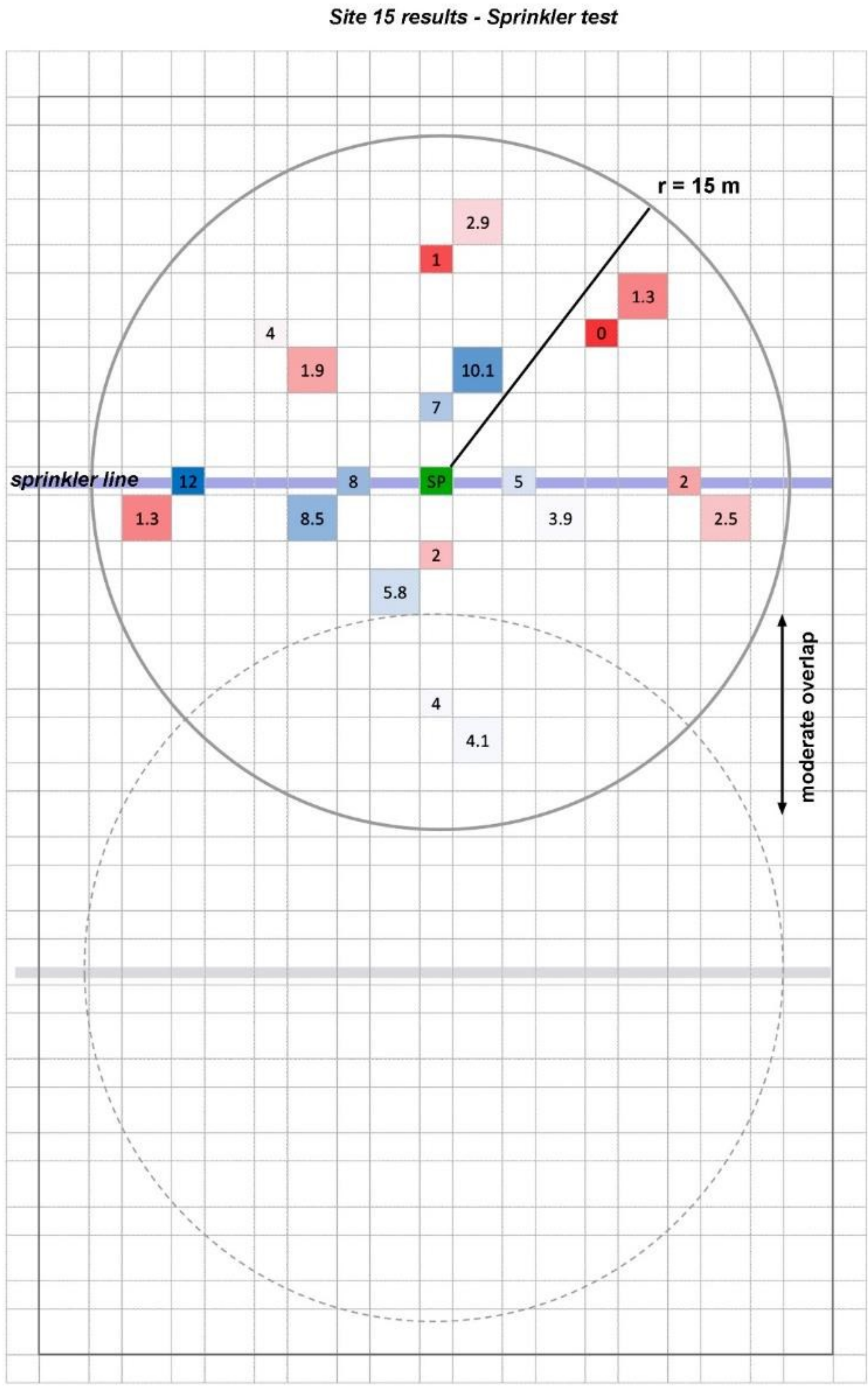
E. Appendix – Comparison of available method for coffee irrigation

Extract from Louelle Seelmann BSc thesis – University of Amsterdam – 2018.

