Master 1 : Environmental Sciences and Technologies

Irrigation

Report : Green Wall Project

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Part I
Introduction

1 Context

Urban expansion and land cover change, to respond at the increasing population in cities, might threat biodiversity and ecosystems (Seto & al., 2012) mostly concerning native species (Czech & al, 2000 cited by Mckinney, 2008). Species richness of animals like birds often decreases while getting closer to cities (McKinney, 2008; Faeth & al., 2011) because the vegetative areas are fewer in cities than pavement and buildings (Blair & Launed, 1997 cited by McKinney, 2008). The spatial heterogeneity causes landscape fragmentation that impede connection between populations. This pressure and competition for territory is enhanced with the introduced exotic plants and it has been observed an extinction of native species (McKinney, 2008 cited by Baudoux, 2018). Nevertheless, urban landscape should not be seen as incompatible with nature. Indeed, high levels of plants biodiversity may flourish towards moderately urban areas (Aronson & al., 2014 cited by McKinney, 2008). Cities might represent a high potential to support vegetal biodiversity. The different land uses and cultivation create small areas able to support plants and insects population (McKinney, 2008 cited by Baudoux, 2018).

The concept of ecosystem services has been created to highlight the importance of biodiversity and ecosystems on human activities (Daily, 1997 ; de Groot, 1992 ; Ehrlich et Ehrlich, 1982 cited by Rives & al, 2016) and well-being. Indeed, more and more studies tempt to identify and quantify the services provided by nature. Because of the economical, social and environmental impacts that has biodiversity on human society (Jato-Espino & al., 2018), implementation of green infrastructures is now promoted through projects like Nature Based Solutions (European commission). It has been proven that vegetation in cities helps with air purification, noise reduction, thermal insulation, creation of microclimates by reducing the urban heat island effect but also increases people productivity, well-being and reduces stress level (Van de Wouw al., 2017). It is therefore important to increase the size and the number of green areas in cities and their connectivity to ensure the carrying capacities of biodiversity and the preservation of urban species (Baudoux, 2018). This is why structures like roofs and walls able to support biodiversity, are becoming popular to alleviate negative impacts of urban expansion (Urrestarazu & al., 2014). Walls are structures that should be seen as having a huge potential to increase diversity and the species richness even if they appear to be globally distributed, locally extensive and artificial ecosystems (Francis, 2011).

Because of the verticality of living walls, the water storage capacity is quite low. To ensure suitable conditions to grow plants, an irrigation system is mandatory. The water needs are highly variable and depend on the light exposition, the substrate, the plants, the humidity condition and the location. This is why, such structures while caring about water management represent a complex challenge for engineers in a matter of uniform distribution and water losses (Urrestarazu & al., 2014). All of this shows that improvement and researches deserve to be lead about living walls and the associated technologies. This document will introduce an experiment that has been realized to design a sustainable green wall and its irrigation system. This system is a microirrigation design which tends to provide the most uniform and efficient irrigation to respond to the crops water needs and to ensure easily available water for the roots (Clark & al., 2007)

2 State of the art

Green walls, as seen in the introduction, are one way to reunite human kind with nature. There are so many urban surfaces that could be covered with plants, flowers, even gardens. Such structures are becoming more and more common in cities all around the world. Historically, green walls exist for a long time. But their main function seems to have changed through the ages. First, they were meant to be only decorative, on castle walls, in royal gardens etc. After, they were used in occidental civilisations for many purposes, like in zoos and for the decoration of terrariums or public aquatic structures for instance. It is only in the early 2000's that an architect proposes to add some uncommon attributes to green walls. *[1] According to him, besides being decorative, green structures could have acoustic and thermic qualities that were never exploited before. With the help of botanic scientists, green walls begun to be studied more deeply and with conscience of all the benefits that they can bring.

Knowing that climatic conditions and vegetation can be very different from a region to another, various types of vegetalized walls exist. Here is a quick review of some of the main types of green walls that can be observed today. First, we have the modular green wall. It consists of several blocks that can be displaced. It has been proven that this kind of surface on a building confers, as said above, thermic and acoustic isolation for this building. Actually, the air layer between the wall and the building ensures a good part of this isolation. No wonder that it is becoming increasingly successful with the years. It also consists on a real entire biotope, which is very needed in numerous urbanised areas.

Then, we have a more technological version of the green wall, called flexible vegetal envelope. Here, the substrate consists in a porous layer of ceramics, fixed to concrete. Many walls can also be a way of depollution or filtration. Thanks to the fixation properties of a chosen moisturized mixture of substrates, it fixes particles and pollutants that are emitted by cars. An example of such a structure is to be seen next to the French city of Lyon. It is located near a highway and uses biofiltration, as said just before.

Generally, a big concern about green walls projects is the fact that some need a lot of maintenance. In fact, it is all about finding the right compromise between letting it grow naturally, avoiding building deterioration and keeping it functional. Indeed, roots can sometimes infiltrate walls, pipes or tiles, which is obviously not what is expected from such a structure but they might also need lots of components to support an irrigation system.

3 Objectives

This report has for objectives the design of a living wall module by using native species and implementing an automated irrigation system to meet plants water needs. This project proposes a sustainable alternative to actual irrigation practices in 3 main steps:

- The theoretical wall design: choice of the plants and their location in the wall, the substrate and the irrigation system and components.
- The installation set to collect datas (different from the theoretical design).
- The computation of a programming code to characterize and monitor a similar system using humidity probes.
- The determination and the conclusion about irrigation doses and schedules.

These several points will be approached in this document. It will start with the site description, then the presentation of all the materials and the method to design the wall and its irrigation code, to end with the results of the whole experiment and a brief conclusion.

[1]Sources from Wikipedia 2015 cited in the web references

Part II
Material and method

1 Site description

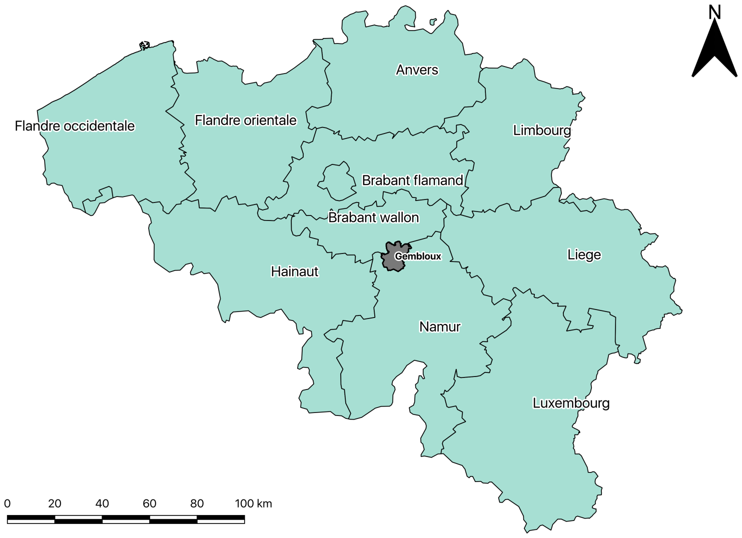

Figure 1: Localisation of the site of study

The wall is set in Gembloux Agro-Bio Tech faculty in Belgium (Coordinates: 50° 33’ 49" N ; 4° 42’ 9" E). The module and the supporting structure of the reservoir are installed on the ground of the geopedological department parking. The wall is exposed to the South with a meteorological station near to it. Concerning the climate, it is warm and temperate. Each year, the mean precipitation is around 830mm (Climate-Data.org, 2020). Even if they seem well scattered during the year, their intensity is much more important during summer due to thundershowers (Climat.be, 2020). The following graph shows that the mean temperatures go from -5°(minimal average) to 23°(maximal average) with a peak reached during July and August.

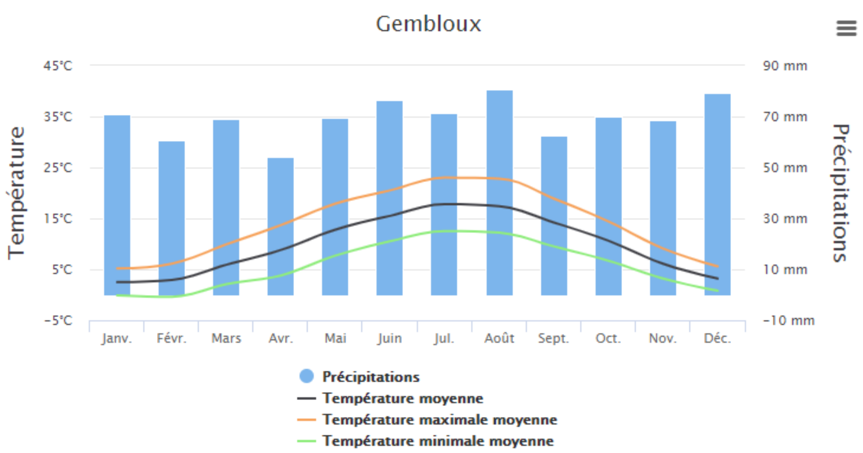

Figure 2: Gembloux precipitations and temperatures (IRM, 2020)

The ET0 calculator application was also used to determine the reference crop evapotranspiration from 2016 to 2019. This information will be necessary to build the irrigation schedule. To use this application, datas of insolation, precipitations, minimum & maximum temperatures and wind speed are downloaded from the NASA power[2] for Gembloux Station. It is observed that the ET0 increases through the years and mostly during Summer. Thanks to these values, we can observe that the range of ET0 values goes from 0mm/day to about 9mm/day. Nevertheless, a tendency is observable: the evapotranspiration increases significantly through the years.

Walls are often dessicated surfaces with a low humidity level and a more important exposition to the wind (Francis, 2011). According to van de Wouw al. (2017), a factor of 1,46 should be applied between an horizontal m² of reference crop and vertical m² of a panel living wall. The panel he refers to is a modular prefabricated hydroponic panel with a vertical surface covered with greenery. Higher reference evapotranspiration should then be expected for the living wall experimented in this work.

