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Stone wool is an inorganic material derived from molten rock characterised by its lightweight, low thermal conductivity and high porosity, being able to store around 95% of water. Hydrorock (HR) is a company focused on sustainable water management, using compacted stone wool in blocks as the basic application for all products of the company. Traditionally, the company has focused in flood management (drainage), but they want to explore if this material can be also used for subsurface irrigation.

The "ASSIST - Advanced subsurface irrigation system using Hydrorock" project, aims to develop a new and cost efficient subsurface irrigation technology based on blocks of stone wool material (Hydrorock blocks), looking for a more efficient water use and higher crop yields, while saving on labour, operation and maintenance cost. The consortium of this project was formed by two Dutch private companies, Hydrorock International BV (HR) and Smart Farm Sensing (SFS) and Wageningen Environmental Research as knowledge institution.

As a result of the project it can be stated that stone wool presents interesting water hydraulic properties, making this material unique in terms of capacity to store water and hydraulic conductivity. The density of fibres clearly affect the hydraulic properties of Hydrorock blocks, with a higher water retention capacity and hydraulic conductivity (Ks) for blocks with higher density. However, water release from Hydrorock blocks to the soil is mainly driven by soil properties (i.e. texture) and preliminary soil conditions (moisture) rather than by the block properties (density or fibre direction), since the hydraulic properties of stone wool largely differ from natural soils, especially for loamy and clay soils.

Hydrorock blocks can be manufactured in multiple configurations, giving the possibility to adapt the system to several crop patterns and/or existing irrigation systems. The use of pressure compensated drippers to release the water within the block allow a better control of the water, providing more homogeneity in water distribution, within the block but also among different blocks of the irrigation unit.

A total of two pilots were developed in Dubai and Bahrein to irrigate date palms on a sandy and loamy soil respectively. From the two pilots carried out during the project, we can state that with 10-30% less water applied to the Hydrorock blocks than in bubblers (control), Hydrorock blocks:

- Achieve a similar yield but a higher water use efficiency.
- Keep soil moisture in similar values, especially for deeper horizons (60-90 cm depths).
- No present evidence of negative effects on date palms or the blocks after two years of operation.
- No present evidence of salinity issues (if system is well managed with regular flushing events).
- Present a lower cost of operation, specially related to weed removal. The use of machinery (i.e. harvesting) is also easier and creates less damage when compared to conventional surface irrigation systems, since the whole irrigation system is buried.

Keywords: water management, stone wool, subsurface irrigation

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Summary

Stone wool (or rock wool, or mineral wool) is an inorganic material derived from molten rock furnaced at a temperature of about 1600 °C. Stone wool is mainly characterised by its lightweight, low thermal conductivity, high sound-absorbing performance, chemical durability, and non-combustibility. Another property of stone wool is its high porosity, being able to store around 95% of water. This capacity, together with a very high hydraulic conductivity, of around 5-200 m/day, allow the material to "absorb" a high quantity of water in a relatively short time.

HR is a company focused on sustainable water management. Stone wool material is the basic application for all products of the company. HR has specially developed stone wool blocks for water management, as a climate adaptive solution. HR was mainly focused in flood management (drainage), thanks to the capacity of their elements to absorb the water from the saturated soil during a rainfall event and deliver it gradually into drainage pipes. However, stone wool material can also be used for irrigation, providing water to the soil according to the crop water requirement. Since the water is provided underground, and therefore close to the roots, no losses from direct evaporation or runoff are expected, increasing the efficiency of the system when compared with other traditional or modern irrigation technologies.

The "ASSIST - Advanced subsurface irrigation system using Hydrorock" project, co-funded by the Top consortium for Knowledge and Innovation (TKI) programme under the topic Delta Technology, aim to develop a new and cost-efficient subsurface irrigation technology based on blocks of stone wool material (Hydrorock blocks), looking for a more efficient water use and higher crop yields, while saving on labour, operation and maintenance cost. The consortium of this project was formed by two Dutch private companies, Hydrorock International BV (HR) and Smart Farm Sensing (SFS) and Wageningen Environmental and Research as knowledge institution. The project had three clear developments lying all in applied research:

1. To modify the current Hydrorock blocks to move from a drainage application into an irrigation system and test its suitability on a pilot scale (field).
2. To develop a remote monitoring and operational system, based on the use of soil sensors and other environmental variables.
3. To further investigate the properties of Hydrorock blocks to deliver water and re-design new elements suitable for different soil and climate conditions (laboratory investigation and modelling).

As a result of all the experiments, discussions and knowledge created during the implementation of the ASSIST project, the most relevant findings can be summarised as:

1. Stone wool has very interesting water hydraulic properties, making this material unique in terms of capacity to store water and hydraulic conductivity. This can be used for many water related applications, among which include subsurface irrigation.
2. Fiber density (and direction) clearly affect some of the hydraulic properties of the stone wool, with a higher water retention capacity and hydraulic conductivity (Ks) for blocks with higher density. This can influence how the water and nutrients are moving within the block and should be considered for the design of new elements.
3. Water release from Hydrorock blocks to the soil is mainly driven by soil properties (i.e. texture) and preliminary soil conditions (moisture) rather than by the block properties (density or fibre direction), since the hydraulic properties of stone wool largely differ from natural soils, especially for loamy and clay soils, both in terms of water retention capacity and hydraulic conductivity.
4. Considering this, we can argue that in case of subsurface irrigation:
   - Density of stone wool is not affecting much how the water is moving from the block to the soil, and therefore it is better to work with cheaper material (lower densities).
   - For light soils (sandy), water is released from the block very fast and can produce water losses to deep horizons (deep drainage), beyond the reach of plant roots. To avoid this, a water management strategy to provide small but regular applications is recommended.

- For heavy soils (loamy to clay), water is stored in the block and released gradually to the soil, according to the moisture conditions. The blocks can improve the storage capacity of the soil. In this case, a strategy based on the application of large quantities of water with less frequency, using the block as a reservoir, is recommended.

5. Hydrorock blocks can be manufactured in multiple configurations, giving the possibility to adapt the system to several crop patterns and/or to new or even existing irrigation systems.
6. The use of control flow devices (with pressure compensated drippers) can provide an added value to the Hydrorock blocks, controlling the flow and giving the possibility to have better homogeneity in water distribution, within the block but also among different blocks of the irrigation unit.
7. The Agriot platform (https://agriot.app/) can be a suitable tool to control and manage the HR system, allowing the users to monitor in real time the soil moisture content, the water quantities and the weather forecast. Although this platform can be used to semi-automatise the irrigation scheduling, according to a set of predefined conditions, it is recommended that the final decision of irrigation should be taken by the farmer, using the system as a decision support system.
8. From the two pilots carried out during the project, we can state that:
   - With 10-30% less water applied to the Hydrorock blocks than in bubblers (control), Hydrorock blocks.
     - Achieve a similar yield but a higher water use efficiency (more production per unit of water).
     - Keeps soil moisture in similar values, especially for deeper horizons (60-90 cm depths).
     - No present evidence of negative effects on date palms after the operation.
     - No present evidence of salinity issues (if system is well managed with regular flushing events).
   - After two years of experiments, there is no concerns regarding the interaction between the root system and the Hydrorock elements, as indicated by healthy and abundant root growth around the block without any root penetration into the blocks.
   - Hydrorock blocks have a lower cost of operation compared to bubbler systems, specially related with weed removing. The use of machinery (i.e. harvesting) is also easier and less expose to damage, since the whole irrigation system is buried.
9. Hydrorock blocks would a higher cost in installation than other surface or subsurface irrigation systems, but this can be drastically reduced if automatic trench systems are used during the construction of the system.

1 Introduction

Water is essential for agriculture. Either water from rainfall (green water) or water from rivers and aquifers applied by irrigation (blue water), the use of water is required to produce food. As the world's population continues to increase, the demand for food will also rise, leading to a greater need for water resources (UN, 2017). Water scarcity, either in terms of water quantity or quality, is already a major challenge for many regions worldwide, and the situation is expected to worsen as climate change leads to more extreme weather patterns (UN, 2009).

One of the most significant factors contributing to water scarcity is the mismanagement of water resources. The inefficient use of water in agriculture, industry and households is a significant issue in many parts of the world. In many cases, water resources are depleted faster than they can be replenished, leading to shortages and droughts. This is particularly true in areas where water is already scarce, such as sub-Saharan Africa, Middle East, and some parts of Asia. Water scarcity also has broader environmental impacts, such as the degradation of ecosystems, biodiversity loss, and soil erosion, generating a clear negative effect on the ecosystem services provided.

Agriculture is the largest consumer of water globally, accounting for approximately 70% of total freshwater use (UN, 2009). With water resources under increasing pressure, many regions are experiencing reduced crop yields, and some are even facing crop failures. As a result, food prices are rising, and food security is becoming a growing concern in many parts of the world.

Water efficiency is still very low in many part of the worlds, with large losses of water during the abstraction, transport and application of water. In some water scarce areas, such as the MENA region, the average water efficiency is established at around 50 to 60 percent, compared to best-practice examples of above 80 percent efficiency under similar climate conditions in Australia and southwest US (Sewilam and Nasr, 2017). The use of modern irrigation technologies would allow to apply the exact amount of water (and nutrients) required by the plants, increasing the efficiency of water use and in some cases, making more water available for other users (i.e. production of more food or environment). Actually, the use of modern and more efficient irrigation technologies is not only linked with a lower on-farm water use, but usually with an increase in yields, improving water use efficiency and productivity (i.e. more food per drop of water) (Bansal et al., 2021).

There are already several irrigation technologies to improve water efficiency and water productivity in comparison with the traditional application of water by flooding. The use of sprinklers, dripper, bubblers, or even subsurface systems can significantly produce water savings at farm scale. All of them have pros and contras, being the requirement of additional energy (pressurised systems) as one of the most relevant challenges. The application of water by subsurface systems is under rapid expansion. This technology involves delivering water directly to the root zone of plants, below the soil surface, usually, by the use of buried drip line systems. This method is more efficient than other surface irrigation technologies because it reduces water loss due to evaporation and runoff. Overall, subsurface irrigation is considered a more efficient and precise method of irrigating crops compared to surface irrigation, improving yields and water productivity (Wang et al., 2022). However, it can also be more expensive and requires more specialized equipment to install and maintain.

2 Background

Hydrorock (HR) is a company focused on sustainable water management. Stone wool material is the basic application for all products of the company. HR has specially developed stone wool blocks for water management, as a climate adaptive solution. The type of stone wool used has a characteristic that it can absorb 95% water of its own weight. That is why it is, among others, suitable as buffer material for water storage. Moreover, the material also releases water gradually to the environment. For the time being, HR was mainly focused in flood management (drainage), thanks to the capacity of their elements to absorb the water from the saturated soil during a rainfall event and deliver it gradually into drainage pipes. At this moment, HR is mainly active in two areas:

- Drainage buffer and o-site infiltration.
- Small- to medium scale (housing) rainwater detention and infiltration systems.

In the last years, multiple clients have been asking HR if the stone wool material can also be used for irrigation, providing water to the soil according to the crop water requirement. Since the water is provided underground, and therefore close to the roots, no losses from direct evaporation or runoff are expected, increasing the efficiency of the system when compared with other traditional or modern irrigation technologies.

HR has already executed some in-house experiments with promising results. Thanks to those experiments and on the proven previous applications from drainage, we can state that at the beginning of this project (2019), the technology was on a TLR 3-4. However, since proper field tests under real conditions were not carried out, the technology was still far away from commercialization.

This new system has the potential to save water compared with the traditional irrigation systems, either sprinkler or drippers, reducing the cost of operation and maintenance (very low pressure required and installed underground), while guaranteeing each crop receives the required amount of water to produce high yields.

However, to deliver the water when needed, a proper monitoring and control system is required. Therefore, Smart Farm Sensing (SFS), a Netherlands based aggrotech. company providing products, services and solutions to the agriculture sector based on intelligent sensor data, remote sensing, and geospatial information, was also involved, in order to develop a joint technology able to remotely operate the system, applying the correct amount of water in volume and time.

After a careful market assessment developed by HR and SFS, it seems that regions located in semi-arid climates have a large potential for this innovation. Both companies also have a common interest to strengthen their position in the MENA region, so Dubai and Bahrein have been identified as suitable places to test the technology. However, the technology is not restricted to these agroclimatic conditions, and the project aims to assess its potential for other climates and soils.

3 Aim

This report provides a summary of the most relevant results obtained during project "ASSIST - Advanced subsurface irrigation system using Hydrorock". The aim is to develop a new and cost-efficient subsurface irrigation technology based on blocks of stone wool material (Hydrorock blocks), looking for a more efficient water use and higher crop yields, while saving on labour, operation and maintenance cost. The project has three clear developments, all in applied research:

1. To modify the current Hydrorock blocks to move from a drainage application into an irrigation system and test its suitability on a pilot scale (field).
2. To develop a remote monitoring and operational system, based on the use of soil sensors and other environmental variables.
3. To further investigate the properties of Hydrorock blocks to deliver water and re-design new elements suitable for different soil and climate conditions (laboratory investigation and modelling).

The main research questions behind this project are:

i. What is needed to adapt the current Hydrorock blocks to be used as a sub-surface irrigation system?
ii. What is an optimal setting-up to use the current Hydrorock blocks as a sub-surface irrigation system for the specific location(s) aimed for?
iii. How should the system be operated and monitored remotely?
iv. What is the performance of the system compared with traditional irrigation systems?
v. Based on the field experiences and the Lab experiments, which improvement can be done to completely re-design the current Hydrorock blocks into a new subsurface irrigation device?
vi. What is the potential of this innovation for scaling-up?

4 The approach of ASSIST

Advanced subsurface irrigation system using Hydrorock (ASSIST) is a project co-funded by the Top consortium for Knowledge and Innovation (TKI) programme under the topic Delta Technology. The consortium of this project was formed by two Dutch private companies, Hydrorock International BV (HR) and Smart Farm Sensing (SFS) and Wageningen Environmental and Research as knowledge institution. To carry out some of the activities in the project, the partners collaborate with the International Centre of Biosaline Agriculture (ICBA) in Dubai and the Arabian Gulf University in Bahrein.

In order to answer the above questions, the project carries out a very practical approach, following the next steps:

i. Quick Scan of the most relevant literature related with the use of stone wool material in water related applications, including their hydraulic properties.
ii. Characterisation of the hydraulic properties of the Hydrorock blocks by laboratory experiments (following the methodology proposed by Baker (2022)).
iii. Iterative design of different Hydrorock blocks configuration.
iv. Simulation of water release behaviours from Hydrorock blocks under different types of blocks (densities and fibre directions) and soil circumstances.
v. Implementation of two showcases in order to assess the suitability of Hydrorock blocks for subsurface irrigation under real conditions in arid regions (Dubai and Bahrein).
vi. Assessment of further potential applications and next steps.