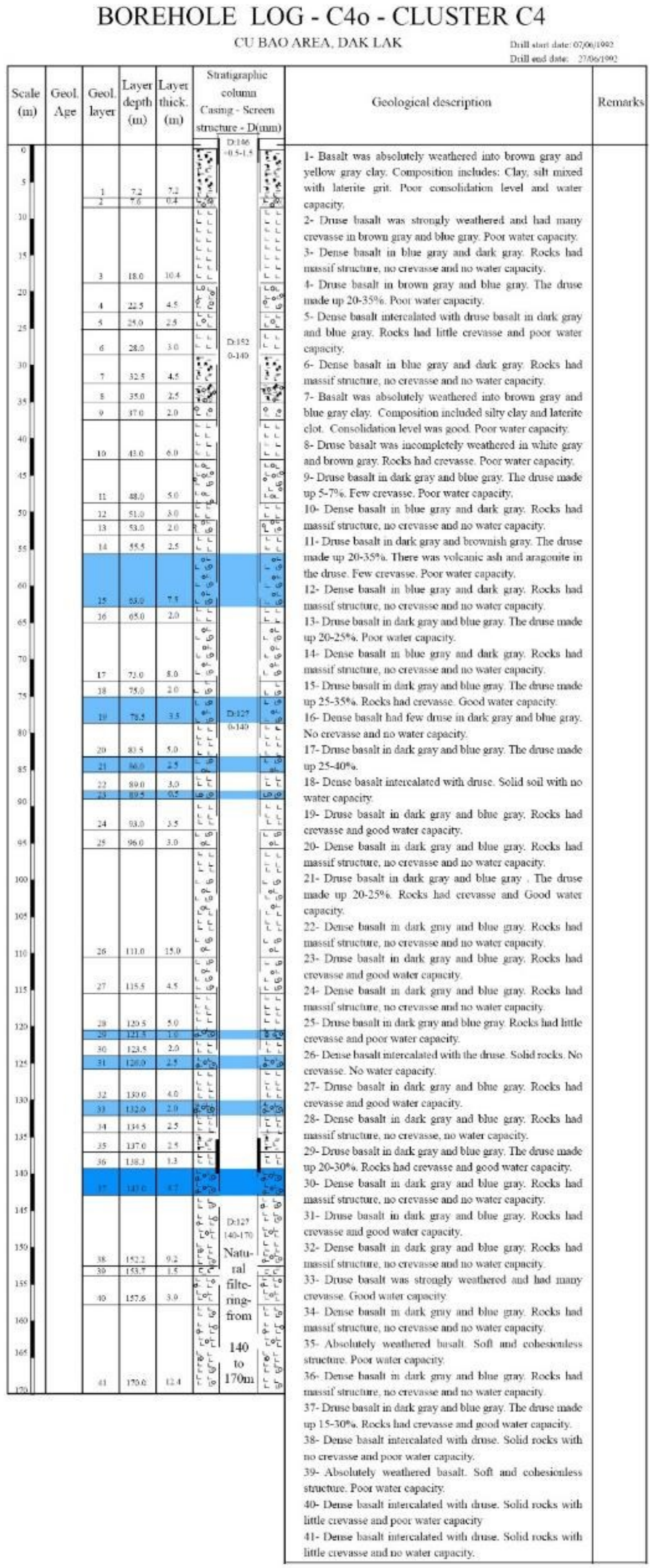
	Equipment	Operation	Advantages	Disadvantages	Counter arguments
Basin Irrigation	• Pump & pipes • Are taken home after use.	• Sometimes 1, but often 2 to 3 persons • Duration: 1 - 10 days depending on a lot of factors • Average farmer spends 2-3 days per irrigation round	• Low costs • Irrigation directly at the basin • Only 1 system for multiple plots	• Labour intensive	
Sprinkler Irrigation	• Pump & several sprinklers • Are taken home after use	• Mostly 1, sometimes 2 people to move, but only for instalment • Between 1-3 days	• Saves labor in comparison to basin irrigation • Not too high investment • Only 1 system for multiple plots • Creates a micro-climate and cleans the tree	• More difficult to target the irrigation and therefore more evaporation • Highest water use • Can only operate when water level in water source is high enough	
Partial Sprinkler Irrigation (WASI)	• Pump, pipe system, sprinklers. • System is fixed	• 1 person to check whether the system functions	• Saves water • Saves labour • Saves electricity • Saves money • Saves fertiliser • Possibility to mix fertiliser • Flexible for adaptions	• Costly • Security • Durability • Farmers question suitability for coffee • Not applicable on sloping land	• Water saving argument questioned • Time spend on irrigation not a significant cost factor
Drip Irrigation (Netafim)	• Pump, pipe system and pressure compensato r • System is fixed.	• 1 person to check whether the system functions	• Saves water • Saves labour • Saves money • Saves electricity • Saves fertiliser • Possibility to mix fertiliser • Pipes are easily moved from one crop to another (contested)	• Security • Very costly • Controversy about compatibility with coffee	• Water saving argument questioned • Time spend on irrigation not a significant cost factor
Precision Agriculture (MimosaTE K)	• Control knob, soil moisture knob, weather station, wifi device. • System is fixed	• 1 person to turn the irrigation system on (through a mobile application)	• Saves water • Saves labour • Saves money	• Security • Very costly • Requires electricity, also for the pump • Requires a smartphone • Controversy about compatibility with coffee	• Water saving argument questioned • Time spend on irrigation not a significant cost factor • Based of FAO crop requirements