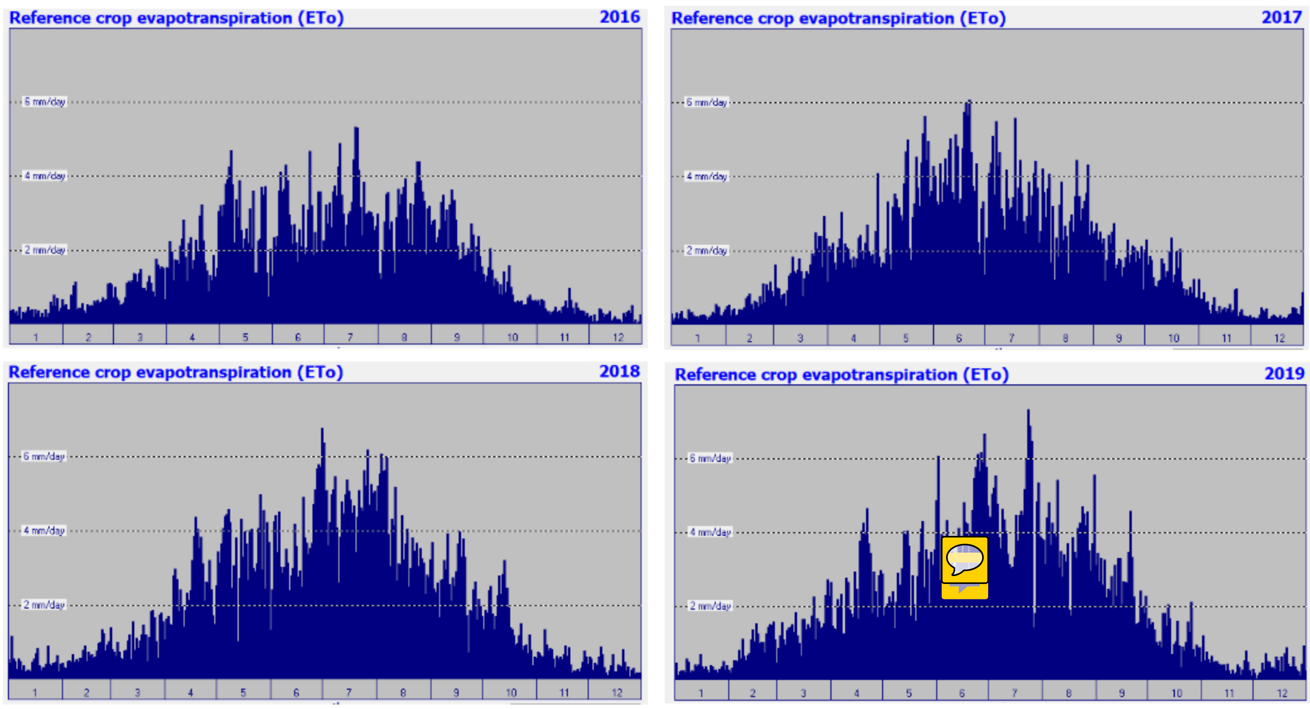

Figure 3: ET_0 of Gembloux from 2016 to 2019 calculated on ET0 calculator

[2] website : https://power.larc.nasa.gov/data-access-viewer/

2 Wall components

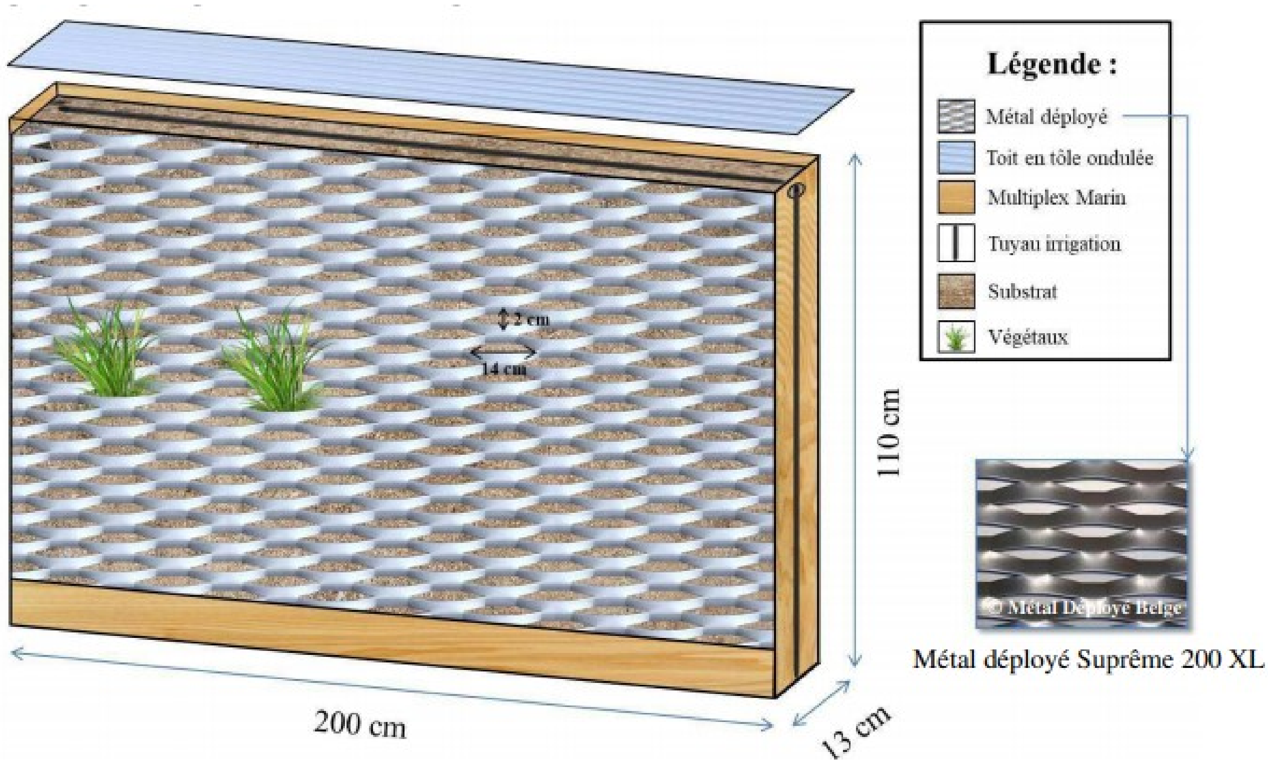

Figure 4: The green wall from Tom Baudoux (2018)

The experimental modules of vegetated walls used were created to correspond to the needs of experimentation. The walls were made as part of Tom Baudoux's graduation work. The following descriptions come from this work.

The design of these walls is inspired by the "anti-noise" walls currently being produced by the firm Métal Déployé Belge (MDB), used in building cladding or as "barriers" along the roads. Self-supporting, these "anti-noise" walls are embedded between 2 HEA beams. Here, the "anti-noise" material has been replaced by substrate in order to create Living Walls with a high level of acoustic insulation modular type where all the plants of the module benefit from a continuous volume of substrate (Figure 4). These are wooden boxes (Marine Multiplex Panels not backelated in Merantis, 18mm thick) of 200 cm long, 110 cm high and 13cm deep (internal volume around 0.286m3). The base of the modules has been drilled with a line of 8 drainage holes of 2 cm of diameter, spaced 22 cm apart and located 6.5 cm from the long lower edge of each module. In addition, to allow drainage water, each module has been raised with a serie of 4 concrete blocks 19cm high and equidistant. All the joints between the various wooden parts have been siliconized to prevent water loss (universal silicone for outdoor use, Soudal ©). The front face is made of a single sheet of expanded metal of type SUPREME 200 XL standard size (3mm raw aluminium, size LD 200 x CD 110cm, © Belgian Deployed Metal). These metal sheets hold the substrate while having opening, called mesh. The opening of the mesh are facing upwards (opening size: 14 cm x 2cm) for planting/sowing.

A note should be made about the figure 4: the irrigation pipes are not kept in the same place. Water is actually supplied to the relevant modules with a drip system automatic drop detailed later.

3 Softwares and communication systems

3.1 Components

The project uses Raspberry Pi components and implements the ELSA software (AKUINO.net) as well as some additional WatWall-specific programs to schedule irrigation events. Here is a list of these components. The assembly was carried out by Christophe Dupriez.

Figure 5: AKUINO central casing front

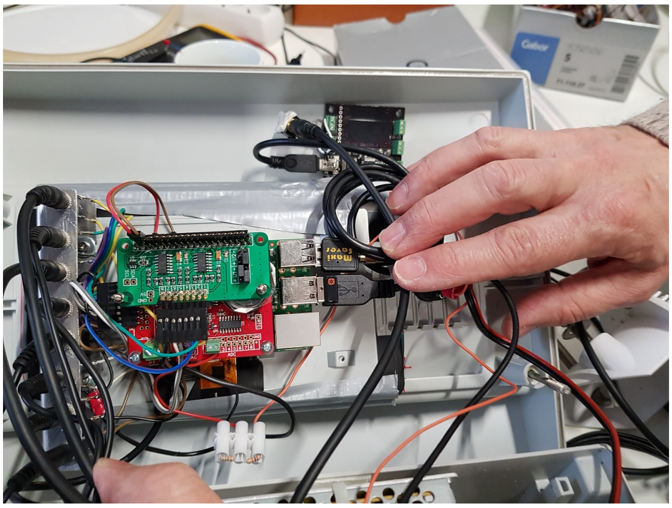

Figure 6: Raspberry Pi and extension boards/Relay board (not on picture, yellow)/SDI 12 serial interface (black)/Converter analog-digital(green)/Multifunctional board (red)/Raspberry Pi (green)

Figure 7: Power supply/Converter DC 5V/DC12-18V/Converter DC 12V/AC 240 V/Battery (connected by orange thread to expander board to monitor battery status

Figure 8: ATMOS41 weather station

Figure 9: EC-5 soil moisture sensors

Figure 10: Electrical ball valve

3.2 Communication and cables between components

Watwall central is composed of different elements. Here is the list of the components and their utility. All the illustrations and the descriptions are provided by our technical supervisor, Christophe Dupriez.

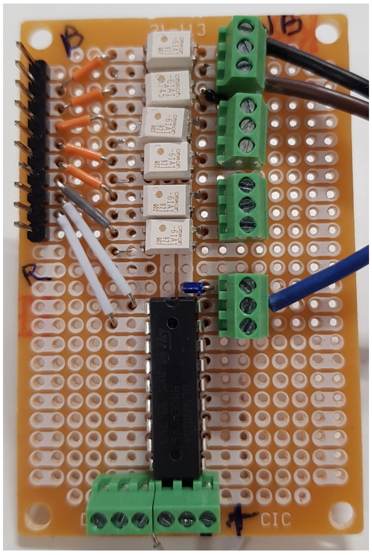

Figure 11: Relays to open/close the valves

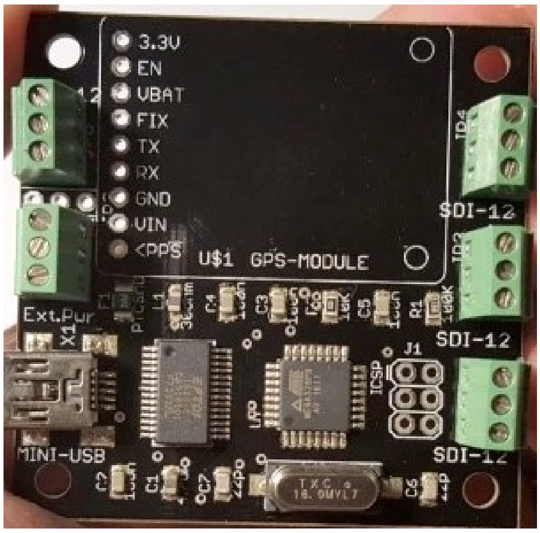

Figure 12: SDI 12 serial interface board (LIUDR) - Interface to ATMOS weather station

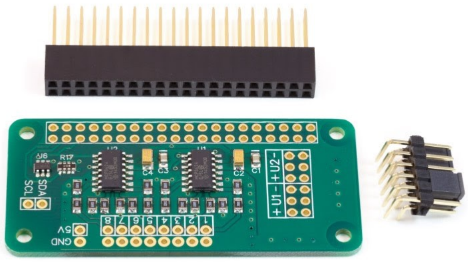

Figure 13: Analog-digital converter board (ADC differential Pi) - Communication with EC-5 soil moisture sensors

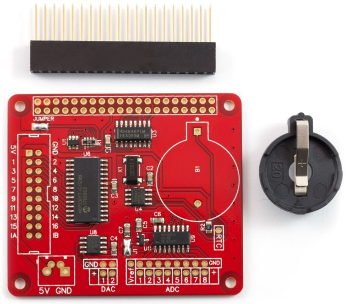

Figure 14: Expander board - Power for sensors common clock

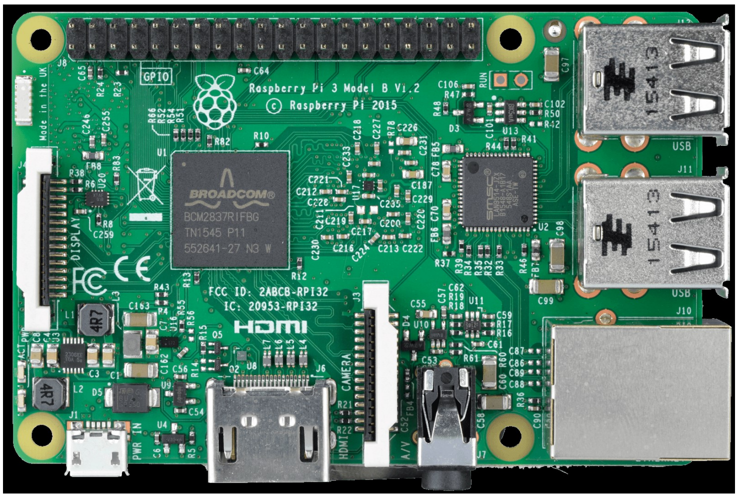

Figure 15: Raspberry Pi 3 Model B - Micro-computer containing software to read sensors and order pumps and/valves

