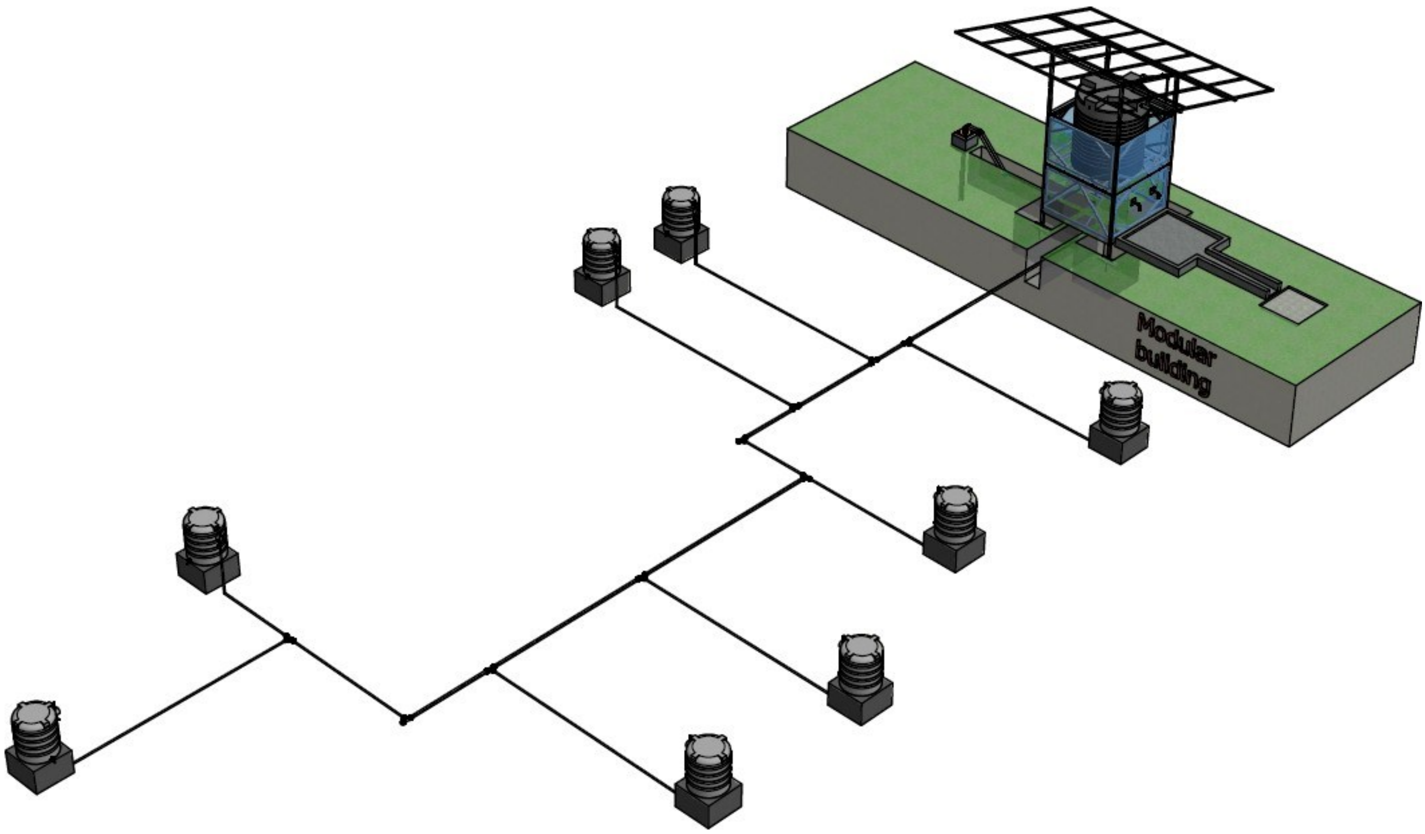

SMALL MODULAR PIPED SYSTEMS

Technical training manual

PRACTICA FOUNDATION

SMALL MODULAR PIPED SYSTEMS

The pathway to business-driven, affordable & quality piped water supply services

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INTRODUCTION

The purpose of this training manual is to serve as reading material and background information for a training about the technical aspects of modular solar drinking water supply systems.

This manual is part of a training package offered by PRACTICA Foundation. The first version of this manual had been made possible by the Orange Knowledge Programme for Tailor-made training financed by NUFFIC Netherlands. Improvements of the manual, based on field experiences, have been funded by Woord en Daad and the WASH SDG Programme.

Three types of trainings are also part of the training package. The objective of the first training is to understand the design and rationale of modular piped systems and how design decisions affect the operational expenses. The second training is about the business case and asset management behind the concept. This training gives tools and insights on how one can maintain and financially monitor the system. The third training is a technical hands-on field training on construction, installation and maintenance of modular systems.

The manual and training are designed for people who are already active in the water supply sector and want to upgrade their knowledge and skills on designing, implementing and managing modular solar water systems. It can be provided to, and adjusted to the needs of governmental agencies, design agencies, NGO's and water system managers. It will be a good resource for people who are charged with the elaboration or selection of design and tender documents, supervision of construction work, as well as for those in charge of operating and managing a modular solar pumped water system.

A secondary target group for this training are (teachers of) training centers who are charged with the provision of trainings to technical staff. These trainers can be trained by PRACTICA Foundation, and equipped with complementary training materials adjusted to the specific needs and characteristics of their region or country, so they will be able to provide a training tailored to the needs of the water sector in their country.

A third target group are decision makers and donor agencies. We are convinced that modular design and construction offers great advantages to the water sector, and has strong potential as alternative to the traditional approach of design and construction of water systems. This manual presents this argument and explains all practicalities related to modular construction.

Photo: satellite tower in Ghana fitted with mechanical prepaid system. Source photo: Project Maji

PREFACE

The subtitle of this manual in Modular Building is: The pathway to business-driven, affordable & quality piped water supply services. We think that using a modular building approach allows to serve more people on a short term through lower initial investments and lower recurrent costs. It creates a business opportunity for the private sector to supply water services in unserved communities.

Africa has one of the highest population growth rates in the world. Between 2015 and 2050 the African population is expected to grow with about 1.3 billion people! It is the highest growth rate of any continent. Villages and small towns in the rural areas are growing fast. For water supply services, it is difficult to keep up with this population growth. For the next ten years, if Africa has to keep up with population growth, the provision of water services needs to accelerate.

The conventional approach to keep up with population growth in rural Africa has been largely done by installing hand pumps. The proportion of people that have access to piped services is limited.

It is generally known that there is a problem with functionality of hand pumps. At any moment, 1/3 of all hand pumps are out of service. The water committees charged with managing the use and maintenance of hand pumps are known to struggle. Many people who are officially counted as "having access to basic water supply" do not have access at all.

A part of the problem is that hand pumps deliver a poor service. People have to pump up their own water and carry it home to their household. Even for this, they have to pay water fees for covering the costs of maintenance and repair. People dream of something better than that: piped water supply closer to home or at home. And we think that this is possible. Technically, and financially.

Sustainability is important. To realize a sustainable acceleration of piped water services in Africa, we will need to recover the recurrent costs. Many countries ignore cost recovery of water services. This results in early breakdown of water systems, and by this, service levels decrease.

In our view, a modular approach provides the solution that is needed. PRACTICA Foundation has done field work in Mali, Mauretania, Uganda, Madagascar and Benin between 2013 and 2018 on design of solar water systems. We concluded that conventional piped water systems are usually over-designed and over-sized and are constructed with little attention to financial optimization. As a result, they are too expensive, in terms of investment as well as in operational costs and therefore have fundamental problems that threaten the sustainably from the start.

Small modular piped systems

PRACTICA Foundation introduces the concept of 'modular building' that:

- Makes system design easy and straightforward, by means of standardization, so that the design costs are low;
- Aims at keeping the initial investment costs low, but above all the operational costs as low as possible;
- Has a limited number of system elements with a limited number of standard sizes;
- Starts with a small piped water system, designed to meet actual demand and local context;
- Involves a step-by-step building approach from low (communal standpipe) to higher service levels (shared house and/or private connections). Standardized modules can be added to the water system when needed;
- Formalizes payments using prepayment technology.

1 THE CONTEXT OF MODULAR BUILDING

1.1 INTRODUCTION

Many African countries face the same challenge in drinking water provision. A large unserved rural population, a high population growth, low functionality of hand pumps and expensive piped water services that are difficult to sustain.

In this chapter, we explain this further. We also explain modular building as a solution to these problems. We present the technical and socio-economic aspects of modular design, and compare modular design with conventional systems in terms of approach and costs.

1.2 THE PROBLEM WITH HAND PUMPS

There is a low functionality of hand pumps. Around 1/3 of the water systems in Africa are non-functioning at any given time[1]. Water User Committees struggle to effectively collect funds for maintenance, repair and replacements. Research shows that only 2 to 3% of the committees[2] have sufficient funds to maintain the hand pumps.

There are many reasons why this happens. Two important reasons that can be pointed out are the willingness to pay for water and the way the pumps are managed.

(I) Willingness to pay for water

Most hand pumps have been provided for free to communities. This practice has been going on for decades. And why pay for something that is provided for free? Yet, somebody needs to pay for the repairs of the hand pump and these expenses are expected to be paid by the community.

On top of that, hand pumps provide a low service level. Meaning – the system doesn't completely fulfil the need of the users. People have to walk a (long) distance, pump the water themselves and then carry it back home. Why pay for a service that still needs a lot of work?

Lastly, there is a general social and political notion that water "should not be paid for". It is a public good and a basic human need. Free water is a human right. This notion is wrong. 'The **right to water** entitles everyone to have access to sufficient, safe, acceptable, physically accessible and affordable water (UNwater)'. Free water is not a human right.

All of this results in a low willingness to pay for water. However, in the end the pump is there to solve the problem of the users. So if they don't want to pay for it, who will?

[1] https://www.rural-water-supply.net/_ressources/documents/default/203.pdf
[2] Blueprint for breakdown? Community Based Management of rural groundwater in Uganda, Marije van den Broek and Julia Brown University of Portsmouth 2015

(II) Community management

The model of community management of water supply starts from thinking that water committees are capable to effectively organize themselves. That they are able to collect and manage the funds that are needed to maintain the system. However, this is not easy at all.

It is not easy to make a good diagnosis of what is wrong with a hand pump, and then find the right parts to repair it, and a person capable to repair it. Repairs are often done substandard – if they are done at all. Preventative maintenance to make sure the pump is always working is something that is rarely done.

Also bookkeeping and money handling is difficult. In rural settings, banks are often far away. It costs a lot of travel time and costs to go to the bank for money deposits or withdrawals. It is not easy to solve conflicts about payments. If one person in the community does not pay, then other people have a reason not to pay either. Also, if there are funds set aside for future repairs it is hard to tell a community member the money is for the pump and can't be used for a child that needs health care for example.

The training of water committees is often not very good. Most development programs promise to achieve a high coverage in a short time frame, against low costs. Once approved, they have to deliver quickly, and keep the costs low. In this tight planning, the training of water committees is often too short. Also, follow up and problem solving support is very limited, if existent at all. As a result, water committees often end up poorly trained, and poorly supported.

As a result, most communities prove unable to manage these systems. So once the system is broken, there is often not enough money for repairs or replacement.

1.3 TRADITIONAL PIPED WATER SYSTEMS

Piped systems are an alternative approach to provide people with drinking water. These systems generally consist of a central water source (in many cases a tube well – but springs are also often used) from which water is extracted and stored in a central tank. Water is distributed to the users by means of pipes.

People like piped systems more than communal hand pumps. Their service level is higher. Water does not need to be pumped up by hand any longer, and can be brought closer to or even into the households. In some cases, the water contains chlorine. People are therefore more willing to pay for this service.

However, piped systems often face a range of problems that result in low service levels and early breakdowns. Many water companies and enterprises struggle with aged and broken water infrastructure, water shortages and high running costs. The systems are large and the costs of running the generators are high.

Water fee collection, billing and administration can cost a lot of administrative effort and therefore money. It can be problematic and prone to fraud. Illegal connections and leakages need to be detected. Defaulters (people that don't pay the bills) need to be detected and approached, reminded to pay and possibly temporarily disconnected and reconnected after payment.

Also, contractual agreements between the caretakers, users and the owners result in conflicts – who pays for a broken pump? Is there a difference between repairing and replacing broken parts? Who should pay if parts are vandalized? What water fee is reasonable? And what if the government sets a water fee, but entrepreneur is unable to run the system for that fee?

As can be seen – there are many causes for a piped system to fail over time. Part of these causes are a result of how the systems are designed. The bigger the system the more expensive it is to maintain. So the design of a system has an effect on the operation and maintenance cost.

To design a system, design criteria are used. Design criteria are certain 'rules' or standards. These rules tell you how much water should be supplied in one day, how big the tank needs to be, where the tap stands should be placed, etc. These rules are not the same in each country.

The most important design criteria that are typically used are:

- **A design horizon of 20 years**. This means the system should be able to provide water to a population that is expected to be there in 20 years. The idea of this is that if you build it big, you solve the problem for a long time. An estimation of the population growth is made to determine the population size in 20 years. For this, the current population is multiplied by a growth factor. So if a population size is 1.000 people now and it is expected to grow with 4% each year, the system should be able to provide water for 2.100 people (which is the expected population size after 20 years).
- The **water demand per person** is often set at 20 litres per day. So the system should be able to provide 20 litres of water per person daily.
- On top of this, in many cases an estimation is made of the **growth of the specific consumption**, and often a **peak flow factor** is used. These factors are to deal with the assumption people will used more water in the future than they do now. And that the system should be able to deal with events that do not happen every day, such as festivities or extremely hot weather.

Design example

A system is designed for a population of 1.000 people. The design criteria are used as described above. This results in the following sizing of the system:

- With a 20 year design horizon the expected population size after 20 years is 2.100 people.
- Consumption is assumed to be 20 liters per person per day. Resulting in an estimated consumption of (20*2.100 people) = 42.000 liters per day.
- On top of that – a peak factor of 1.4 is used. Meaning the system needs to designed to supply 1.4*42.000 liter = **58.800** liter per day.

All these design criteria seem to be rational. However, they can lead to considerable problems during the lifetime of the system. These design criteria result in grossly over-dimensioned water systems. They are generally designed for a 3-6 times higher water demand than the actual current water demand. This makes it more expensive to build the systems. But, more important, they also result in very high operational and maintenance costs that have to be paid by a very small community relative to the size of the system.

On top of this, the fees that people have to pay for water are based on 'social desirable' fees. It is not uncommon that the population is asked what they are willing to pay. And this is set as a water fee. But what if this fee is so low that it will never be able to cover the cost for, for example, replacing the pump?

The population is not able to collect enough funds to maintain the system as a result of all these decisions. Causing the system to break down. Making it clear that what seems 'a rational design' actually isn't rational at all. And what seemed to be socially desirable is actually the opposite.

1.4 MODULAR DESIGN AS ALTERNATIVE

The previous chapter explained that hand pumps and piped systems are the most common systems to provide safe drinking water. Piped systems are oftenpreferred by the users because people don't have to pump themselves to access the water. In other words, they provide a higher service level.

However, piped systems are hard to maintain with the current way of designing piped systems. They are made so big that the relative small population isn't able to pay for the maintenance and the replacement costs of broken parts.

With modular piped system design, we want to achieve a situation in which water systems are sustainable, and provide a good service level. And after they are constructed, they should be able to be maintained with the fees that users pay for the water.

To achieve this the design of modular systems is very different than the conventional designs of piped systems:

- The capacity of the system should be enough to serve the current population size. However, this capacity should be able to **grow over time** when the population grows. It is adaptable design rather than a static design. This means that we no longer need to use a design horizon.
- We also use water **consumption figures** that is based on field data – rather than desk studies. Meaning that the general consumption figure of 20 liters per person is reduced by half. It should be mentioned that these consumption patterns can highly differ depending per country/region. See also text box example on page 9. Resulting in smaller and therefore cheaper systems.
- Conventional piped systems are custom made for each setting. We want a **standard design**, we bring down the costs of all studies, designs and bills of quantity that need to be made to prepare the construction. This brings down the initial investment costs.
- **Prepayment technology** is used to charge user for tapping water. This technology ensures that all users pay. If you don't pay, you can't get water. In this way the payments are 'formalized' – meaning that nobody can argue with a care taker and cause social conflicts. It also opens an opportunity for entrepreneurs. They now can run multiple systems and monitor the financial performance behind a computer.

- By **choosing solar energy**, the initial investment is somewhat higher, but the operational expenses are much lower. This increases the potential to be financially sustainable.

By choosing these design standards we end up with a much smaller system. Resulting in a system that is much cheaper to build and much cheaper to run and maintain. And on top of that, by using prepaid technology, we make sure that customers pay if they fetch water – ensuring income to pay the bills.

Example calculation actual water need

In the previous example, we sized the system for a population of 1.000 people. With the design criteria we determined the size of the system to be 58.800 liters.

However, research based on the monitoring of systems throughout Africa shows that the actual water consumption of people is actually closer to 7 to 8 liters per day. With a peak of 10 liters per day in the driest month of the year. So the current population only needs 10*1.000 = 10.000 liters per day to deal with the peak demand in the driest month.

As a result, in this example, the system is nearly 58.800/10.000= 5.9 times bigger than needed! Meaning that a population of 1.000 people have to be able

Equally important in the concept is that **water fees** should be based on the expected cost of the water. Meaning that the income as a result of water sales is higher than the expected cost of the system. Depending on the price this can even open up opportunities to save so much that the system can grow by adding extra water towers.

Each technical aspect will be separately discussed in more detail in this manual. Calculating the correct water price will be done in the following training.

In the table below, there is an overview of how we compare conventional piped water systems, hand pumps and the modular systems.

	Hand pump	Conventional piped system	Modular system	Rationale
Number of users	Limited to 300 persons per day	A fixed number of expected users based on the estimated growth of current population. The design horizon taken is generally 15 to 20 years.	One module can serve 350 people. By adding or removing modules the capacity of the system can be adjusted to the actual need. Household/yard connections can be added as extensions as well.	One module should serve at least the amount of users of a hand pump. Unnecessary oversizing increases investment and running costs.
Design	Off-the-shelf	Design based on local circumstances: Infrastructure is permanent and unable to adjust to (growing or shrinking or misjudged) water need.	Off-the-shelf (Infra)-structure is able to adjust to (growing or shrinking or misjudged) water need in small incremental steps.	Oversizing of the system is limited by creating flexibility in the system size. By using off the shelf standardized modules the engineering costs are limited compared to the conventional approach.
Maintenance	Standardized	Systems differ in design and principles. Standard maintenance schemes are therefore difficult.	As modules are standardized, standardized maintenance is possible.	The system grows by adding similar modules
Water consumption (L/p/d)	(-)	20	10	Field data and experience indicate that consumption is lower than 20 l/p/d. Especially for paid services.
Payment mechanism & pricing	None	Differs per community: payment per public stand post (based on volume	Pre-paid. Pricing preferably based on actual	Payments should ensure financial sustainability to ensure

		sold) or per individual. Pricing often based on 'Ability to pay' principle. Often no inflation correction.	cost & inflation corrected.	independent & continued delivery of raised service levels.
Power source & pump type	Human powered	Divers: fuel, grid and solar	Solar based	Stand alone and future proof modular concept dictates solar energy.
Reservoir type and size	None	Size depending on estimated water use combined with projected number of users at project horizon. Concrete tanks are mostly encountered.	Standard volume. Plastic tanks in order to allow removal of the reservoir in case of downsizing the system.	Low cost and replaceable concept that allows removal to reduce financial risk in case there is no consumer uptake.
Source	Existing boreholes and hand dug wells.	Divers. Including boreholes, springs, river & lake intakes, hand dug wells.	Groundwater (tube well). Preferably manually drilled.	First step in the increase service level is the replacement of a hand pump on a tube well with one module. Well installed and tested tube wells assure good quality water with no water treatment needed.

Photo: satellite tower in Ghana fitted with mechanical prepaid system. Source photo: Project Maji

2 THE TECHNICAL LAY-OUT OF A MODULAR SYSTEM

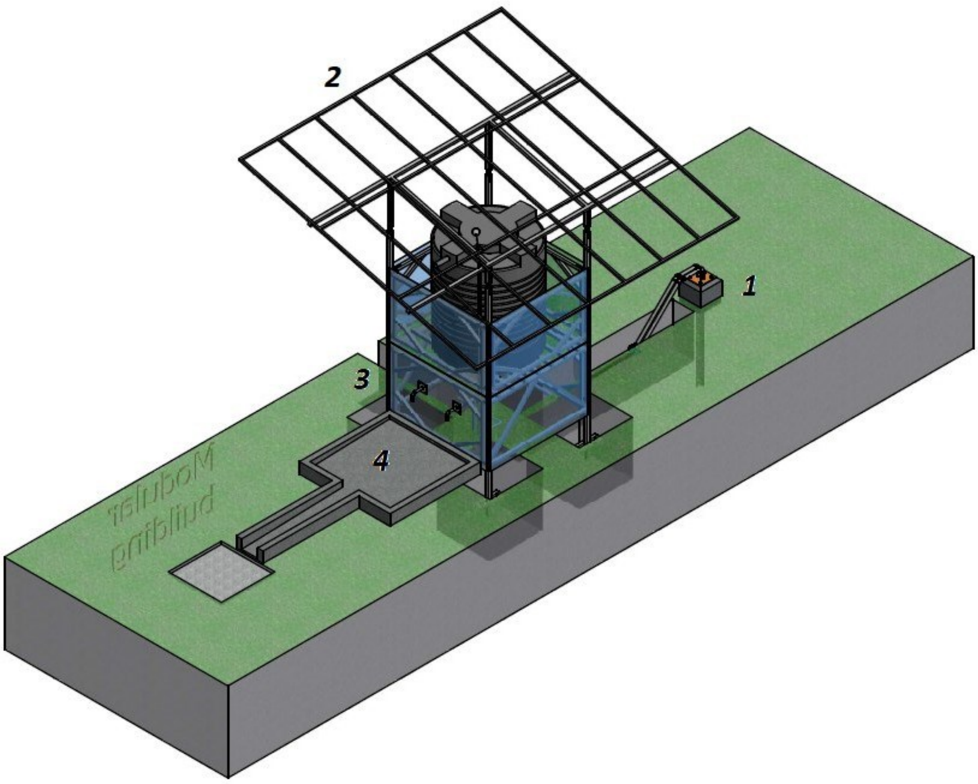
2.1 INTRODUCTION

In this chapter, we introduce what a modular system technically looks like. We introduce the service levels, and discuss the technical details of the system components. In this discussion, we do not go into great depth of explanation, but present the most important information.

2.2 THREE SERVICE LEVELS.

In a modular system, we have three service levels. Service level 1 is the most basic module. Service level 2 and 3 can be seen as options for expanding the water system in two different ways.