Source: Louelle Seelmann - University of Amsterdam - BSc Thesis -2018

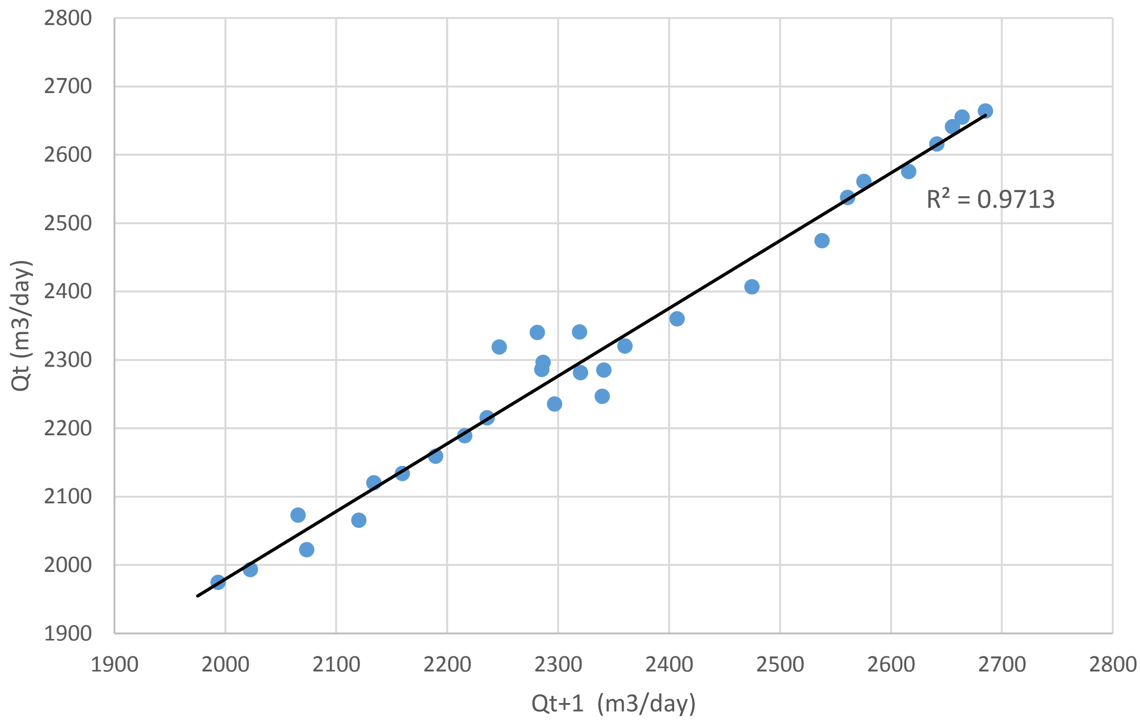
F. Appendix – Sample of sprinkler results mapping



G. Appendix - c40 borehole geological log



H. Appendix - Flow recession analysis Eckhartdt parameter



I. Appendix - Field photographs

Pictures 1 Left: Overview of the experimental catchment. Right: the V-notch gauging station

Picture 2 - Major crop grown in the catchment: left: coffee trees. Middle and right: pepper in fields and under plastic shade.

Pictures 3- A drilling rig in operation near the catchment

Picture 4 left: A field expert from HRNS surveys groundwater levels – right: Programming groundwater level loggers

Picture 5 - Left: a Dugwell and nearby newly drilled borehole in coffee plantation. Middle and right: assessing groundwater levels prior to logger installation

Picture 6 – Irrigation methods: Left: Basin irrigation . Right: Sprinkler irrigation

Picture 7- Irrigation water sources: Left: well with pumps fitted. right: Pumping from pond storage

Picture 8 - steps to create catch-cans for measuring sprinkler uniformity