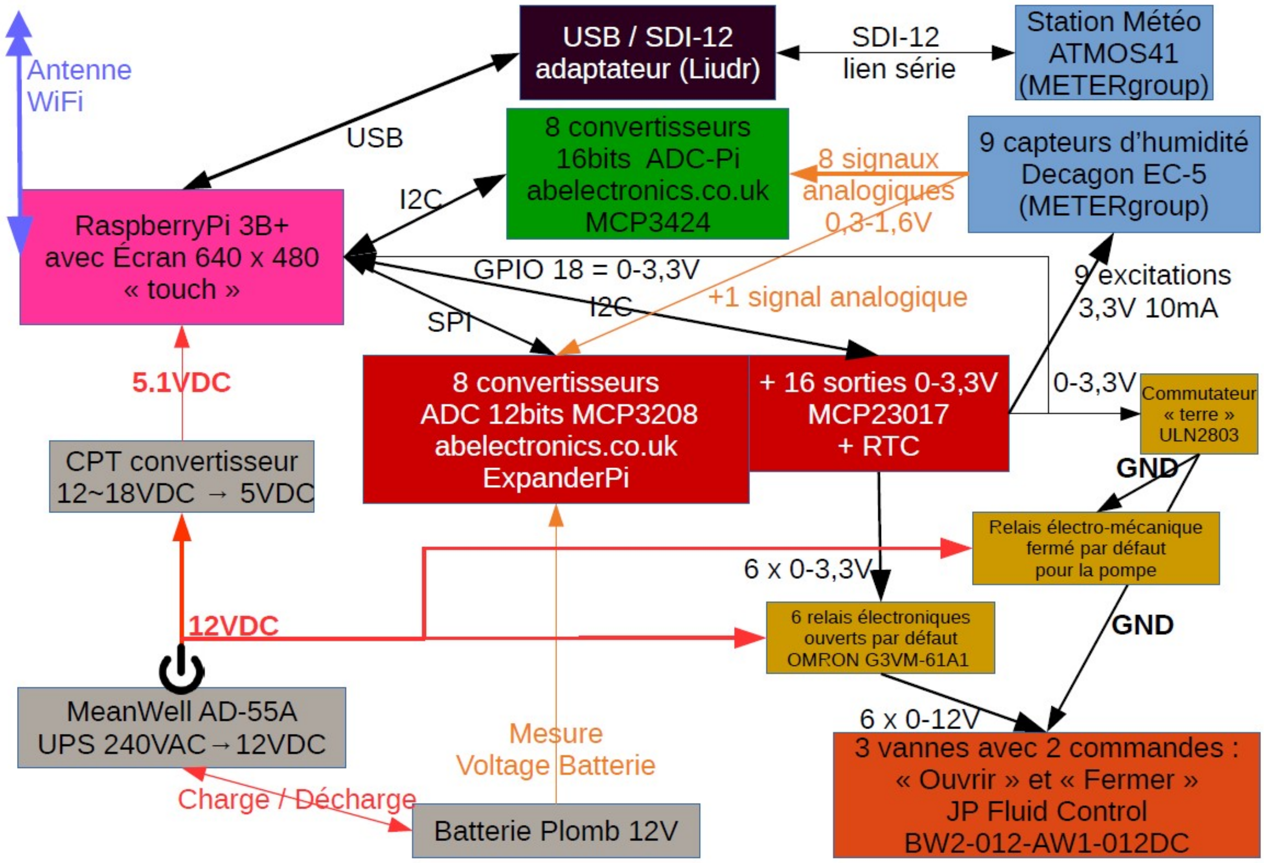

Figure 16: Representation of the communication and cables between the components (by Christophe Dupriez)

The table 1 summarizes the materials used for the green wall.

The WatWall hardware and software project are essential electronic components. They aim to implement a fully automated irrigation system of green wall modules based on soil moisture sensors and a weather station. The project uses Raspberry Pi components described above and implements the ELSA software (AKUINO.net). The figure 17, taken from a document provided by our supervisors, gives a global visualization of the software and hardware used in this project.

Irrigation material	Water source: reservoir 1000 l (cubi) 2 Valves: Electric ball valve ¾” 2-way (BW2-012-AW1-012DC tameson) 3 Valves: Ball valve BW2 1/2” 2-way 12V DC 3-pointGardena Micro Drips Gardena tuyau microporous and accessories Gardena 1000 pressure reducer
Sensors & logging	Soil moisture: EC-5 Weather station (ATMOS41) : Air temperature (°C) Relative humidity (%) Vapour pressure (kPa) Barometric pressure (kPa) Rainfall (mm/h) Solar radiation (W/m²) Wind speed (m/s) and direction Raspberry Pi and plugging boards, ELSA system installed. Relays Internet server to drop data and perform irrigation decision making: http://greenwall.gembloux.uliege.be/
Energy provisioning	AC power grid

Table 1: Material, sensors and logging used for the green wall (given by the supervisors)

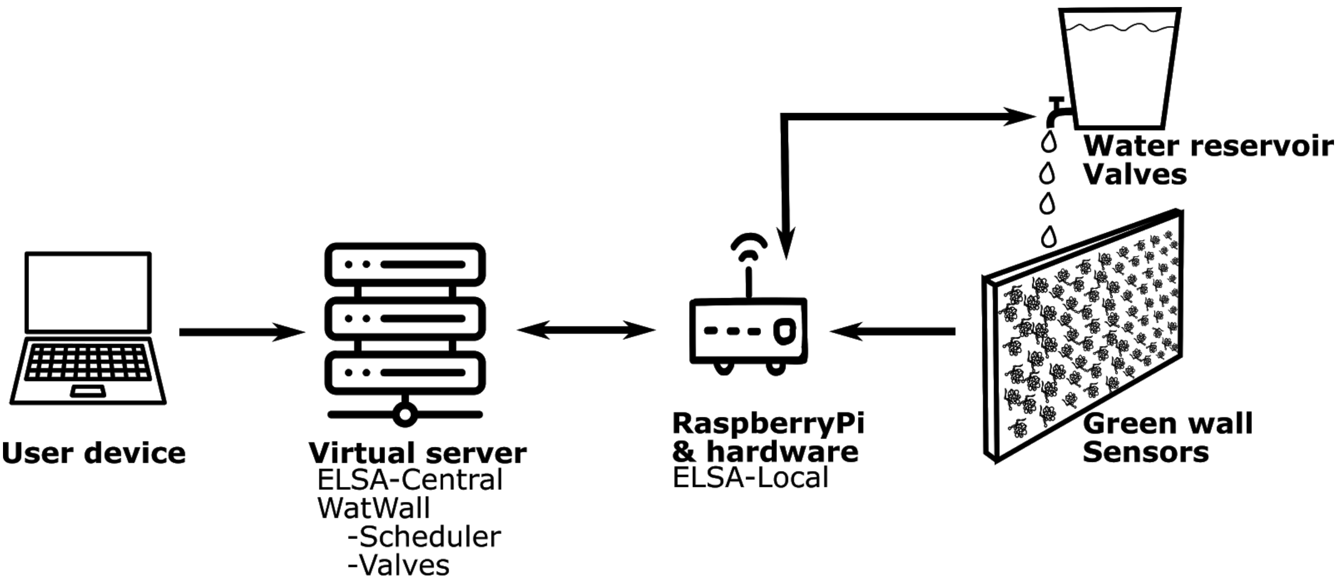

Figure 17: Global visualization of the software and hardware (given by the supervisors)

Two ‘computers’ compose the system: the first one is AKUINO with ELSA-local, a local computer that collects the data. The second one is ELSA-central wat1/2/3.py program: a (virtual) university server on which the data is copied and which allows to execute programs making decisions about the irrigation schedule.

3.3 AKUINO - ELSA

According to the website of ELSA and Github, ELSA ("Recording of Production Lots for Monitoring and Analysis / for Food Safety") is a computer system (hardware + software) generally used by companies to monitor their production. This system allows the manager to specify the production recipes and the batches to be produced, for several users to record the tasks they perform and for all, to indicate precisely the tasks to be performed. The usefulness of this system is to record the automatic measurements carried out at the same time by different sensors in order to have complete traceability in case of quality problems or if you wish to analyse your production processes. In this project, this system will enable the collection of data from the EC5 sensors and the weather station.

The sensors are connected by wire or radio to the AKUINO data collection central. The ELSA software works in AKUINO autonomously or in cooperation with external systems. Each member of the group can consult the detailed data history of each sensor at any time. All this information can be exported in spreadsheet format (Excel, OpenOffice, CSV) and can be reused by different analysis software. According to Akuino.net, ELSA offers a serie of decisive advantages: real-time monitoring, full traceability, works independently or in collaboration with other softwares and accessible developers involved in collaborative development (Open Hardware, Open Source).

3.4 Virtual server setup for this specific project

The WatWall project needs a set of Python programs to automatically irrigate a green wall based on sensors giving indications about the state of wall. These programs are facilitated by the creation of a server specific to the project. Here is an overview of the computer facilities necessary and useful for this project : ELSA-Central, ELSA-Local, WatValves (gathers irrigation commands and opens the valves when requested), WatScheduler-dummy (example of an irrigation control program generating commands) and WatScheduler1 (irrigation control program of our Team1).

Here is a description of the softwares used in order to achieve the objectives of this project, i.e. automatic irrigation.

3.4.1 Pycharm

Pycharm is an integrated development environment used in computer programming, specifically for the Python language. It allows to code in Python and also connects to Github project to push and pull changes in the master code (pycharm website).

3.4.2 Grafana

Grafana is an open source software for database analysis and monitoring. It is coupled with Elsa. For green walls project, we use it to visualize the data generated by the probes and the weather station on the online server.

3.4.3 Jupyter

Project Jupyter is a non-profit, open-source project, born out of the IPython Project in 2014 as it evolved to support interactive data science and scientific computing across all programming languages. Jupyter is increasingly used and excellent to share scripts and programs with other users. Uses include: data cleaning and transformation, numerical simulation, statistical modeling, data visualization, machine learning, and much more (according to Jupyter website).

3.4.4 Communication

Given the context of covid-19, physical encounters were no longer possible. Communication between group members and supervisors became more complicated. With this in mind, a project on Slack was created to disseminate information as quickly as possible and to promote communication. In addition, face-to-face courses were replaced by Cisco Webex Meetings. Finally, Skype was used to facilitate internal group discussions.

4 Design

4.1 Plants, Substrate & Orientation

The main constraints for walls are the hydric stress due to the verticality, the light stress when it is exposed to the South and the soil depth which is only of 13cm for this experiment. This last factor affects the water storage capacity and the roots spreading. Roots might compete with each other through the different stages of the wall. Francis (2011) uses four main key factors to define this environment: the physical substrate, nutrients, moisture and microclimate, which are highly dependent on the geographical localisation of the wall, the climate of the region and the cultural factors of the used plants.

First of all, the substrate is the one that limits the accumulation of organic matter and micronutrients. Walls bases and wall tops are locations that accumulate more sediments and where biota is mostly found (Darlington, 1981; Duchoslav, 2002; La´nı´kova´and Lososova´, 2009; Pavlova and Tonkov,2005; Segal, 1969 cited by Francis, 2011). Nutrients are important because walls are generally nutrient-poor environment. On the wall, there are two potential sources of nutrients: from the fractures of the materials (when it is rocks, bricks, etc) and from the airborne and waterborne deposition (Francis, 2011). In the presented situation, the only sources of nutrients are the ones initally present in the substrate, the biomass return and the sediments gained from the water and from the air. Having a rich substrate is therefore a key parameter. Besides the organic matter, the porosity of the substrate is also really important to take into account to accumulate water and nutrients. The moisture is a key variable that determines the ability of the wall to support biodiversity (Duchoslav, 2002; Gilbert, 1992; Segal,1969 cited by Francis, 2011). The higher water storage, the richer biota (Francis, 2011). This is why a good texture and structure must be considered knowing the hydric stress that can meet walls.

A wall, regardless to the region, might present microclimatic conditions according to its position in the urban landscape. Temperatures are influenced by the substrate and its thickness. North, East and West exposition tend to have more plants (Segal, 1969 cited by Francis, 2011) while South-facing walls are more dominated by a higher insolation and therefore higher values of temperatures and evapotranspiration during the day. They are also exposed to more important climatic fluctuations because of the rapid decrease of temperature at night (Francis, 2011). South exposition, for these reasons, might cause higher variations of climate and greater water needs. Having this orientation is a more challenging situation to raise a sustainable living wall.

This wall wants to avoid exotic species as the ones that are generally used for green walls. The idea is to grow native species that are easily spread and available in Belgium. The available plants were: *Dianthus carthusianum, Geranium sanguineum, Asplenium trichomanes, Melica ciliata, Origanum vulgare, Thymus pulegioides and Tragopogon pratensis.* Within these species, the ones that appear to be more adapted to grow with wall conditions are kept.