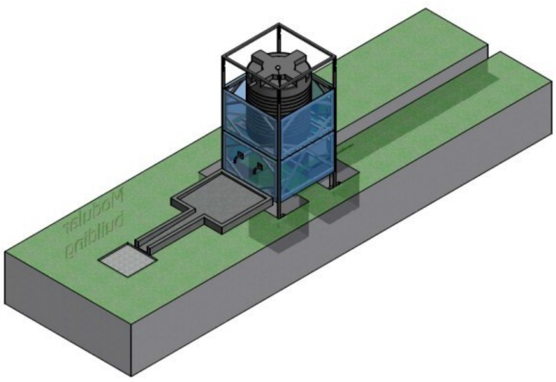
Service level 1 (SL1) – the central tower. The module consists of a borehole (1) withsubmersible pump powered by solar panels (2), a small raised reservoir with taps
(3) and an apron with soaking pit (4). The system is solar operated and provides water to the piped system as a whole. Prepaid technology ensures everybody pays for water.



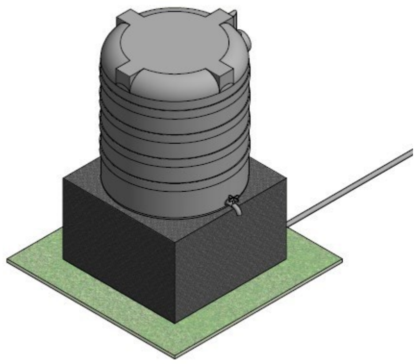
This module can be placed on a new or existing borehole, replacing a hand pump and thereby improving the service level. It is designed to serve the same number of people using a hand pump: around 300-350 people.

However, if the population is larger or grows larger over time, there are 2 modules that can be added:

1. **Service level 2 (SL2): A satellite tower** – this generally serves as a public water point. The satellite module is almost the same as the first module –it only misses the pump with the solar panels. It brings the water to a newsection of a village, thus reducing walking distance to the water point and thereby increasing the service level for the village.
2. **Service level 3 (SL3): A yard or household connection** – this is a private connection with a much smaller tank placed in a yard. It therefore increases the service level – compared to the other public towers – evenmore.

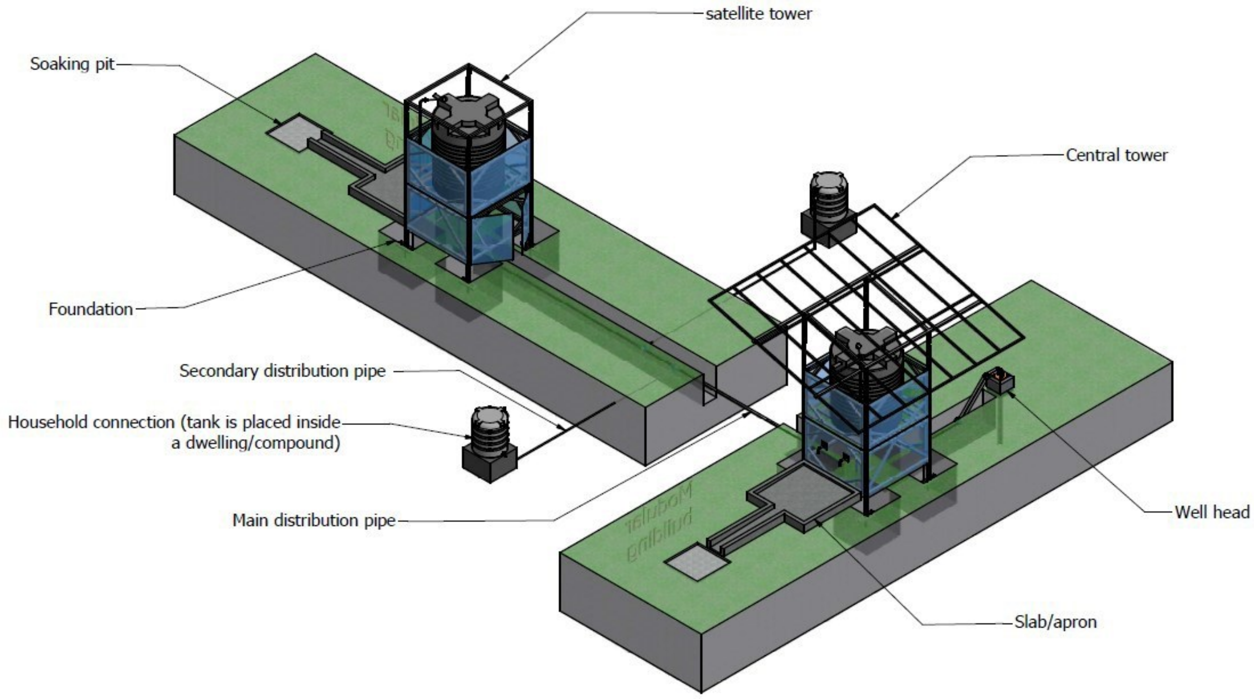


Satellite tower



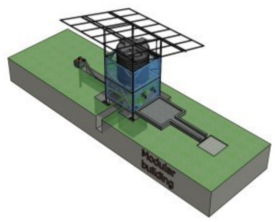
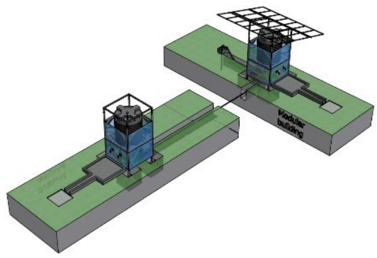
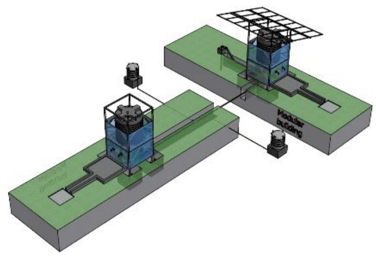
Yard/household connection

Both modules are served by the pump of the service level one, using a distribution pipe.

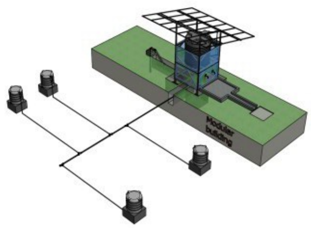
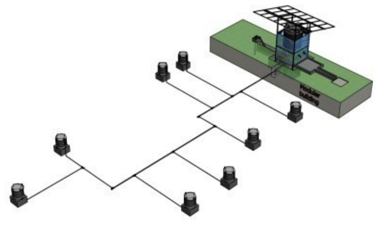
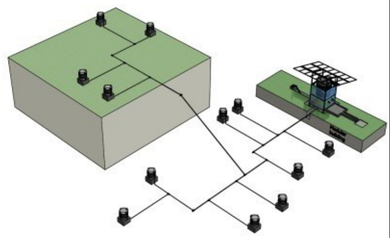


With these 3 modules the system can be configured and adjusted overtime – depending on the need. In this way the piped system can expand itself over time and continue to increase the service level. Without being grossly over dimensioned. Expected expansion plans – will however – be needed to take into account when designing the system. This particularly applies to the piping and pump sizing.

The following pictures show possible growing scenario overtime – depending on locations and needs. Scenario 1 starts with a single tower – but overtime the water need increases so an additional satellite tower is added – and at the end some yard connections are added.

Scenario 1		
		
Starting configuration	Expansion step 1	Expansion step 2

In scenario 2 there is less need for public water provision and there is a stronger focus on yard connections. The expansion consists of increasing the number of yard connections.

Scenario 2		
		
Starting configuration	Expansion step 1	Expansion step 2

Photos: Examples of different service levels.

3 TECHNICAL DESIGN ASPECTS OF MODULAR BUILDING

In this chapter, we go into more detail of the technical aspects of modular building. We will explain how piped systems work, why certain design decisions are made and how the correct pumps can be selected. A step wise approach is used for this.

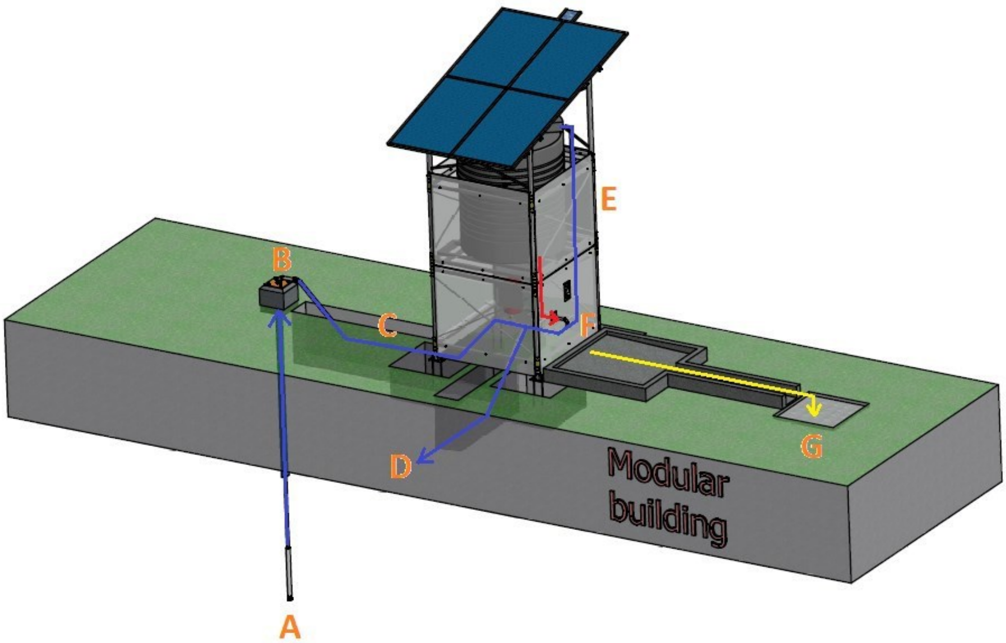
This chapter will provide the theoretical framework. It is attempted to provide as much actual field data to make is as concrete as possible.

In the appendix one can find the technical drawings of the system. It contains drawings of the towers, how the pipework should be laid out and what the household connections look like. These drawings should be used as a guiding principle: local variations are possible. These can be found in, for example, the removal of the metal cladding and use brick work around the tower. However, to ensure structural soundness, the quantity and sizing of the metal framework and foundation of the tower should not be changed.

3.1 TECHNICAL PRINCIPLE OF THE SYSTEM

There are many different principles of piped systems. Some systems are fed by a spring and use gravity to transport water to tap stands. Some use surface water and have a complete water treatment plant to make sure the quality of the water is good.

The modular system uses a submersible solar pump (A) that is placed in a tube well. The pump pumps the water to the surface where a well head (B) is placed on top of the well. This is a concrete block to protect the well and it helps to the install the pump properly. From there a pipe goes through the ground (C) to the water tower. In the water tower there are some parts that control the pump by switching it on/off so the tanks don't overflow. In the water tower the pipe goes into two directions. Water is either pumped to another water tower through a pipe in the ground, called a distribution network (D) or is pumped into the tank (E). Water can be tapped from this tank (F). The spillage water is collected by the apron and soaked into the ground in the soak pit (G).



IMPORTANT NOTE

The central tower contains a lot of hardware that is needed to run the solar pump. This includes solar panels, control boxes, pressure sensors etc. For that matter, the central tower will always need to be placed directly next to the well (ideally within 25 meters). This is to ensure that the cables between the pump and the controller inside the towers have a limited length. This is a very important factor to take into account during the selection of the site.

If it is decided that there is no need for a central tower that serves a water kiosk one can opt for a solution where one places just the tower without the tank and prepaid technology.

All these parts need to be sized and sizing depends on how large the system will need to be to serve the community. The more water needs to be delivered, the larger the pump, the more solar panels we need and the larger the pipes need to be.

To design the system, we can use a step wise approach containing the following steps:

1. **Site assessment:** In this site assessment you determine if the site is suitable for the system and, if so, what the system would look like. For example, which well are we going to use? Where are we going to place the towers and where will the distributions line run?
2. **Collection of technical data for the design:** If we now know which well we use, we can determine the characteristics of the site. How much water do we need to pump on a daily basis? How far and high do we need to pump the water? Can the well provide sufficient clean water?
3. **Technical design:** if we know all the parameters, we can make a design. We can determine how large the pump will need to be, what the diameter of the pipes will need to be, etc.

We will go over each step and use an example to make it as practical is possible. Once there is a clear technical design, the sourcing of materials, construction and implementation can start.

4 DESIGN STEP 1: SITE ASSESSMENT – THE THEORY

A site assessment has the aim to determine whether the location is a suitable location for the system. This chapter first covers the theory and then provides a practical field example.

To assess the feasibility of the implementation of the system, one should use a combination of 2 types of assessments:

1. **A socio-economic assessment**: this can be used to determine if the system can generate enough income to cover the operational costs. It is a good start to assess the economic feasibility of a water tower.
2. **A technical assessment**: this is used to determine what the system will look like and what the technical characteristics are. For example: how much water do I need, what kind of pump is needed? Are there any obstructions in the field that will hamper the installation?

This manual excludes the description of negotiations related to water price, asset ownership, management etc. as it is a technical manual. It is – however – a very important step in the implementation of the water system that should be taken into the account when implementing a water system.

It is also recognized that the design of a system has a direct impact on the water price. An asset management teaching module is available that explains this impact and howone can calculate a water price that is needed to recover operation and maintenance costs.

To assess a new location of a water system one needs to visit the site, walk around and talk to the population (leaders) and all responsible institutions.

One wants to get a 'feel' for the location. From both a technical as well as a socio (economic) point of view. This will take multiple visits with different people that are specialized in different disciplines that asses the location from different perspectives.

It is important to take time for this step: if the location is assessed incorrectly – for example there are too many other free water sources that compete with the new system based on a pay as you go principle – the project will fail. No matter how well the technical design has been made.

It is important to keep the communications with the local population clear and consistent of what you are doing: you are assessing the location. This means that that the assessment might result in the conclusion that the site is unsuitable – so ensure no promises are made that might result unrealistic or false expectations.

Important questions to be answered in a socio-economic assessment are:

- **Water need, willingness to pay & social acceptance:** this step assesses if a new system is actually needed by determining (1) if the new system would solve a problem (2) how big the problem currently is (3) if the population shares the vision of the solution (4) and is willing to pay for it.

  To assess the need for a new piped system the following topics will need to be assessed:
  - **Current water sources:** What are the water sources that the population is using now? Are they improved – (for example a tube well) – or unimproved (for example a river)?
  - **Status of water sources**: Are there any broken down water points? If so, what is the reason of the breakdown? Is this a technical cause of more social cause?
  - **Value of water**: How do people value water? Would they be willing to pay? Or do people already pay for water? If so, where and how and how much? What seems to be a socially acceptable rate?
  - **Location of water sources**: Where are the sources located and how reliable are they? For example, a river might run dry during the dry season, or the sources are located at considerable distances from where people live.
  - **Water consumption**: How many people live in the community? How much water does the population use in general per day? Water consumption can heavily depend on cultural practices and economic activity. Are there any institutions, schools, etc. that should be taken into account when making the design?

  Interviews, site visits, general observations, group discussions etc. can be used to retrieve this type of information.

From a more technical perspective the following points can be assessed:

- **Setup of the system & technical constraints.** This step assesses if there are any technical constraints that can be easily identified that might form a risk in the project. To identify those constraints, one has to know what the system would look like.
  a. **Location of hardware:** Is there a well that can be used for the system? Or is there a need for a new well? What is the location of the well? What are logical places to place (a) public water tower(s), yard connections and where would the distribution lines be located. Logical locations for towers are generally places where there are enough consumers: densely populated areas, rural growth centers, certain institutions, etc.

b. **Social constraints:** Who owns the ground that we place the hardware on and in? Are there any objections or (unwanted) financial compensations that need to be made to construct the system?
c. **Technical risks and constraints:** Based on the information above one has a first indication of the design. Identify technical constraints based on this information. For example: are there any tarmac roads/rivers/hard rock outcrops that need to be crossed with the distribution network? Is the location of the well as such that the solar panels will receive sun or is the sun blocked by buildings? Do the distribution lines cross fields that are plowed deeply with heavy machinery? Is the location of the well close to the point of consumption? Are there any potential sources of contamination near the well?
d. **Hazards:** Are the locations chosen safe for the public? Is there any traffic that might harm users? Is it accessible for children, elderly and disabled? Are there any alternative locations that might be better suited?

Ideally, one makes a map of the situation. This will help to collect all the technical data needed in the next step.

Based on the information above one can make a decision if it is worthwhile to proceed in the process of design. There are no fixed set criteria that can be provided to make this decision other than general common sense and a clear vision of what one tries to achieve. If there are (many) alternative safe and free water sources or people are not willing to pay for water, then it makes no sense constructing a new water point if a solid business case it the aim. If a site is prone to flooding every year then one should wonder if another location might be better if a long term intervention is the aim.

Ideally, one makes an assessment for multiple locations so one can compare one site to another and pick the best one suited.

Lastly, if a location has been selected it might turn out that certain technical constraints – that will be investigated in a later stage (see next chapter) – will result in the conclusion that the site is unsuitable. This is particularly the case for the well. In a later stage the water quality and quantity will need to be determined that the well provides. It is possible that the well is not able to provide enough water quality or quantity. This would mean that one has to assess a second location.

Photo: central tower in northern Uganda.

5 DESIGN STEP 1: SITE ASSESSMENT - AN EXAMPLE

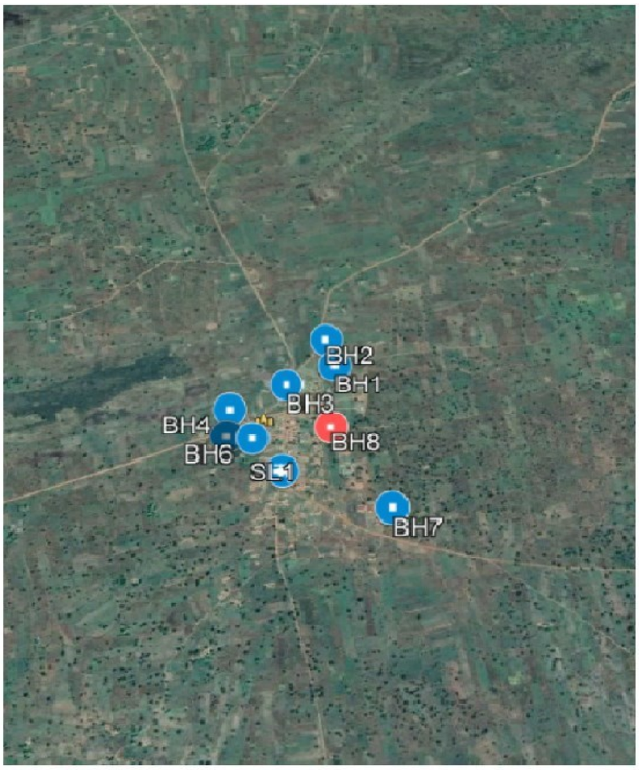
In this example two real life cases are presented and compared to assess the expected successfulness of the implementation of a new piped system. Based on the comparison the most promising will be technically detailed in the following chapter.

The examples are based on real examples from the field that were considered for implementation of the systems. Minor changes have been made to make the examples more compelling.

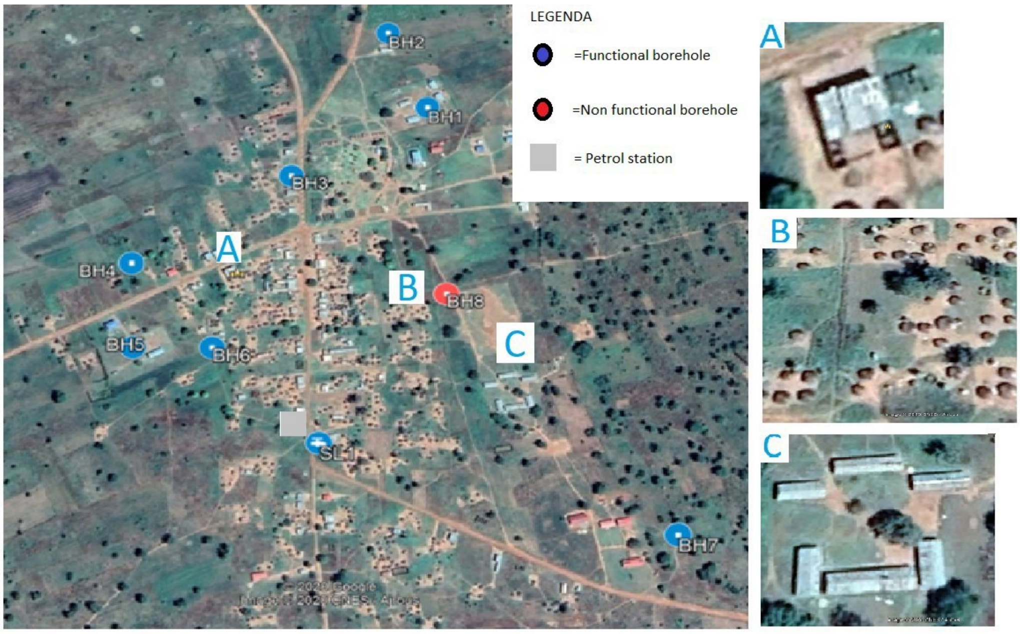
5.1 OPTION 1

The first example is a remote village in the north of Uganda. It is a village with about 150 households. The village was suggested by a local NGO as promising as there is a – relative – high concentration of dwellings.

The village has a strong agricultural focus and the social economic status of the average inhabitant is relatively low. As a result, the ability to pay for water is relatively low. As a first indication it is suggested that people are willing to pay about 50 Uganda Shilling per jerry can. This is the common tariff in the province.



The following picture shows a more detailed impression. The village itself is a long stretched growth center with a considerable amount of basic dwellings surrounding the village (B). Also a school (C) and church (A) are present.



From a technical perspective there are hardly any constraints. The village is flat and no tarmac roads are presents. The wells are said to be high yielding. One aspects to be taken into consideration is the petrol station which could form a source of contamination for the surrounding wells.

In (the near surrounding of) the village 8 functioning boreholes are present. By means of interviews it becomes clear a good functioning water user committee is in place. One borehole is not functioning. The borehole is abandoned due to water quality problems.

Given the large amount of present wells the village already agreed that one well could be used for free as a source for the water system.

5.2 OPTION 2

Option 2 is a location in the west – a relative richer part of Uganda. A rural growth center relies on 2 remote water sources – being tube wells. 2 other wells – of which one is located in the village – are non-functional. During the rainy season the villagers use a small flooding area as a water source. A school is present in the village.

The village itself has approximately 150 households. Water vendors sell water in the village as the safe water sources are located at quite a distance (approx. 1500 meter). Jerry cans can sell up to 200 Uganda Shilling.

The roads are all dirt roads – there are no tarmac roads or any other obstacles that would cause trouble during trenching for the piping. However, the flooding area should be avoided as it could cause harm to the piping during the rainy season. Also multiple farmers already mentioned they are not willing to allow piping to cross their land.

Of the two functional boreholes one (location D) is very remote. The borehole on location C is located next to a dwelling. Both wells are located in a valley. The cause of failure of the 2 non-functional boreholes are unknown. The water user committee appears not to be able to provide insight in the causes nor show direct interest in restoring the well.

5.3 COMPARISON AND SELECTION

If one would be able to fund only one of the two sites, one would need to assess the likeliness of a successful implementation of a site. The choice would depend on the criteria one uses to make a decision.

The following table provides an overview of some threats, strengths, opportunities and weaknesses of each location.