Up to this, during the execution of the project, two Master Thesis under the MSc International Land and Water Management of Wageningen University were also carried out. The most relevant results from these Thesis are also showed in this report (Menezes, 2023 and Arikan, 2023).

5 Use of Stone wool for water related applications

Stone wool (or rock wool, or mineral wool) is an inorganic material derived from molten rock furnaced and spun at a temperature of about 1600 °C. The final product is a mass of intertwined fibres with a typical diameter of 2 to 6 micrometres, which can be compacted in different shapes and densities, according to the final use (Bougoul et al., 2005). Stone wool is mainly characterised by its lightweight, low thermal conductivity, high sound-absorbing performance, chemical durability, and non-combustibility. Therefore, these inorganic materials have been widely used as high-quality heat-insulating and sound-absorbing materials in transport systems, the nuclear power industry, refrigeration as well as buildings (Chen and Liu, 2022).

Another property of stone wool is its high porosity, being able to hold around 95% of water. This capacity, together with a very high hydraulic conductivity, of around 5-200 m/day, allow the material to "absorb" a high quantity of water in a relatively short time (Lapinus, 2018). Thanks to those "unique" hydraulic properties, the stone wool can be also used in other water-related applications, such as drainage or as a substrate in soilless cultivation (hydroponics). The latter is probably the most common application, since this material has been used as substrate in hydroponics greenhouses for already several years (Savvas and Gruda, 2018). In hydroponic agriculture, stone wool is often used as a growing medium for plants. It is an inert material that does not contain any nutrients, so the plants must be fed with a nutrient solution that is delivered through the irrigation system. The stone wool acts as a substrate for the plant roots to anchor onto and absorb water and nutrients from. Other water related application is the use of stone wool fibres as soil remediate substances, increasing soil sorption capacity (Baran et al., 2008) or as a part in the mixture of other substrates, for example peat, bark or compost (Bussell and McKennie, 2004). However, the application of rock wool in field plantations are very rare and there are very little examples available in the scientific literature (Gilewska, 2005; Kováčik, 2006; Kováčik et al., 2010).

Hydraulic conductivity and water retention curves are the most crucial physical parameters to understand how the water is moving and retained by the rock wool substrates (Bougoul et al., 2005). But only limited data is available in the scientific literature. Most of the existing studies have been focused on determining the hydraulic properties of the material to understand the dynamics of water and nutrients, aiming to improve their management in time and space according to plant needs during each step of the crop cycle (Bougoul and Boulard, 2006). In Figure 1, a comparison of the water retention curves between stone wool and other inorganic and organic materials potentially used for soil less media can be found. It is clear that stone wool is the material with a higher capacity to store water (95%) in comparison with other materials. This capacity is limited to very low matric potential (5 to 50 hPa), mainly related with the range of easily available water (EAW).

The hydraulic conductivity of stone wool varies depending on factors such as density, moisture content, and temperature. Bougoul et al. (2005) found a saturated hydraulic conductivity of 0.002 m/s for Floriculture stonewool (density of 0.0675 kg/dm^3) and 0.006 m/s for Expert stonewool (density of 0.046 kg/dm^3). However, those values are 3 times higher for Floriculture and 10 times higher for Expert, than the value reported by Da Silva et al. (1995). The unsaturated hydraulic conductivity was also measured by Bougoul et al. (2005), indicating that hydraulic conductivity systematically decreases when suction increases. They also found that the less dense material presented the highest conductivity for the suction values usually observed in the cropping conditions (range: 0–5 cm or pressure head). However, it is important to note, that in all cases, the hydraulic conductivity reported for stone wool is much higher than the one reported for soils, which is usually in the order of 0.01 to 0.0001 m/s for sandy soils, 10^{-5} to 10^{-7} for loamy soils or lower than 10^{-8} for clay soils.

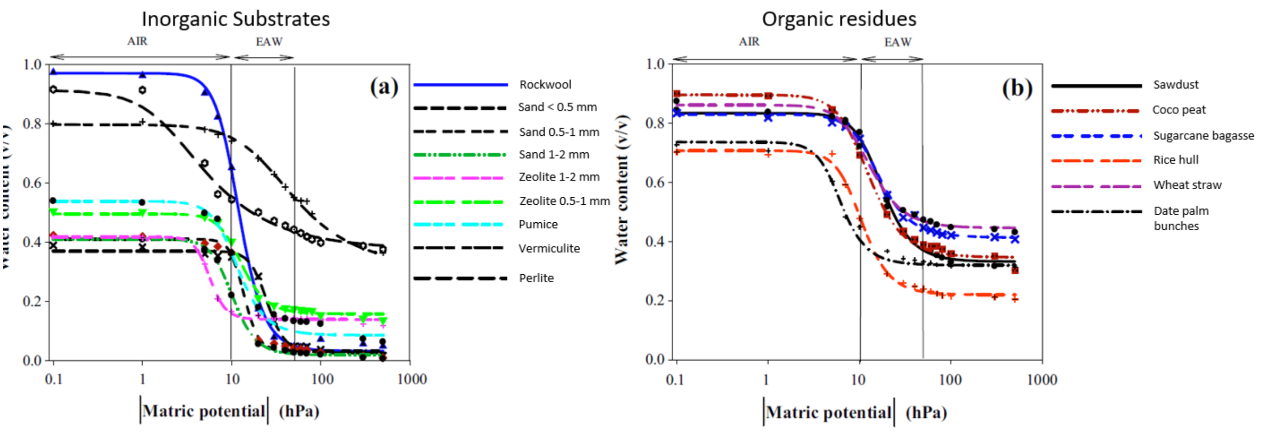

Figure 1 *Comparison of water retention curves of stone wool (rockwool) material with other potential inorganic (left) and organic (right) substrates (Banitalebi et al. (2019)). Values predicted by van Genuchten model.*

6 Characterisation of the hydraulic properties of Hydrorock blocks under laboratory conditions

To use the rock wool material for water related applications (drainage, but also irrigation), Hydrorock manufactures its blocks in different sizes, fibre orientations and densities. To protect them from external agents, they cover them with a cotton-based geotextile, which also aim to reduce root penetration. For some applications, such as irrigation, Hydrorock includes an extra membrane to seal the blocks on the bottom and some laterals, forcing the water to be released from the open sides.

Aiming to have a better understanding of the hydraulic properties of the Hydrorock blocks, a set of tests has been developed in the laboratories of Wageningen University and Research. In order to do so, the hydraulic conductivity (saturated and unsaturated) as well as the water retention curve using the Wind's evaporation method has been evaluated for three different types of blocks with different densities and fibre direction[1].

Figure 2 *Different configuration of Hydrorock blocks.*

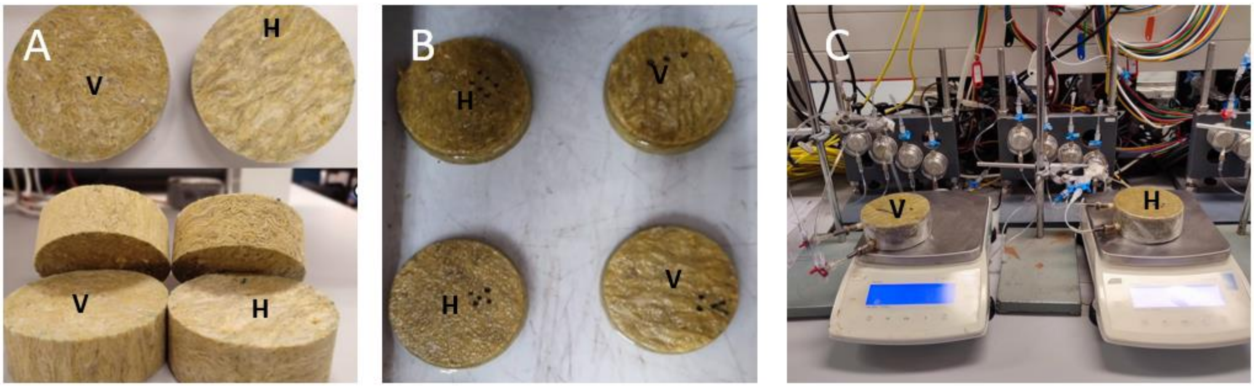

Figure 3 *Hydrorock samples used for Wind's evaporation method. A) dry samples; B) saturated samples; C) experimental configuration (Arikan. 2023).*

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1 These properties were measured in the Soil Hydro-Physics Laboratory of Wageningen University and Research, by following: the Wind's evaporation method, for the water retention curve (Wind's evaporation method ISO/FDIS 11275:2004 (E)); (NEN5789/1991) for Ks; ISO 11272:2017 for the dry bulk density and volumetric water content at saturation. More details of the methodology used can be found in Baker (2022) and Arikan (2023).

The Hydrorock material presents the following water related properties (Table 1):

Table 1 *Water related properties of Hydrorock material.*

Type of HR block	Volumetric water content at saturation (cm^3/cm^3)	Dry bulk density (g/cm^3)	Ks (cm/d)
Low density	0.978	0.098	6,174
High density, vertical fibres	0.980	0.121	10,026
High density, horizontal fibres	0.988	0.141	12,808

From those properties, it can be stated that Hydrorock blocks present:

- A very high capacity to store water under saturated conditions, with values of around 98%, meaning that the material is able to store a lot of water per unit of volume.
- A very low dry bulk density, with values of around 0.08-0.12 g per cm^3.
- A very high saturated hydraulic conductivity (Ks) of around 6,100 to 12,000 cm/d, meaning that this material has a high capacity to transmit water under saturated conditions.
- Blocks with high density present a higher Ks than those with lower densities.

In Figure 4, a comparison of the water retention curve measured by the Sandbox method (Klute. 1986)[2] for two different densities (75 and 120 kg/m^3) and for three replicants can be found. The variability of the replicants is minimal, especially for the 3 samples of high density. There is a clear effect of fibre density in how the water is stored in the block at the different pressure heads (suction), with water releasing at lower pressure for the blocks with lower density. However, in both cases, the water content at pF 2 (also known as field capacity) is minimal.

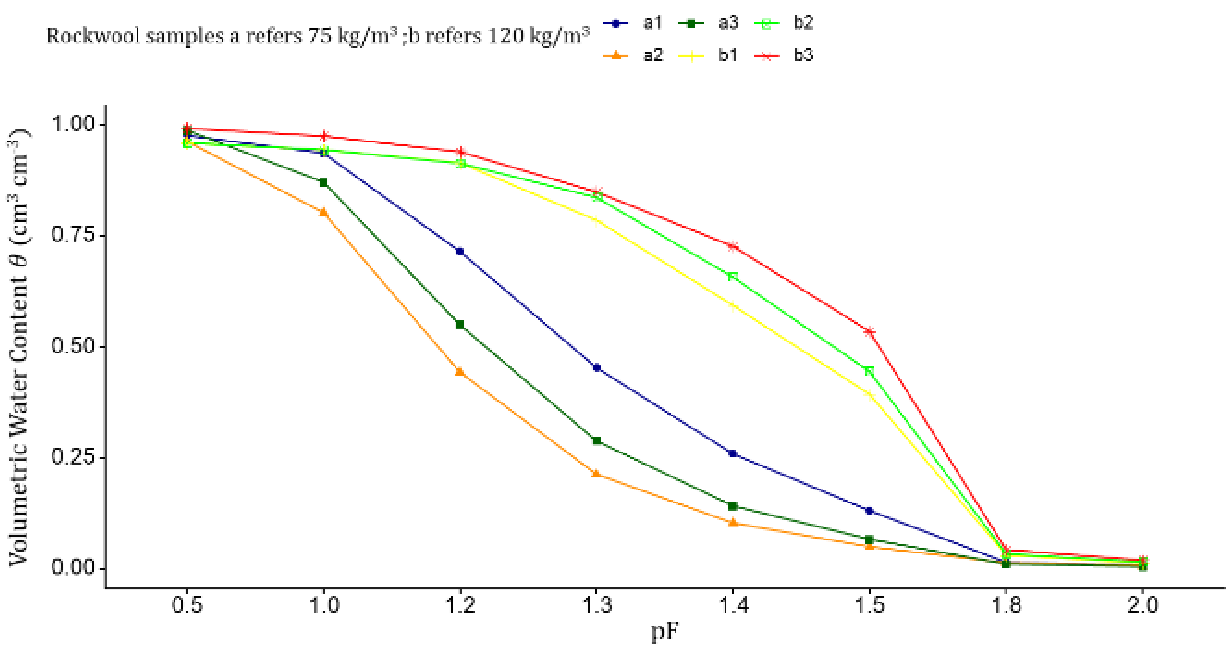

Figure 4 *High and low-density types of stone wool cylinder samples representing each sample's water content changes with suction between 0 to 2 pF.*

[2] This property was measured in the Soil Hydro-Physics Laboratory of Wageningen University and Research, by following the determination of the water-retention characteristic-Sandbox method (ISO 11274:1998(E)) for the pF curve; an adaptation of the "constant head method".

Finally, a water retention curve was developed for 4 types of Hydrorock blocks assessed (densities and fibre direction) and compared with the values reported by the literature (Bougoul et al., 2005) (Figure 5). From those curves, it can be stated that:

- The data reported from literature results in less water retention and lower conductivity than the one we found for Hydrorock blocks.
- According to the sandbox measurements, there is a clear difference in water retention and conductivities depending on the density, with less water retention and lower conductivities for low density material.
- According to the evaporation method the impact of fibre orientation at high density samples is relatively small: for horizontal fibre orientation slightly less water retention and slightly lower conductivities are seen. Moreover, these are also somewhat lower than according to the sandbox measurements. This sounds somewhat counter-intuitive, as one would expect for horizontal fibre orientation an increased water holding capacity and lower conductivities. Since the Hydrorock sample with vertical fibres had a greater dry bulk density than the sample with horizontal fibres (see results evaporation method), this might have caused the current findings (due to lower porosity, and possibly different pore-size distribution).

In Figure 6, a comparison of the hydraulic properties of the Hydrorock blocks with some natural soils can be also found. Natural soils have a greater water holding capacity under more dry conditions (h < -100 cm). However, under wet conditions (h > -100 cm) the hydraulic conductivity of soils is much lower. For dry conditions (h < -100 cm) the conductivity for sand resembles the one for Hydrorock, whereas for loam and clay the conductivity is greater than for Hydrorock. It is therefore clear than Hydrorock blocks have a water related behaviour completely different from natural soils, especially for loam and clay soils, being able to store a lot of water under relatively wet conditions. This, together with the high hydraulic conductivity of Hydrorock blocks, will determine the water transfer from the blocks to the soil, with little effect of the type of fibre direction or density used in the blocks.