To make this choice, it is essential to understand a wall ecosystem and the physical and environmental factors that determine their capacity to support biodiversity (Francis, 2011). A table has been designed to gather the species and to compare the luminosity, the soil properties, the water needs and the trophic level they require. Than the choice was made by keeping the ones that seem more adapted. The quantities are chosen following an esthetical aspect and to ensure a certain homogeneity.

Finally, knowing all of this, the choice of the substrate is done within two possibilities

- A heavy substrate very draining with:
10% Expansed clay 8-16 mm
10% Zinco (Substrate used for green roofs)
60% Pouzzolan 2-11 mm
20% Pot soil
- A lighter substrate with:
10% Expansed clay 8-16 mm
10% Zinco
20% Pouzzolan 2-11 mm
60% Pot soil

4.2 Hydraulic installation

For this designed installation, a tank of 1000 liters is placed at three meters high and receives tap water. The pipes to irrigate are three branches of porous tube as long as the wall interconnected by non-porous branchements. The akuino central should be fixed on the structure as seen on the scheme and a weather station should be placed at two meters high near to the installation to collect climatic datas. The probes position was also selected to ensure the best reading. Indeed, the EC-5 probes read the water content for 5 cm long and measure a volume of 0,3 liters (Metos, 2020). Therefore, to avoid mistakes, it is important to place the probe far enough from the porous tube and from the impermeable layer.

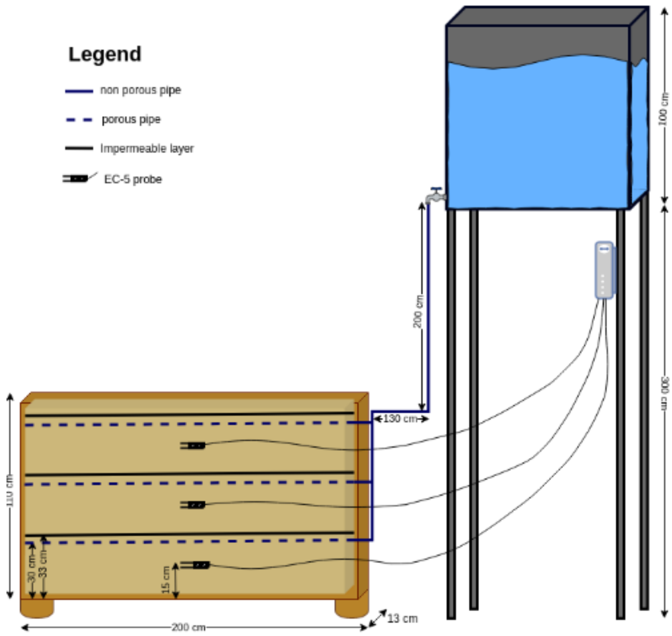

Figure 18: Hydraulic installation scheme

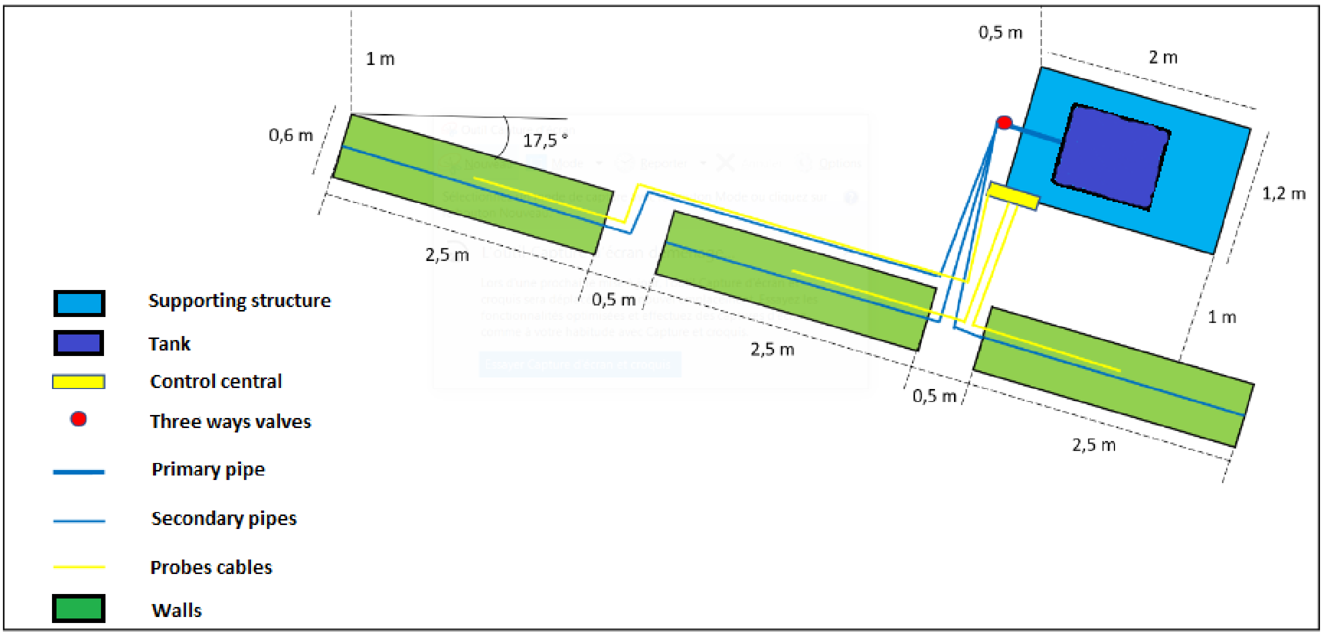

Figure 19: Spatial view of the installation on the site

In microirrigation systems, the energy to distribute water comes from the elevation, internal pressure and velocity (Clark & al., 2007). This is why the height and the tubes length must be optimized. The friction losses have influence on the discharge to the wall, therefore the optimal pipe length is determined on the figure 18. The conservation of mass principle is essential to analyze the velocity and the volume flow rate. This sequence explains how to determine the minimum and the maximum discharge, knowing that the volume flow rate varies with the height of water into the tank and the related pressures head losses. It is essential to know all these components to control the entire system and the irrigated volumes.

To know the discharge variations two measures are possible. These two possibilities are based on the assumption that since speeds are very low and distances are only a few metres, we can neglect pressure losses and assume that this pressure is directly related to the height of water. For the calculation of pressure we therefore consider a hydrostatic case. It is simpler because porous tubes would add a lot of complexity and uncertainty to Bernouilli equation (and for the pressure losses also) even if the equation is normally quite simple.

The first one is based on the assumption of having a relation pressure-discharge, given by the pipe constructor. This relation is considered for the upper layer pipe which is the one that will have the smaller discharge. The water height above this pipe varies from three meters to two meters. It represents respectively 0,3 bars and 0,2 bars. If we had a function Q = f(p) the formula to have the difference of discharge would have been :

$$\delta Q = f(0,3) - f(0,2) \tag{1}$$

The second solution is the one we would have applied if there was no covid 19 crisis. It would be based on measurement of the discharge with two meters of water height and 3 meters of water height.

These walls require an irrigation system because the water and nutrients availability is limited. The rain, the irrigation and the condensation are the processes that increase the water mass. On the contrary, runoff and substrate throughflow as evapotranspiration are the processes that cause a decrease of the water mass (Van de Wouw & al., 2017). To get knowledge of the wall water balance, several assumptions are done: first of all, it is considered that the wall is protected from the rain with a sheet metal roof.

Indeed, the perception of water depends on the wind direction, the size of the plants alveoli, the perception by the leaf system, etc. This choice is made because each layer of the wall is separated by an impermeable layer to avoid roots competition. The rain that will reach each horizon is not quantifiable and we can't afford too considerable moisture variations because each layer is irrigated the same way. Therefore, the assumption of no rain reaching the wall is chosen. The condensation is neglected for the same reasons and for it's limited effect. Moreover, it is supposed that the water content will never be higher than the field capacity, so that there will not have losses by percolation. However, a drainage system must be though in case of problem because of the impermeable layers. The following picture represents all the important fluxes that generally reach the wall. For this experiment, only irrigation and evapotranspiration will be taken into account. This choice is discussed at the end of the document.

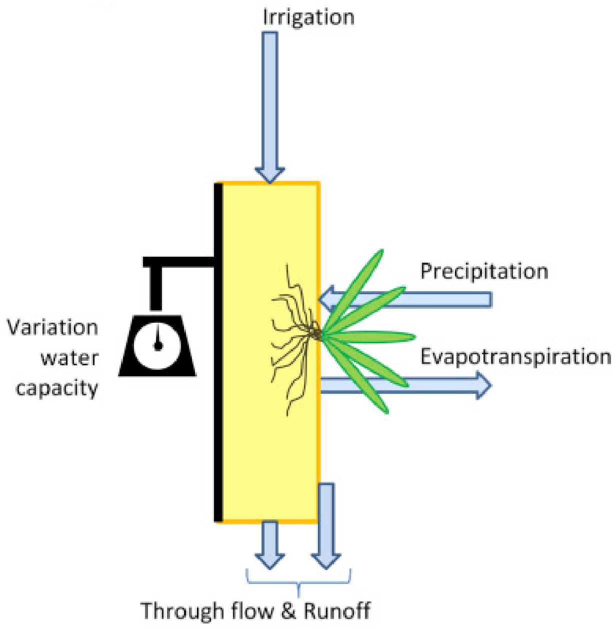

Figure 20: Water balance illustration (van de Wouw & al., 2017)

Some cultural practices exist to reduce water needs and can be considered. Mulching, for example, can be a sustainable way to increase soil moisture. Covering the ground prevents soil evaporation. Moreover, with organic mulch, humus is brought to the soil and can increase its water retention capacity (Unger, 1974 cited by McMillien, 2013) such as its ability to preserve ions. Placing mulch around the alveoli and on top of the wall can be helpful to decrease water needs. Using plastic film or mulch increases the albedo, which allows a higher reflectance (Fan, 2014).

5 Sensors calibration

To measure soil moisture, EC-5 probes are being used. The calibration was led in Gembloux Agro-Bio Tech labs. First of all, the soil was dried in the oven for several days. Then, dried soil was introduced into four different cylindrical containers of approximately 4,8 cm radius and 14 cm high. The volume is then well higher than the one suggested the paragraph before of 0,3l. Nevertheless, according to the manual wrote by Cobos & al., "the sensor should be surrounded by continuous soil for a radius of at least 5 cm from the flat sensing portion of the sensor" during calibration. The mass and the volume of soil were the same for each container (a density of 0,876 g/cm³). Four different volumes of water were put into the soil: 15 %, 30 %, 45 %, 100 %. But after thinking, it was decided to use only the three firsts. Indeed, there is no sense to measure 100 % of water content for a soil. The measures were repeated five times for each container and for the three sensors. One calibration line and the linked equation were calculated with

Excel for each sensor (see curves below). It is important to note that those equations will not be used during data collection because the conditions were not the same.