Criteria	Option 1	Option 2
Strength	Nearly all wells are functional; it appears that water is valued. WUC is able to sustain the currently present hardware. From a technical perspective the site is less complex than option 2. A flat landscape and short distribution lines provide an opportunity for a simple design.	The water scarcity appears to be an issue with only 2 functional wells located at a considerable distance to the village. Willingness to pay appears to be high and the ability to pay appears to be higher than option 1.
Weakness	The water scarcity is low – there are a considerable amount of wells present in the village. Introducing a paid water service in a setting where there are available free water sources will be a challenge.	From a technical perspective this site will pose some challenges – particular long distribution lines and slopes in the landscape if borehole 2&3 are the only option. In addition to this there might be potential trouble with land owners and considerable effort will need to be put in using one (of the two) wells for the system.

Threat	The ability to pay is relatively low. This inability might threaten the financial sustainability or might have negative influence on the well-being of the population when water services might turn from free sources to paid sources.	It is unclear why the well in the village is non-functional. This might be due to low social cohesion, a technical reason, a non-functional WUC or maybe people value water to only a limited extend.
Opportunity	Chlorination (adding chlorine to the water to kill bacteria, viruses and other microbes in water) of the water and household connections might provide a service level increase that results in willingness to pay for water.	The current distance to the water source appears to be a reason to pay for water fetching given the presence of water vendors. Higher water rates per jerry (compared to option 1) can might be possible with new water points located close to the dwellings. If borehole 4 proves functional than a simpler design is possible. Also – limited conflicts are expected when the non-functional borehole is used for the pipedsystem.

The decision which site to select is – in the end - an arbitrary decision depending on what one finds important. In this example the option 2 is chosen – as the water scarcity combined with the ability to pay is perceived to create a better condition for paid water services.

To serve the community it is chosen to:

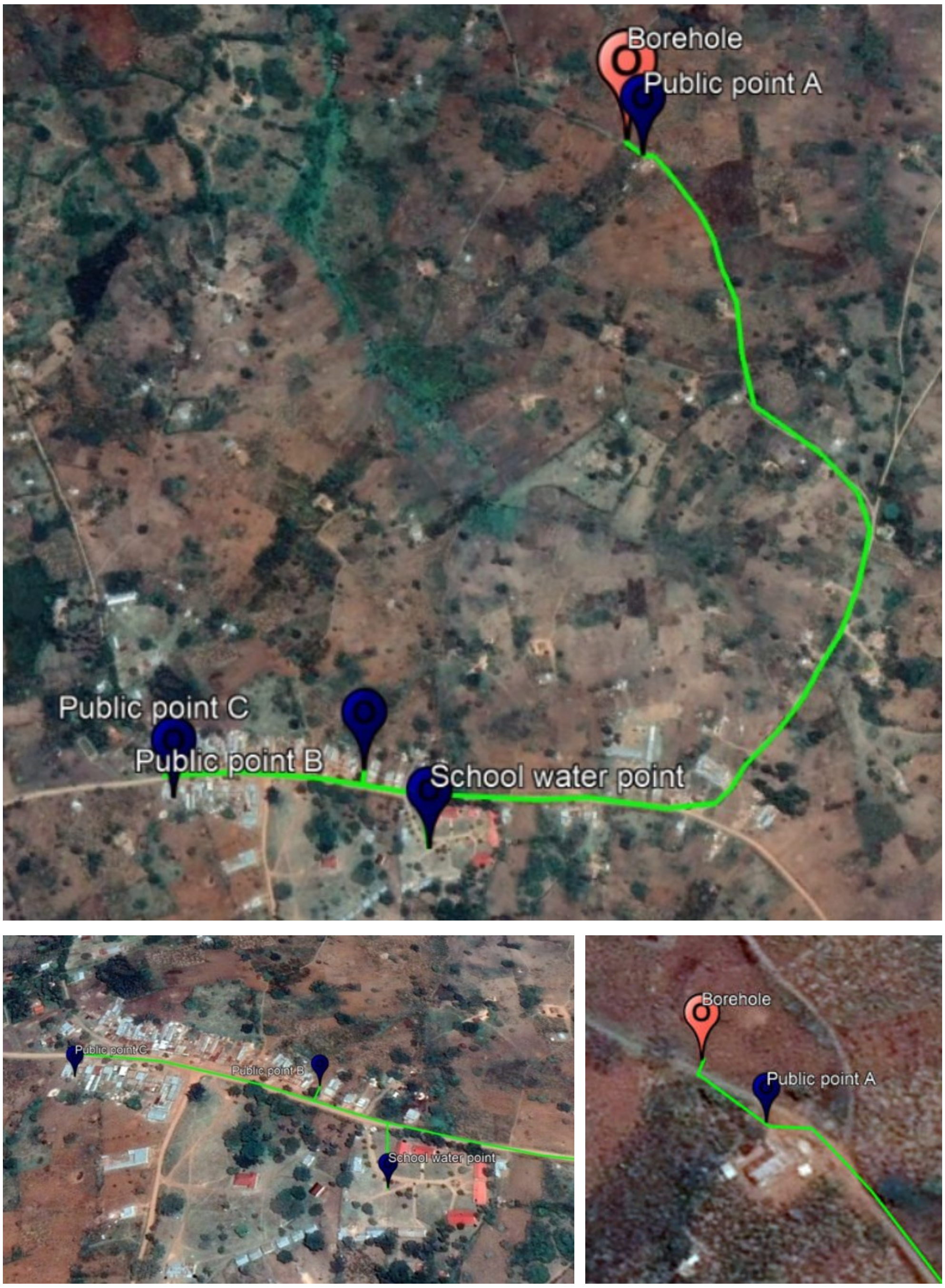
1. Asses borehole 4: can it be made functional?;
2. If borehole 4 can't be made functional borehole 3 will be chosen as the water source. Provide a public water point at the well so current users are still able to fetch water at the present location of the well;
3. Provide two public water points in the village;
4. Provide a water point at the school;
5. Run the distribution lines along the road to (1) prevent damage due to flooding and (2) prevent social conflict with farmers related to land issues.

With a distribution line running through the village the technical option is provided to expand the system later on with yard connections. It is decided to take 5 future household connections into the future prognosis.

5.4 TENTATIVE DESIGN

After a quick assessment of borehole 4 it is concluded that borehole 4 is not functional due to technical reasons and can't be used for the system. For that purpose, borehole 3 is chosen as a source of the system.

The following overview is made as the tentative setup:



The locations of all water points are chosen based on the safety and accessibility of the location. Particularly children, elderly & vulnerable should be able to access the water points without any risk of traffic accidents.

This manual only focuses on the technical design of the system. Yet, the next step after making a tentative design is to calculate the investment and operational cost of the system. Combined with the water sales an estimation can be made on the financial sustainability.

Social sensitization and discussions will need to follow to assess the social acceptance of the plan. Particular the introduction of paid water services, water price negotiations and the use of a public well for these paid water services can the sensitive processes.

6 DESIGN STEP 2: COLLECTING DATA FOR THE TECHNICAL DESIGN – THE THEORY

Once we have selected the site we now need to start making a design. This starts with collecting all the data you need to make the final design. Some of the data needs to be gathered from the field. Some can be done from behind the computer and with estimations.

This chapter gives an overview of all data that needs to be gathered.

6.1 OVERVIEW OF DATA TO BE COLLECTED

There is a range of data needed to design a piped water system. To make a design (next chapter) one will need to know:

- **How much** water is consumed per day;
- **How high and how far water** needs to be pumped from the well to the user**;**
- **The well characteristics.** Is the well able to provide the needed amount of water, how much does the water drop in the well while pumping and is this water safe to drink.

The last two points are needed to determine the '**total hydraulic head'**. In other words, we need to answer the question how high the pump needs to pump the water. The word hydraulic refers to the fact we try to pump a liquid[3]. And head is another word in which the amount of vertical meters the pump needs to pump is expressed.

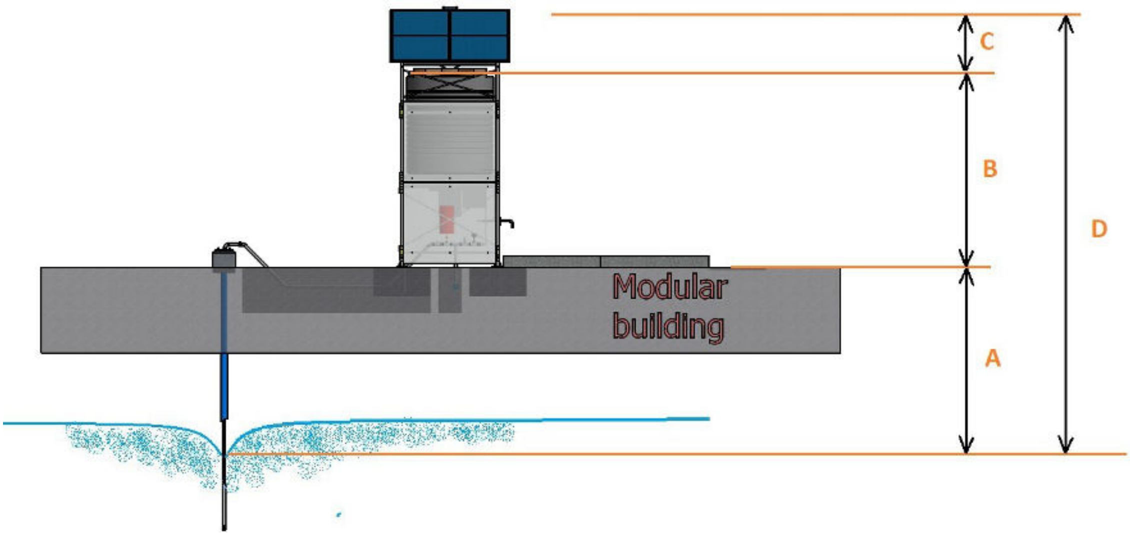
The total hydraulic head is the sum of 3 factors:

1. During pumping the water level in the well drops. It stabilizes at a certain point when the amount of water being pumped is equal to the amount of water that the aquifer provides. The depth of this water – relative to the ground surface - is called the '**dynamic water level**'. This dynamic level should be determined at the peakflow, expressed in meters. This information can be found in the pump test.It is shown with the letter 'A' in the picture below.
2. Secondly, the pump needs to pump the water in the tank. It is shown with the letter 'B' in the picture below. Be aware – the picture shows a nice flat ground on which the water tower of service level 1 is placed on. But there might also be a height difference between 2 tanks if a second service level

[3] To be exact: The word "hydraulics" originates from the Greek word ὑδραυλικός (hydraulikos) whichin turn originates from ὕδωρ (hydor, Greek for water) and αὐλός (aulos, meaning pipe). Source Wikipedia 2018.

is used. Or there might be a high peak in the terrain. This needs to be taken into account too!

3. Thirdly, we need to determine the amount of **friction** of the water in the pipes/hoses expressed in meters '**head loss'**. The friction losses will be explained later in this chapter. On also needs to take into account **'residual pressure'**: this is the pressure one needs at the delivery point. In the picture this shown with the letter 'C'.



The total hydraulic head is depicted as D in the picture. It is the sum of A, B and C.

Each of these topics will be discussed separately in the following paragraphs. First the daily water need is determined after which the total dynamic head is explained.

6.2 EXPECTED WATER CONSUMPTION

In the past chapter it has been mentioned that only the current (=now!) waterneed is provided by the modular piped system. Additional water towers can beplaced if the water need grows overtime. Determining the total water need **perwater point** is therefore quite straight forward – design horizons are no longerneeded. The following formula has been used to determine the total daily waterneed:

$$Total\ water\ need\ per\ day\ (liters) = Number\ of\ users\ x\ maximum\ water\ consumption\ (liters\ per\ person\ per\ day)$$

So to know the total daily water need, we need to know the number of users and their daily water consumption.

6.2.1 Number of users

The number of users depend on where the water point is placed. One can expect more customers if there is a water scarcity or if the tower is placed in a very densely populated area. Also, if there are institutions located close by one can expect more customers.

A first start is therefore to have a look at the village where the system will be placed. How many inhabitants are there in the village? How many alternative safe water sources are around? What percentage of the population do we expect to use the system? Arial maps (like from Google maps) generally work well for this purpose.

Is also helps to place the expected uptake in the perspective of:

- A hand pump: a hand pump can serve about 300 people. Do we expect more customers for the tower than we would expect for a hand pump?
- Walking distance: some literature suggest that people are willing to spend a maximum of 30 minutes roundtrip for water collections. So about 10-15 minutes walking distance from their dwelling to the water point. This would suggest that a tower would attract people that are within a (+/-) 1 km radius of the tower. Some sources even suggest this is limited to 300 meter. In the end, the willingness to walk to a safe water source will be highly influenced by the scarcity of alternative sources. So a service radius in mind combined with information regarding alternative safe water sources, one can visit the site and make an estimation of the number of people living in the service distance of the water point.

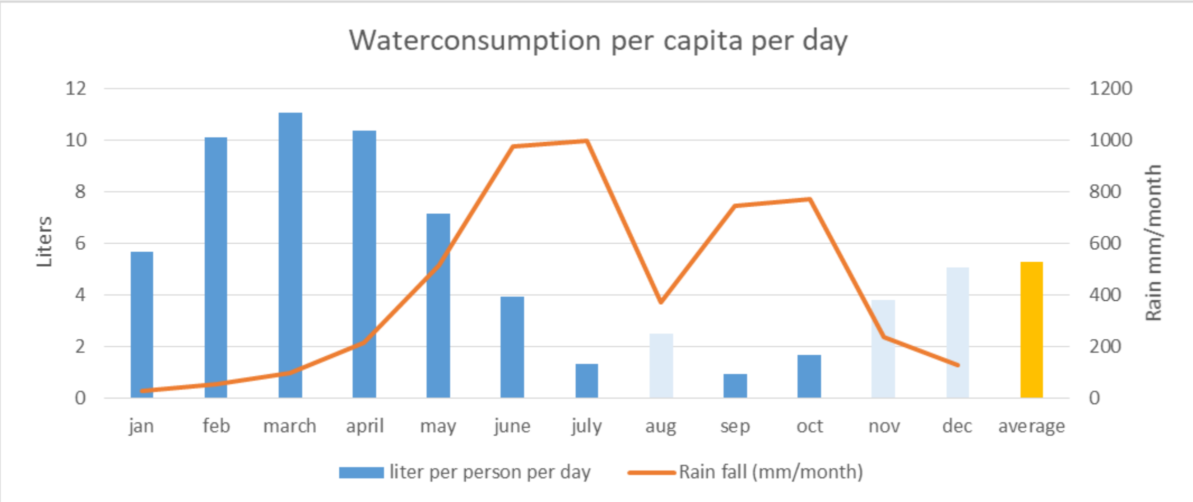
Experience learns that the amount of customers is highly over estimated. A slight over estimation will not have a major effect. Yet, in some field cases there was an overestimation of 5-6 times. This will have a negative impact on the business case.

6.2.2 Water consumption

Most designers use a number of 20 liters per person water consumption per day when designing a public piped system in rural settings. This is a generalization: water consumption heavily changes depending on the country and/or area in a country. The use of those 20 liters can be divided in water consumption (drinking and cooking), hygiene (personal and domestic washing) and amenity use (water plants, washing motorbikes, etc.).

An average of 7.5 liters is used for drinking water and food preparation. This an important figure because in this concept people will need to pay for their water. In practice one will see that people are willing to pay for safe drinking water. It keeps you healthy. But if the health is not at risk, for example when cleaning your bike, people easily find alternative water sources such as rivers or rainwater.

This figure of 7.5 liters in an average. The water need changes during the year. When it is the dry season the demand is higher than in the wet season. The following graph[4], based on field data of Liberia, shows this effect:



In the graph you can see that – in this case, the average consumption is even lower: 5 liters per person per day. In the wet season people consume about 2-4 liters per person per day. But when it is the peak of the dry season, this figure will double to about 10 liters per person. One can conclude that if the system is able to supply 10 liters per person per day, it will be able to provide enough drinking water throughout the year!

It should be noted that these consumption figures will depend on the location of the tower. It is known that due to cultural behaviour water consumption can be much higher than these presented figures. For that matter it is always good to double check the figures and assure the correctness.

[4] This is data tracked by means of prepaid technology from a small modular system in Monrovia in the year 2019. The light blue columns are added based on consumption data of 2020. The 2019 datawas lacking due to a downtime as a result of a breakdown of the prepayment technology.

There are also guidelines for other type of consumers, like school children, yard connections, hospitals, hotels, shops etc. Generally, there are guidelines per country present that give an indication. The following table shows the guidelines of Uganda[5] for a rural setting:

Type of consumer	Daily water need (liters per day per consumer)
Public kiosk	20
Yard tap (multiple households)	40
Yard tap (single households)	50
Day school	10
Simple health center	20 (liters per bed)
Administrative office	10

It should be noted that, in these guidelines, the guideline provides double the consumption figure of what is generally measured in the field. In the end it is up to the designer to gain more experience with the numbers, backed up with field data, to get a better understanding of the actual consumption patterns in their country/region. Using data from existing schemes can be of help. Field observations (ideally during the dry season over multiple days) at existing water points, including hand pumps, can also help to get a grip on the water demand.

Indicators can differ considerably among actors, situations and countries. For example, UNHCR standards state that pupils need 3 liters per student per day. And emergency settings generally state lower volumes than in post emergency settings. For example, the Sphere Standard (2018) recommends to assume the total water need to be between 7.5 & 15 liters per person per day.

Now we know the number of people we are expecting to use the water point and how much they consume. So we can determine the total water daily need. So for example, if we expect 350 users with a maximum water consumption of 10 liters per person per day, one can expect the following daily water peak consumption:

350 people x 10 liter per person per day= 3.500 liters/day.

This exercise will need to be done for each water point. The cumulative number of all these water points gives an indication of the expected daily water demand. The total figure can be adjusted to deal with demand peaks and water losses in the system.

5 https://www.mwe.go.ug/sites/default/files/library/Water%20Supply%20Design%20Manual%20v.v 1.1.pdf

6.3 WELL CHARACTERISTICS

The piped system will use a water pump out of a tube well. Open wells or surface water should not be used. These sources have a high risk of pollution. During the dry season they can dry up and often they contain particles in the water (sand/silt) that will damage the pump.

An important first step when building a piped system is to determine if the borehole is suitable. This is determined by the following two factors:

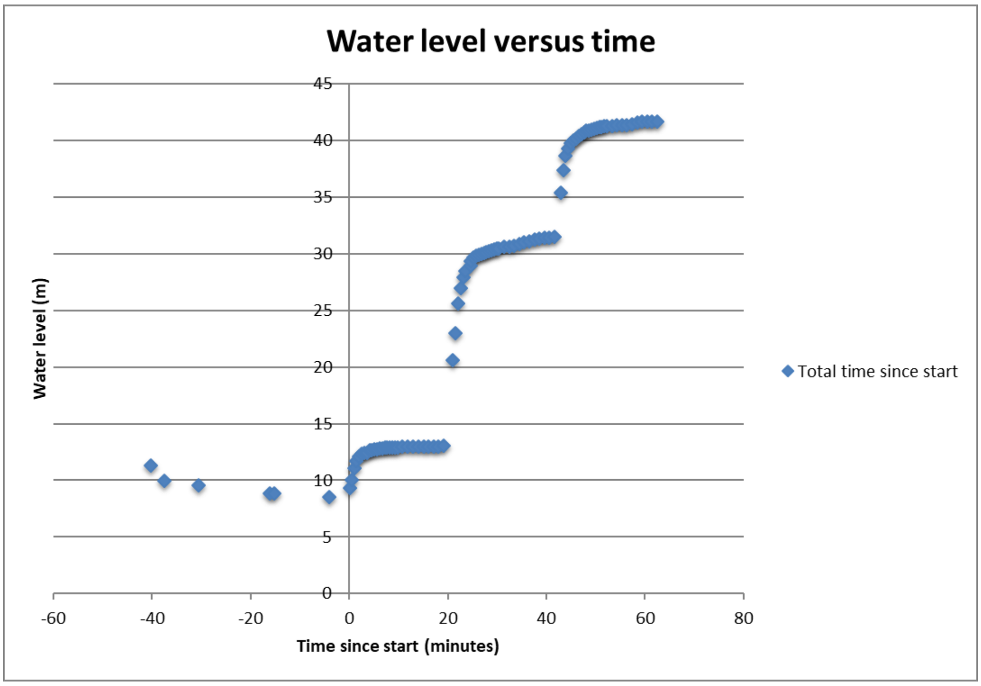
1. The quality of the water: Water quality tests are used to determine the existence of pollution in the water. Government institutions or enterprises are often available to do these tests. The water needs to be free of contaminants (or within acceptable range) – water treatment can be difficult and will cause an increase of the water price. Be aware that adding chlorination units in the water tower can cause significant damage to electrical equipment.
2. The quantity of water: the well will need to provide enough water throughout the year to serve the customers. The amount of water that is needed will depend on the size of the system (number of water towers and household connections). The yield the well can provide without running dry is called the maximum safe yield.
3. Dynamic level of the water: how deep is the water in the well when the pump pumps water at different pumping rates?

To determine the dynamic level and the maximum safe yield a **step drawdown test** will need to be done. A step drawdown test should always be done to measure the production capacity and maximum drawdown of the borehole, before a system is installed. If this pump test is not done and the borehole proves not able to provide the needed amount of water, the pump will run dry and overheat at peak pumping hours.

With this test, one pumps water from the well at different flow rates. You start with a low flow rate, and measure the drawdown in the borehole. When the level stabilizes you raise the flow rate, and measure again.

One continues raising the flow rate every half hour (or time interval until the level stabilizes), until the maximum production capacity of the well is met. Or until the production is considerably more than the needed production for the piped system. The test ends by measuring the water level while it rises (recovers) once the pump is turned off.

This step drawdown test provides a graph that looks like this. In this test a well is pumped at 3 different pump rates. The graph will be different for each well.



The graph will provide the following data:

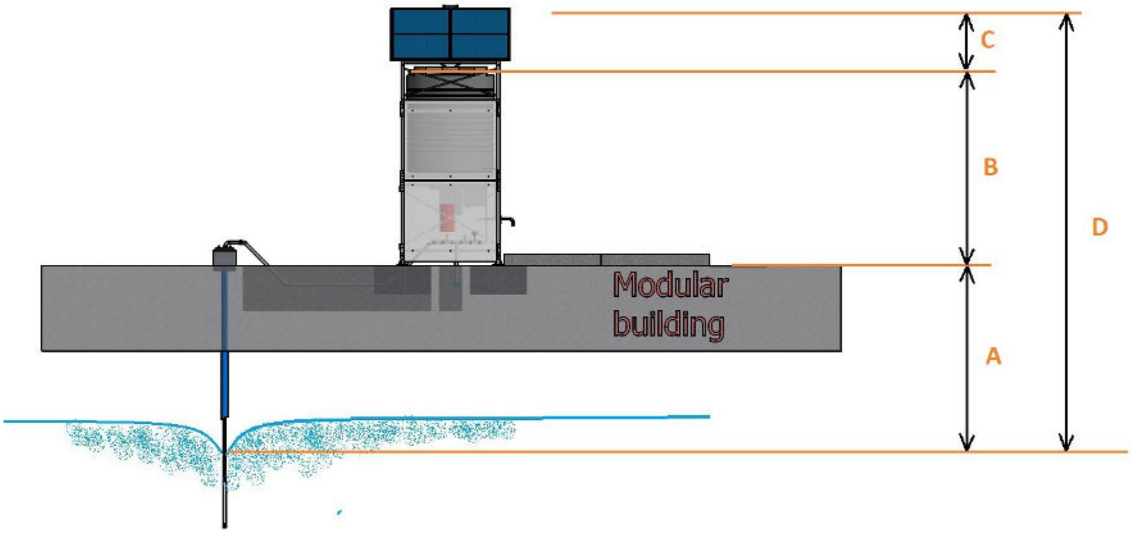
- The '**maximum safe yield'**: So this provides you with the information how much can you extract from the well without running it dry.
- The '**expected draw down'** at a certain pump rate: So this tells you how much the water drops when you extract a certain amount of water from the well. Or, in other words, how high the pump needs to pump the water to reach the surface. This is called ***the dynamic water level***.