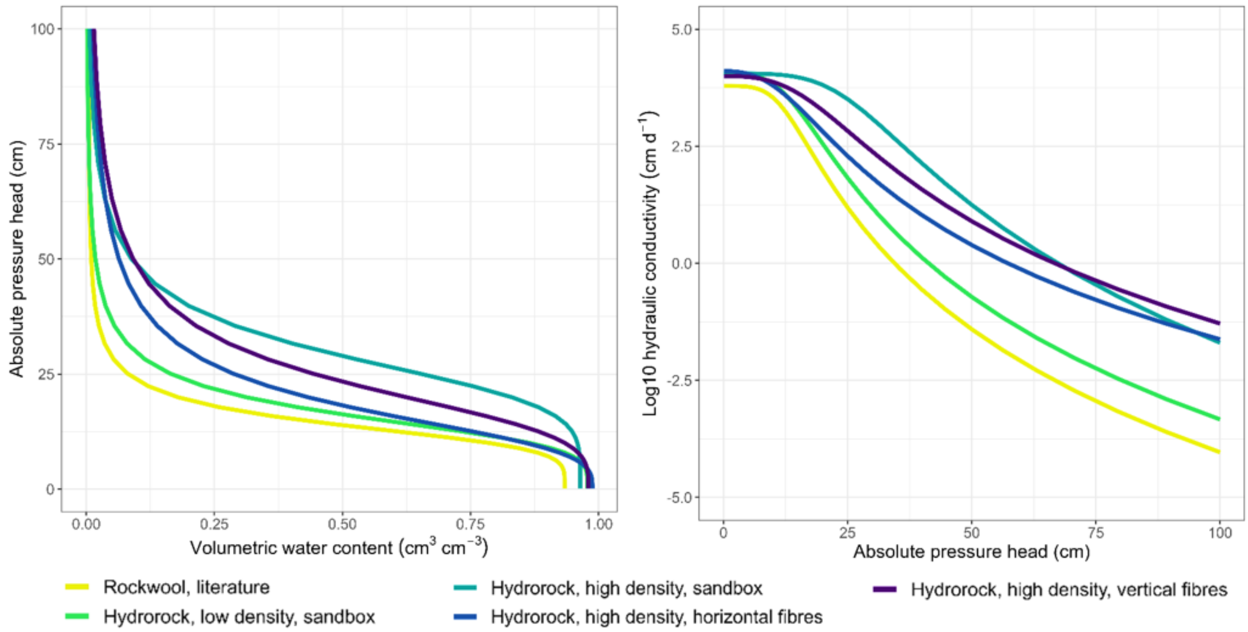

Figure 5 *Water retention characteristics (left) and Hydraulic conductivity characteristics for different configurations of HR blocks.*

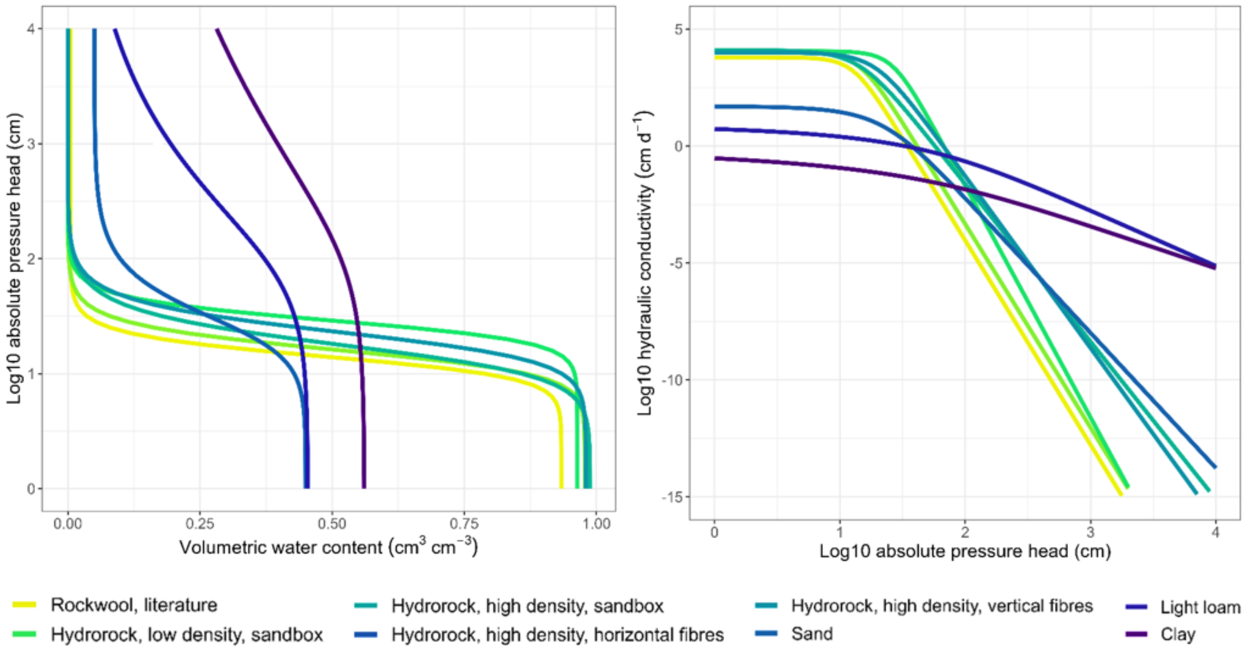

Figure 6 *Water retention characteristics (left) and Hydraulic conductivity characteristics for different configurations of HR blocks and different type of soils.*

7 Potential configurations of Hydrock blocks as a subsurface irrigation system

Hydrorock blocks can be manufactured in multiple configurations, according to the needs of the client. Hydrorock blocks are mainly recommended for subsurface irrigation for orchards, either for a completely new irrigation layout or as individual elements to be connected to the existing irrigation system (plug & play). However, Hydrorock already has some pre-configurated blocks (Table 2), that can be accommodated to different type of crops, water requirements or the capacity of existing irrigation systems.

Table 2 *Hydrock blocks configuration.*

Product code	Description	Volume (L)	Dimensions (cm)	Weight (Kg)	Water cont. (L)
D20 ir irrigation unit	bottom and three lateral sealed, with horizontal fibers	20	50x20x20	1.7	19
D40 ir irrigation unit	bottom and three lateral sealed, with horizontal fibers	40	100x20x20	3.4	38
D45 ir irrigation unit	bottom and three lateral sealed, with horizontal fibers	45	120x20x20	3.6	42.75
D112 ir irrigation unit	bottom and three lateral sealed, with integrated perforated drainage pipe 100mm	112	120x30x30	9	106.4

The water to the Hydrorock block can be supplied with normal 16 mm or even 25 mm pipe. However, in order to keep control of the water released, in terms of flow and volume, Hydrorock can be also equipped with an internal regulated pipe (pressure compensated), allowing the release of a controlled flow. In this case, three type of blocks can be used:

A. non-flow control block, where water is provided by an open 16 or even 25 mm pipe.
B. low-flow control block, with flows of 1.2 and 2.4 l/h per 30 cm of block.
C. high-flow control block, with flows of 12 l/h per 30 cm of block.

In all cases, Hydrorock blocks can be installed in line or in parallel to the (existing)piping network and the number of elements per tree can be calculated according to the irrigation requirements. The size and number of blocks per tree should at least allow to apply the water demand of 1 day of irrigation during the peak season (Figure 7). It is important to note that the Hydrorock blocks are sealed, with only one lateral and the top of the block unsealed. When the blocks are placed underground, the unsealed lateral should be placed against the tree. The blocks can be connected to the supplier pipe by two ways (Figure 8):

- Connecting the open end of pipe to the top of the block by introducing the end of pipe between the stone wool and the protective geotextile membrane. This is mainly recommended for D20, D40 and D45 block and for an "in parallel" configuration.
- Connecting the blocks trough a 100 mm pipe, by introducing the pipe in the integrated perforated drainage pipe. This is mainly recommended for D112 block and for an "in line" configuration.

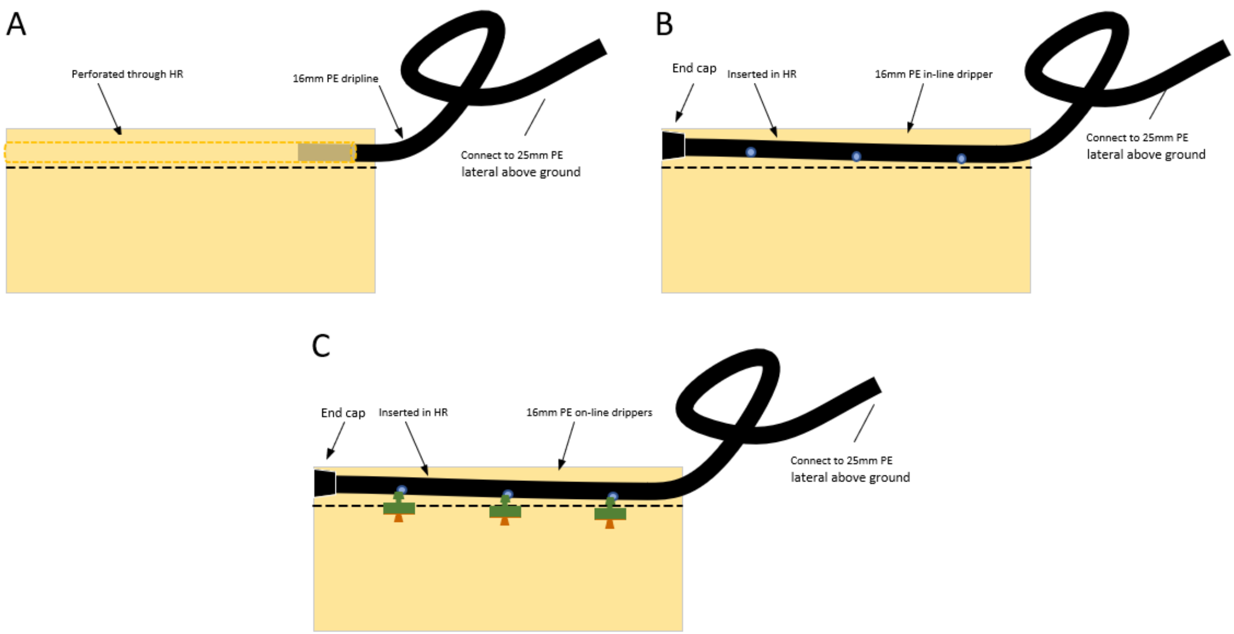

Figure 7 *Potential configuration of Hydrorock blocks, depending on their capacity to control the flow of water.*

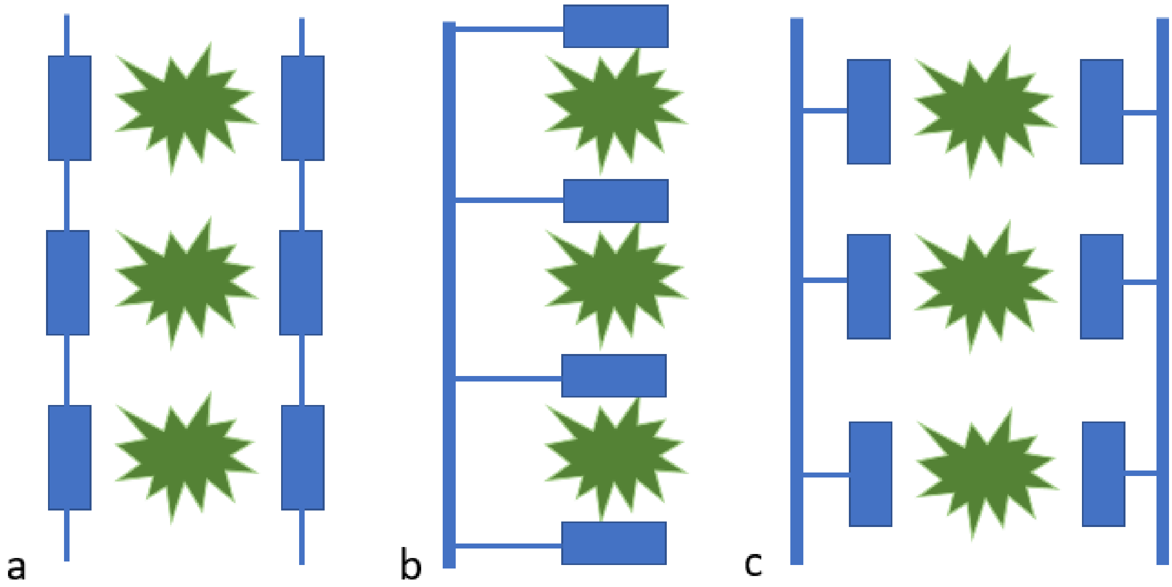

Figure 8 *Different configuration option: a) in line with two elements per tree and blocks connected to a lateral pipe; b) in parallel, with two elements per tree and directly connected to a main/secondary pipe; c) in parallel, with two elements per tree and connected to a lateral pipe.*

Figure 9 *Different configuration options: a) in line for date palm trees; b) in parallel, for olive trees.*

8 How is the water moving through the Hydrorock blocks?

The functioning of the Hydrorock blocks is very simple. The water is applied to the block through an irrigation pipe and the block will be filled, depending on the size/volume of the block and the flow of water. Once the Hydrorock element is filled, the water is delivered into the soil gradually through the non-sealed lateral, according to the type of soil, moisture conditions and the suction capacity of the roots (Figure 10). It is important to place the unsealed lateral against the tree, to favour root water uptake. The water can be provided from a pipe to the block by two different ways, either using a non-control system (open pipe connected to the block) or by a control-flow system (inlet pipe with pressure compensated drippers). Once the water is provided to the block, this water will be distributed within the block before being released to the soil. The movement of water withing the block is therefore driven by the hydraulic properties of the stone wool. Since the hydraulic conductivity of the block is usually much higher than the one of the surrounding soil (even in case of sandy soil), the water will first start to fill the block and when partially(saturated) the water start to be released to the soil, depending on the hydraulic properties and moisture conditions of the surrounding soil.