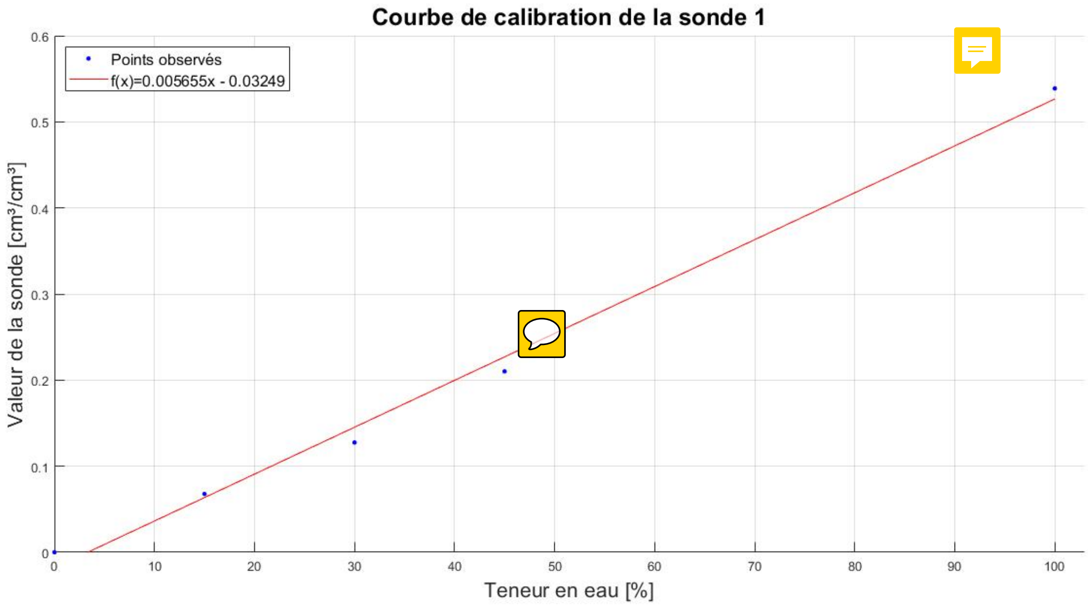

Figure 21: Probe calibration 1

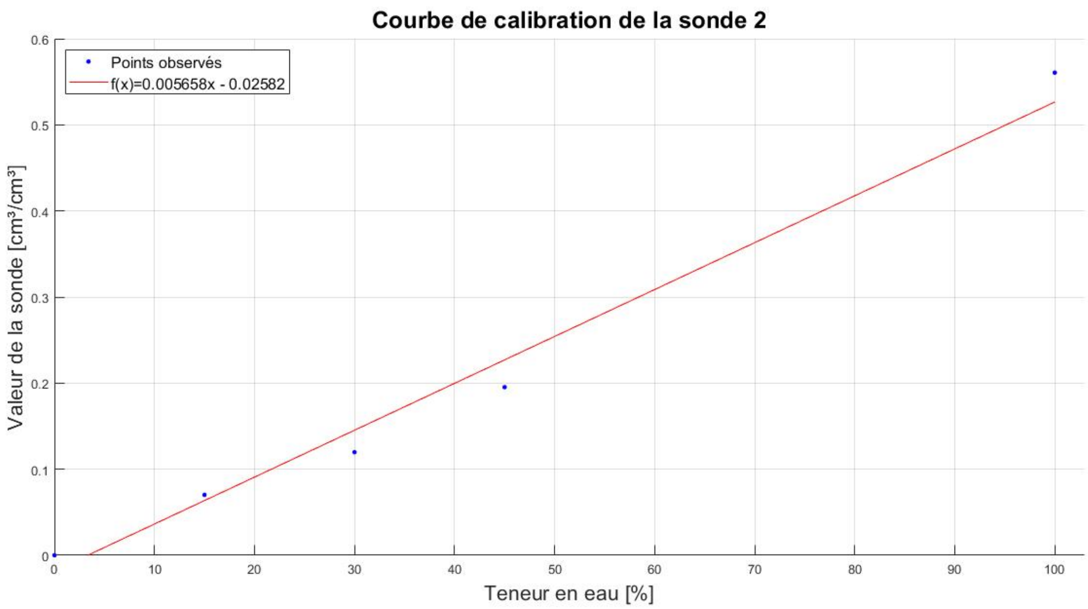

Figure 22: Probe calibration 2

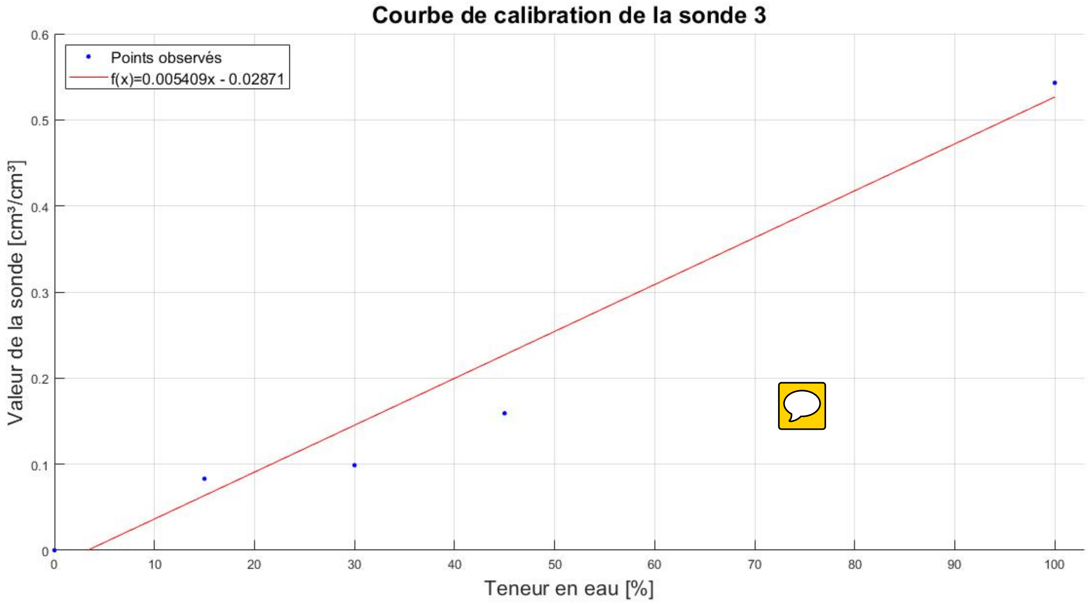

Figure 23: Probe calibration 3

5.1 Wall installation

For the installation, the first thing to do was to calculate the good amount of soil, in the aim of having the same density as the one used for calibration described below. The mass was measured for each layer of 10 cm to be as homogeneous as possible. Here is the formula.

$$m_{Soil} = \rho_{soil} * V_{soil} \tag{2}$$

With :

V_{soil}, the volume of soil [cm^3].
m_{Soil}, the mass of soil [g].
ρ_{soil}, the density of soil, the same as during calibration, 0,876 g cm^{-3}.

Then, the soil was weighted thanks to a human scale and then poured into the wall. A broom thin enough to fit into the wall was used for compaction. As a reminder, the weighted soil had to fit in a 10 cm layer. It was an homemade method but we tried to be as meticulous as possible.

6 Irrigation plans

In this section, decisions about irrigation will be explained thanks to a flow chart. In this flow chart, several steps need calculations. All the methods to determine the values used for the flowchart are described below as the justifications of our choices.

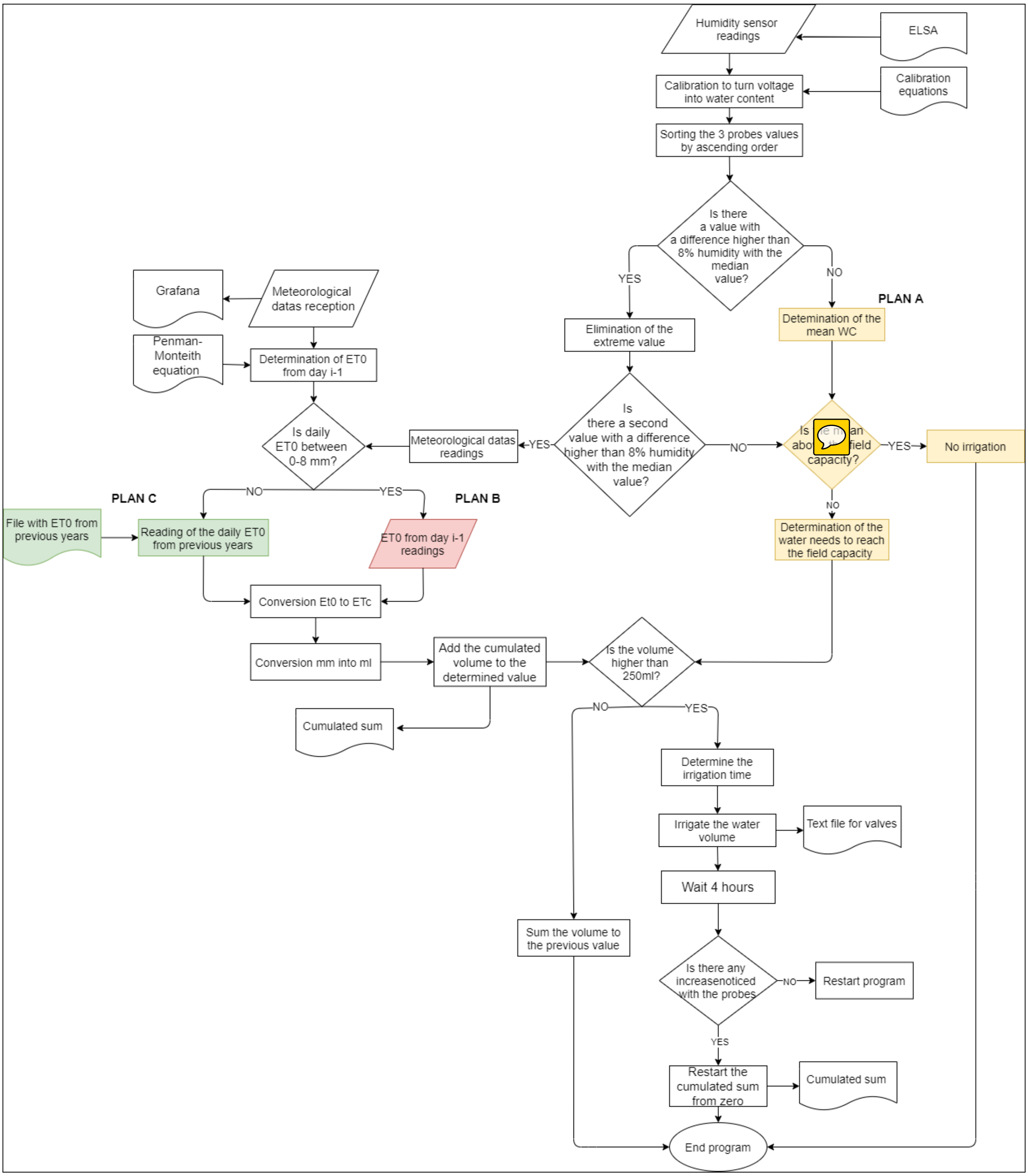

Figure 24: Flowchart

6.1 The three plans

Before explaining the calculations, the global method will be explained. The flowchart is divided into three plans. The goal is to make sure that if there is any technical problem, the system will continue to irrigate. Each plan will be detailed.

The aim of the plan A is to irrigate the volume needed for the soil to reach field capacity. But the first thing to do is to check if the three sensors work well. This verification is based on the fact that the three sensors are supposed to give approximately the same values because the water balance of the three horizons is nearly the same and is actually from the same horizon considering the conditions of data collection. If one sensor value is too far from the median value (more than 8 %), the probe is excluded for this run. The value of 8 % has been chosen arbitrary in the beginning of the experiment after noticing that probe values varied generally of 5% maximum from the median. The value of 8 % can be changed if it does not fit well. We never had to change it. If the three probes show too different values, plan B is launched (described later). After the quality check, the mean water content is calculated and compared to the field capacity. The average is used because, as explained before, the three horizons should have the same water balance. If the mean water content is higher than field capacity, no irrigation is scheduled. However when the water content is lower, the volume to reach field capacity is calculated and is irrigated if it is larger than 250 mL. [3] When an irrigation is scheduled, the volume needed is converted into an irrigation time lapse thanks to the known discharge value. If the no irrigation path is followed because of too small quantities of water, the volume that should have been irrigated is added to a file. This information will be important during plan B. When the irrigation takes place, four hours after, a checking is computed to ensure an increase of the general water content. If everything goes well, the cumulated volume file is restarted at 0. If there is no increase of the moisture, then the program restarts.

The plan B and the plan C, are based on evapotranspiration. For the plan B, the ET_o is calculated thanks to meteorological station measurements. Once again, a quality control checks if the ETo is higher than 9 mm for one day. Because it is the maximum that has been observed on figure 3, if it is higher, the value is considered as a mistake and plan C is computed with a file containing ET0 means (2016 to 2019) from the data described earlier. Whether it's plan B or plan C, the ET_c is calculated by considering no hydric stress and so the water stress coefficients, K_s, equals one and $ET_r = ET_c$. The K_c is also equals one. In fact, the different plants in the Green Wall have different K_c and that K_c changes with the developing phases. K_c is a value that fluctuate around one. Searching a unique value for several plants that are not cultivated plants is hard to determine. However it usually turns around one. Moreover another Green Wall could use other plants with other K_c. It is the reason why a K_c of one has been chosen, to meet practical facilities. If we go back to the flowchart we can see next that the ET_c, in mm, is converted into a volume to be irrigated thanks to the surface of the wall and this volume is added to the same file than for plan A. Then, it is the same than for plan A, the cumulated volume is irrigated when it is higher than 250 mL. The cumulated volume is used because it is possible that the daily volume is lower than 250 mL for several days and so no irrigation will be programmed. The skiped volumes are then added to the cumulated value until it reaches a volume higher than 250ml.