To increase the reliability of the data often a '**constant discharge test is performed'**. In a constant discharge test the well is pumped at a specific rate for a prolonged period (up to 2-3 days). This test is aimed to see if the well can provide the design yield over longer periods of time.

Testing of the well is a specialist job. One can hire consultants for this. It is also possible to do this yourself but one will need at least a high yielding pump and a dipper (device to measure the water level). More information on the pump tests can be found at: https://www.practica.org/publications/well-drilling-basic-understanding/.

6.4 TERRAIN CHARACTERISTICS AND GENERAL LAYOUT OF SYSTEM

With the pump test (as described in the previous chapter) we determined the dynamic water level. So in other words, how high the pump needs to pump the water to the surface. Remember this picture?

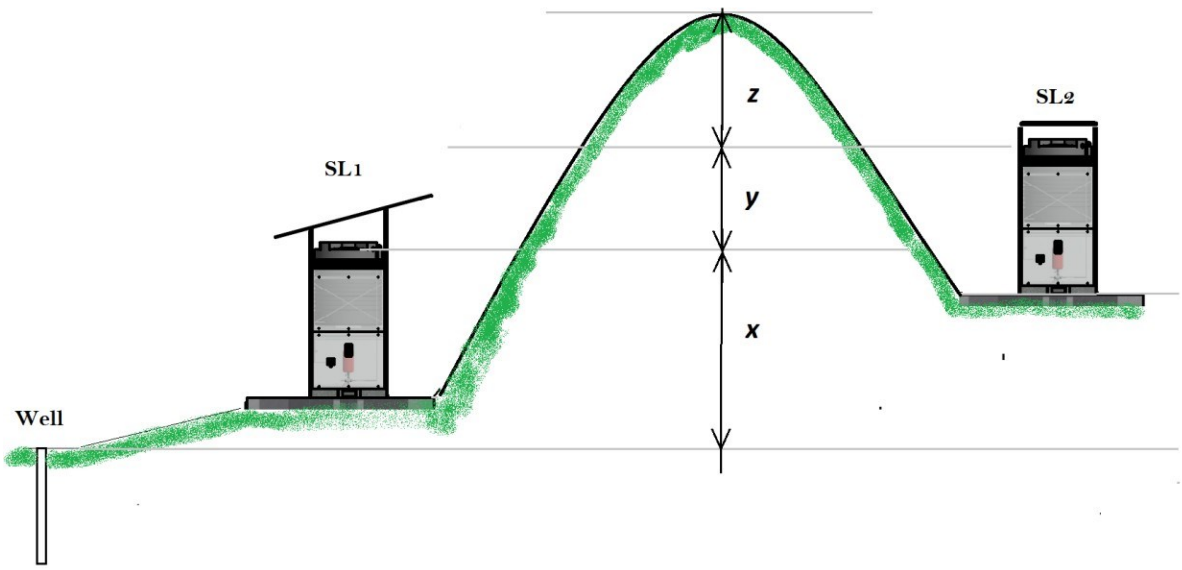


The dynamic head refers to the distance labelled with 'A'. We now need to determine B and C.

6.4.1 B: The height of the highest water point in the system

To size the pump one needs to know the highest point in the water system. This can either be:

- (x) – In case of one tower only and no peak higher than the inlet of the tank;
- (X+Y) – In case there are multiple water points where there are no peaks higher in the landscape than the inlet of the highest tower or;
- (X+Y+Z) - When the peak in the landscape is the highest point of the water system.



For this one needs to map the layout of the system and determine the heights of the pipes and water points. In the end one has to height of the highest point in the system relative to the well. Google Earth pro has a function that allows to determine the height of system on a distance.

6.4.2 C: the head loss and residual pressure

The head loss of a system represents the **friction losses** of the water in the pipes/hoses expressed in meters. These are energy losses in the pipeline, due to the friction of the water when it moves through the pipe. One meter head loss means that the pump has to provide a pressure of one meter extra to pump the water through the pipes to overcome the friction.

There will always be friction and therefore head losses, but it is important to limit them. High friction losses result in the need for bigger pumps and more solar panels, and therefore higher investments.

A complex equation used to calculate the friction loss in a pipe line is the formula of Hazen-Williams, which is the following:

$$\Delta H_L = (10{,}69 * Q^{1{,}85} * L)/(c^{1{,}85} * D^{4{,}87})$$

In which:

ΔHL = the head loss in meter due to friction
Q = the water flow in m^3/s
L = the length of the pipe line in m.
c= the Williams-Hazen coefficient for the roughness of the pipe(around 140 for PVC and PE pipes depending on type/age). Is has no unit.
D = diameter of the pipe line in m.

If one analyses the equation in more detail one can see:

- If you double the length of a pipe, the head loss doubles.
- If you pump more water through a pipe, the head loss will increase. It increases non-linear. Meaning, if you double the flow through a pipe, the head loss increases more than double.
- The rougher the surface of a pipe, the higher the head loss. This is influenced by the material of the pipe but also the age. For example, a brand new GI pipe will have a smoother surface than an old rusted pipe. The head loss of a new GI pipe will therefore be less than an old GI pipe[6].
- The diameter of a pipe. This is the most important factor in the formula. Doubling the diameter of the pipe line results in a reduction factor of the friction by $2^{4.87} = 29.2$! Therefore the best way of reducing the head lossin a pipe is increasing the diameter.

The explanation above gives a first insight in the theory.

For this phase it is important to determine the lengths of the pipes only. The diameter of the pipes is a design decision in the next step. Again, drawing the design of the pipes in Google Earth Pro allows one to determine the lengths of the pipes. In the next paragraph one can find an example how this can be done.

[6] Lists of the roughness coefficients can be found here: https://en.wikipedia.org/wiki/Hazen%E2%80%93Williams_equation and here https://www.engineeringtoolbox.com/hazen-williams-coefficients-d_798.html

It is also good to realize that elbows, valves, T-pieces etc. will increase the friction of the piping. This can be calculated per piece of hardware. Or, as an alternative, use a faction of the total head loss of the pipe to cover the head loss of the elbows, valves, etc. The following table shows an overview of head losses per item. Note the numbers are the equivalent length of straight pipe added to the total length of the distribution network. They are *not* the head losses expressed in meters.

		Equivalent length of straight pipe in meters							
Pipe size (inch)		¼	⅜	½	¾	1	1 ¼	1 ½	2
Elbow 90° degree		0.7	0.9	1.1	1.3	1.6	2	2.3	2.6
Elbow 45° degree		0.1	0.2	0.2	0.3	0.4	0.5	0.6	0.8
T piece (straight flow)		0.2	0.4	0.5	0.7	1	1.4	1.7	2.3
T piece (branched flow)		0.7	1.1	1.3	1.6	2	2.7	3	3.7
One way valve (swing type)		2.2	2.2	2.4	2.7	3.4	4	4.6	5.8

One can see if one adds 10% to a total length of distribution pipe of 1000 meter of 1 inch (to account for head losses in fitting work) one will account for (100/1.6=) nearly 60 elbows.

For the residual pressure one can take a fixed number: 1 bar is generally more than enough. This translates to 10 meter of hydraulic head.

7 DESIGN STEP 2: COLLECTING DATA FOR THE TECHNICAL DESIGN – AN EXAMPLE

As a start the expected consumption level is estimated for the selected site. The site exists of 3 public points and a school. Future expansion with 5 yard connections is taken into account for the sizing of the system.

For the consumption of the public water sources B and C it is assumed that:

- The 150 households, as mentioned in the site assessment, consist of 5 people per household. Resulting in 750 people.
- Of those 750 people, 80% will use the system. So about 600 people.
- 300 people will use water point B and 300 will use point C.

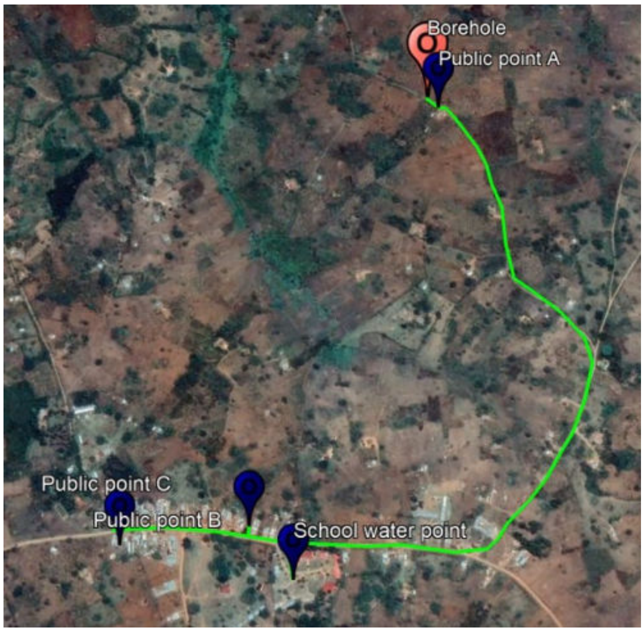
For the consumption point A less consumers are expected as the location is quite remote and has a limited population density.

The following table provides an overview of the consumption expectation. Note that one is looking for the maximum daily water consumption and not the average!

Water point	**Number of users** **Per water point per day**	**Maximum consumption** **Liter per user per day**	**Total maximum daily water consumption (liter)**
A	100	10	1.000
B	300	10	3.000
C	300	10	3.000
School	200	2.5	500
Yard connection	20 people per yard connection x 5 yard connections = 100 people	35	3.500
Total expected maximum daily water consumption			11.000
Expected water losses & safety margin			25%
Design (round off)			14.000

The next step is to determine the pipe lengths and the highest point of delivery. This data is later needed to determine the head loss of the piping.

The main distribution line (green line) is plotted with Google Earth Pro. This allows to determine both factors remotely from the site. There are also telephone apps available to measure the height and lengths in the field itself.



The following plot shows both the length as well as the elevation of the distribution line. The green arrows show the locations of the intended water points.

The data shows that the horizontal distances – so in bird's view – between the tube well and water point C is 1670 meters. Yet with the slopes in the landscape the pipe needs be longer. A total length of 1682[7] meter pipe is needed to transport the water from the well to point C.

[7] This data can be extracted from Google Earth Pro by pressing the right button on the mouse on the path in the 'places' menu. The elevation profile shows the elevation and the horizontal distance of the path. Under properties one can find the actual length of the path.

To determine the highest point of delivery (relative to the tube well) we assume that the water points are water towers with a height of 4 meters (height of water inlet). Based on this information the highest point in the system can be calculated:

Point	**Elevation in meters (incl. heightinlet of water tower)**	**Elevation of tube well In meters**	**Total height difference relative to tube well**
A	1239 + 4 = 1243	1237	6
B	1245 + 4 = 1249	1237	12
C	1247+4 = 1251	1237	**14**
School	1243+4 = 1247	1237	10
Highest point in landscape	1251	1237	**14**

The last step in the data collection is determining the well characteristics. The water quality test and the step drawdown tests are outsourced and provide the following data:

CONSULTANTS COMPANY LIMITED.

Tel
Dealers in: *Hyddrogeological investigation,borehole drilling,electric and solar pump installations,maintenance and capacity training etc*

BOREHOLE TEST PUMPING REPORT

BOREHOLE NAME ;
LOCATION ;
DATE CONDUCTED ; 18/10/ 2018
TIME OF COMENCEMENT ; 0800HRS
BOREHOLE DEPTH ; 75M
STATIC WATER LEVEL ; 12.00M
PUMP INTAKE ; 66M BGL,
PUMP TYPE ; SP3A-17
DISCHARGE ; 3.0M3/HR
DRAWDOWN ; 27.60M
DURATION ; 12HRS.

Starting time	Elapsed time (minutes)	Water level(m)	Drawdown (m)	Discharge (m3/hr)	Observation/ Comment
0800 hrs	0	12.00		4.0	turbid
	1	12.10			
	2	12.80			
	3	13.20			
	4	13.58			
	5	13.90			
	6	14.41		4.0	
	7	14.80			
	8	15.52			
	9	15.90			
	10	16.43			
	12	16.88			
	14	17.76		4.0	
	16	18.01			
	18	18.70			
	20	21.90			
	25	25.21			
0830hrs	30	27.62			
	35	29.70			
	40	30.50			
	45	32.40			
	50	32.53			
	55	33.07		4.0	turbid
0900hrs	60	33.54			
	75	33.66			
	90	33.98			
	105	33.99			
	120	34.49			
	150	34.80		3.0	
1100hrs	180	35.90			
	210	36.69			
	240	36.88			
	270	36.93			
	300	37.78			
	360	37.99			
	420	38.20		3.0	clear
	480	38.42			
	540	39.60			
	600	39.60			
	660	39.60			
2000hrs	720	39.60			

RESIDUAL DRAW DOWN/RECOVERY DATA SHEET

Starting time	Time elapsed	Water level	Residual drawdown
1719hrs	0	39.60	
	02	34.00	
	05	32.20	
	07	30.60	
	09	29.99	
	15	27.70	
	20	26.00	
	30	25.20	
	45	24.60	
	60	23.00	
	90	22.00	

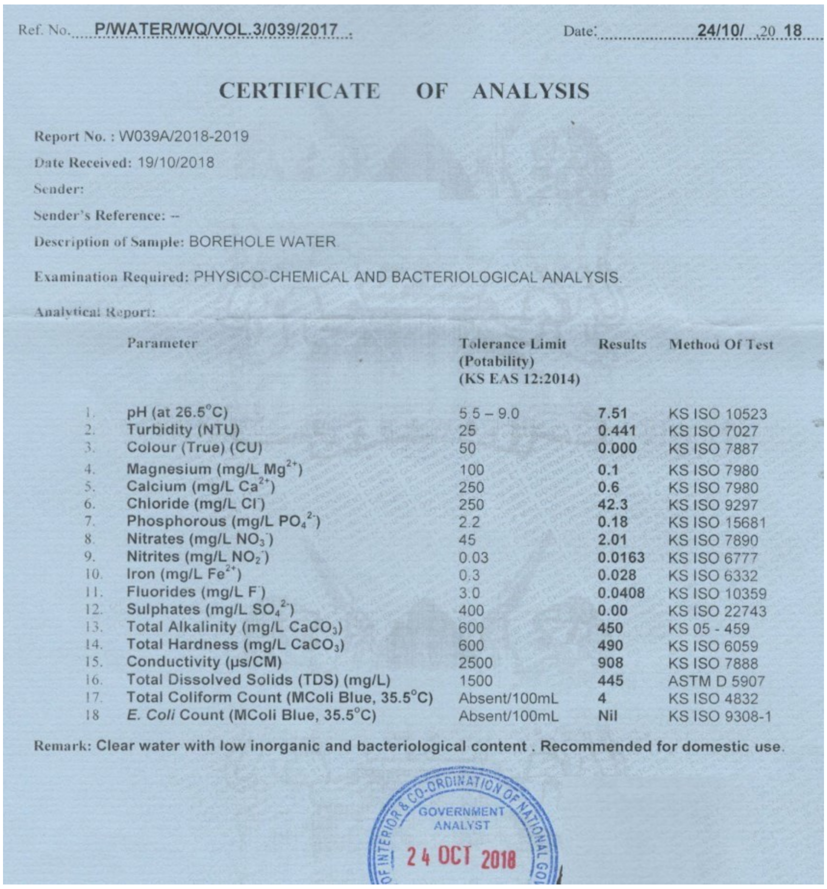
This test shows that, when the pump is pumped at a rate of 3 m^3/hour, the water level stabilizes around 39.6 meter depth. A higher pump rate shows the well is over pumped – meaning the water level continues to drop as more water from the well is extracted than the aquifer can deliver. Although this data does not provide any insight in lower pumping rates, it gives us a good first indication on the well behaviour.

It is advised to ensure that the maximum pump yield doesn't come too close to the maximum well yield. A safety margin of about 20% should be applied. In this case a maximum well yield of 3 m³ is determined. This means that the maximum pump yield should be below (3*0.8=) 2.4 m³/hr.

The water quality analysis shows that the water is recommended for domestic use.

It is worth noting that this is the water quality of the water extracted from the well. Water quality – however – at point of use is affected by the users. Due to handling (e.g. dirty containers) the water quality can deteriorate and fall below standards.

Chlorination – that is a disinfectant – is a way to improve water quality at point of use.



Ref. No. P/WATER/WQ/VOL.3/039/2017 Date: 24/10/ 20 18

CERTIFICATE OF ANALYSIS

Report No. : W039A/2018-2019
Date Received: 19/10/2018
Sender:
Sender's Reference: --
Description of Sample: BOREHOLE WATER
Examination Required: PHYSICO-CHEMICAL AND BACTERIOLOGICAL ANALYSIS.
Analytical Report:

	Parameter	Tolerance Limit (Potability) (KS EAS 12:2014)	Results	Method Of Test
1.	pH (at 26.5°C)	5.5 – 9.0	7.51	KS ISO 10523
2.	Turbidity (NTU)	25	0.441	KS ISO 7027
3.	Colour (True) (CU)	50	0.000	KS ISO 7887
4.	Magnesium (mg/L Mg^{2+})	100	0.1	KS ISO 7980
5.	Calcium (mg/L Ca^{2+})	250	0.6	KS ISO 7980
6.	Chloride (mg/L Cl^-)	250	42.3	KS ISO 9297
7.	Phosphorous (mg/L PO_4^{2-})	2.2	0.18	KS ISO 15681
8.	Nitrates (mg/L NO_3^-)	45	2.01	KS ISO 7890
9.	Nitrites (mg/L NO_2^-)	0.03	0.0163	KS ISO 6777
10.	Iron (mg/L Fe^{2+})	0.3	0.028	KS ISO 6332
11.	Fluorides (mg/L F^-)	3.0	0.0408	KS ISO 10359
12.	Sulphates (mg/L SO_4^{2-})	400	0.00	KS ISO 22743
13.	Total Alkalinity (mg/L $CaCO_3$)	600	450	KS 05 - 459
14.	Total Hardness (mg/L $CaCO_3$)	600	490	KS ISO 6059
15.	Conductivity (µs/CM)	2500	908	KS ISO 7888
16.	Total Dissolved Solids (TDS) (mg/L)	1500	445	ASTM D 5907
17.	Total Coliform Count (MColi Blue, 35.5°C)	Absent/100mL	4	KS ISO 4832
18	*E. Coli* Count (MColi Blue, 35.5°C)	Absent/100mL	Nil	KS ISO 9308-1

Remark: Clear water with low inorganic and bacteriological content . Recommended for domestic use.

CO-ORDINATION OF NATIONAL GO
GOVERNMENT ANALYST
24 OCT 2018

Photo: construction of central tower in Rwenyawa, Uganda

8 DESIGN STEP 3: SIZING OF THE SYSTEM – THE THEORY

In step 2 we collected all the information that we need to design a system. The amount of water that we need daily, the height the pump needs to pump the water to. And the lengths of the pipes to determine the friction losses.

Step 3 is now the technical design where we specify all the parts and pieces of the system. It is the last step before construction of the system. The chapter starts with understanding solar energy and then goes into detail of the system itself.

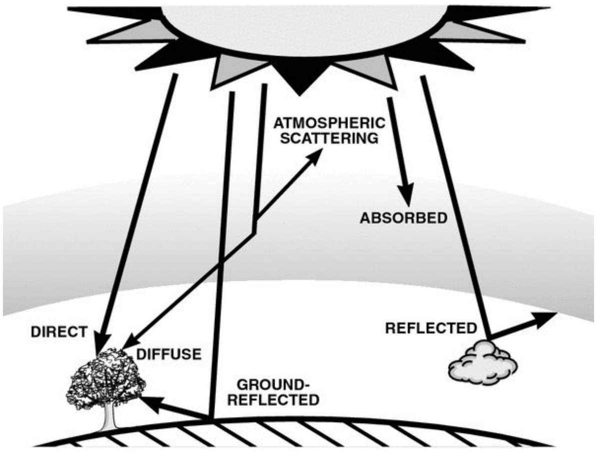
8.1 SOLAR ENERGY

Although it might seem strange, the first thing that needs to be understood is how the sun works. Using the sun as a power source will let the system 'behave' in certain way. You will see that solar energy does not only affect the choice of the (number of) solar panels and the pump, but also the size of the water tank, the selection of the well, the diameter of the distribution lines and even the consumption of the people!

The sun provides the energy needed to sustain life on earth. In one hour, the earth receives enough energy from the sun to meet its energy needs for nearly one year.

Almost all energy used on earth comes from the sun, directly or indirectly. Oil, gas and coals are substances produced by plants that have been growing (powered by the sun!) in earlier times. One great problem with these sources of energy is that they are finite sources of energy which are getting depleted. Oil and gas represent the energy converted by plants during millions of years while we consume it in a few hundred years. Another great problem is that you have to burn them to extract their energy, and this causes the emission of greenhouse gases and the related climatic change.

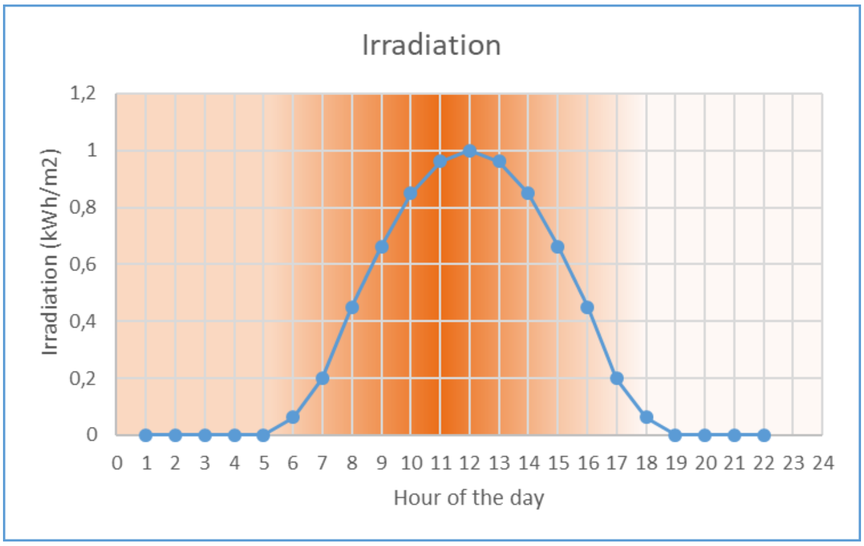
When the sunlight enters the atmosphere of the earth, some is absorbed, some is scattered, and some part is reflected back by clouds. The rest of the sun beams pass through unaffectedly in the atmosphere. The part which is absorbed does not reach the surface, but raises the temperature of particles in the air. The part which is scattered turns into diffuse radiation, and the part which passes unaffectedly is called direct beam radiation.