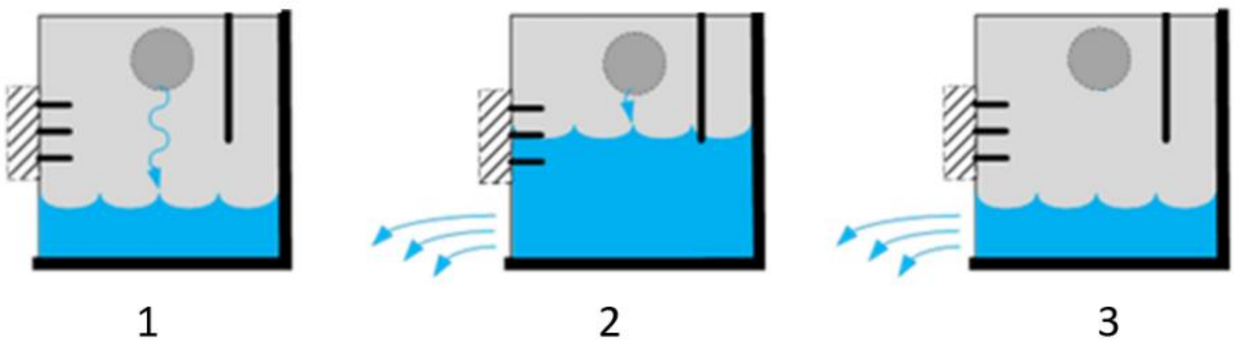

Figure 10 *Schematisation of the functioning of a Hydrorock block.*

In order to better understand how the water is moving withing the block, but also how the different stone wool properties can affect the distribution of water (i.e. fibres density and direction), several simulations have been done using the model FUSSIM2[3]. Simulations considering three equally spaced drippers (at 30 cm distance) at the top of the block, and a seepage bottom condition was assumed (water outflow only starts after the bottom of the Hydrock becomes saturated). The hydraulic properties of the block differs in terms of fibres direction (vertical and horizontal) and density (75 and 120 kg/m^3) according to the results obtained during the characterisation of the material in the laboratory (Table 1). Two different flow rates were used to assess the effects of low and high flow on the water distribution.

As we can see in Figure 11, the different configurations of the Hydrorock blocks (density and fibres direction) don't have a large influence on how the water is distributed within the block. In most of the cases, the steady state condition (input of water is in equilibrium with the output) is reached after 90-100 min of operation (150-160 min for low flow) drippers. In most of the cases, an important part of the block is not active in releasing water to the soil, with only half of the block getting almost saturated conditions. However, this simulation was done considering a constant pressure head of the surrounding soil, what would not be the case in real conditions (see next section to understand how the water is moving from the block to the soil).

An experimental setup to replicate the simulations was performed in the lab, applying water to different control-flow blocks and checking the evolution of the soil moisture over time. For doing this, a visual method was used, trying to assess the area saturated on a cross section once the steady state conditions (water

[3] FUSSIM2 is a two-dimensional simulation model for water flow, solute transport, and root uptake of water and nutrients in partly unsaturated porous media (Heinen and De Willigen (1998)).

input similar to water output) were achieved. More details about the methodology used and the results can be found in Arikan., (2023).

As it can be shown in Figure 12*,* the water is gradually released by the control-flow pipe, creating a moisture inverse cone and mainly accumulated at the bottom of the block. Once the water reached a certain level (12-20% of the cross-section area, depending on the type of block and flow) the water starts to be released outside the block. It is important to note that in this experiment, the block was sealed on the bottom but not in the laterals and the water is only subjected to gravity pressure forces, since no soil media were placed around the block.

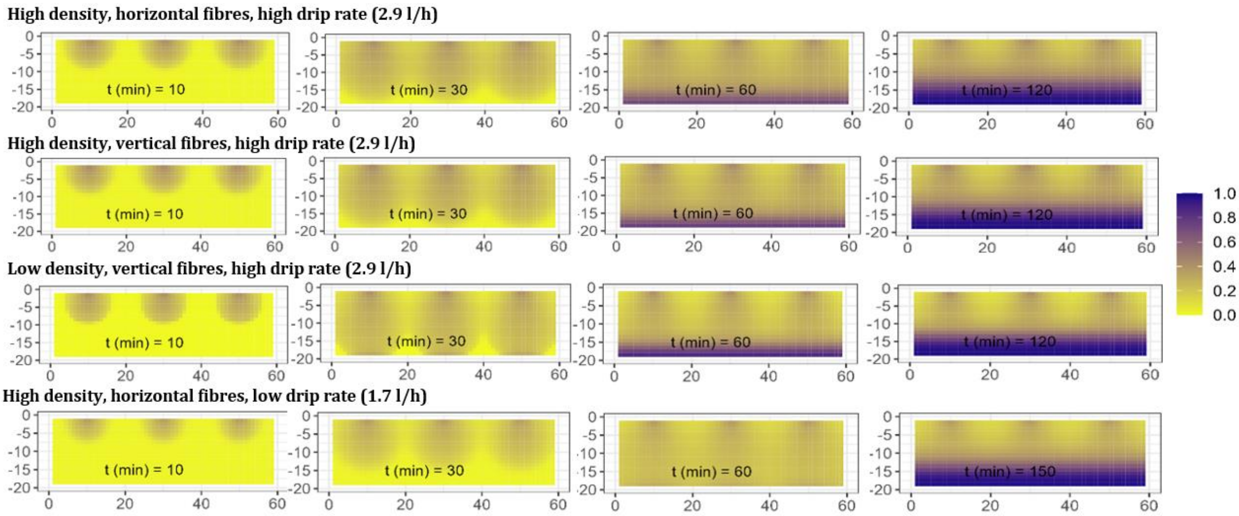

Figure 11 *Distribution of water within the Hydrorock block on a single irrigation event using a D112 IR flow control block with different rockwool properties (density and fibre direction).*

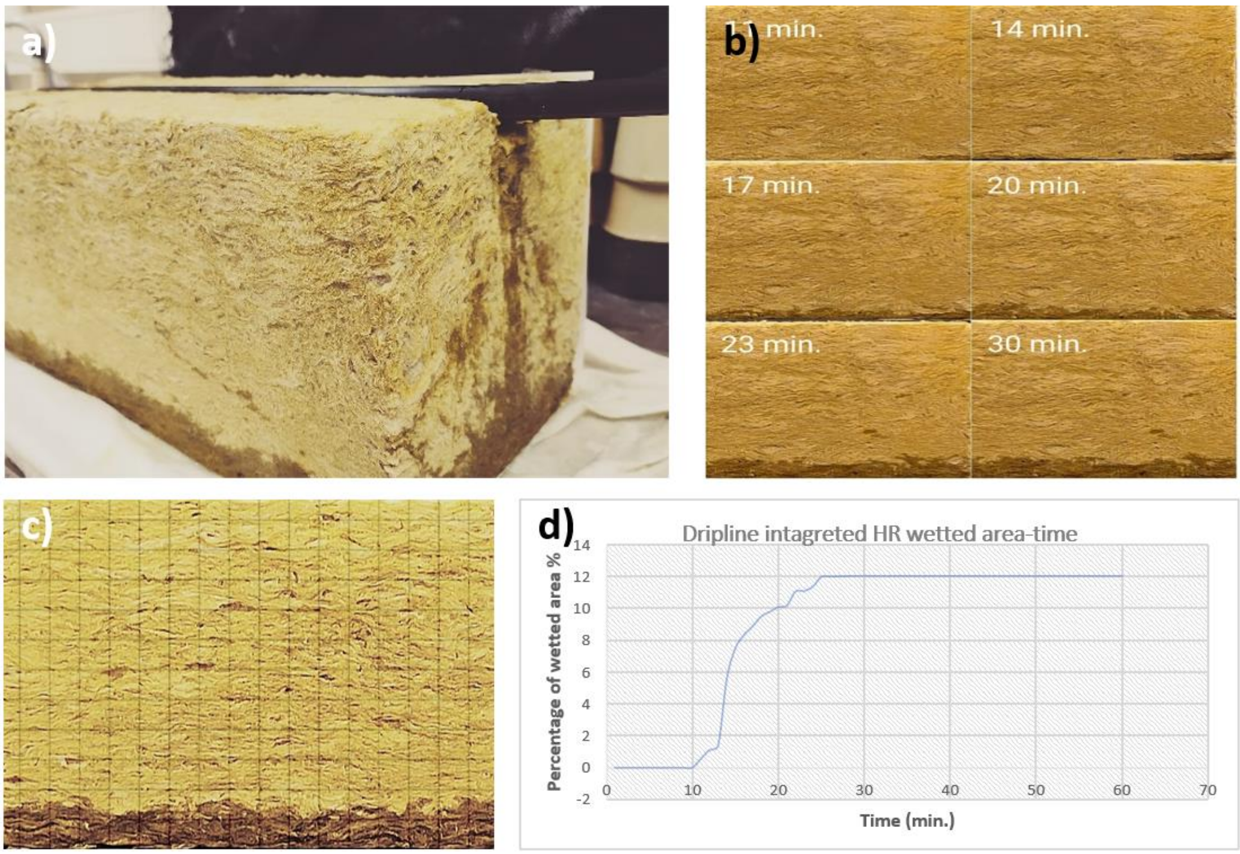

Figure 12 *Distribution of water within a stand-alone Hydrorock pressure compensated block over time during an irrigation event.*

9 How is the water delivered from Hydrorock blocks to the soil?

Due to the hydraulic properties of Hydrorock blocks, water is delivered gradually into the soil, but this will depend mainly on the soil type (texture) and soil moisture conditions. In order to understand how the water is moving from the Hydrorock block to the soil, a simulation has been done using the 2D model FUSSIM2 for a D112 IR non-flow control block under three different types of soils: sandy, loam and clay soil (Figure 13). The hydraulic properties of the Hydrorock block used in the simulation are the one corresponding with a high density and horizontal fibre block. The simulation starts with the Hydrorock block fully filled with water, replicating the application of water through a large diameter pipe (filled in few minutes).

The release of water from the Hydrorock block is driven both by the hydraulic properties of the block but also by the ones of the surrounding soil. In case of sandy soils, with a very high hydraulic conductivity, the water moves quickly to the soil. After a short period of 24h, most of the water is in the soil, moving mainly in the vertical direction. In case of loamy soils, with a lower hydraulic conductivity, water will be released from the block in a more gradual way, with still some water storage in the block after 24h of the irrigation event. Hydrorock blocks on clay soils, with a very low hydraulic conductivity, will perform completely different, storing water in the block itself even after 72h of the irrigation events.

In all cases, water can be available by plants either in the surrounding soil or in the block itself. However, in sandy soils, the risk of water losses into deep horizons is higher. In case clay soils, probably the roots will uptake the water directly from the block.

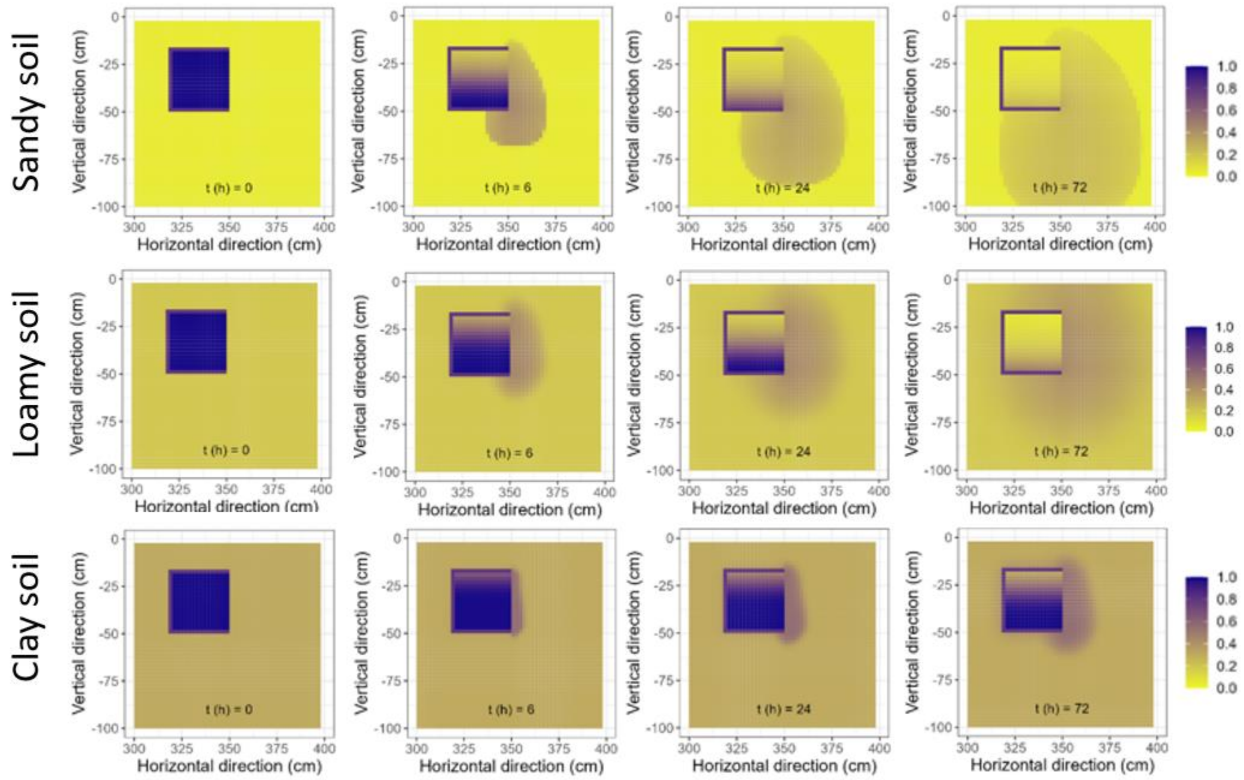

Figure 13 *Simulation of a single irrigation event using a D112 IR non-flow control block under three different types of soils: sandy, loamy and clay.*

A similar simulation but using a flow control block were also performed. In this case, D112 IR flow control block with both low flow (2.3 l/h) and high flow (12 l/h) were evaluated.

In case of high control flow (Figure 14), the block would need around 2 h to be almost filled. However, in all cases, water from the block start to be released before the block is fully filled. As in the previous case, the block under sandy soil delivers the water very quickly to the soil, while the water is mainly stored in the block under clay soils. However, the release of water for the three types of soils with a flow-control block is slower than with the non-control flow.