6.2 Calculations

We can now start to explain the calculations. First, the water content at field capacity is needed. An experiment was realized in Gembloux Agro-Bio Tech soil laboratory. Four samples of soils were tested. the samples had approximately the same density as the soil in the green wall. As results of the experiment, we obtained the net mass of dry soil and the net mass of wet soil in g at 300 hPa for a volume of 100 cm^3. Here are the equations to find water content at field capacity with those results:

$$V_{water} = (m_{wet} - m_{dry})/\rho_{water} \tag{3}$$

$$\theta_{fc} = (V_{water}/V_{soil}) * 100 \tag{4}$$

[3] When the volume is smaller than 250ml, the uncertainty about the volume that is really irrigated is too high due to the time lapse to open valves (about 1 minute).

With :

V_{water}, the volume of water in the soil sample [cm^3].
m_{wet} and m_{dry}, the mass of wet and dry soil [g].
ρ_{water}, the specific mass of water [g/cm^3]. In this units, it is equal to 1.
V_{soil}, the volume of the soil sample [cm^3].
θ_{fc}, the volumetric water content at field capacity [%].

Moreover, evapotranspiration will be used for the flow chart. Calculations for it are plentiful and are described below.

The real evapotranspiration for a specific culture is determined through the use of Penman-Monteith equation given by the FAO [Raes and Munoz, 2009]. The evapotranspiration is used to determine the output water and thus the quantity of water that should be provided. To do so, the evapotranspiration in a day is found by summing the evapotranspiration calculated each minute thanks to the weather station.

$$ET_r = K_c * K_s * ET_o \tag{5}$$

$$ET_0 = \frac{0.408\Delta\left(R_n - G\right) + \gamma\frac{0.625}{T+273}u_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34u_2\right)} \tag{6}$$

With :

ET_c : real evapotranspiration [mm.min^{-1}]
ET_0 : reference evapotranspiration [mm.min^{-1}]
K_c : cultural coeficient [-]
K_s : hydric stress coeficient [-]
Δ : slope vapor pressure curve [kPa.°C^{-1}]
R_n : net radiation at the crop surface [MJ.m^{-2}.min^{-1}]
G : soil heat flux density [MJ.m^{-2}.min $^{-1}$]
γ : psychrometric constant [kPa.°C^{-1}]
T : mean air temperature during the minute [°C]
u_2 : mean wind speed at 2m during the minute [m.s^{-1}]
e_s : saturation vapor pressure [kPa]
e_a : actual vapor pressure [kPa]

Each part of the equation is developed below.

Slope vapor pressure curve (7)

$$\Delta = \frac{4098\left[0.6108\exp\left(\frac{17.27T}{T+237.3}\right)\right]}{(T+237.3)^2} \tag{7}$$

With :

T : mean air temperature during the minute [°C]

Psychrometric constant (8)

$$\gamma = \frac{C_p P}{\varepsilon\lambda} = 0.665 \times 10^{-3}P \tag{8}$$

With :

C_p : Specific heat at constant pressure, 1.013 10^{-3} [$MJ.kg^{-1}.°C^{-1}$]
P: Atmospheric pressure [kPa]
ε : Ratio molecular weight of water vapour/dry air , 0,622 [-]
λ: latent heat of vaporization, 2.45 [$MJ.kg^{-1}$]

Saturation vapor pressure (9)

$$e_s = \frac{e_a}{RH} \tag{9}$$

With :

e_a : Vapor pressure [kPa]
RH : Relative humidity [%]

Net radiation (10)

$$\mathrm{R_n = R_{ns} - R_{nl}} \tag{10}$$

With :

R_n : Net radiation [MJ/m^{2}min]
R_{ns} : Longwave radiation [MJ/m^{2}min]
R_{nl} : Shortwave radiation [MJ/m^{2}min]

$$\mathrm{R_{ns}} = (1-\alpha)\mathrm{R_s} \tag{11}$$

With :

α : Albédo [-]
R_s : Solar radiation [MJ/m^{2}min]

$$\mathrm{R_{nl}} = \sigma(T^4 + 273)(0.34 - 0.14\sqrt{\mathrm{e_a}})\left(1.35\frac{\mathrm{R_s}}{\mathrm{R_{so}}} - 0.35\right) \tag{12}$$

With :

R_{nl} : Longwave radiation [MJ/m^{2}min]
T : mean air temperature during the minute [°C]
e_a : Vapor pressure [kPa]
σ : Constante de Stephan-Boltzmann 4.903×10^{-9} [MJ K^{-4} m^{-2} day^{-1}]
R_s : Solar radiation [MJ/m^{2}day]
R_{so} : Clear sky radiation [MJ/m^{2}min]

$$\mathrm{R_{so}} = \left(0.75 + 210^{-5}\mathrm{z}\right)\mathrm{R_a} \tag{13}$$

With :

z : Station altitude, 150 [m]
R_a : Extraterrestrial radiation [MJ/m^{2}min]

$$\mathrm{R_a} = \frac{1}{\pi}\mathrm{G_{sc}d_r}\left[\omega_\mathrm{s}\sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_\mathrm{s})\right] \tag{14}$$

With :

Gsc : Solar constant [0.0820 MJ/m^{2}min]
d_r : The earth-sun inverse relative distance [MJ/m^{2}day]
ω_s : Hour angle [rad]
ϕ : Latitude [rad]
δ : Declination [rad]

The earth-sun inverse relative distance, d_r, the declination and the hour angle:

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right) \tag{15}$$

And :

$$\delta = 0.409 \sin\left(\frac{2\pi}{365} J - 1.39\right) \tag{16}$$

And :

$$\omega_\text{s} = \arccos[-\tan(\varphi)\tan(\delta)] \tag{17}$$

With:

J : Day of the Julian calendar [-]

The ETr is now known as well as water content at field capacity and wilting point. Now, calculation about volume of water needed to irrigate will be developed. First it is important to know which volume should be irrigated to compensate loss by evapotranspiration. Here are the equations :

$$V_{irrigation} = (ETr * S_1 + ETr * S_2) \tag{18}$$

$$S_1 = 22 * 10 = 220 \tag{19}$$

$$S_2 = 22 * 1.3 = 28.6 \tag{20}$$

With :

$V_{irrigation}$, the volume to irrigate [L].
ET_c, the evapotranspiration [mm].
S_1, the vertical surface [dm^2].
S_2, the horizontal surface [dm^2].

Concerning the volume to irrigate if the mean value is below field capacity, in the plan A, here are the equations :

$$V_{irrigation} = (\theta_{fc} - \theta_{mean}) * V_{tot} \tag{21}$$

$$V_{tot} = 22 * 10 * 1.3 = 286 \tag{22}$$

With :

$V_{irrigation}$, the volume to irrigate [L].
θ_{fc}, the volumetric water content at field capacity [cm^3/ cm^3].
θ_{mean}, the mean water content [cm^3/ cm^3].

V_{tot}, the volume of the wall [L].

But for the programming, we need the time of irrigation and not the volume. Here is the method to calculate the time of irrigation :

$$t_{irrigation} = V_{irrigation}/Q_{tot} \quad (23)$$

With :

$t_{irrigation}$, the time of the irrigation [s].
$V_{irrigation}$, the volume to irrigate [L].
Q_{tot}, the total discharge of the three pipes [L/s].

7 Data collection

Due to the covid-19, the data collection has been led by the supervisory staff and with different conditions than the ones that were designed. New pots were installed to ensure the collection of water contents datas while running the designed program. They were installed in Mont-Saint-Guibert on a balcony. The weather station is placed at the height of 10 meters from the ground (third floor) with a south exposition and protected from the North by another balcony. The pots are 75cm long, 14cm wide and 12 cm soil height. The weight of soil is of 3.5kg. The pots are placed horizontally and sewed with arugula and parsley. The used substrate is made of: pot soil, peat, 10 % organic matter, 20 % dry matter, NPK 11-16-18 fertilizer & oligoelements. The water is provided by a tank of 200 liters filled with tap water and initially filled at 2/3. The flow rate for a porous tube is between 1 and 1,5 L/hour and the tank is loosing a drop every second. The height of water in the tank varies from 40cm above the tap to 80cm. The tank tap is at one meter above the pots. All the sensors are installed at the same depth from the porous tube and should give similar soil moisture values. There are holes at the bottom of the pot to drain the water.

Because the output given by the probes is in Volts, it is necessary to convert it into water content. To do so, a calibration equation has been used and comes from the experiment led by Cedric Bernard on a zinco substrate for green roofs. The experimental conditions were very similar to ours: an excitation of 5V and the same setup (Akuino central & EC-5 probes, etc.). Here is the equation and the calibration curve for this adjustment.

$$y = (35.24 * x - 15.44)/(x - 0.3747) \quad (24)$$

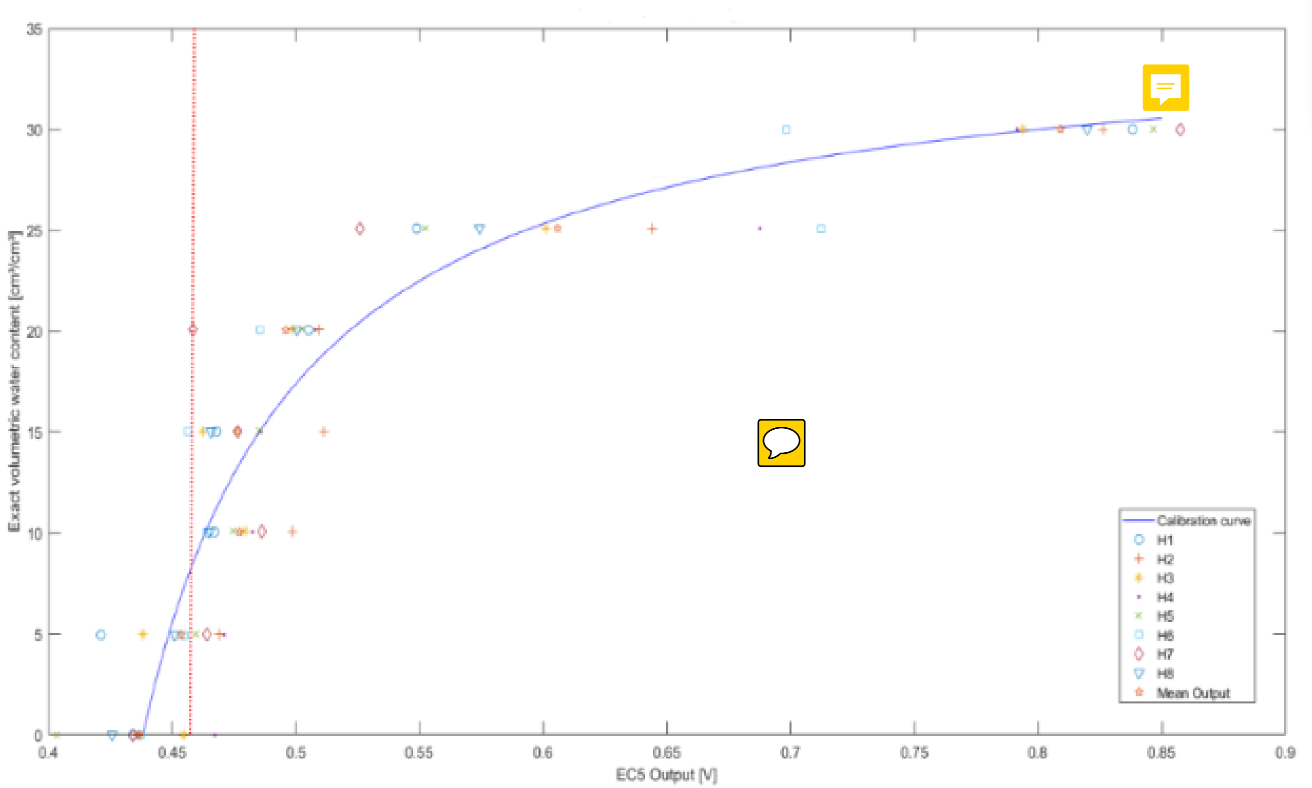

Figure 25: Calibration curve Voltage to water content

The implementation of the code started on Sunday the 6th of May, and several plans were then tested. Before that, the valves were controlled through the automation of a simple excel file.