The force of the sunshine is not constant during the day, even when there are no clouds. In the morning, the sun is low in the sky at the east. It steadily moves up, higher in the sky. At its highest point, called solar noon, the force of the sun beams is also the highest. And after solar noon, the sun travels further westwards[8], gradually lowering its position until night falls.

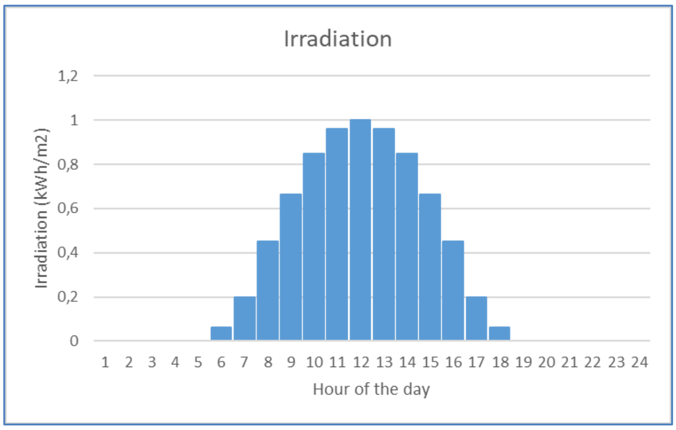
Irradiance is the measure of power density of sunlight at a certain moment. In other words, it is the power of the sunlight measured in Watt per m^2. When entering the atmosphere, the irradiance level is around 1350 W/m^2. After having passed the atmosphere, at sea level, the irradiance is approximately 1000 W/m^2, or 1 kW/m^2 during noon *at the equator*. This is a combination of direct beam and diffuse radiation.

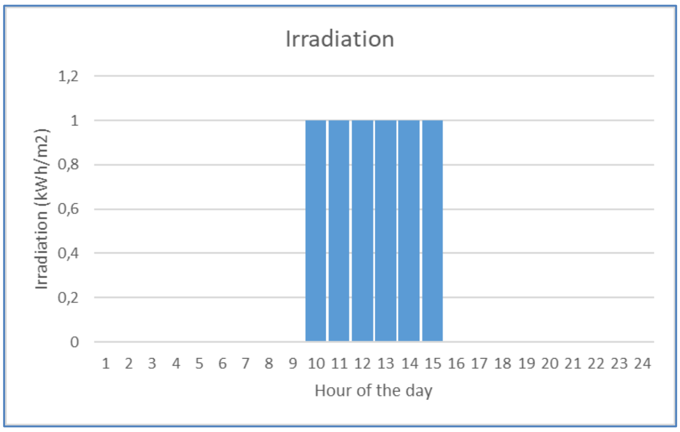
Irradiation (also called insolation) is the total amount of energy received on the earth surface during a certain period on one square meter of horizontal surface. It is usually expressed in kWh/m^2. The following graph shows how the irradiation changes during the day.



[8] *Of course, in reality, it is not the sun that travels, but the earth that turns. We now describe howwe see the sun from a place on the earth.*

An important number to get is the total amount of energy received by the sun in one day. This is equal to the total surface under the blue line. But with a curved line this is quite a job to calculate. To make it easier, we can make the following graphs:

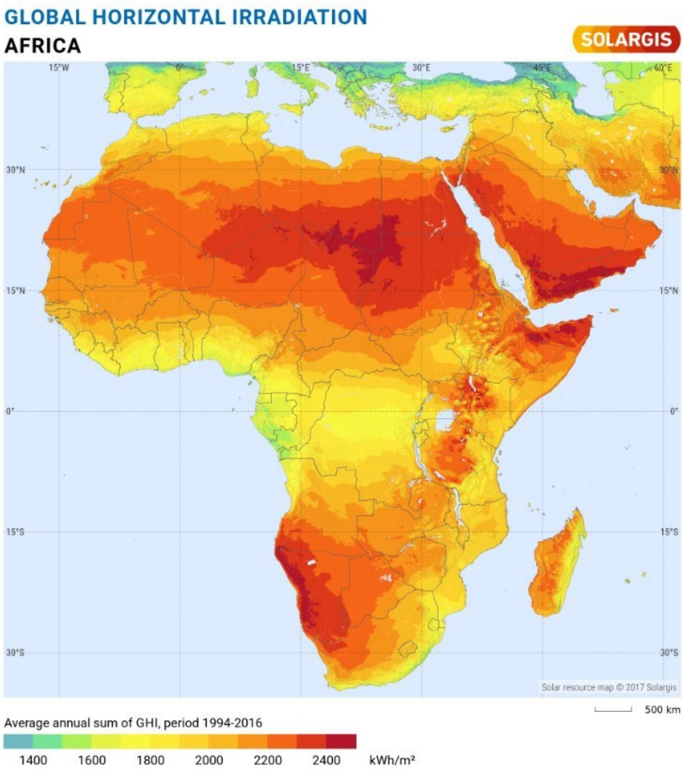




In the left graph we made it easier by making small bars that represent the amount of energy produced in one hour. But still we need to add up all the bars to get the right number. If we now start adding the small bars to the bigger bars until the reach 1 kWh/m2, you will get the right graph. As you can see, we were able to make 6 full bars out of it. We would say this day would have 6 **peak sunshine hours**. So **peak sunshine hours** are the number of hours at an irradiance level of 1 kW/m^2 required to produce the energy received during one day.

The figure of 6 peak sun shine hours is a quite a common standard to be used in calculations. It basically gives a good indication how much energy we can expect per square meter. You will see we will use this number quite a bit in the calculations. This can change depending on the location on the earth, the season and the weather. It can be a bit more and a bit less.

The following map shows the average annual sum of horizontal irradiation[9]. By dividing it by 365 days one gets the average daily irradiation. Or, in other words, the average peak sunshine hours. One can see it differs from location to location[7]: from about 4 to about 7 peak sunshine hours[10]. The website (solargis.com) provides more detailed country specific data.

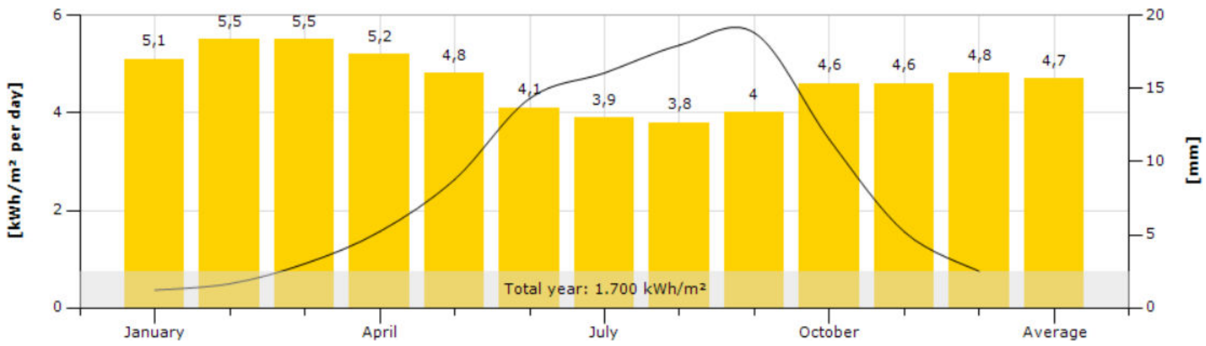


It is important to know the data – as mentioned above – is the average horizontal irradiation. However, the irradiation will change during the day. A second effect that can be observed is the influence of seasons. In sub Saharan African countries this is a cycle of dry- and rainy seasons. In countries more towards the North- and South Pole this cycle consists of autumn-winter-spring and summer cycle. The change of irradiation is much bigger with this cycle. The following graphs[11] show this seasonal effect.

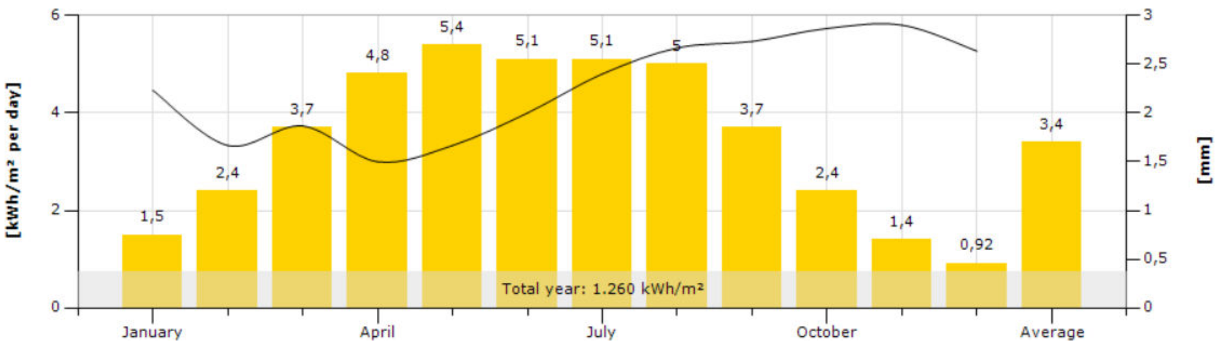
[9] Solar resource map © 2019 The World Bank, Source: Global Solar Atlas 2.0, Solar resource data: Solargis.
[10] 1400/365≈4 and 2500/365≈7 peak sunshine hours

[11] Source graphs: Lorentz Compass 3.1

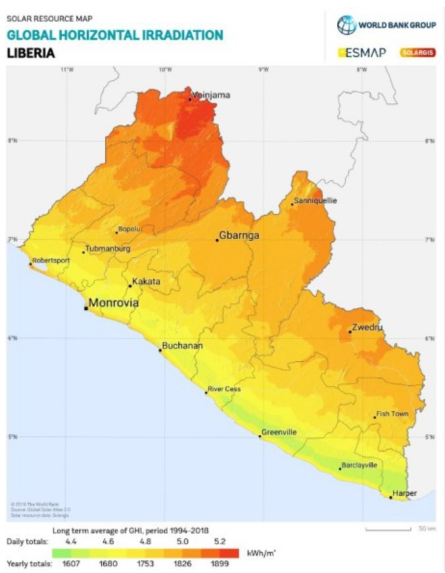
The graph below shows the irradiation (left axis) and the average rainfall in mm (right axis) in Monrovia, being the capital of Liberia.

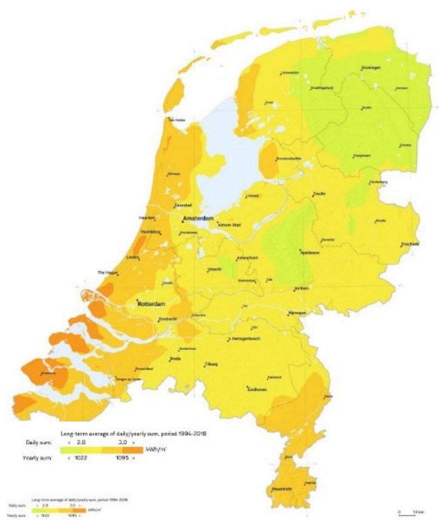


If one observes the following graph that shows the irradiation in the Netherlands, one can see the difference:



Note that the peak sunshine hours are about 4.7 for Monrovia and 3.4 for the Netherlands. This corresponds with the data of the global horizontal irradiation on the following graph[12]:





[12] © 2019 The World Bank, Source: Global Solar Atlas 2.0, Solar resource data: Solargis.

One can conclude that the irradiation depends on:

- **The time of day:** At noon the irradiance is at its highest and after sunset there is no irradiance.
- **The time of the season**: winter and rainy seasons will reduce the irradiance.
- **The location on the earth**: on the equator there is a higher and more consistent irradiance than close to the north/south pole.

And lastly, one will see that there will be fluctuations during the day. If there is a cloud blocking the sun or a sand storm passing by the irradiance will drop. So this is the fourth factor determining the irradiance.

It is important to understand that the design of a piped system – as presented in this manual – is based on averages. This means that – depending on the weather – the output of a system will vary. Sometimes the output is more, sometimes the output is less and in worst cases there will be no water delivery.

This is a rational choice: basing the design of a system on worst case scenario's will heavily increase the cost of the system. The needed over capacity to ensure water delivery in worst case scenarios will only be used in rare occasions.

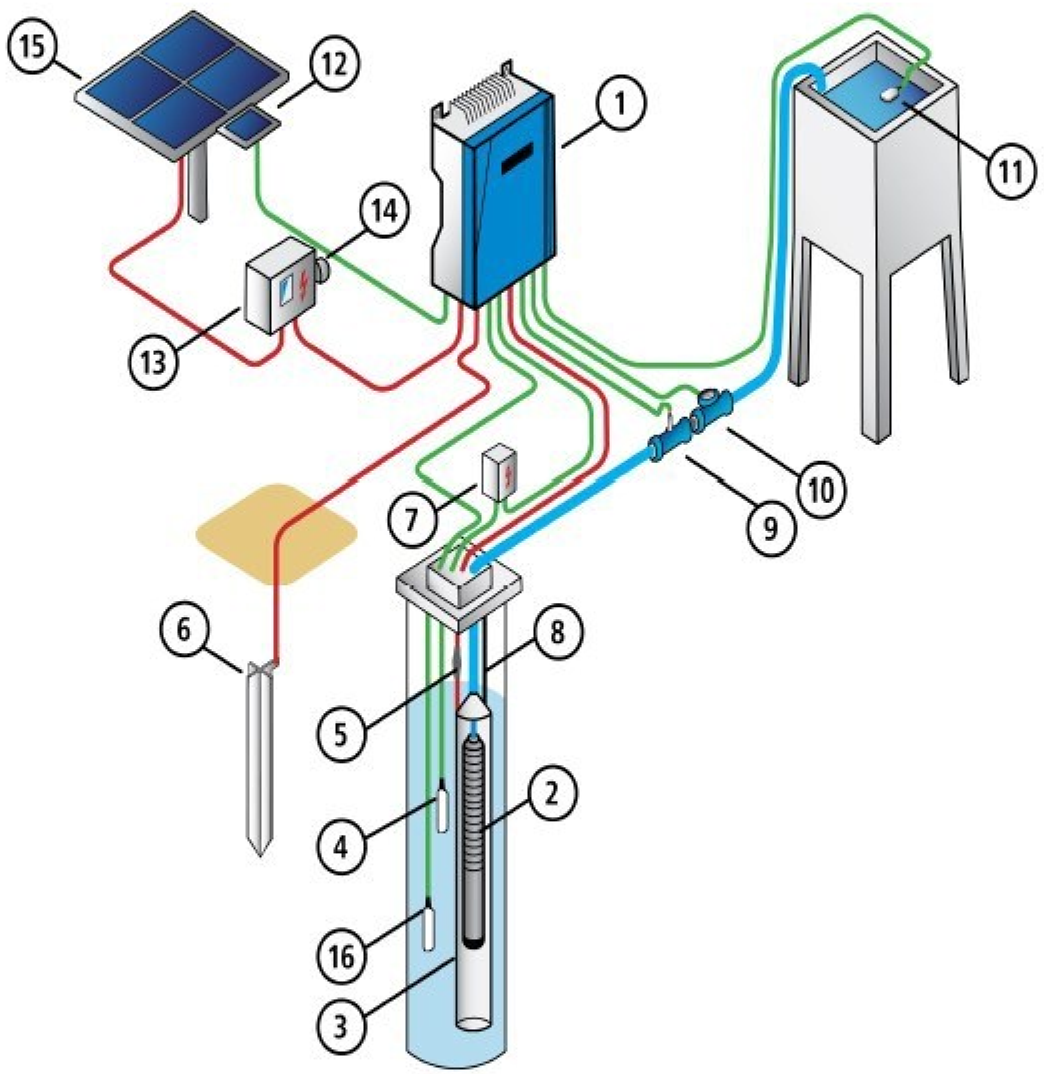
If one wants to ensure 100% water availability one will need to increase the size of the tanks, pumps and solar panels. One can, for example, ensure water storage for 3 days in a tank. And ensure the pump can fill this tank timely.

We now know how the sun behaves. The following paragraphs will go into de details of the different technical components of the modular piped system. And one will see that the behavior of the sun does have its effect on the design of most of the components.

8.2 TECHNICAL OVERVIEW

There are quite a few components in a piped system and the design of each individual component is interlinked. For example, a smaller pipe might result in the need of a bigger pump. Or a larger pump results in the reduction of the need for water storage.

The following picture[13] gives an overview of the different components that can be used in a solar system. It provides a general overview – our modular system will differ in details that will be discussed later. It should also be noted that not all items are critical for the functioning of the system. Some optimize the system and extend the life span of the different items.



[13] Source: Lorentz Compass 3.1

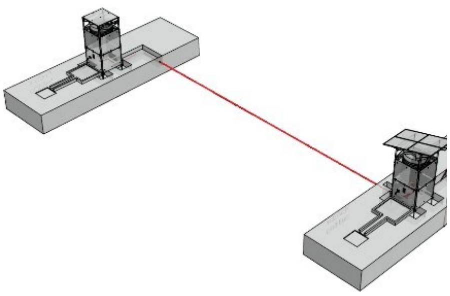
The most important parts are:

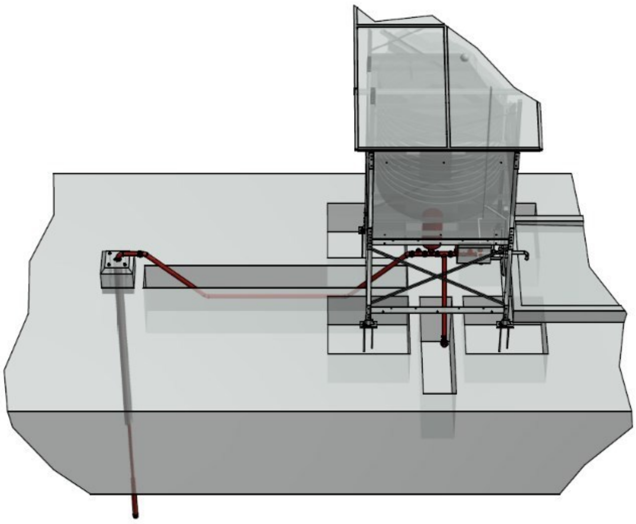
- The pump (2) and the control box (1): The control box regulates the speed of the pump so it runs the most efficient (called MMPT which is short for maximum power point tracker). It is also used to switch the pump on/off using, for example,
    - Pressure sensors (10): if the pressure in the pipe rises the pump can be switched off.
    - Well probe (4): this device switches the pump off when the water tables is too low. It therefore protects the pump against running without water – which damages the pump.
    - Sun switch (12): this device measures the solar power and will switch off the pump when the energy is not enough to bring the water up to the tank.
- The solar panels (15): these power the system by transforming solar energy into electricity.
- PV disconnect (13): this is switch that disconnects the solar panels from the rest of the system. It is used for safety reasons – if you do work on the system you ensure there is no electricity/power on the parts you work on.
- A grounding rod (6) can be used to increase the safety of the system. It provides a route for the lighting when it strikes or when there is a short cut in the electrical system. It is 'of good custom' to install one. However, when the PV system operates under 48V DC, electrical shortcuts can't do any damage to the human.
- Surge protectors (7 and 14) are used to protect the system against voltage spikes, such as lightning.
- The piping is in place to transport the water from the pump to the tank – ideally without any or limited losses of water.

In the following paragraphs the sizing of the different components will be discussed.

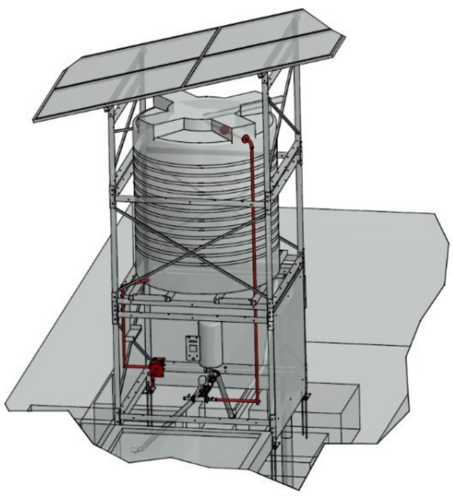
8.3 THE DISTRIBUTION NETWORK

The distribution network has the function to transport the water from the pump to the tanks. It consists of pipes. There are two diameter pipes integrated in the design. A large diameter pipe that transports the water from the pump to the water towers. It has a large diameter because it should be able to supply water to all the water towers and yard connections connected to the network (colored red in the pictures below).





And secondly, there are the pipes that connect the main distribution line with to the individual tanks and yard connections. These pipes are much smaller: they only need to transport the water for one tank only. These pipes are also called **'transmission lines'**.



Designing a distribution system is complex. The following factors should be taken into account:

1. The material of the pipe;
2. The pressure rating;
3. Diameter of the pipe;
4. The effect of using solar energy.

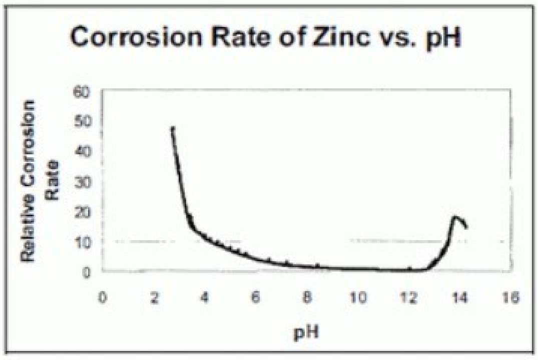
We will discuss each point in more detail in the paragraphs below to provide a fundamental understanding. A more general guideline can be found in the technical specifications that can be found in the attachment.

8.3.1 Pipe material

Most water pipes are made of Galvanized Iron (GI), or Polyethylene (PE) or Polyvinyl Chloride (PVC).

To design a piped system one has to select a suitable material of the piping. Generally, the selection of the pipes will depend on availability (also available quality), affordability and intended lifetime of material. A combination is also possible, for example using GI piping above ground where the public can reach the piping and using PE pipes on all other places.

GI pipes, valves and fittings are strong, have a long lifetime, and are the most expensive choice. It is therefore recommended to use **GI for all pipe works above the ground**. It is more expensive, but very strong and robust. When working with GI pipes, you will also need to have the tools for it: Pipe cutters and pipe threading sets. Ensure that the pH (scale for how acidic or basic the water is) of the water is between 5 and 12. Higher and lower value will result in an increased rate of corrosion of the pipes.



(Source: galvanizeit.org)

Most often**, PE material** is black or dark grey. PE pipes can be bought in long rolls, or in pieces of 3 or 6 meters. It is a bit flexible. It is available in many sizes.You can melt the pipes together to join pipe ends and make longer pipes. But you need good, specialized equipment for this. For long pipelines, and if you work oftenwith PE pipes, it can be a financial advantage to invest in a PE pipe joining set. You can also join them by using couplers. For smaller projects and systems withoutlong pipelines, this is probably better.