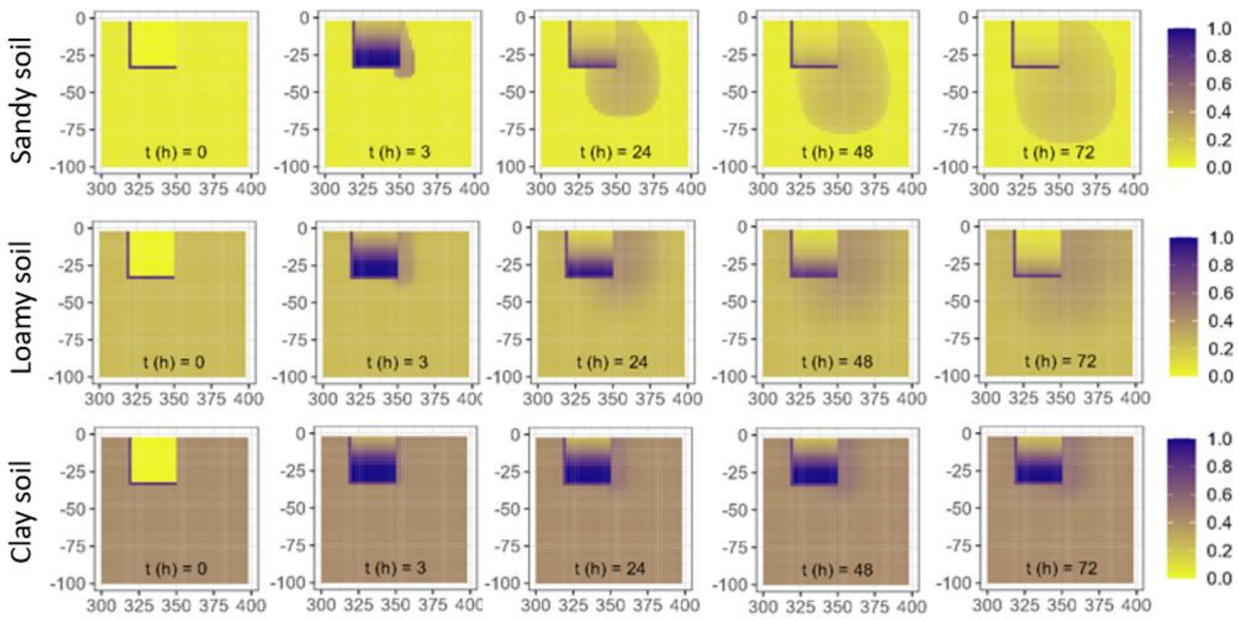

Figure 14 *Simulation of a single irrigation event using a D112 IR high flow (12 l/h) control block under three different types of soils: sandy, loam and clay.*

In case of low control flow (Figure 15), the block would need around 10 h to be fully filled. However, since the flow of water is much lower than in the case before, the block is never fully filled and the water is released to the soil before this happens.

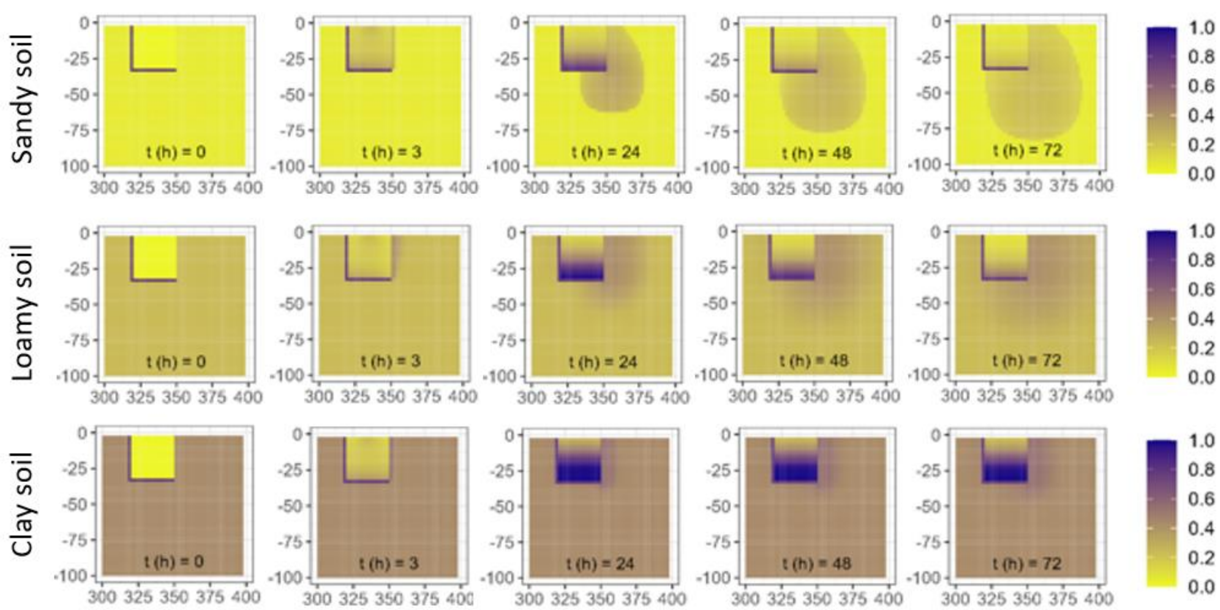

Figure 15 *Simulation of a single irrigation event using a D112 IR low flow (2.3 l/h) control block under three different types of soils: sandy, loam and clay.*

The simulations have been compared with the soil water content recorder by soil moisture sensors located at different depths from two pilot experiments in Dubai (sandy soil) and Bahrain (loamy soil), with very similar results both for blocks with non-control flow and for high control flow (see sections 11 and 12 of this report for further details). As it can be shown in Figure 16, the soil moisture level increases very quickly after an irrigation event in sandy soils with non-control flow block, with a very quickly release of water from the block to the soil. Water can easily be detected even in deeper horizons a few minutes after the irrigation, with the risk of water losses to deeper horizons. On the other hand, in loamy soils with a high control flow block, the soil moisture levels are rather constant, even after an irrigation event, with a gradual release of water from the block into the soil.

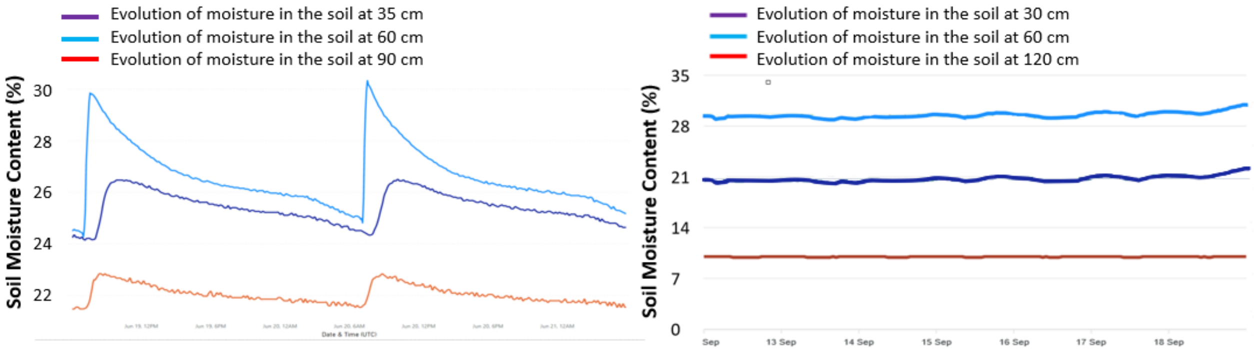

Figure 16 *Soil moisture behaviour over 144 hours in the Hydrorock system (soil), at 3 different depths for a sandy soil with non-control flow block (left) and a loamy soil with high flow control block (right)[4].*

[4] Data monitored with Teros12 sensors on a real plantation of date palms in Dubai (sandy soil) and Bahrein (loamy soil) at three different depths. Blocks used Hydrorock D112IR, placed at 30 cm depth.

10 AGRIOT platform: a tool to monitor and manage irrigation

The Hydrorock blocks can be also part of a more integrated irrigation system, allowing the users to monitor in real time the soil moisture content, the water applied and the weather forecast (Figure 17). Those system can be also designed to semi-automatise the irrigation scheduling, according to a set of predefined conditions, such as soil moisture levels in the different irrigation sectors or a soil water balance. However, it is important to remark that the final decision of irrigation should be taken by the farmer, using the system as a decision tool.

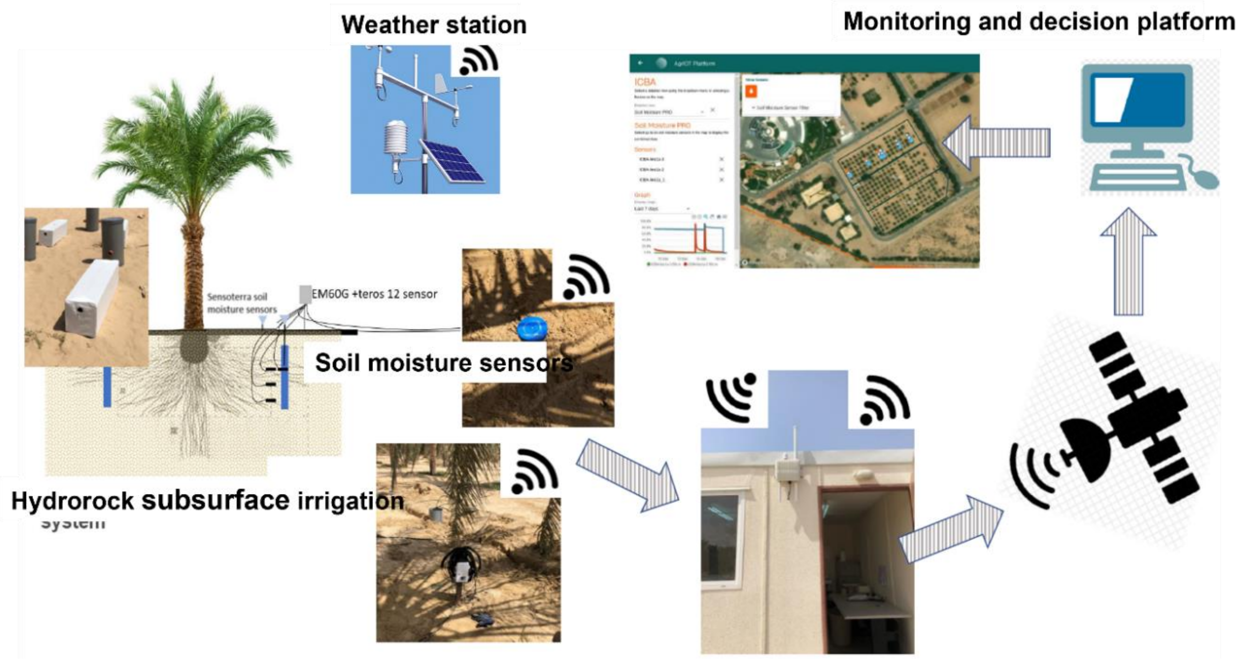

Figure 17 *Potential layout of an operational irrigation system with HR blocks in a date palm plantation.*

In order to monitor the results of the pilots performed in the project, the Agriot platform (https://agriot.app/), a geo-spatial agriculture data management platform developed by SFS, was used. This platform allowed the project to collect and visualise real time data of soil moisture, water flows and weather information (Figure 18) thanks to the possibility of connect it with different type of sensors (i.e. soil moisture sensor, flowmeter, weather station, etc.). The information can be also downloaded in different formats and periods, in order to analyse it further. Different soil moisture sensors were connected with the platform during the project, such as Sensoterra (wireless soil moisture) and Teros12 (soil water content, temperature and electrical conductivity) to track how the water is moving from the blocks to the soil. Weather information from the nearest weather station was also included in the platform.

Several improvements were done to the platform during the ASSIST project to improve the user experience, but also to increase the capacity of the platform to analyse data. For example, the platform was updated in order to simultaneously visualise data from different sensors. It also allows to download both interpolated and raw data, but also to introduce calibration or transformation equations, that can be directly applied to the raw data provided by multiple sensors when downloaded. In this sense, during the ASSIST project, the platform was updated with some calibration equations for the Teros12 soil moisture sensors under sandy soils and different levels of salinity in irrigation (see section below for further information). The platform was also updated with the possibility to transform the EC data from bulk EC (raw data provided by Teros12 sensors) into Pore EC.

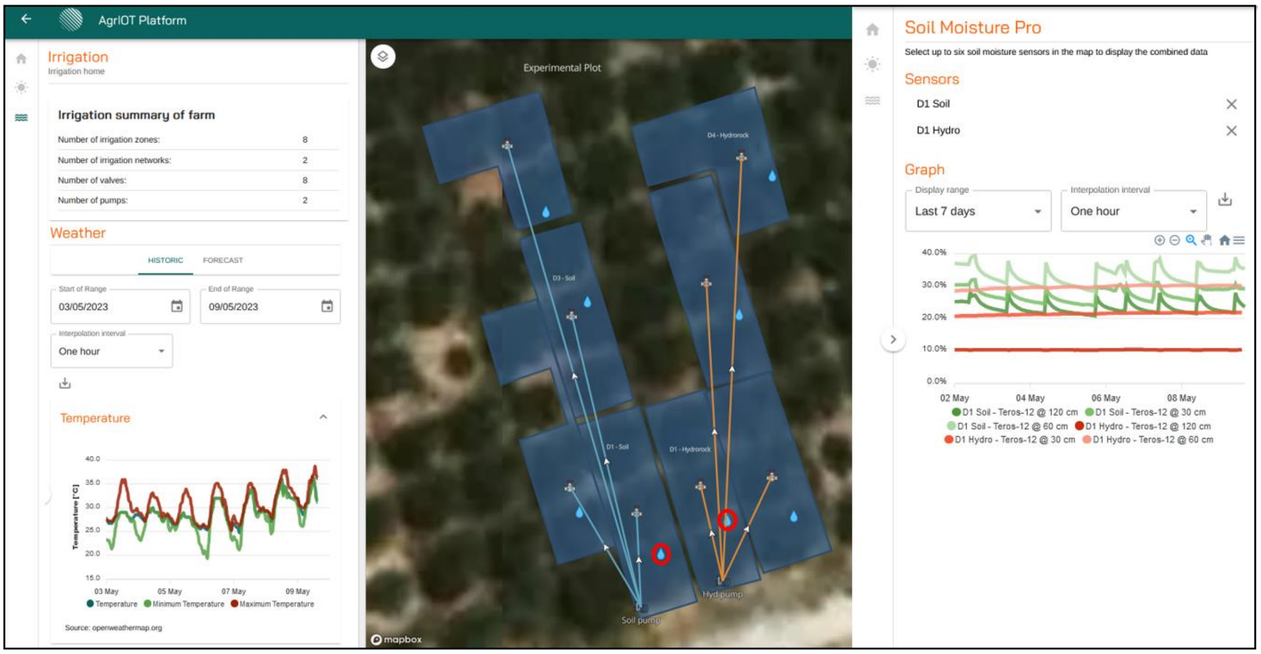

Figure 18 *Agriot platform developed by SFS. Real-time data from soil moisture sensors as well as weather information can be visualise and downloaded for further analysis. Example showed for the pilot developed in Bahrein at the Hoarat A'ali farm.*

Data from the platform was mainly used to understand the behaviour of the Hydrorock blocks under real conditions, both in the pilots implemented in Dubai and Bahrein. It was also used to take some operational decisions of the irrigation system, such as the increase of irrigation volumes to promote salt leaching.

11 Pilot case 1. Dubai. Comparison of the performance of Hydrorock with a traditional irrigation system (bubblers) with different levels of salinity

11.1 Experimental Setup & Background

In order to determine the performance of the Hydrorock system and compare it with a traditional irrigation system (such as bubblers), a pilot was carried out at the facilities of the International Center for Biosaline Agriculture (ICBA) located in Dubai. The system was installed in September-October 2020 and the experiment took place over two consecutive growing seasons (2021 and 2022). The pilot consisted of a date palm plantation irrigated with Hydrorock D112IR, with two blocks placed at both sides of each palm at 30 cm depth and fed by a 50mm pressurize pipe. As a control, a bubbler system was also monitored.