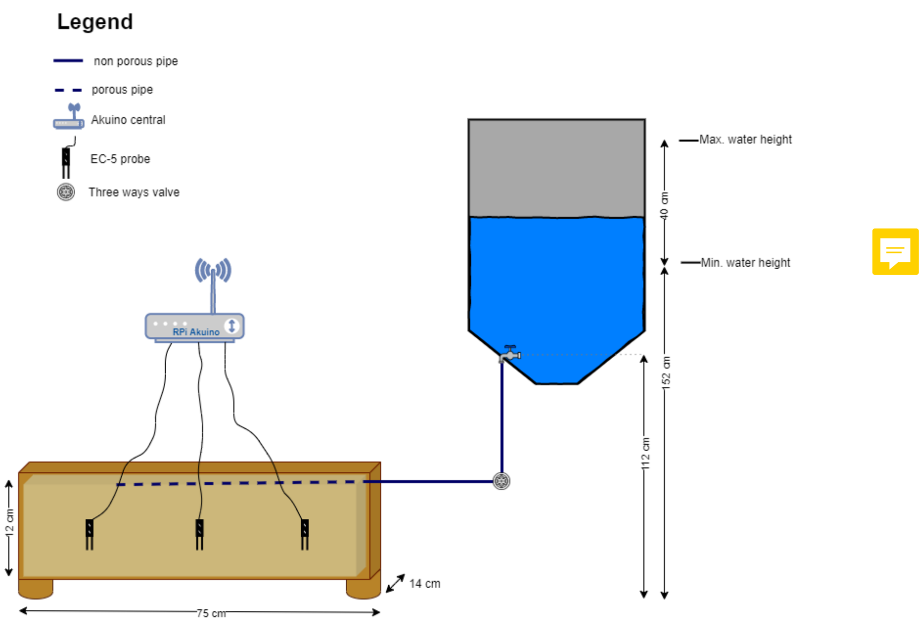

Figure 26: System of data collection

Figure 27: Wheater station, reservoir, akuino central & pots

Part III
Results and discussion

1 Final wall design

Species	Humidity	Luminosity	Soil properties or high	Trophic level	More
Dianthus carthusianorum (Caryophyllaceae)	Dry	High	Height: 20-30cm	Poor	/
Geranium sanguineum (Geraniaceae)	Dry	High - middle high	Height: 10-40cm	Poor	Highly resistant, evergreen
Asplenium trichomanes (Aspleniaceae)	Dry	High - middle high - low	Height: 6-35cm	Poor	Better not directly exposed to radiation, saxicolous
Melica ciliata (Poaceae)	Middle dry	High	Height: 30-80cm Depth: 10-15cm	Middle poor	Can be invasive
Origanum vulgare (Lamiaceae)	Middle dry	Middle high	Height: 30-60cm Light soil, well drained	Middle poor	Can be invasive, bushy (D=30cm), Rocks
Thymus pulegioides (Lamiaceae)	Dry	High	Height: 5-40cm Light soil, well drained	Poor	Rocks, walls, pavement
Tragopogon pratensis (Asteraceae)	Dry	High	Height: 30-80cm	Middle rich	/

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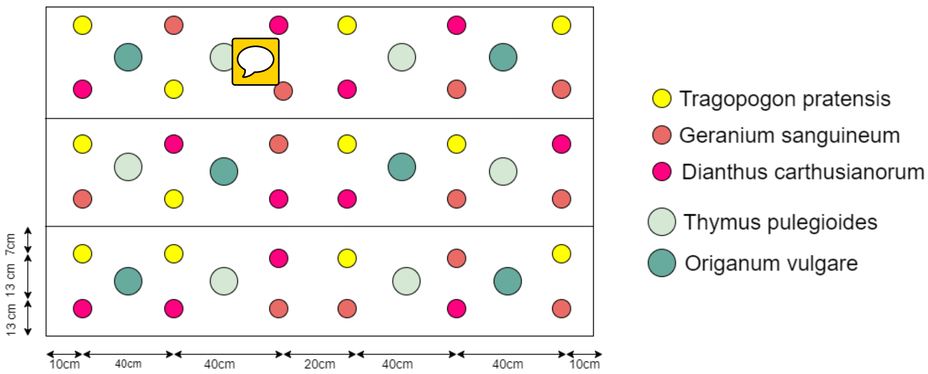
Figure 28: Species characteritics

There is the table that has been made, resuming the main characteristics of each species. It has been noticed that almost all of them are supporting hydric stress. Nevertheless, the fern Asplenium trichomanes does- not appear to be resistant to direct radiation and drying winds. The grass Melica ciliata might stifler the development of other plants. To avoid competition and to give the best chance of growing, it has been decided to focus on the 5 species: *Dianthus carthusianorum, Geranium sanguineum, Origanum vulgare, Thymus pulegioides and Tragopogon pratensis.* The following table (figure 29) is showing the quantities that has been bought. A total of 48 plants will constitute the wall. The quantities of the aromatics one are twice less than the other ones because they are more likely to cover a higher soil surface. Indeed, Origanum vulgare and Thymus pulegioides are bushy, respectively herbaceous and sub-shrubs perennial plants. Moreover, both belong to the family Lamiaceae, so it corresponds to 12 pieces of each family.



Species	Quantities
Origanum vulgare	6
Thymus pulegioides	6
Dianthus carthusianorum	12
Geranium sanguineum	12
Tragopogon pratensis	12

Figure 29: Wall design

It has been decided to create an aesthetic mosaic of species according to three different layers. So each quantity of species has been divided into three groups. The idea is to notice if there is any variation or any preference observable between the species with the stages. Their positions has been thought in a way to give enough space to the roots by leaving at least 13cm space from the impermeable layer or from the bottom. More space is also allocated for the aromatics that tend to spread a little bit more.

Finally, as said before, the wall is covered by a metal sheet roof that impede the perception of the rain. The impermeable layers are posed with a slope of several percents and connected to the outside in a way to allow the drainage of the surplus and to avoid an overflow above each layer. Indeed, normally if the plan A works correctly, there will be no risk of percolation because the field capacity will never be exceeded. Nevertheless, for plan B, the volume irrigated based on the day before might be more important than the water needs on the d-day. These layers are also helpful to separate each layer in term of water mass balance, but also to avoid competition for roots space. Mulch should also be placed around the alveoli as suggested before.

2 Python Code

In this section the main parts of the code used for irrigation will be explained. The full code can be found in the appendix of this report.

In the figure 30 the code converts the tension of the probes into water contents that we can analyse. It also sorts the water content values. That way, it is easier to compare them afterwards.

```
# Conversion des tensions en teneur en eau puis trie de celles-ci par ordre croissant
for o in range(0, 3):
    humidite[0][o] = ((35.24 * humidite[0][o] - 15.44) / (humidite[0][o] - 0.3747)) / 100
humidite[0].sort()  # trie les valeurs d'humidité dans l'ordre croissant
```

Figure 30: Conversion and sorting of water content data.

In the figure 31, the quality check is made by comparing the two extreme values with the median value. The "t" variable is used to decide which plan is used afterwards.

```
t=0
if humidite[0][1]-humidite[0][0]>0.08 :
    del humidite[0][0]
    t=1
elif humidite[0][2]-humidite[0][1]>0.08:
    del humidite[0][2]
    t+=2
```

Figure 31: Quality check

If "t" is other than three it means that only one or zero water content value has been deleted. So plan A is used for irrigation as seen in figure 32. In this figure, the volume of irrigation is calculated.

```
if t!=3:
    moyenne_humidite=[sum(humidite[0])/len(humidite[0])]
    supplement_ET0=0 # remet à 0 le complément d'irrigation si entre temps les sondes sont redevenues fonctionnelles
    print("Plan effectué : plan A")
    print("Teneur en eau moyenne avant irrigation : "+str(round(moyenne_humidite[0]*100,4))+" %")

    # Où se situe l'humidité moyenne ?
    if moyenne_humidite[0]>0.285: # regarde si elle est supérieure à la CC
        V_irrigation=0 # y'a assez d'eau on n'irrigue pas
        ET0=0
        print("Volume irrigué : 0 mL")
    else:
        V_irrigation = (0.285 - moyenne_humidite[0]) * 12.6 # volume d'irrigation nécessaire pour atteindre la CC
        print("Volume irrigué : "+str(int(V_irrigation*1000))+" mL")
```

Figure 32: Plan A: volume of irrigation

On the other hand, if "t" equals three, plan B or C will be used for irrigation. It is useless to show here the calculations for ET_0 because they are the same as in the calculation section. Here is the check of the final value of ET_0 and also the plan C programming. Both volumes are also in this figure.

```
if 0<ET0<9:
    print("Pan effectué : plan B")
    ETR = (ET0+supplement_ET0) * Kc  # valeur réelle de l'ETP en considérant le type et le stade de la culture
    V_irrigation = ETR * 10 ** (-2) * 10.5 # volume qui a été perdu par évapotranspiration
    moyenne_humidite= [humidite[0]]
    print("Volume irrigué : "+str(int(V_irrigation*1000))+" mL")
    print("Teneur en eau moyenne avant irrigation : "+str(round(moyenne_humidite[0]*100,4))+" %")
else:
    print("Plan effectué : plan C")
    ET0=float(open("../WatWall/gw1/ET0.csv", 'r').read().split("\n")[J - 1]) # trouve la valeur moyenne d'ET0 pour aujourd'hui
    print("Nouvelle valeur d'ET0 : "+str(ET0))
    ETR = (ET0+supplement_ET0) * Kc
    V_irrigation = ETR * 10 ** (-2) * 10.5
    moyenne_humidite= [humidite[0][0]]
    print("Volume irrigué : "+str(int(V_irrigation*1000))+" mL")
    print("Teneur en eau moyenne avant irrigation : "+str(round(moyenne_humidite[0]*100,4))+" %")
```

Figure 33: Plan B and C: volume of irrigation

The volume is then converted into a time if the volume is high enough and the irrigation takes place in writing in 'valve.txt' as in the figure 34.

```
temps_irrigation = round(V_irrigation / 0.000416)  # calcul le temps correspondant au volume précédemment calculé
print("Durée d'ouverture de la valve : "+str(int(temps_irrigation/60))+" minutes")
timestamp = get_timestamp()
n = 0
if temps_irrigation <= 1200:
    open("valve.txt", 'w').write(str(timestamp) + ";1\n")  # crée un nouveau planning et demande d'ouvrir la vanne à l'instant mê
    open("valve.txt", 'a').write(str(int(timestamp + 1200)) + ";0\n")  # demande la fermeture de la vanne après le temps d'irriga
else:
    open("valve.txt", 'w').write(str(timestamp) + ";1\n")
    open("valve.txt", 'a').write(str(int(timestamp + 1200)) + ";0\n")
    temps_irrigation -= 1200
    n = 1
    while temps_irrigation > 1200:  # implémente le temps non applicable dans cette heure aux heures d'après
        open("valve.txt", 'a').write(str(int(timestamp + n * 3600)) + ";1\n")
        open("valve.txt", 'a').write(str(int(timestamp + n * 3600 + 1200)) + ";0\n")
        temps_irrigation -= 1200
        n += 1
    open("valve.txt", 'a').write(str(int(timestamp + n * 3600)) + ";1\n")
    open("valve.txt", 'a').write(str(int(timestamp + n * 3600 + temps_irrigation)) + ";0\n")
if n==0:
    print("On peut donc uniquement irriguer sur l'heure actuelle")
else:
    print("On va donc irriguer sur "+str(n+1)+" heures différentes")
```

Figure 34: Time of irrigation

Finally, the program verifies whether irrigation has taken place by comparing the water content before and after irrigation. The message "Aïe, l'irrigation n'a pas fonctionné, bon bah on recommence" tells us that irrigation does not work but its light tone reminds us that it is not the end of the world.

```
if moyenne_humidite[1] - moyenne_humidite[0] > 0:  # regarde si la différence d'humidité moyenne est positive, preuve qu'elle a 
    print("C'est donc plus élevé que 4 heures plus tôt, l'irrigation a fonctionné :)")
    print("")
    print("######## Fin du processus d'irrigation : " + time.strftime("%A %d %B %Y %H:%M:%S") + " ########") # indique quand le 
    print("") # met une ligne vide pour séparer les irrigations, ça rend les choses plus lisibles
    sys.stdout.flush()
    time.sleep(20*60*60)  # fait une pause de 20h dans l'éxécution
else:
    print("Aïe l'irrigation n'a pas fonctionné, bon bah on recommence:(") # si celle-ci n'a pas augmenté le programme recommence
    print("")
```

Figure 35: Verification

3 Graphs

In this section the results of the irrigation will be analyzed by looking at the water contents with respect to time. Plans A and B have been tested as you can see on the three next figures. The changeover to plan B has been forced in the code.