PVC material is a harder type of plastic. It is less flexible, and more brittle. Meaning that it will break faster when you bend it. Most often they are grey. Pipes can be bought with joining ends, or just straight. By careful heating, the plastic becomes soft and you can make your own ends, or bend the pipes, and then let them cool down. **Do not use drainage pipes or any other of lower quality pipe material**. We need to take into account that we want to avoid leaks, and we need pipes that have a long lifetime.

Glue can be used to join parts. Actually this is not a glue, but a chemical wielding. But it works like a glue.

8.3.2 Pipe thickness and strength

The thicker the pipe material, the stronger it is. A PN rating is given to the pipes to provide an indication which pressure the pipe can withstand. PN stands for ‘pressure numbers’. A PN 10 rating means that the pipe can withstand 10 bar: this is equal to (about) 100 meter of water pressure. The higher the rating, the more expensive the pipe becomes.

In modular building a PN rating of 10 for the PE pipes will be sufficient in most of the cases. Only in case of high elevation, stronger pipes may be required. Also combinations of different pressure ratings can be made. For example, a pump needs to pump water from a well to the surface with dynamic level of 60 meters and then another 50 vertical meters to the tank. And for simplicity we neglect head losses. To do so the pump will need to provide a pressure of 11 bar. The rising main in the well can then be made of PN16, while the pipeline to the tank can be made of PN 10.

GI pipes and parts have a very high PN rating. The exact rating depends on the quality of the steel. But for the modular design the PN rating of the GI pipes are well within acceptable range.

8.3.3 Head loss

In the previous chapter we already explained how one can calculate the head loss of a pipe with the following formula:

$$\Delta H_L = (10{,}69 * Q^{1{,}85} * L)/(c^{1{,}85} * D^{4{,}87})$$

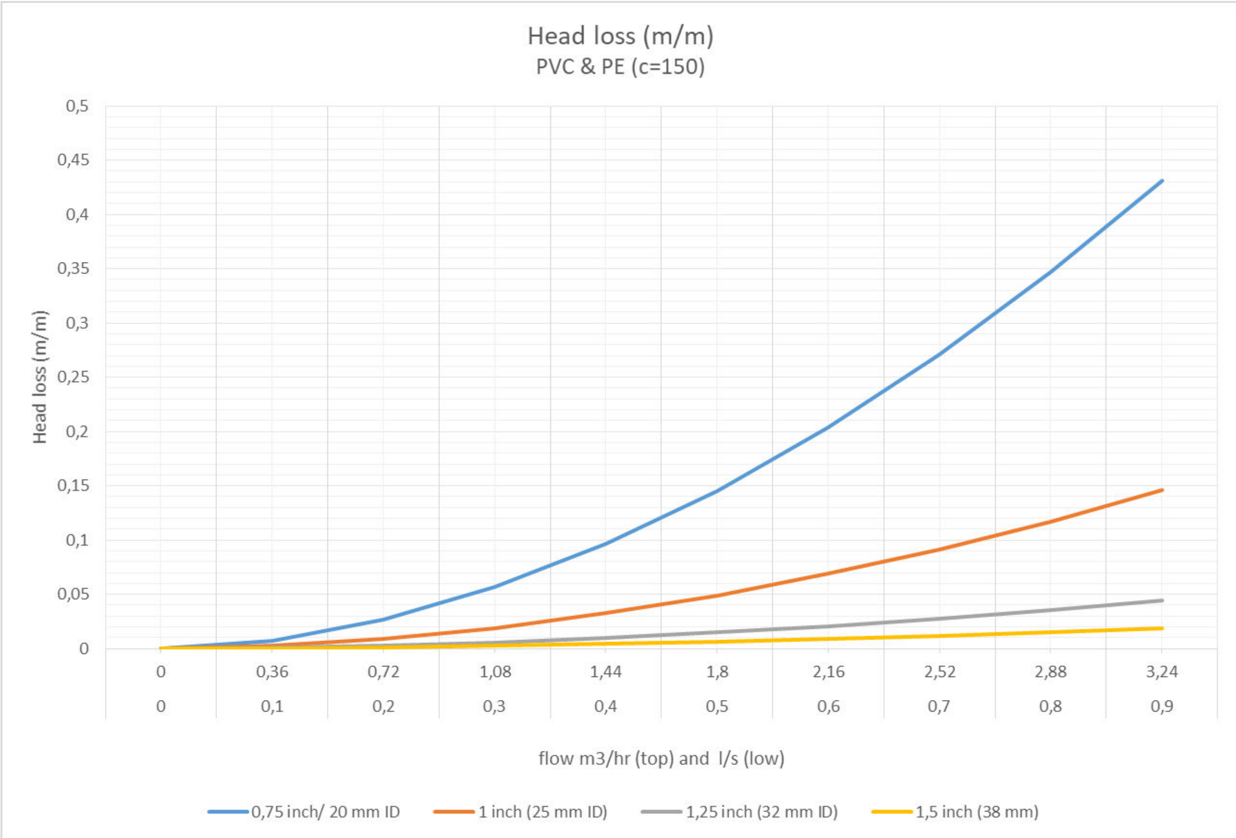
In which:

ΔHL = the head loss in meter due to friction
Q = the water flow in m^3/s
L = the length of the pipe line in m.
c = the Hazen - Williams coefficient for the roughness of the pipe(150 for PVC and PE pipes)
D = diameter of the pipe line in m.

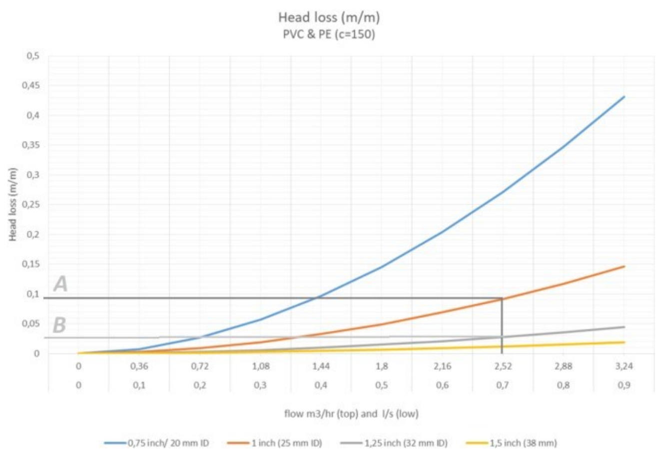
In short the formula states that the head loss of a pipe depends on (1) how much water one runs through the pipe (2) the material of the pipe (3) the length of the pipe and the (4) diameter.

Given the complexity of the formula, software[14] or tables are used in which the hydraulic losses of a certain pipe diameter can be found for a certain water flow. In these tables the head loss is expressed as head loss (expressed in meters) per meter pipe. The table below shows such a table.

[14] Spreadsheets for calculation can be found at https://www.engineeringtoolbox.com/hazen-williams-water-d_797.html



Note: the internal diameters (ID) as shown in the graph will vary according to the PN rating. This graph should be used as an indication only. Also, valves, elbows, restrictions, etc., further increase the friction. This will be neglected in this manual.



Example:

A: if we pump 2.5 m³/hr with a pump through a pipe of 25 mm internal diameter that is 500 meters long we will have a head loss of:

500 meter x 0.095 meter head loss per meter pipe = 47.5 meter.

B: If we would increase the diameter to 32 mm internal the head loss would reduce to:

500 meter x 0.025 meter head loss per meter pipe = 12.5 meter

From this graph it might appear that the bigger the pipe the better. When it comes to head losses this might be true. Large pipe diameters and slow flow speed have one disadvantage: there is a risk of **accumulation of sediment in the pipe**, at low spots in the pipeline. The pump can always bring up some sediment. With high flow speeds, this is washed away.

To determine a suitable (internal) diameter of the pipe one has to apply the following rule of thumbs:

1) **Maximum speed of water**: As a rule of thumb, to limit the head loss the maximum velocity of the water should be less than:
   - 3.0 m/s for the small pipes in the tower itself (the transmission lines)
   - 1.5 m/s for the thick pipes between the towers (the distribution lines)
2) **Minimum speed of water**: to avoid the accumulation of sediments the minimal speed of water should be higher than 0.4 m/s in all pipes.
3) **Allowable head losses**: try to limit the head losses to about 10 m/1.000m. This becomes more important when distribution lines are very long. With shorter lines higher losses are acceptable.

One can use the following formula to calculate the speed in the pipe:

$$v = \frac{Q}{A}$$

Where:

- *Q* = liquid flow rate (m^3/s)
- *A* = area of the pipe or channel (m^2)
- *V* = velocity of the liquid (*m/s*)

When a system is constructed and taken into operation one will need to adjust valve settings at each water point to ensure all the tanks will fill at the same time.

With a system containing multiple tanks at different heights, the tank with the least total head in the system (either short pipes or at a low elevation) will fill first. By partially closing the ball valve located at this water point (each water point has its own valve, see technical drawings), one creates additional head(loss).

Tanks will start to fill at an equal rate when the additional head loss due to the setting of the valve is equal to the total head difference between the water point which is adjusted and the tank with the highest total head in the system.

By setting each valve at each water point one can adjust the system as such that each tank is filled at the same rate.

Note that all calculations to size the pump are based on the tank with the highest total head. Meaning the system will still operate as predicted although additional head is created in parts of the system.

To flush the system of sediments on has to install wash-outs. These are particular important in longer pipelines. They can be opened (plug or valve) to drain the pipes and let sediment out. Wash-outs are placed where the pipeline can be reached and opened in low points of the systems.

Also, the risk of **airlocks** becomes larger when flow speed is low. In some pipes, depending on how they are laid down in the field, there is a risk that air bubbles will accumulate and block the pipe flow at higher points. In that case, **air release valves** can be installed. They open to let air out, and close when immerged in water.

Also – analogue **water meters and valves** can be added on at the central tower (SL1) when separate distribution lines start from that point.

These valves can be used to ensure all the tanks fill at the same time. And that this can be done centrally.

Ensuring that the same amount of water goes to each brand can be done by slightly closing the valves to the branches where the tanks fill first. This will create a bit of additional resistance. And thereby ensuring the other branches fill with water more quickly.

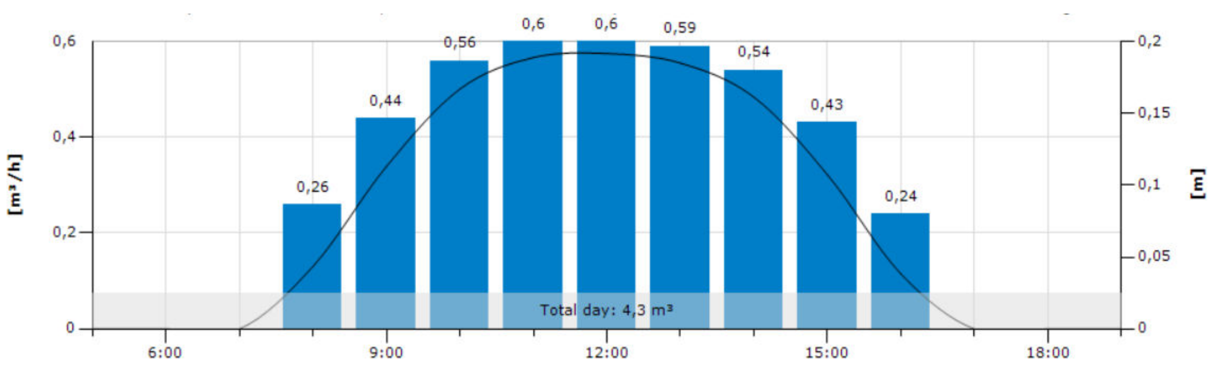
The water meters will allow to monitor the system in more detail. This allows the caretaker adjustments in a more informed way compared to adjusting valves at the location of each separate tank.

8.3.4 The effect of solar energy on the distribution network

Remember that we started this chapter about solar energy? In this chapter we explained that the intensity of the sun isn't constant throughout the day. In the morning the sun is weak, around noon it peaks, and then it becomes less during the afternoon.

This has an effect on the pump that is powered by the sun. In the morning it will pump very little. Around noon it peaks. And it pumps less in the afternoon. This has a consequence of the head loss. It will vary during the day.

The following graph shows, as an example, a pump that provides about 4 m³ per day. The black line shows the head loss (right axis, in meters).



So how should the right diameter of the pipe be calculated if the head loss changes during the day? The answer is that we calculate it on the peak. So around 12:00. Do you remember the figure of 6 peak sunshine hours? Because we have solar systems, the peak pumping hour is the hour with the strongest sunshine during the day. In this hour, approximately 1/6 of the daily water need is pumped up. Meaning that in this case, the maximum average production peak is 4 (m³/day) / 6 (peak sunshine hours) = 0.6 m³/hr.

8.4 PUMP DESIGN

To select the right pump there are 2 things that you will need to know:

5. How much water do I need daily?
6. How high should the pump be able to pump this water – also called the hydraulic head?

Part of this has been discussed in the chapter of data collection. In the following paragraphs these topics will be discussed further and explained how one can use this data to size the pump, solar panels and pipes.

This chapter however starts with an overview of the different type of pumps.

8.4.1 Different pumps types

When opting for an electric submersible pump, one can choose between DC (Direct Current) pumps and AC (Alternating Current). Solar panels provide direct current, so a direct current pump doesn't need a convertor.

AC (Alternating Current) pumps require a converter, and this is more complex and more vulnerable. The advantage of AC pumps is that there is more choice on the market. For larger piped water systems, AC pumps are more suitable. They can be combined easily with generators, or connected to the electric grid. For the smaller rural solar systems, DC pumps are more suitable.

For installation as submersible pump in a borehole for water supply purposes, two types of pumps are important to elaborate upon a bit more: the **centrifugal pump** and the **helical rotary pump**.

A **centrifugal submersible pump**[15] is the type of pump most often used in boreholes. It operates with a high speed rotating impeller in a casing that is called a stage. The impeller throws the water radially out of the casing by centrifugal force. If more pressure is required than a single stage can produce, additional stages are added (similar to adding solar panels to increase voltage output). A centrifugalpump must rotate at a certain speed before it can overcome the static lift required to pump the water into the storage tank. Before this situation, **thepump can be rotating but does not yield any water**.

As a consequence, a centrifugal pump does not pump any water in the early morning or later in the afternoon, even when it receives some energy from the solar panels.

There is a **risk of overheating** the pump. When no water flows, the pump motor is not cooled down by the water flowing around it. To prevent this, often **a sun switch** is installed. The control box senses at what moment there is enough power to starts up the pump motor and make the water flow.

[15] Source picture: Grundfoss SQF and SP pump

An alternative type of submersible pump for boreholes is the **Helical screw rotary pump**. These pumps have a spiral rotor, generally made of stainless steel, which rotates inside a helical stator made of flexible, wear-resistant rubber inside a metal casting. As the rotor rotates, the meshing helical surfaces force the water up by positive displacement. No valves are required for this type of pump, because the rotor and stator provide a seal against backflow.

The maximum water flow of this type of pump is around 3 m^3/hr (= 18m^3/day), which makes him suitable for the smaller water supply systems only.

When choosing a type of pump, the following considerations can be used as a guiding principle:

1. For hydraulic heads less than 20 meters, a centrifugal pump is often more suitable. For deeper wells, a helical screw pump is often more suitable.
2. A helical screw pump has a bit longer pumping hours under equal sunshine conditions.
3. For high flow rates, a centrifugal pump is more suitable. For low flow rates, a helical screw is more suitable. (Remember that a small modular system has low flow rates!)
4. Helical pumps are said to be less sensitive to sand and silt loads.

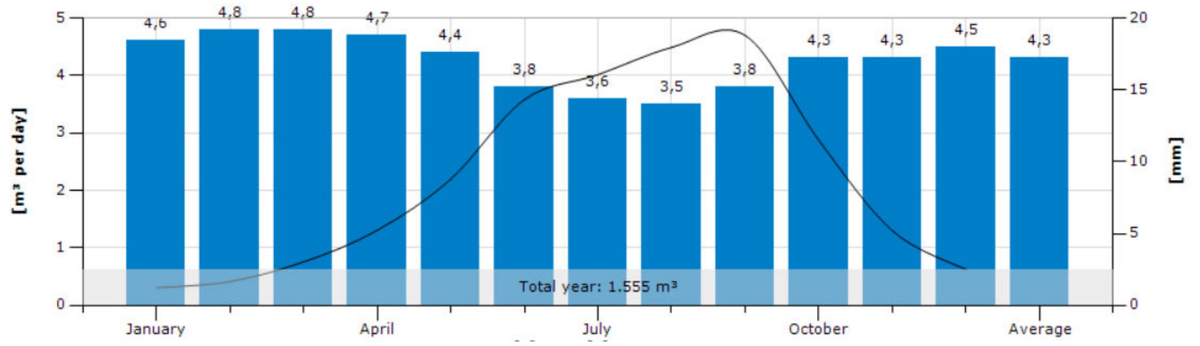
The pump is one of the most important parts to select correctly. If the pump doesn't function correctly the system as a whole will be influenced by it. It is not easy to standardize the pump choice. This because it differs for each location.

8.4.2 Daily water demand

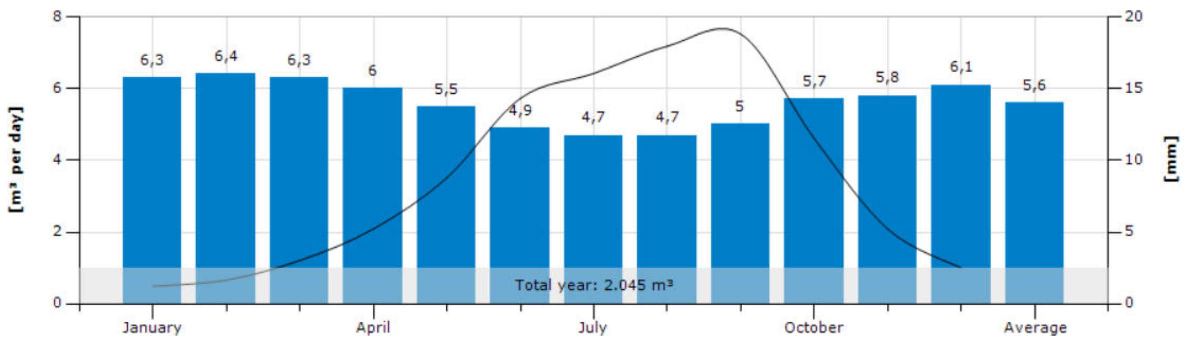
In the previous chapter we determined the water need of the system by calculating the water need of each water point.

But this answer of this exercise is only half the answer. Because the next question is, **when** do we need this amount of water? Remember the first paragraph of this chapter that explained how the irradiation changes during the season? The change of irradiation over the year will result in the fact that the pump will not pump the same amount of water during the year.

There is no right or wrong in answering this question. Most important is to understand the consequences of your decision. In the following graphs[16] the effect is shown when you decide you want 4.5 m³/day in the driest month of the year. Interestingly enough, this is the month with the highest irradiation. The consequence would be that during the wet season the pump will provide less water. But this still might be sufficient because people need less water in the wet season.



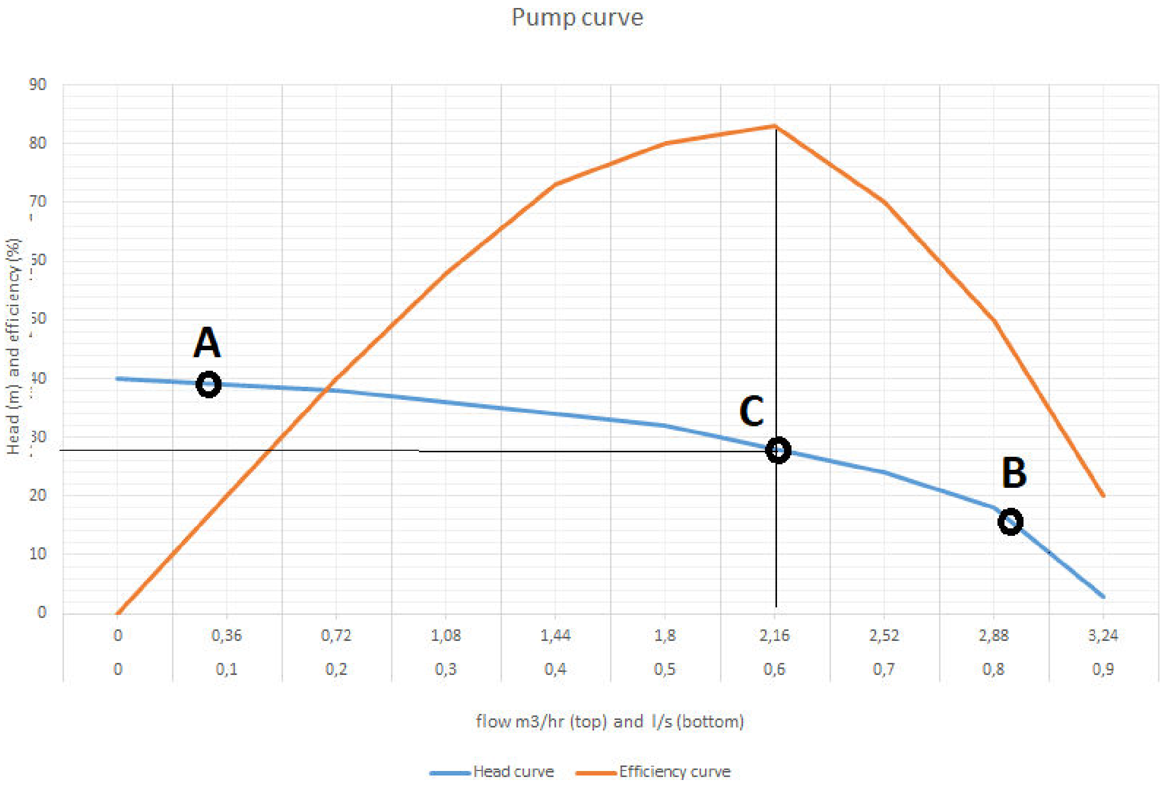
As an alternative, you could say you want 4,5 m³/day as a minimum. Meaning that the pump will still pump 4,5 m³ per day in the month with the least irradiation. If you decide so, you will see the system will have an over capacity in the dry season.