Eighteen local and imported date palm varieties (ten from UAE, seven from Saudi Arabia, and one from Iraq) were grown under three irrigation water quality treatments (5, 10, 15 dSm-1), in 15 rows for the whole experiment. The date palms were about 20 years old. The date palms were grouped in three plots, each of which consisted of 5 rows. Each salinity level was applied to one plot group (5 rows). A gap of 20 meters is kept between each plot group of 5 rows.

TEROS-12 soil moisture sensors were installed in the soil below the bubbler and HR systems (Figure 19) to measure the volumetric soil water content, temperature and salinity (bulk EC) at 3 different depths (30, 60 and 90 cm). In some cases, a sensor was also installed in the HR (only for 5 dS/cm). The data were accessible online through the AgrIOT platform.

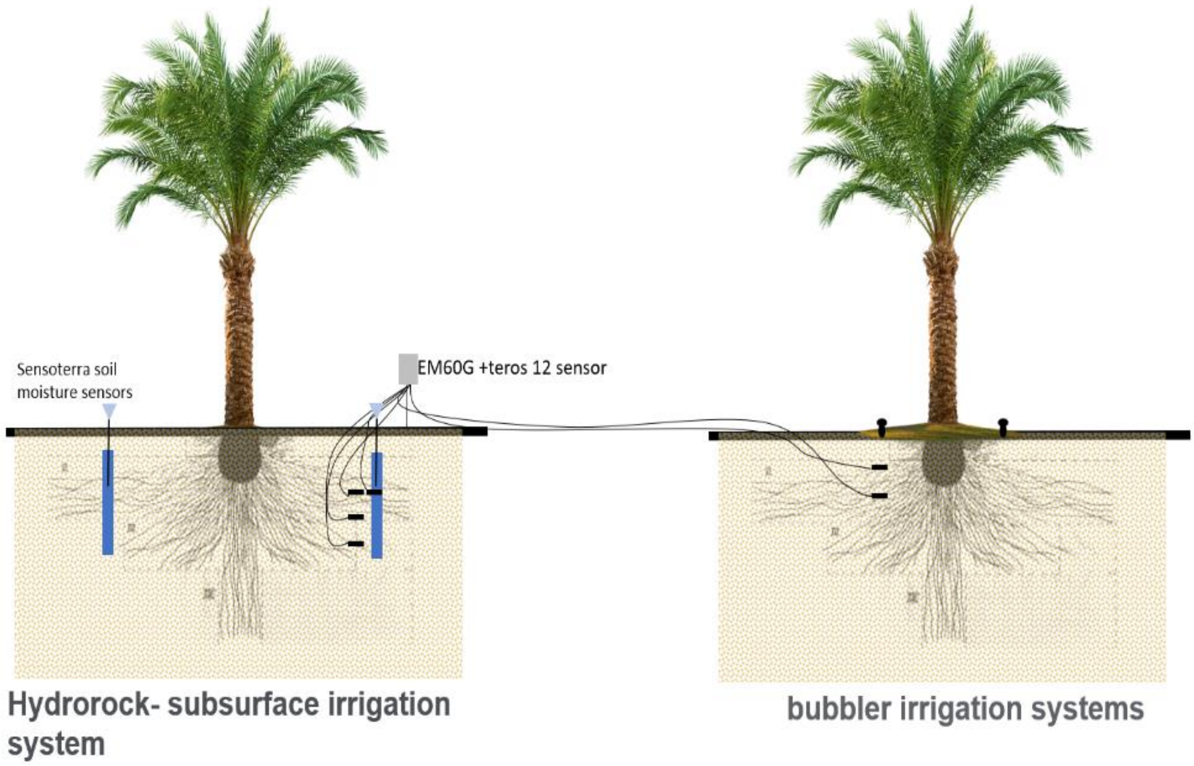

Figure 19 *Layout of HR blocks and bubblers and soil moisture sensors.*

11.2 Irrigation water applied

Irrigation was applied according to the calculated ETc, considering that in case of Hydrorock, there is no direct evaporation. In case of bubblers, the same estimation method was used, but including a leaching and security factor, as farmers usually do in this region (as suggested by Al-Muaini et al. (2019)).

In order to make a comparison between the effects of Hydrorock and bubbler, the analysis was mainly focused in the water with the best quality (5 dS/m), keeping the analysis of the more saline water to understand the effects of salinity.

At the beginning of the experiment, blocks were filled daily, considering the HR capacity of 214 L. This continued until November 18 (2021) and was then reduced to once every two to three days. During the winter season, Hydrorock blocks were filled twice a week on average until the end of March. From the beginning of April as the ETc increased, the blocks were filled every two days as one-on, one-off. For the bubbler system, water was applied daily throughout the experiment. During the 2022 growing season the irrigation frequency in Hydrorock was increased, to avoid salt build-up. The total amounts of water applied over both growing seasons can be observed in Table 3.

Table 3 *Water applied by Hydrorock and bubbler system in 5 dS/m (m^3/per tree).*

Water applied (M^3)	**2021**	**2022**
Bubbler	64.0	72.2
Hydrorock	42.2	41.7

As it can be shown in Figure 20, the total amount of water applied to Hydrorock was slightly higher than the ETc values, in order to wash some of the salts accumulated in the soil. The water applied to the Hydrorock was almost 40% less than the water applied to the bubblers. This is because the security factors used to determine the water to be applied by bubblers.

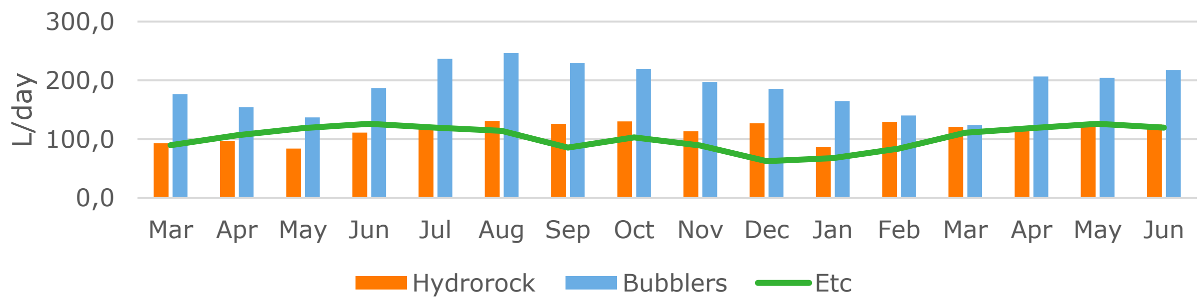

Figure 20 *ETc versus irrigation applied by Hydrorock and Bubblers in 5 dS/m (L/tree/day). Data from March 2021 to June 2022.*

11.3 Effects of Hydrorock irrigation on soil moisture levels

A comparison of the soil moisture levels was done for the two systems in order to evaluate the potential differences. Although the water applied to Hydrorock was lower than the one to the bubblers, in average, the soil moisture levels were very similar in both cases (Figure 21). Since the water with Hydrorock is directly applied into the subsoil and therefore no subjected to direct evaporation on the top-layer levels, the soil moisture levels between both systems remains very similar. In case of the top level (30 cm), the soil moisture for bubblers were always higher than for HR, but the opposite occurs when more deeper horizons are assessed, where a higher soil moisture value is reported for Hydrorock at 60 and 90 cm in comparison with the one found for bubblers at 60 cm.

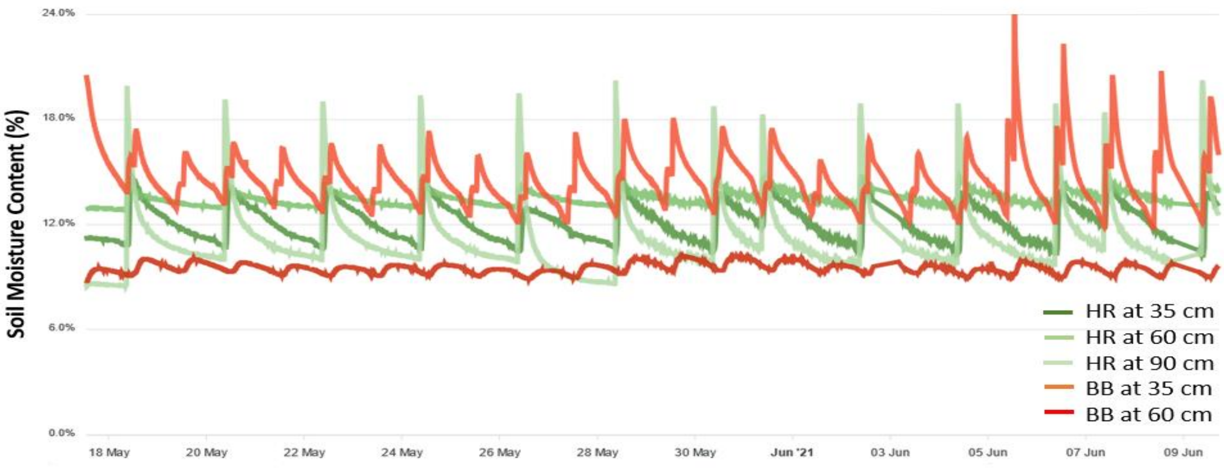

Figure 21 *Evolution of soil moisture at different soil depths for a date palm line irrigated with Hydrorock block (green lines) and a date palm line irrigated with bubblers (red lines). Data showed from 18 May 2022 to 10 June 2022.*

11.4 Effects of Hydrorock irrigation on date palm yield

The yields reported under bubbler was always higher than the one reported by Hydrorock system. However, although the volume of water applied with Hydrorock was significantly lower than the one applied with the bubblers, the difference in yields were minimal, specially in 2021 (Figure 22). Yields reported in 2021 and 2022 were also very similar, with a small decline in yields for Hydrorock system in 2022.

As we mentioned before, the experiment was carried out with different date palms varieties. Those varieties were grouped by ICBA according to their capacity to cope with salts, being salinity tolerant and salinity sensitive varieties. Under 5.0 dSm-1 the bubbler and Hydrorock system performed similar with 70 kg yield per tree for salt tolerant varieties, and about 45 kg per tree for salt sensitive varieties. However, bubbler system showed advantages over Hydrorock in the higher salinity levels, with about 50% higher yields for salinity tolerant varieties, probably related with the higher application of water.

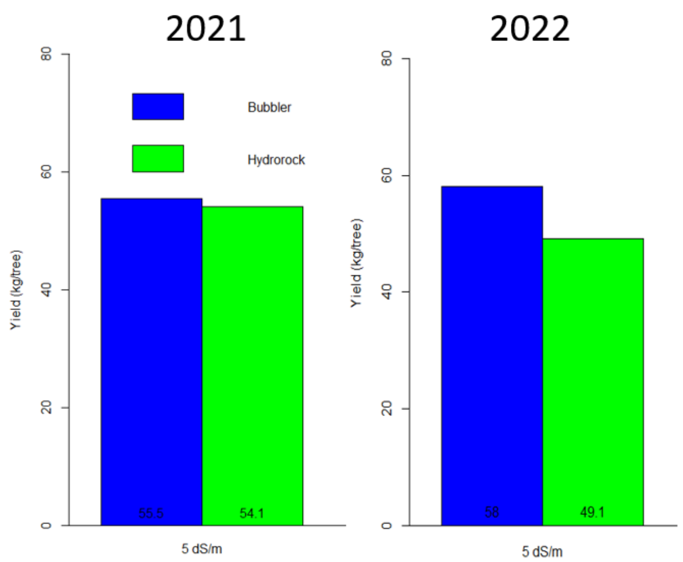

Figure 22 *Water use efficiency of date palms irrigated with Hydrorock (green) and with bubblers (blue), for 5 dS/cm.*

11.5 Effects of Hydrorock irrigation on Water Use Efficiency

Water use efficiency in this study was defined as product / water applied. In this case the kg yield per tree, divided by the amount of water applied per tree. In the 2021 and 2022 growing season, the WUE of Hydrorock was 45% higher than under the bubbler system in the 5 dS/m treatment, with values of 1.3 kg of date palm per m^3 of water used. This is because, although the yields reported for bubblers were slightly higher than the one reported for Hydrorock systems, since the water applied was much lower in case of Hydrorock, the WUE is much higher.

In the 2022 growing season the Hydrorock system had also a 45% higher WUE than the bubbler system in the 5.0 dSm-1 treatment. Under the 10 dSm-1 treatment the Hydrorock system has a 80% higher WUE than bubbler, and under the 15 dSm-1 treatment Hydrorock performs 50% better than bubbler (data not shown). This leads to an overall 60% higher WUE for Hydrorock over all three salinities (Figure 23). Important to note here is the higher application of water to the bubbler system, which even increased compared to Hydrorock over the 2022 season. ICBA supplies the bubbler system with a lot more water (approximately 50%) to account for extra evaporation, and as a safety element. This additional water will contribute to salt leaching in the bubbler system. Although the bubbler system consistently gives higher yields over all salinity levels in both growing seasons, the WUE of the bubbler system will be lower than for the Hydrorock system.

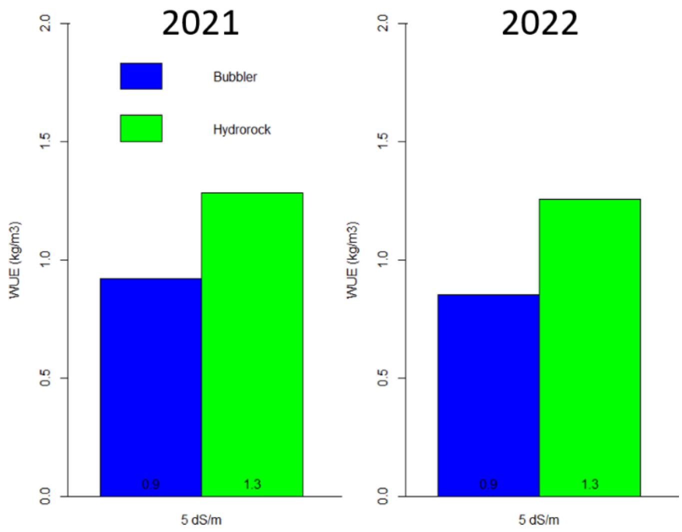

Figure 23 *Water use efficiency of date palms irrigated with Hydrorock (green) and with bubblers (blue), for 5 dS/cm.*

11.6 Salinity development around the HR system

At the start and end of season 2021, soil samples were collected around the Hydrorock and bubbler system for the three levels of salinity (5, 10 and 15 dS/m). These were analyzed for soil salinity (ECe) by using the soil paste extract method. Results indicate an increase in salinity in the rows irrigated with high saline water (10 and 15 dS/m), both at the beginning and end of season. The salt build-up under the Hydrorock system was higher than under the bubbler system, irrespective of irrigation water salinity of the soil depth of the sample. This may be because the amount of water applied to the Hydrorock system is enough to meet crop water demand but does not provide for sufficient leaching. This situation can threaten the crop production under the Hydrorock system and could be solved by periodic flushing with freshwater.