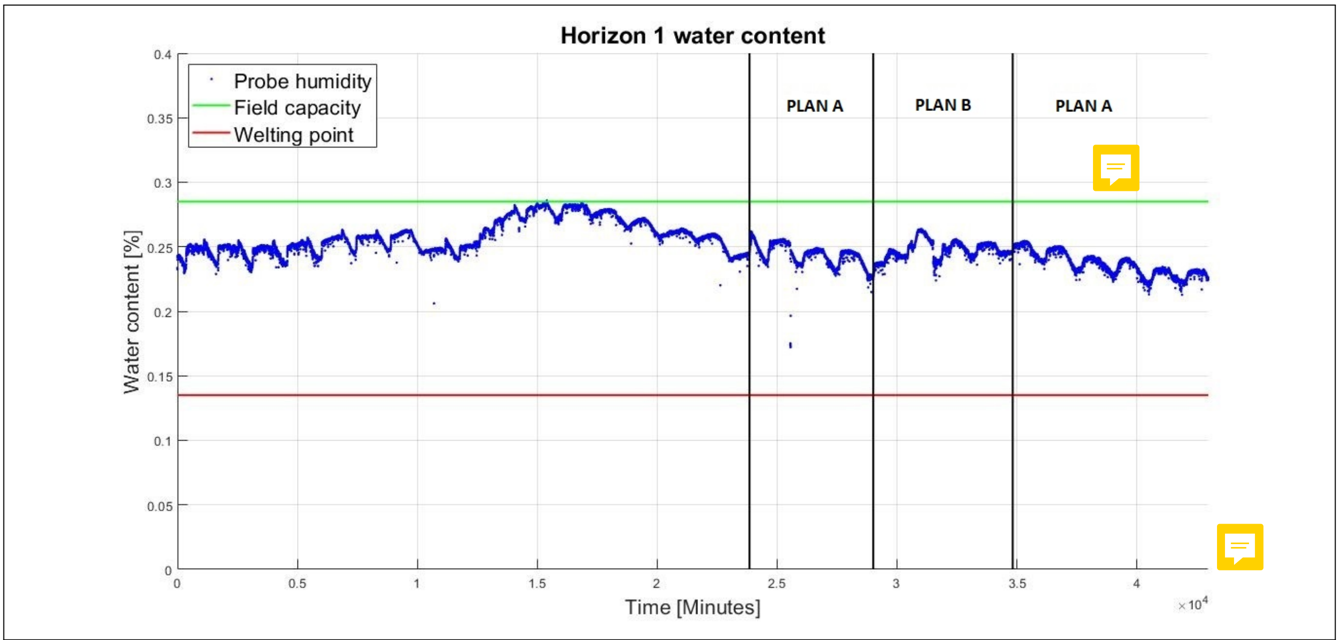


Figure 36: Probe 1

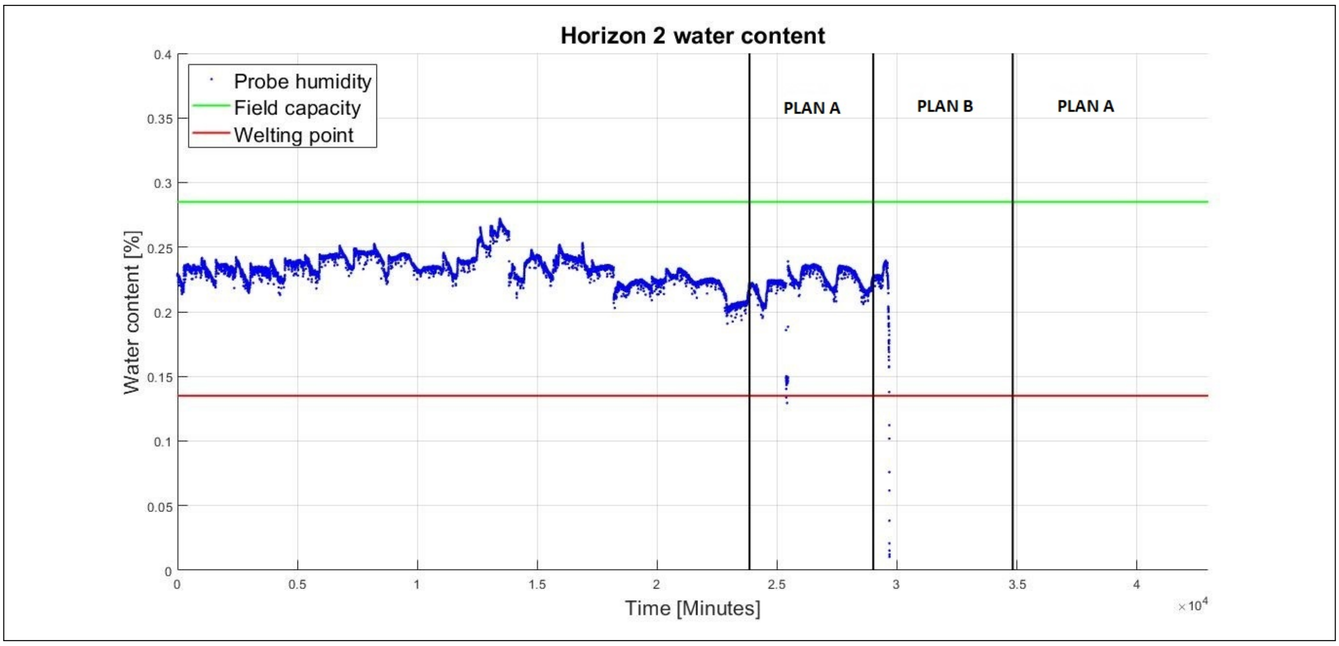


Figure 37: Probe 2

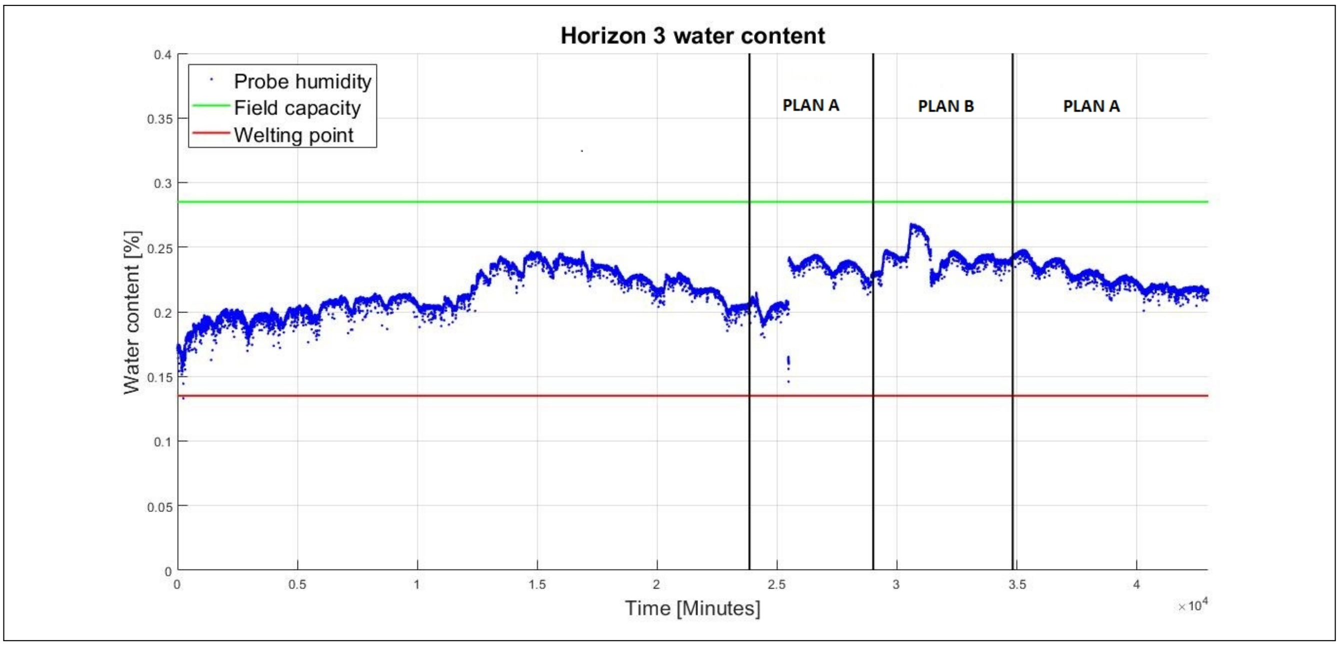


Figure 38: Probe 3

Neither plan A or B worked perfectly: the increase of water content were each day too small and the water contents never reached field capacity. The only exception is before the code started running, when it was manually irrigated. Moreover water contents showed a decreasing trend when plan A was applied. It is important to note that the probe number two stopped working a little after the beginning of the plan B. Moreover there is a jump during plan B for the third probe because the probe was removed and then put back into the soil. The water content seems more realistic afterwards. There was certainly a bad contact with the soil.

Those results can be explained by several factors. First there is a larger uncertainty concerning the actual discharge at Christophe Dupriez home. A lower discharge than expected could of course explain why the irrigation doesn't work as well as desired. Moreover the calibration of the probe for the soil of Mr Dupriez has not been done. It certainly introduces an error in the value. There is also an uncertainty about the conversion of the value from volts into water contents. Finally the temperature might impact the soil electrical characteristics that influence the probes values (Cobos D. and Chambers C., 2007).

4 Critics and Perspectives

4.1 Concerning the installation choices

Firstly, isolate the wall from the precipitations decreases the chance to catch particles of nutrients. A ferti-irrigation system with organic fertilizer might therefore be considered. Nevertheless, it would be pertinent to benefit the rain and then, to reduce the irrigation dosis. In this case, the mass changes due to the precipitation collection should be measured. For example, Van de Wouw al. (2017) designed in its system two rain gauges with a tipping-bucket mechanism and an horizontal orifice to measure the horizontal precipitations. An effective drainage system should also be set to evacuate the surplus in case of heavy rain and with a the measurement of the water wastage by a collecting container.

Secondly, a float could be installed in the tank, to avoid potential energy variations during irrigation. This solution would ensure a constant volume flow rate, facilitate the calculations and decrease the uncertainties.

4.2 Concerning the calibration

To collect the datas on the pots, no specific calibration was led. Nevertheless, Metergroup suggests to perform a soil-specific calibration to get more accurate equations and volumetric water contents. The accuracy approximates ±5% for soilless growth substrates such as potting soil but increases to ±1-2% for all substrates with soil-specific calibration. This might also explain the uncertainties met.

Part IV
Conclusion

In order to conclude this report, we will make a quick review of its structure and the conclusions that have been made. As a reminder, the objectives of this Green Wall project were to design a functional vegetalized wall and its irrigation system, from the building of the module on the field and the choice of plants, to the code instructions to open the water valves.

The wall was set in Gembloux Agro-Bio Tech university. EC-5 soil moisture sensors and a weather station were placed in and next to the wall, connected with an ELSA software and Raspberry Pi components. An optimization of the substrate choice, plants location and hydraulic system was though. The probes were calibrated in order to be valid for the experiment, the irrigation strategy and the way that data was collected. Thanks to a Python code, opening instructions were given, in function of the information we received from the moisture sensors and the weather station. This last topic was actually the heart of the work, and we made it by building a flowchart to guide the user into the strategy. This flowchart articulates itself around three situations, and is fueled by different calculations based on the reading of the water contents or the ET_0 calculation. Finally the third part of the report was all about the results and graphs we received after execution of the code, and the final wall decisions. The water contents varied as desired and the program seemed efficient to ensure a fluctuation between field capacity and wilting point. Nevertheless, some sensibilities and tendencies were also noticed, therefore the application efficiency appeared to be lower than expected.

Finally, despite the uncommon context, the experiment has been successfully managed. Lots of improvement and researches might still be done to this work by studying the response of the plants and the running of the code on a long term, and thus adjust our moves. But generally, this project allows an interesting overview of theoretical concepts to raise a technical situation.

Part V
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