8.4.3 PUMP SELECTION

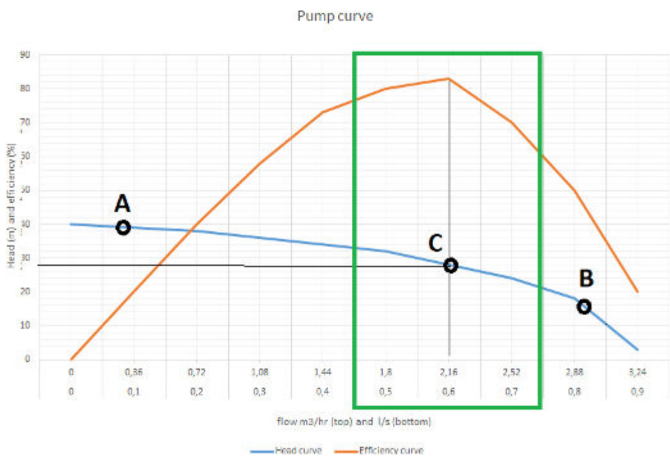
Once we know the needed flow and the total hydraulic head we can select the pump. The pump selection can be done based on a **pump curve**. Each pump has its own pump performance curve. The pump curve is a graph, displaying what flow the pump will give at what hydraulic head. On the following picture, you see an example of such a pump curve:

[16] Source: Lorentz Compass 3.1

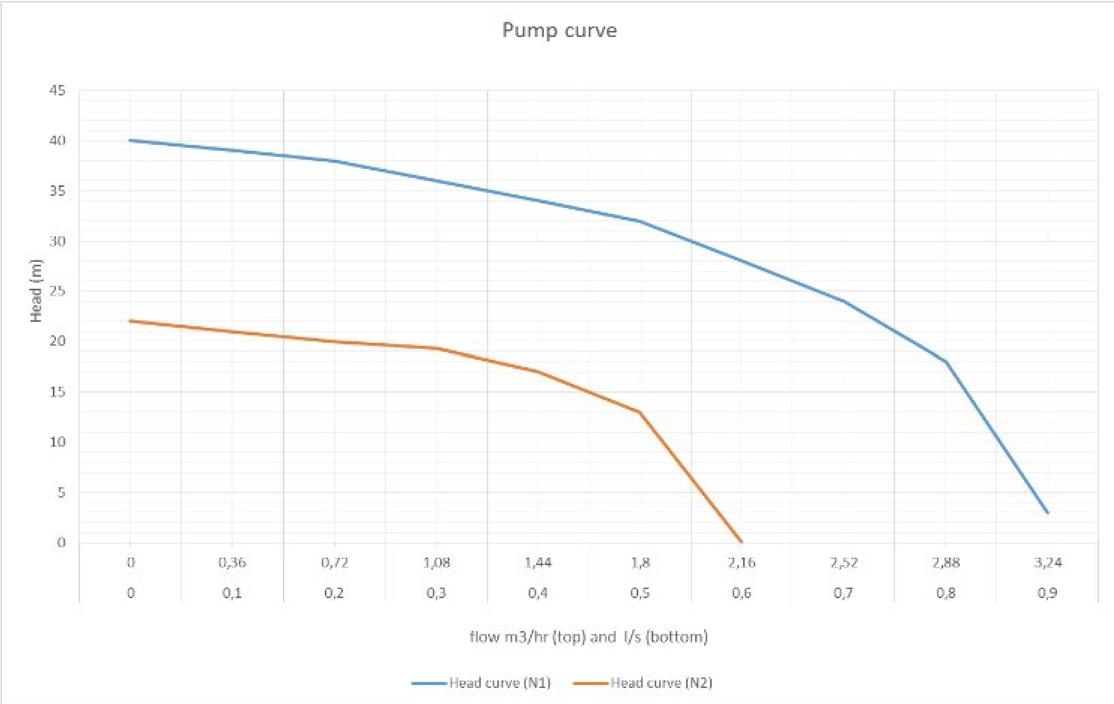


What you can see, is that when the pump gives a high flow (point B), it cannot give a high pressure at the same time. Nor is the efficiency good. When the pump has to overcome a high hydraulic head (point A), the flow will be less. The pump performs at its best at point C, where the efficiency is at its highest. This point is referred to as 'Best efficiency pump'.

In practice it will be very hard to find a pump that exactly will hit the operating point on point C. The pumps selected should be in the recommended operating range indicated in green in the picture on the right.



How much flow a pump can give at a certain hydraulic head, also depends on how much **power** the pump receives from the solar panels. This means that for the same pump, different pump curves can be drawn in the same graph, showing the **pump curve at *different power levels***. The following picture is an example of such a pump curve graph:

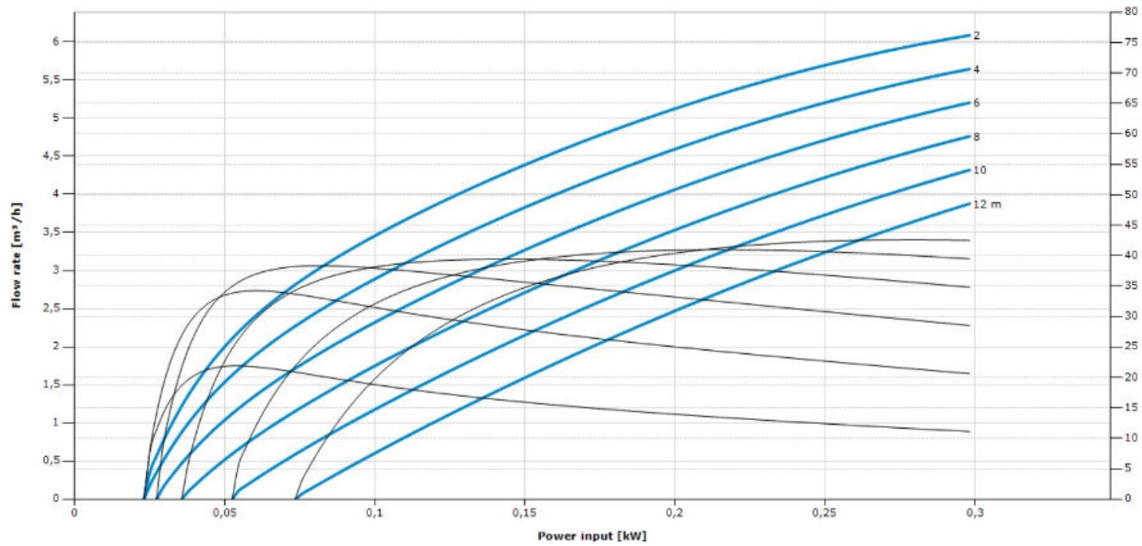


On the picture, you see two pump curves for exactly the same pump. The blue pump curve is for the situation in which the pump receives a lot of power: it can pump more water over a higher hydraulic head. The red pump curve is when the pump receives 50% of the power of N2.

Producers of pumps often have different pumps on the market, each with their own pump curves. So in order to choose what pump makes a good match with what your water system needs, you will have to compare many different pump curves.

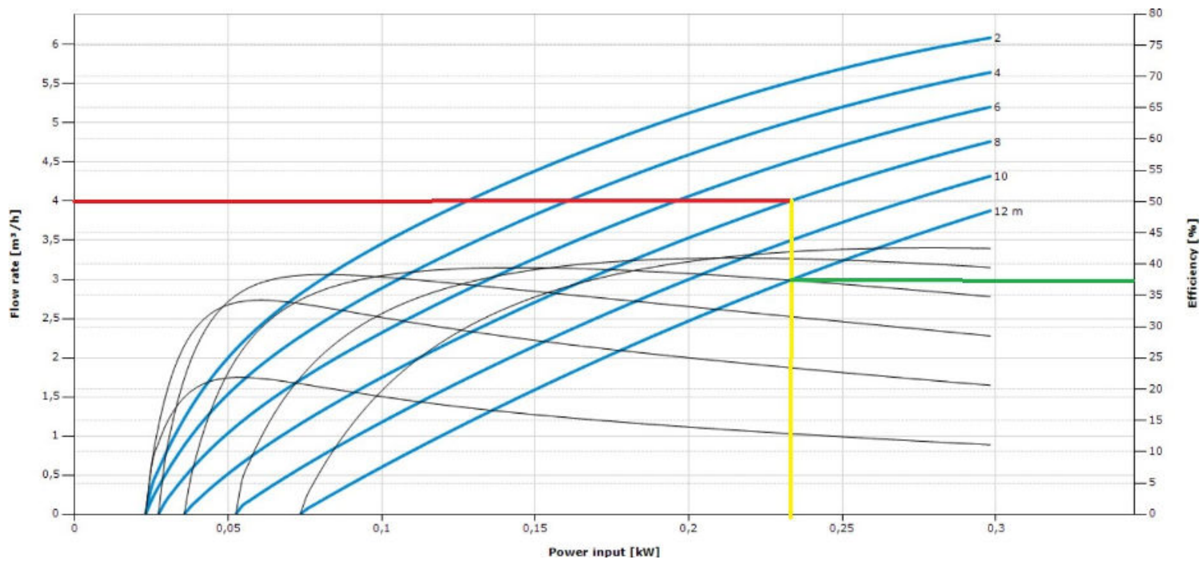
8.4.4 POWER-FLOW CURVES

In the figure above, you can conclude that **4 things need to be combined** to select the right pump: the hydraulic head, the flow (rate), the power the pump motor receives (from the solar panels) and efficiency. Now, you can also combine these 4 elements in a different way. The following graph maybe helps to make this clearer. It is the Power-Flow curve for a PS2-150 Lorentz pump:



The blue lines have numbers at the end. Those are the heads in meter. So the top blue line shows the curve of a head of 2 meter. The grey lines are the efficiencies of the pump at that specific head. So each blue line has a grey line that are linked.

If we want, for example a flow of 4 m3/hr at a head of 8 meters we can draw the following lines:



We start with the red line and make a horizontal line starting at the needed yield of 4 m³/hr until it hits the blue line that corresponds to the 8 meter. A vertical yellow line tells us the needed power input of the pump to work on that specific point. This is about 0.24 kW. Note that this is the power the pumps need – it is **not** the size of the solar panels.

Where the yellow line crosses the efficiency curveof (that corresponds with the head of 8 meters) we can draw the green horizontalline to know the efficiency. Which is about 37%.

It is also possible to calculate the power that the pump needs. This can be done by using the following formula:

$$Power_{pump}(Watt) = \frac{liters\ pumped\ in\ 1\ hour\ x\ 10\ x\ total\ head}{3600}\ x\ \frac{1}{pump\ efficiency}$$

In our example it would look like this:

$$Power_{pump}(Watt) = \frac{4000\ x\ 10\ x\ 8}{3600}\ x\ \frac{1}{0.37} = 240W$$

It is important to note this pump – as with all pumps – is efficient in only a very specific range. At very low flows the efficiency drops considerably. And with high heads the pump stops working. These graphs can therefore be used to select the right pump for a specific design. Selecting the wrong pump will either result in low efficiency (and therefore the need of a lot of solar panels) or that the pump will not work at all as it can't provide the needed pressure.

There is one additional remark to be made for selecting the right pump for the modular system: the modular system is able to expand. If this expansion is expected within the lifespan of the pump (which is generally about 7 years) than it is advised to choose for a pump that is also capable of providing water to the expansion. Less solar panels will be needed to let the pump operate in the first phase. But when the expansion happens only additional panels will need to be placed on the tower.

8.4.5 Solar panels

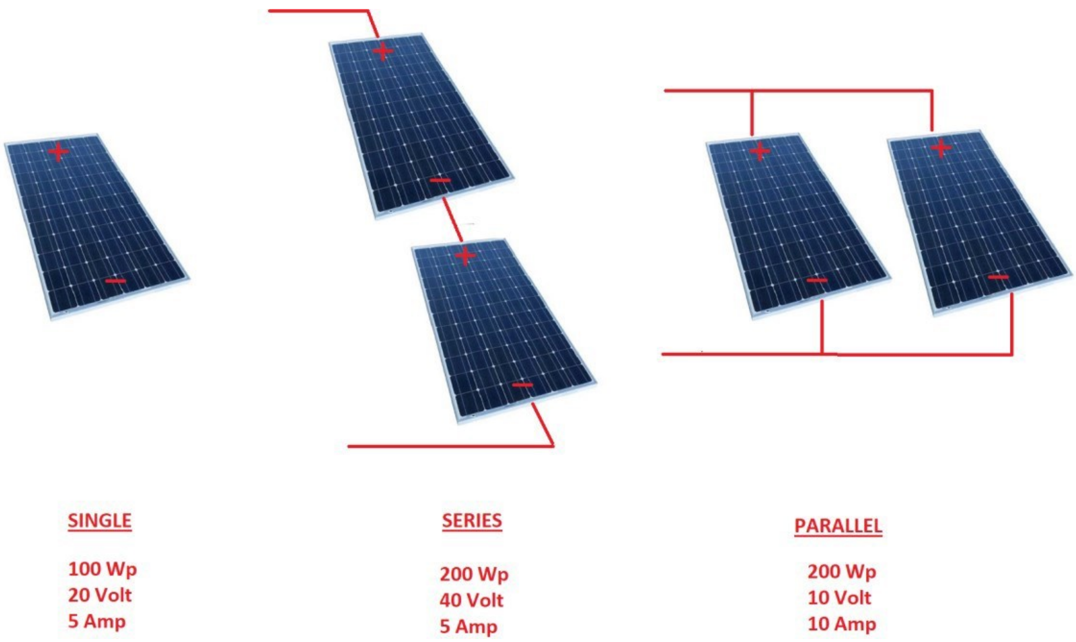
Solar panels are used to produce electric power, and to then send it to the pump. The basic element of a solar panel is the photo-voltaic cell, or PV-cell. They are made of materials that can convert sunlight directly into electricity.

PV cells that are combined to make solar panels, are also called **a module**. The panels have such a size that they yield a reasonable amount of electricity, but are still easy to handle and transport. **Solar arrays** are a group of solar panels, placed together in a certain configuration. The panels are grouped together in order to produce the right amount power for the purpose they serve.

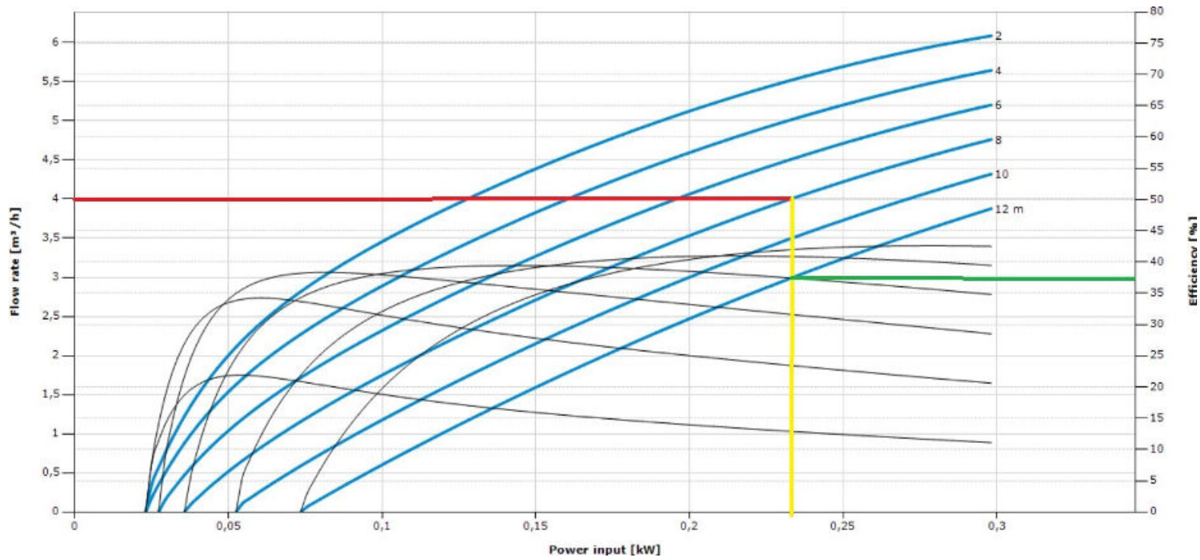
The most important characteristics of a solar module are:

- How much **power** (unit = Watt) it can produce in full sunshine conditions. This figure is called Watt Peak (Wp). It is obtained by multiplying V x A.
- How much **voltage** (unit = Volt) it produces (in full sunshine conditions)
- How much **current** (unit = Amperes) it produces (in full sunshine conditions)

These characteristics changes when multiple modules are placed in an array. Basically, solar panels can be connected in series, or parallel. This is important because during installation you will need to be aware of how the panels should be connected.



When solar modules are connected end to end, they are said to be connected in **series**. It doubles the voltage and the amperage stays the same. When the positive poles of each modular are joined to each other, and also the negative poles are joined – then the panels are connected **parallel**. It doubles the amperage and the voltage stays the same. The preferred way of wiring is generally explained in the manual of the pumps.



Remember this graph? During the selection of the pump we have determined the power need to the pump. In this case we need to power the pump with 142W. But this power is not equal to the power of the solar panels needed. We have to take into account that between the solar panels and the pump there will be considerable losses.

And altogether, this is can be a lot of energy.

- Electric transport costs energy. In the electric wires, energy is lost. It depends on the thickness of the cables, and the length of the cables, how much this is. We can call them **wire losses.** They can be around **2-5%,** but much more with long thin wires.
- In the control box, energy is lost. (You notice this because the box needs to be cooled). We can call these control box losses**.** They are around **1-5%**
- When there is dust on the panels, they cannot use all the solar energy that hits the panel. This causes **dust losses**. This can be around **5-15%**
- When the solar panels are very hot, they work less efficient than when they are cooler. This is called **heat losses**. This can be around **5-15%**
- When panels get older, they very slowly become less efficient. Panels of 25 years old can have lost 20% of their capacity. We call them **panel aging losses**, and take an average of 10%.

The best way to describe and calculate this, is using the **efficiencies (=100 minus loss)** of every element of the system. To calculate the total efficiency of the system, we **multiply all efficiencies**.

If we use the example of the pump that needs 240W input and take into account the following losses:

- Electric loss: 3%. Equals 97% efficiency.
- Dust loss: 5% Equals 95% efficiency.
- Heat loss: 10%. Equals 90% efficiency.
- Control box loss: 3%. Equals 97% efficiency.
- Panel age loss: 10%. Equals 90% efficiency.

The total efficiency off the system therefore becomes: 0.97*0.95*0.90*0.97*0.90= 72%.

How much more energy the solar array must produce (above the hydraulic energy required to lift the water) is then calculated. This can be done by using the following formula:

$$P_{\text{needed by Pump}} = \text{Efficiency}_{\text{total}} \times P_{\text{Solar panel}}$$

In our example we needed about 240W. The solar array - given an assumed efficiency of 72% would be the following:

$$P_{\text{Solar panel}} = 240/0.72 \approx 330\text{Wp}$$

The sizing of the cables and the configuration of the solar panels can be calculated. However, this is not easy. For that matter we excluded it from the manual. Generally pump suppliers have software packages to calculate it: they will be able provide the right configuration and cable sizes.

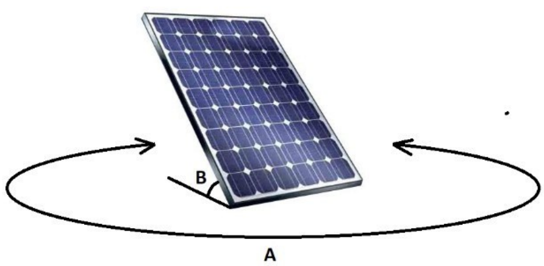
If one wants to attempt to calculate it manually a good source is the book: "Solar Pumping for water supply. Harnessing solar power in humanitarian and developmental contexts." Kiprono and Ilario, 2020. It can be downloaded for free at Practical Action Publishing.

The sizing of the solar array is only correct if the panels are placed correctly. There are three main factors that need to be taken into account for this:

1. The orientation of the solar panels
2. Shadow

Orientation of the solar panels You can orient a panel in 2 different ways:

1. The direction it faces (A): north, west, east or south.
2. The angle it is placed in with the ground (B).



To get as much sun as possible on the panels the following rules should be applied:

The earth can be divided in the northern and southern hemisphere. You live in the northern hemisphere if you live above the equator (red dotted line in the picture on the right). You live in the southern hemisphere if you live below the equator.

Panels should always face the equator. So if you live in northern hemisphere the panels should face south. If you live in the southern hemisphere, the panels should face north.

Secondly, the latitude is used to express how close or far you are located from the equator. They are expressed in degrees. The panels you place should be in an angle on the degree you are on. And the angle should never be less than 15 degrees to make sure the panel stays clean.

Shadow

Shadow on the solar panels must be avoided at all cost. The effects of shadow are often underestimated and not well understood, and sometimes not well described in manuals.

Shadow, even the slightest bit, can have a disruptive effect on the functionality of the entire panel and array. Just 10% shading of a solar array can lead to a considerable decline in efficiency and even, on occasion, total loss of water flow.

How vulnerable the panel is to shadow, also depends on the quality of the panel. To prevent the whole string of cells failing when one cell underperforms, a good solar panel is equipped with "bypass diodes." These diodes reroute the current around the underperforming cells. The risk and amount of damage also depends on the irradiance level. Early in the morning, irradiance is not so high, so the potential damage or power loss of shadow is also less.

As mentioned earlier, apart from the placement of the panels the efficiency of the panels will be influenced by dust. The power as indicated on the panel is produced under conditions of a clean solar panel. In practice, often some dust is accumulated on the panel surface, reducing the output power of the solar array. These dust losses can be around 0-15%. The panel should be cleaned regular, with clean water and only during the early morning/late afternoon when the panels are no longer hot.

8.4.6 Online tools

The calculations that need to be done to match the size of the solar array with a pump choice under your particular situation (location, water system characteristics), taking into account all energy losses, are complex. It is difficult to find the right type of pump that matches your pumping needs.

Most pump suppliers have computer programs and web-based utilities for selecting and sizing pumps for specified values of borehole diameter, available solar radiation, pump flow rate, and hydraulic head. This way, of course they also hope that the buyers will come to them.

Before you visit the pump supplier, it is very useful to already have an idea of what kind of pump you will need. So it is wise to check for yourself, and use the internet calculation tool.

Examples of these tools are:

1. The Grundfos product selection tool: This tool is freely available for everybody to use on https://product-selection.grundfos.com/
2. The Lorentz Compass solar pump system planner. You need to subscribe at Lorentz, and request an account. You can then download and use the software.

These tools show only the products in their own product range. But they form a good reference to your calculations. But most important - you will need to understand the theory described in this chapter to make use of these tools.

8.5 WELL

The **borehole production capacity** needs to be able to accommodate the peak pumping hour of the water system. Because we have solar systems, the peak pumping hour is the hour with the strongest sunshine during the day. Therefore, the following formula can be used to calculate the minimum production capacity of the borehole:

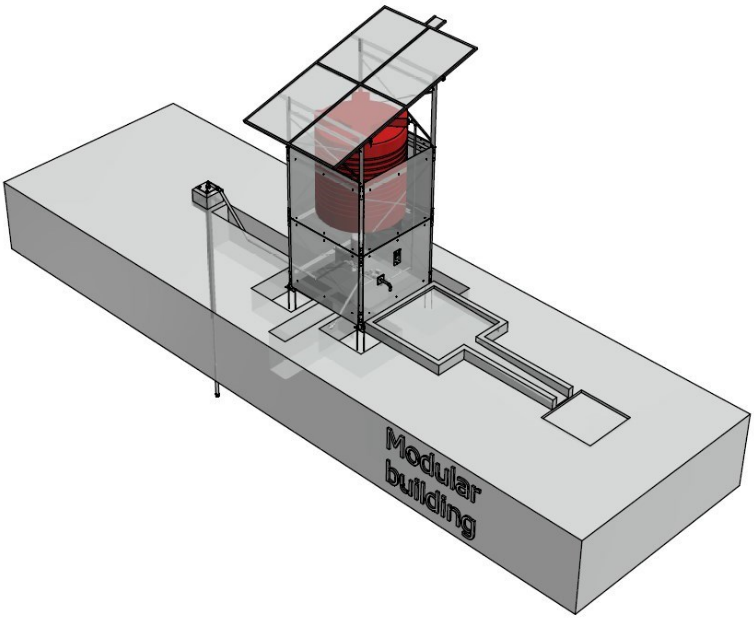
$$\text{Minimum production capacity of the borehole } \left(\frac{liters}{hour}\right) = \frac{Daily\ water\ demand\ (liters)}{peak\ sunshine\ hours}$$

So, as an example, a tower has a daily water demand of 350 people x 10 liters = 3500 liters. If we assume 6 peak sunshine hours the minimum production capacity of the well should be 3500/6 = 583 liters/hour. It is an indication only – so using a safety margin and more exact calculations (with for example the software of the pump suppliers) are advised.