Results of soil salinity tests in February 2022 showed better performance by the Hydrorock system, and salinity levels were comparable with the bubbler system. An additional analysis in June 2022 gives even lower salinity levels in Hydrorock compared to bubbler. This shows that the modified irrigation schedule in 2022 was successful in leaching salts.

Salinity levels were also monitored with the Teros12 sensors, providing regular readings of the bulk EC (soil/water/air matrix). As it can be shown in Figure 24, the reported bulk EC is rather constant for 5 and 10 dS/m, but clearly increases in the date palms irrigated with 15 dS/m, due to a lack of salt leaching. Salinity levels at 60 and 90 cm depth are always very similar among them, while bulk EC at 35 cm depth is usually lower. This is probably because most of the water applied by the blocks are below this depth and the moisture and salinity available is mainly due to capillary rise.

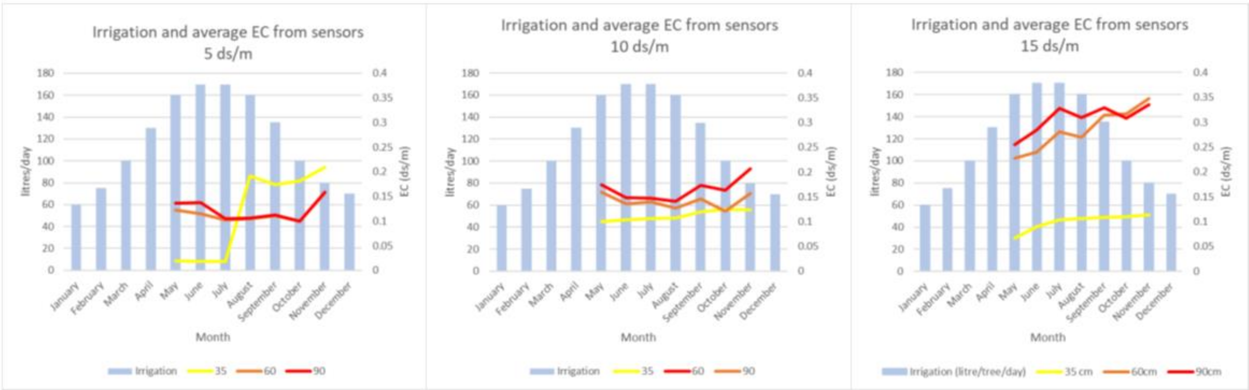

Figure 24 *Evolution of soil salinity (Bulk EC) measured with Teros12 sensors for the Hydrorock lines irrigated with 5, 10 and 15 dS/m.*

11.7 Calibration of Teros12 soil moisture sensors under high saline irrigation

According to the provider, the use of Teros12 sensors for monitoring soil moisture levels is recommended for water with salinity levels up to 20 dS/m (Meter., 2022). However, according to the tests done by the provider, the generic calibration equation for soil moisture provided for mineral soils works for EC ranged between 0 to 8 dS/m saturation extract. The salinity levels of the water used in this pilot ranges between 5 and 15 dS/m. Soil moisture readings can be influenced by salinity, since the sensors use an electromagnetic field to measure the dielectric permittivity of the surrounding medium. The sensor supplies a 70-MHz oscillating wave to the sensor needles, which charge according to the dielectric of the material. The charge time is proportional to substrate dielectric and substrate VWC but can be also affected by salinity when concentrations are high.

In order to have a more reliable reading of the sensors for the pilots, especially in the treatments where a high saline water for irrigation is applied, a calibration curve for the 3 water qualities used in the pilots (5, 10 and 15 dS/m), but also for a high-quality water (0 dS/m), was done and compared with the generic calibration equation proposed. This calibration was done at ICBA facilities following the methodology proposed by the Teros12 manual for mineral soils (Meter., 2022).

As we can see in figures Figure 25 and Figure 27, the calibration curves for water with high salinity content (5, 10 and 15 dS/m) varies significantly from the one proposed by the provider for mineral soils. The latter is very similar to the one found for the water with no salt concentration (0 dS/m), both for linear and polynomial curves. The 3rd degree polynomial curve fits much better that the linear one in all cases. Although the polynomial calibration curve for 15 dS/m shows a different trend in high water content (RAW > 2500), checking the RAW data of the installed sensors, they usually range between 2000 and 2400, being values higher than 2300 almost a saturation conditions that hardly happen in sandy soils (only in very punctual moments after irrigation).

Based on this, it was decided to use a different calibration curve than the one proposed by the provider and use the same 3rd degree polynomial calibration curve for the 3 different levels of water quality, that is defined as:

$$y = 0.00000000369820x^3 - 0.00002523444729x^2 + 0.05759602697294x - 43.68790195718780 \ (R^2 = 0.99)$$

The calibration curve was uploaded into the Agriot platform in order to provide a direct transformation of the data obtained by the Teros12 sensors.

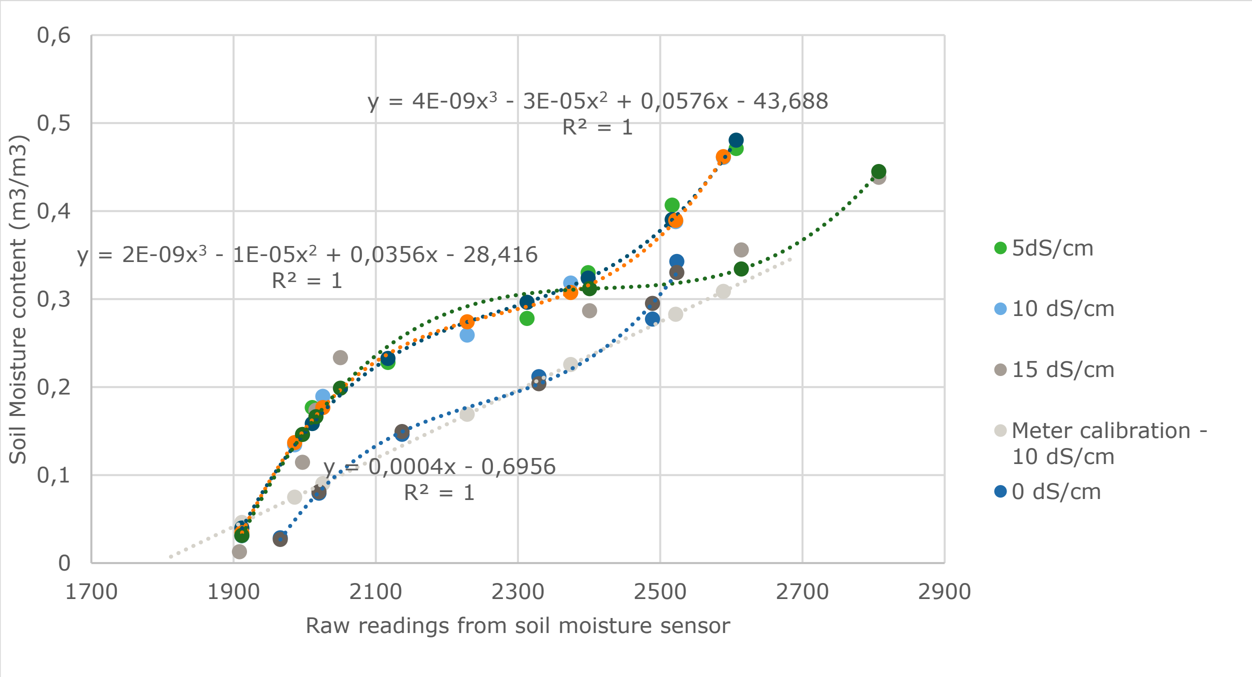

Figure 25 *Polynomial calibration curves of soil moisture sensor signal for 4 water qualities (0, 5, 10 and 15 dS/m) and comparison with the generic calibration curve proposed by the provider.*

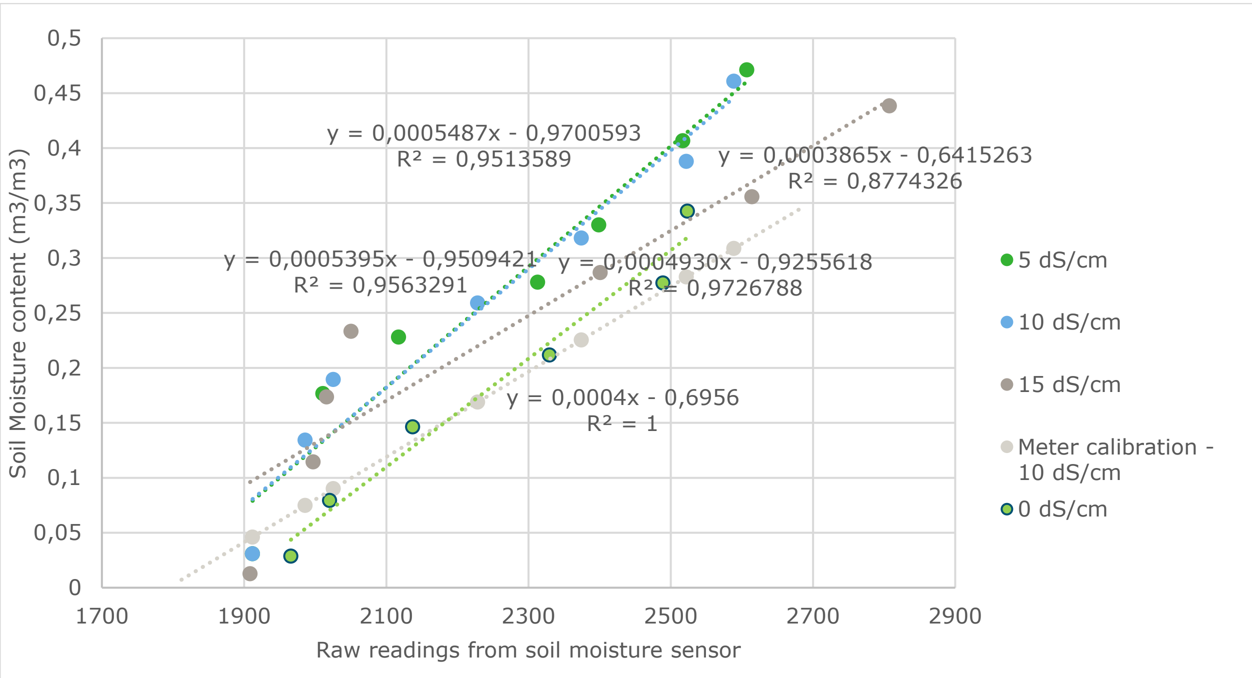

Figure 26 *Linear calibration curves of soil moisture sensor signal for 4 water qualities (0, 5, 10 and 15 dS/m) and comparison with the generic calibration curve proposed by the provider.*

11.8 Other considerations

Based on the daily operation and field observations by the ICBA technicians, the following considerations can be also stated:

- The Hydrorock system showed no weed pressure, which was the case in the bubbler system (Figure 27). This can reduce considerable the competition of water by weeds and reduce the operational cost.
- The Hydrorock system did not show any stress damage on trees and was comparable to the bubbler system for most of the planted varieties.
- There was no difference in fruit quality (aspects, size of fruits, color) between trees irrigated with bubblers and trees irrigated with Hydrorock.

Figure 27 *Growth of weed under bubbler (left) and Hydrorock system (right).*

An excavation was also performed in June 2022 to check the root development around the Hydrorock system. The roots were healthy and abundant around the Hydrorock element and did not penetrate the element itself. So after two years it seems that the risk of root intrusion into the Hydrorock element is limited, as long as the irrigation scheduling allows for water availability around the blocks.

Figure 28 *Excavation performed in June 2022 to check on roots health and status.*

11.9 Main conclusions from the pilot in Dubai

- Irrigating the Hydrorock system once every two days under low salinity irrigation water (5 dSm-1) gave the best results as indicated by WUE of 1.3 kg m-3 compared with 0.9 kg m-3 by the bubbler system.
- The Hydrorock system has the potential to apply less water compared to the bubbler system, this comes however with a decrease in yield.
- Irrigating the Hydrorock system daily is highly recommended during the hot summer season when irrigating with medium and high salinity water (≥ 10 dSm-1) as indicated by increased yield and WUE and reduced soil salinity build-up.
- Compared with the bubbler system, the Hydrorock system has a considerable advantage in weed control.
- Additional salt leaching should be practiced for Hydrorock systems with high-salinity water. The leaching requirements should be calculated considering the salinity of irrigation water (ECw) and the soil (ECe) in the root zone.
- There should not be any concerns regarding the interaction between the plant root system and the Hydrorock elements in the soil, as indicated by healthy and abundant root growth around the block without any root penetration into the blocks.

12 Pilot case 2. Bahrein. Comparison of the performance of Hydrorock with a traditional irrigation system (bubblers) and different levels of irrigation (deficit irrigation)

12.1 Experimental Setup & Background

The aim of this pilot was to evaluate the Hydrock technology for subsurface irrigation for date palms on a loamy soil in arid climate.

The experiment was carried out in Bahrein, at the Hoarat A'ali farm, a commercial date palm farm associated with the Arabian Gulf University. It involves two primary plot treatments, namely classic bubbler irrigation and subsoil irrigation with Hydrorock blocks in loamy soils. The Hydrorock used for this experiment are the D45 IR high-flow control block, with a flow of 45 l/h (with three drippers of 12 l/h). The blocks were placed at 30 cm depth. Each plot is divided into four sub-plot treatments, which include 1) irrigation based on crop water requirements calculation (100%, D1), 2) Deficit irrigation level one (80%, D2), 3) Deficit irrigation level two (70%, D3), and 4) Deficit irrigation level three (50%, D4). Each sub-plot treatment comprises three "Khalas" date palm trees. Therefore, a total of 24 trees were used for the experiment, with four sub-plots and three replications per sub-plot in both main plots. The 24 mature Khalas date palm trees, approximately 10-years old, were selected based on similarity, including variety, age, size, health, among others (Figure 29).

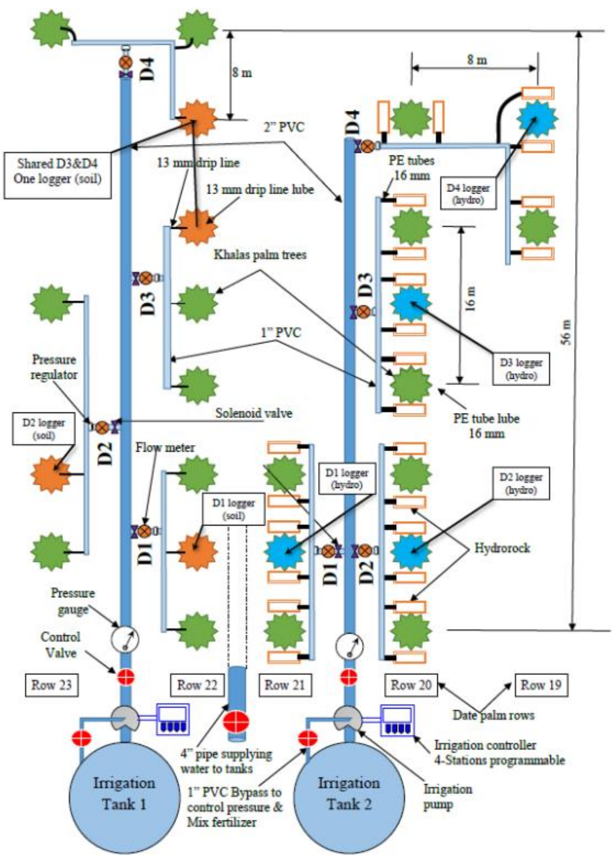

Figure 29 *Lay-out experiment date palms with sensor location.*

Soil moisture levels were tracked using the Teros12 soil moisture sensors placed within the field alongside date palms at three different depths, specifically 30, 60, and 120 cm below the surface. Data was collected throughout the entire season (January to September). This should be sufficient to study trends throughout the season. The SFS sensing platform AGRIOT was used to remotely store the data. Data from yields was also measured at the end of the season. An initial characterization of the soil was also done to determine the texture (loamy soil), and hydraulic properties, such as field capacity and wilting point.

12.2 Preliminary results: effects of Hydrorock irrigation on date palm yield

A preliminary analysis using the data of D1 (100% ETP) was done to compare the yields between date palms irrigated with Hydrorock blocks and Bubblers. Data for other treatments (D2, D3 and D4) are not shown, since they are under validation due to problems with water delivery. Although the designed water scheduling was the same both for Hydrorock and the bubblers, during the operation of the bubbler system, around 10% more water was added, in order to cope with some of the losses (runoff) produced by the bubblers around the tree pits (Figure 30). However, the yield obtained at the end of the seasons was around 15% higher in case of the trees irrigated with Hydrorock. The water use efficiency, defined as the total average yield per unit of water applied, was also calculated. The water productivity for HR was found to be 3.6 kg/m^3 while for soil it was 2.8 kg/m^3, showing that the HR element is using the water more productive than the bubblers in terms of water usage. However these results could be influenced by many factors and therefore can not be stated using these results alone that using the HR blocks will indeed lead to a higher water productivity. The reasons could be leakages of the water out of the system, small sample size for yield analysis (3 trees for HR analysis and 3 trees for the soil analysis), 1 season of harvest (preferable 2 or more seasons), as well as some data collection errors. Therefore, follow up research is needed to check the outcomes and refine the results.

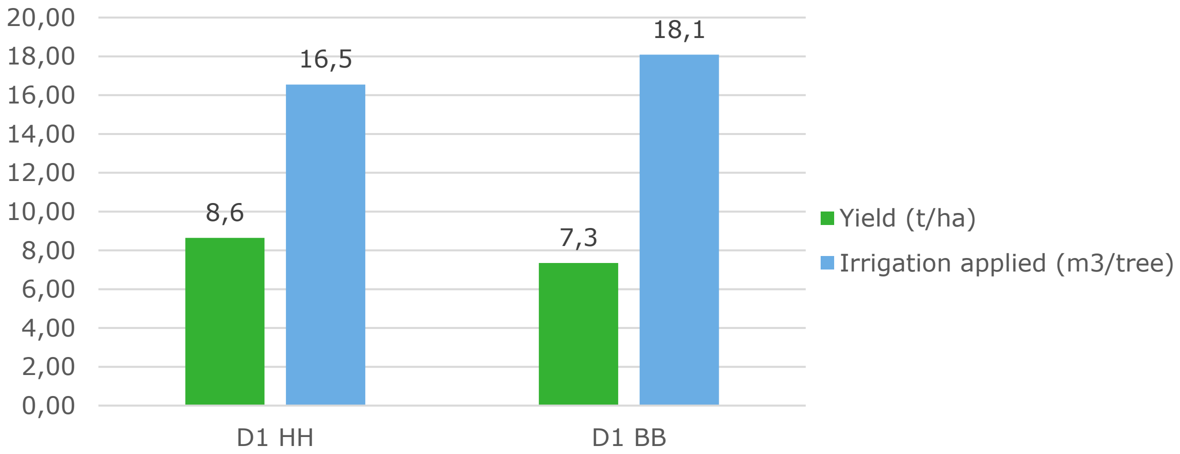

Figure 30 *Total water applied (m3/tree in the summer season) and yield (ton/ha) for date palms irrigated with Hydrorock blocks (HH) and bubbler (BB).*

The soil moisture analysis was focused on the critical growth period for crops, from June to September, during which high temperatures prevail. In general, the soil moisture values are very similar between Hydrorock and Bubblers at 60 cm depth, while the values are higher for bubblers both at 30 cm and 120 cm depth (Figure 31*).* This is especially true for 120 cm, where values for bubblers are much higher (ranging between 19-25% for bubbler, while 10% for Hydrorock blocks). This is related not only with the high amount of water applied by the bubblers, what clearly translates into the movement of water to deep horizons (and probably not available for the root systems), but also in the way of application. While water by Hydrorock is delivered gradually to the soil (see the slight variation of soil moisture for Hydrorock blocks), water from bubblers is delivery is short irrigation events (max 10 min). In case of the soil moisture at 30 cm depth, it is important to note that the Hydrorock blocks are buried at 30 cm, so the soils moisture content in Hydrorock blocks is mainly because of capillary rise.

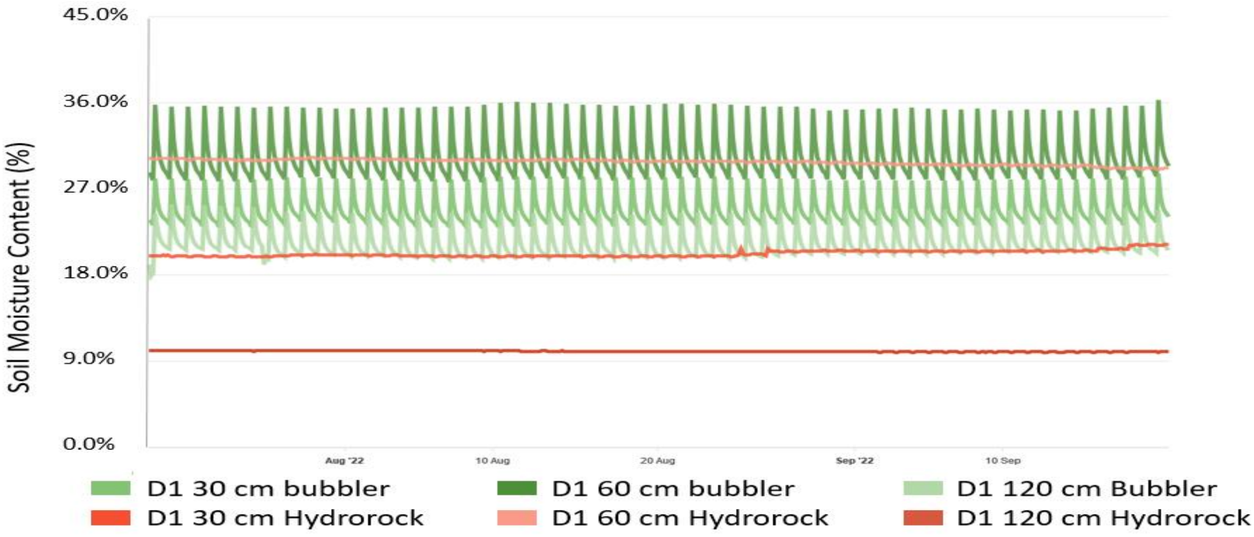

Figure 31 *Evolution of soil moisture levels for date palms irrigated with Hydrorock blocks (red) and bubbler (green) at different depths (30, 60 and 120 cm).*

12.3 Main conclusions of the pilot in Bahrein

- The Hydrorock blocks translate into a bigger yield for date palm that the one found with bubbler, although the amount of water applied by the bubblers was higher. However, this is only a preliminary result based on 3 trees and needs long term analysis to confirm the results.
- The use of high-flow control block in loamy soils is related with almost constant values of soil moisture, meaning that the water is releasing gradually from the block to the soil according to the moisture conditions. This produces very low values of soil moisture at deeper levels, reducing the amount of water lost by deep percolation.
- Although with low water volumes applied, soil moisture conditions at 60 cm are rather similar for both systems.

13 Most relevant findings

As a result of all the experiments, discussions among the partners and the knowledge created during the implementation of the ASSIST project, the most relevant findings can be summarised as:

1. Stone wool has very interesting water hydraulic properties, making this material unique in terms of capacity to store water and hydraulic conductivity. This can be used for many water related applications, among which include subsurface irrigation.
2. Fiber density (and direction) clearly affect some of the hydraulic properties of the stone wool, with a higher water retention capacity and hydraulic conductivity (Ks) for blocks with higher density. This can influence how the water (and nutrients) is moving within the block and should be considered for the design of new elements.
3. However, water release from Hydrorock blocks to the soil is mainly driven by the soil properties (i.e. texture) and preliminary soil conditions (moisture) rather than by the block properties (density or fibre direction). This is because the hydraulic properties of stone wool largely differ from natural soils, especially for loamy and clay soils, both in terms of water retention capacity and hydraulic conductivity.
4. Considering this, we can argue that in case of stone wool used for subsurface irrigation, as in the case of the Hydrorock blocks:
    - Density of stone wool is not affecting much how the water is moving from the block to the soil, and therefore it is better to work with cheaper material (lower densities).
    - For light soils (sandy), water is released from the block very fast and can produce water losses to deep horizons. To avoid this, a water management strategy to provide small but regular applications is recommended.
    - For heavy soils (loamy to clay), water is stored in the block and released gradually to the soil, according to the moisture conditions. The blocks can improve the storage capacity of the soil. In this case, a strategy based on the application of large quantities of water with less frequency, using the block as a reservoir, is recommended.
5. Hydrorock blocks can be manufactured in multiple configurations, giving the possibility to adapt the system to several crop patterns and/or existing irrigation systems. The dimension of the blocks and its location (i.e. distance to the crop, installation depth) could be designed according to the specific agronomic conditions.
6. The use of control flow devices (i.e. with pressure compensated drippers) can provide an added value to the Hydrorock blocks, controlling the flow and giving the possibility to have better homogeneity in water distribution, within the block but also among different blocks of the irrigation unit.
7. The Agriot platform can be a suitable tool for control and manage the HR system, allowing the users to monitor in real time the soil moisture content, the water applied and the weather forecast, among other parameters. Although this platform can be used to (semi)automatise the irrigation scheduling by the connection of the system with automatic electro valves and flowmeters, able to provide the water according to a set of predefined conditions (i.e. certain soil moisture conditions), it is recommended that the final decision of irrigation should be taken by the farmer, using the system as a decision tool.
8. From the two pilots carried out during the project in arid conditions (Dubai and Bahrein) on date palms plantation, we can conclude that:
    - With 10-30% less water applied to the Hydrorock blocks than to the bubbler system (control), Hydrorock blocks:
        - Achieve a similar yield but a higher water use efficiency (more product per unit of water used).
        - Keeps soil moisture content in similar values, especially for deeper horizons (60-90 cm depth).
        - No present evidence of negative affection to date palms after the two year operation.
        - No present evidence of salinity build-up (with the irrigation scheduling designed to generate regular flushing events).
    - After two years of experiments, there is no concerns regarding the interaction between the root system and the Hydrorock elements, as indicated by healthy and abundant root growth around the block without any root penetration into the blocks.

- Hydrorock blocks have a lower cost of operation compared to bubbler systems, specially related with weed removing. The use of machinery (i.e. harvesting) is also easier and less expose to damage, since the whole irrigation system is buried. However, the location of the blocks (specially the depth) is key to avoid damage due to transit of farming machinery.

9. Hydrorock blocks could have a higher cost of installation than other surface or subsurface irrigation systems, but this can be drastically reduced if automatic trench systems are used during the construction of the irrigation system.

14 Further developments

This project assessed the technical suitability of Hydrorock blocks (stone wool) as a subsurface irrigation system, in order to reduce the water application and reduce operational cost, while ensuring the required soil moisture level by the crops in the root system. Although the product is ready to be marketed for irrigation purposes, there are still some aspects that required further research or improvements:

- The model used to simulate the movement of water within the block and from the block to the soil is a 2D model. The use of a 3D model (i.e. Hydrus 3D) can provide a more realistic overview of the water transfer and the area of the wetted bulb around the blocks.
- Hydrorock blocks would act as a filter of the suspended solids in water. The blocks can also serve as a media for the growth of microbiota (biofilms). Both factors could affects some of the hydraulic properties of stone wool, potentially reducing the lifespan of the blocks. Long term experiments are required to assess this potential risk. However, a good preliminary filtration, as recommended with any other subsurface irrigation system, can mitigate this risk.
- In certain type of soils (i.e. sandy soils) the transfer of water from the block to the soil occurs very fast due to the hydraulic properties of both materials, potentially causing loss of water due to leaching. In order to increase the contact time of the water with the roots, the blocks can be sealed completely, keeping only open the top part and in direct contact with the soil/roots. The transfer of water from the block to the soil/plant would happen by capillary rise according to the suction capacity of the roots.
- Hydrorock blocks effectively transfer water to the soil and could be used in different shapes and formats. The construction of stone-wool pipes or cylinders (instead of rectangular blocks) would allow to have a (continuous)large area for water transfer in comparison with the existing subsurface irrigation systems, which usually provide the water at a certain distance (drippers). This would also facilitate the installation process, due to a reduction in excavation cost and the possibility to use existing drench systems.
- The production of stone wool is a highly consuming energy process, which also include the emission of certain nitrogen compounds to the atmosphere. A detailed assessment of the environmental impacts associated with the life cycle of the Hydrorock blocks for irrigation purposes would be recommended.

Other people involved in the ASSIST project

In addition to the authors of this report, the achievement of the results of this project has been possible thanks to the active participation of several institutions and people. Among others, the most relevant are:

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- Joost van der Gaag, software architect at Smart Farm Sensing B.V.
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- Dr. Zied Hammami, research agronomist at International Center for Biosaline Agriculture (ICBA).
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