8.6 TANK SIZING AND TOWER SELECTION

The tank, colored in red in the picture below, has the function to buffer (= to hold) water. It has to buffer water for periods when the water consumption is higher than the water production.

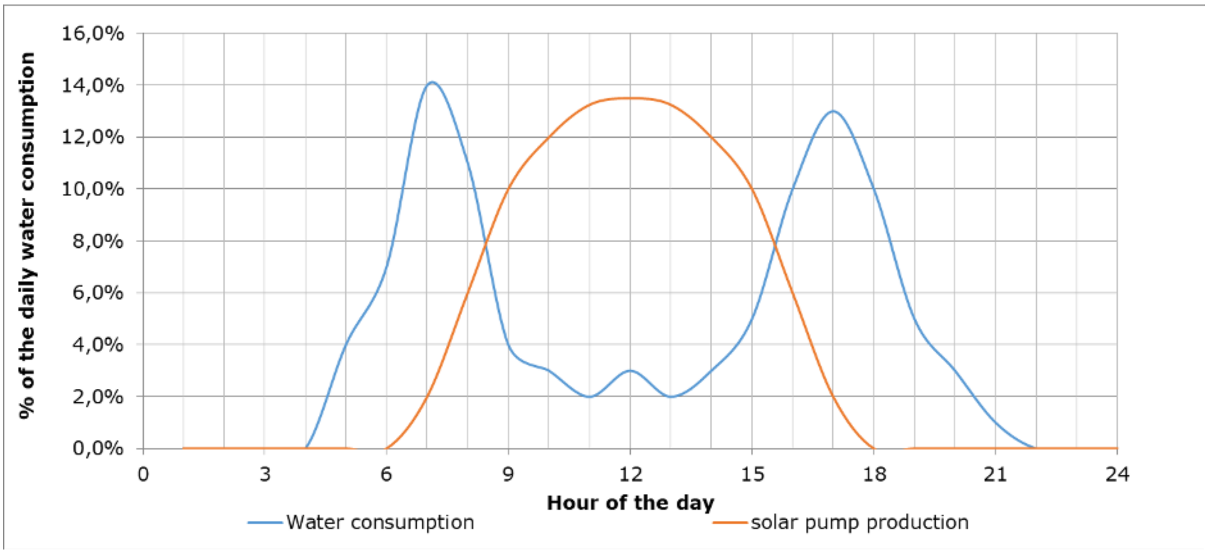
There are multiple tank sizes available in the design: 1,3,5,8 and 10 m³. In this chapter it is explained how one can choose the right tank size.



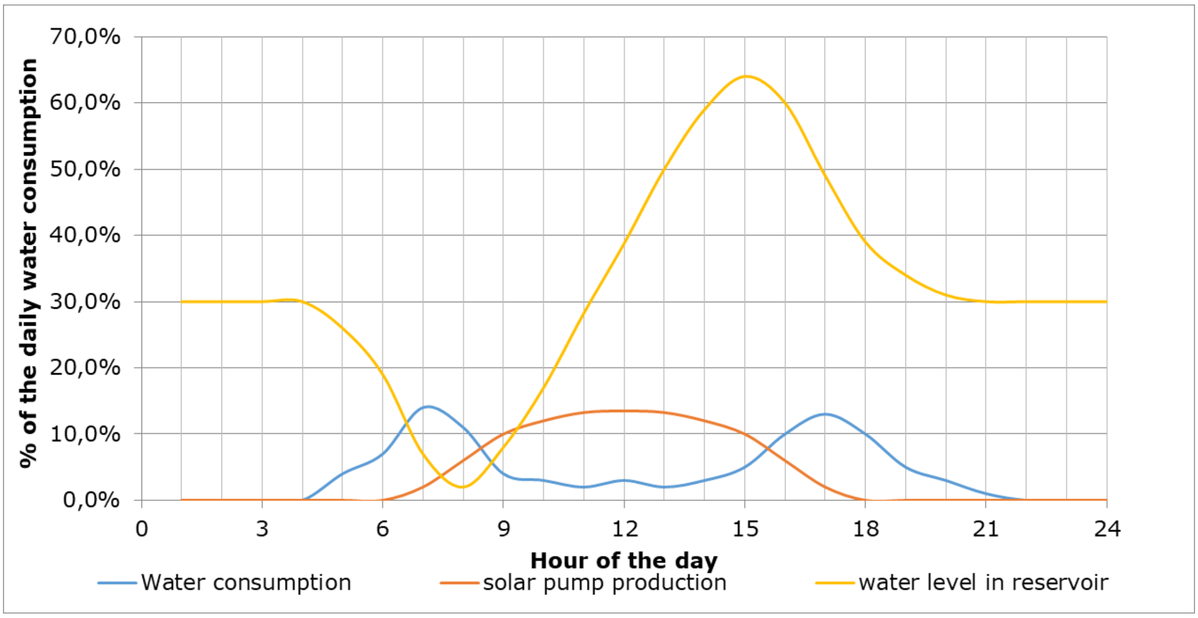
Here comes the first consequence of using solar energy. A solar pump will not provide the same amount of water over the day. The amount of water pumped is directly linked by the power of the sun. This is expressed in the red line in the graph below. You see that the pump provides most water during noon. And when the sun shines weaker (at the beginning and end of the day), the pump will provide less water.

If the water production would exactly meet the water consumption one would not need a reservoir. People could directly take what the pump would produce. But this is clearly not the case in practice.

The blue line shows the water consumption of the people. In this case we *assume* most people are expected to fetch water either in the morning or afternoon. And that is exactly when the power of the sun, and therefore the water production, is the lowest during the day!

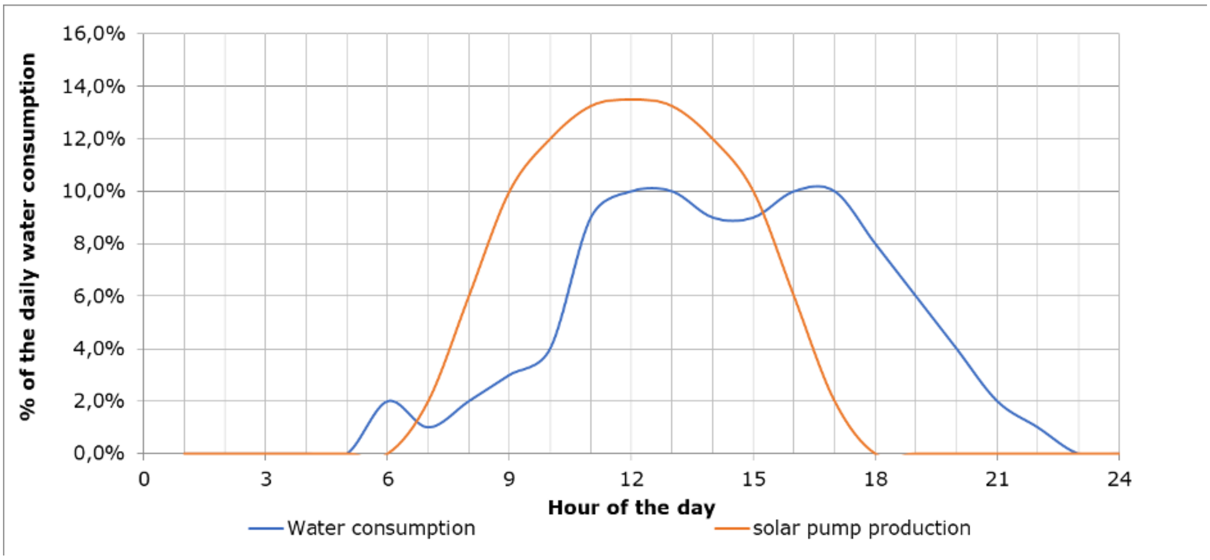


We can use the water tank to buffer water to overcome this problem. This tank will not need to be 3.500 liters (in our example), but it can be smaller because there is some overlap between production and consumption. The yellow line is added in the graph to understand how big the tank needs to be as a percentage of the daily water consumption.

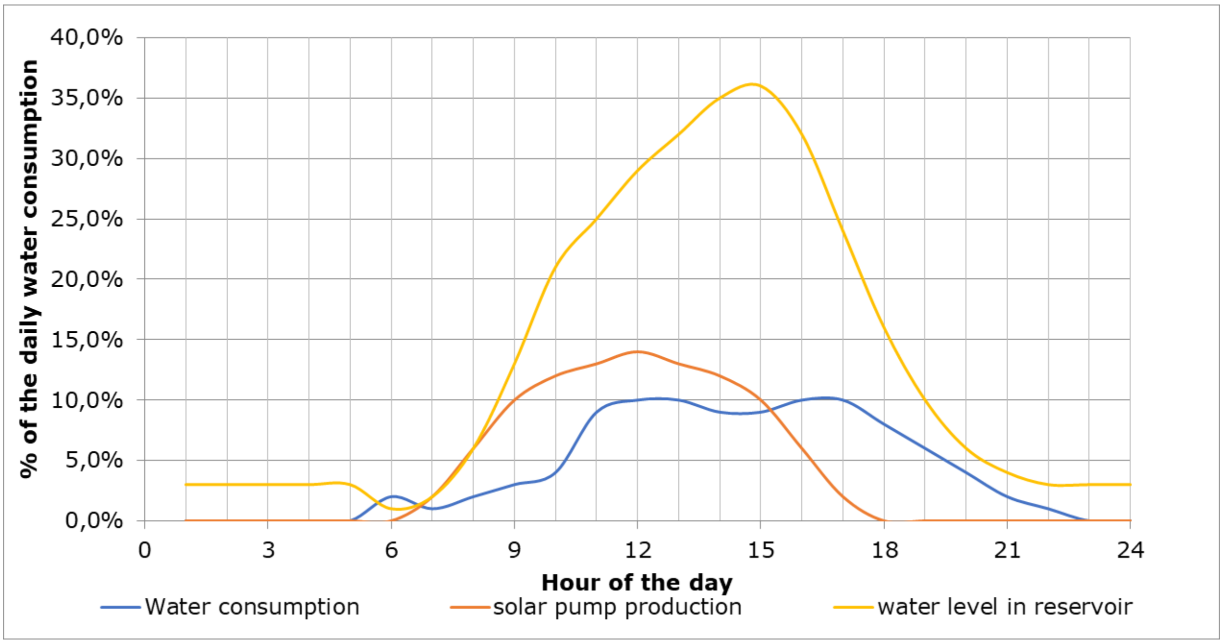


You can see that in the morning about 30% of the daily water need needs to be buffered to ensure there is enough water for the consumption peak in the morning. And another 30% to deal with the consumption peak in the afternoon. In total the tank size needs to be about 65% of the daily water need. This means that the tank needs to be, at least, 65% x 3.500 liters = 2.275 liters. In this case one wouldopt for a tank size of 3 m^3.

One should realize the consumption pattern heavily influences the tank design. The following graph shows the actual measured consumption pattern in Liberia:



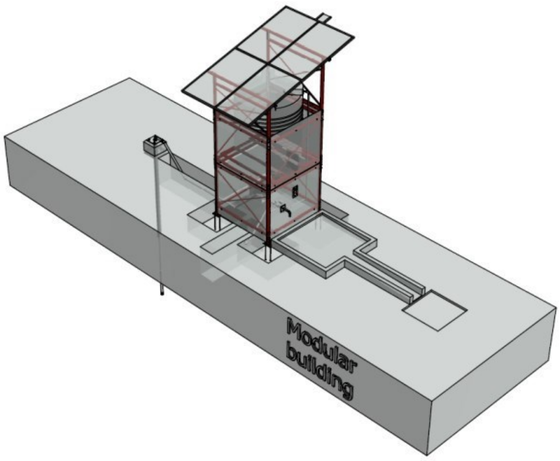
It is clear that this pattern is very different than the assumption that was initially made. This consumption pattern would provide the following graph for tank sizing – suggesting that the tank size can even be 35% of the daily water need:



With these numbers (10 liters per person per day – and both 65% and 35% as tank size of the daily water consumption) the following tank sizes equal the following number of customers.

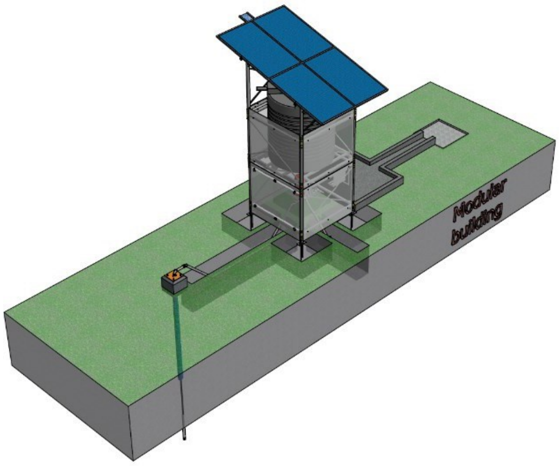
Number of customers (round off)		
Tank size (m3)	Main consumption during morning & evening	Main consumption during afternoon
1	150	280
3	450	850
5	750	1.400
8	1.200	2.250
10	1.500	2.800

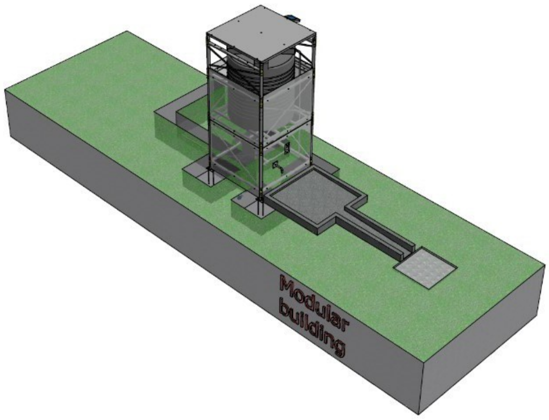
The tank is placed on a water tower (coloured red in picture below). The function ofthe water tower is to elevate the tank so water can be tapped from it without using a pump. It is a metal structure consisting of repeating elements that can be taken apart for transport. The outside the structure is covered in metal plates to ensure people can't get inside. The electronics of the solar pump and the prepayment units can be placed inside.



The tower is bolted to a foundation. Underneath each leg there is a block of concrete to ensure that the tower doesn't tip over when there is a storm.

The towers for service level 1 and 2 are similar. With one exception. Solar planes can be placed on top of the tower of service level 1. On service level 2 a small roof can be placed to provide a bit of shade on the tank and prevent rain to come in.





In the technical drawings – as provided in the attachment – one can find:

- **The drawings of the towers and the specifications of the yard connections**. The drawings are generic – in tables the exact specifications are provided with type of profile one can choose depending on the tank size and the wall thickness.
- **The size of the foundations**. For the foundations to work stable, solid ground is needed. If built on unstable ground –for example a swamp or loose sand – the tower will be structurally unsound.

In the technical drawings the towers are made as such that one can take them apart and transport them more easily. For this connections are made using flanges and bolts. In case the tower can be transported as a whole (without the need of disassembly) one can opt for welding all connections instead of using the bolt/flange connection. This makes the fabrication easier. Be aware that:

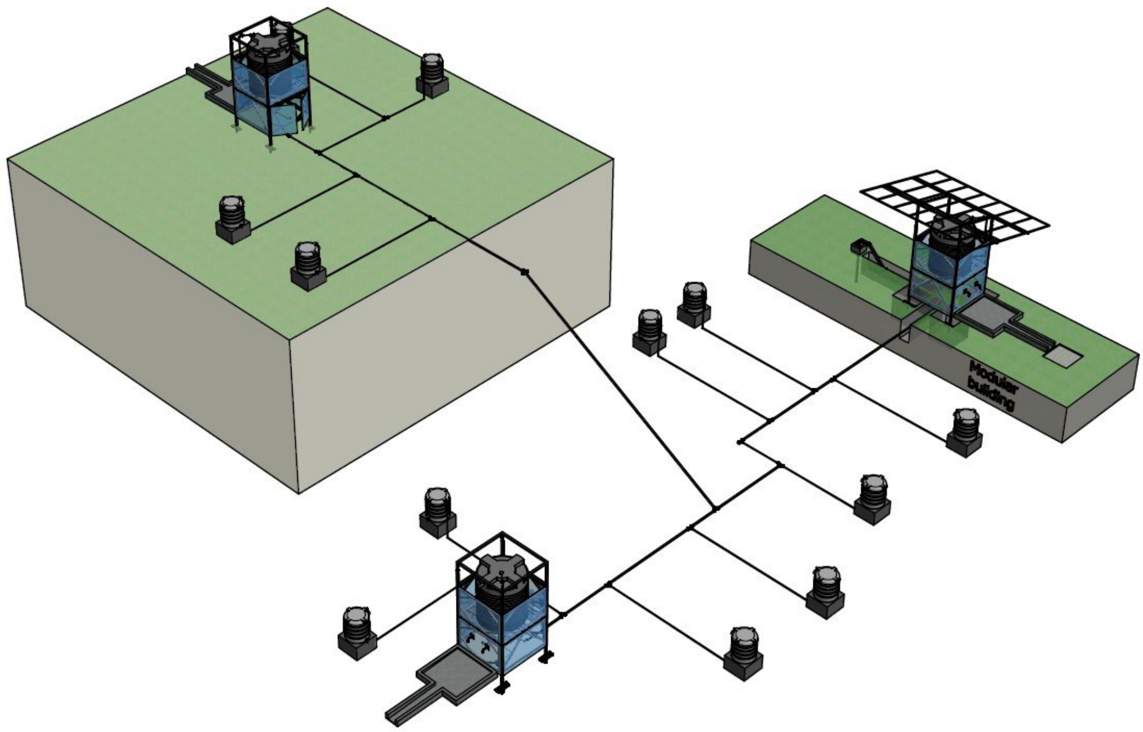
- placing the tower (including pouring the concrete) will be harder when using a tower that can’t be disassembled;
- The cladding still should be removable: this is needed to install piping etc.;
- The tank can still be inserted and removed from the tower.

The numbers provided above are averages and based on field experiences. However, the experience also shows that local circumstances might vary considerably. If the water consumption is expected to be higher, or if the presence of local institutions or schools suggest other numbers, than these calculations need to be reworked to fit the local context.

8.6.1 Pump control

A pump needs to be switched of when the tank is (or tanks are) full. The most common way is to use a float which to control the pump. This switch measures if the tank is full. Once full, it switches off the pump.

Using this device forms a challenge in this concept. Image the following situation. A central tower is located in a valley. And there are 12 yard connections and 2 satellite towers attached to the network. One tower and 4 yard connections are located much higher than the central tower.



If in this case a float switch is used than there would be 2 options:

- **Place the float switch in the central tower**: however, the higher tower would never receive water because the tank of the central tower would be full before the filling of the higher tower would begin. And as the float switch is located in the central tower the pump would have been switched off.
- **Place the float switch in the highest tower**: from a technical perspective this would be the best solution. Yet from a practical point of view this will face problems. In some cases, the satellite tower might be located a few kilometers away from central tower. This would mean a very long (and vulnerable) cable would need to be used to let it work.

To control the tank filling in a network of tanks from a central location one can control the pump based on water pressure in the distribution lines. The system works on the principle that the pump pumps the water directly into the distribution pipes. When a reservoir is full, a float valve closes the inlet. When all reservoirs are filled, all inlets are closed. As a result, the pressure increases in the distribution pipelines. The pressure sensor –located in the central tower - measures this pressure.

The pressure sensor is wired to the pump control box. The pump is switched off when the pressure is higher than a certain level. It is possible to adjust thesettings of this pressure switch to the circumstances of the system.

The technical drawings also specify to use a pressure relief valve: this mechanical valve ensures that when the sensor fails the water can be disposed before the pipes burst.

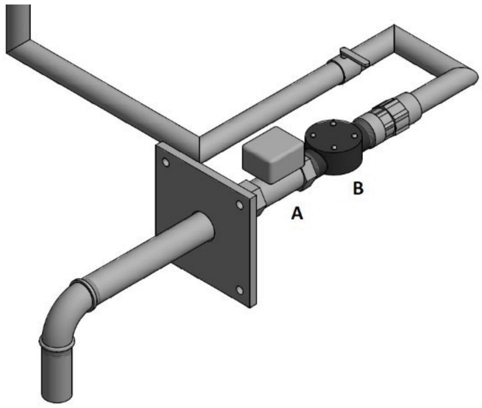
For both devices to work – one will need to adjust the settings. The pressure sensor needs to be set as such that the pump is switched off when the pressure is higher than the total expected hydraulic head during tank filling. The pressure setting of the pressure relief valve should be set higher than the pressure setting of the pressure sensor. Yet, below the maximum pressure rating of the piping.

If only one water point is installed, then a float switch –as mentioned before - can be used. This device is simpler than a pressure sensor. It switches the pump off when a certain water level in the storage tank is reached.

8.6.2 Prepaid

The last part that will be discussed is the prepaid module. The function of it is to ensure that people will pay when they tap water. The prepaid module is placed between the tap and the tank.

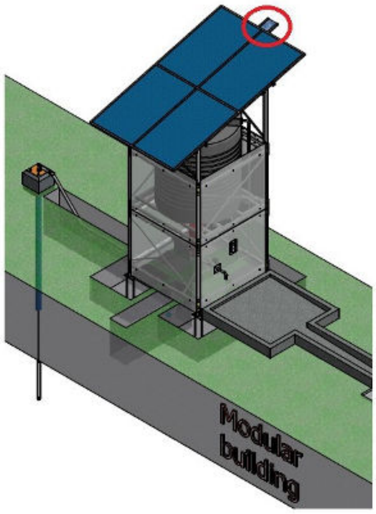
There are multiple devices on the market. The most common ones are based on electronics. The prepaid modules generally consist of an electric valve (A) that can open/close and a water meter (B). A customer will need to open the valve. The water meter measures the amount of water tapped. If a size of a jerry can is tapped, the valve closes.



To open the valve, customers will have to present a tag to a device (see picture left) placed on the water tower called a 'hub'. The tags work like telephone credits – you will have to pay money to get credits. By presenting the tag, a certain amount of credits is taken from the tag.

All the sales are records and stored in a central database. It shows how much water has been sold when and how much money is generated.

A small solar panel is installed on each tower to power the prepaid modules.



An alternative to the electronic versions is a coin operated mechanic prepaid meter. It is developed to reduce complexity and allow mechanics to do simple repairs. These mechanical devices are particular helpful in rural settings where supply chains for a challenge and where local capacity is often lacking to maintain complex electronic devices.

Because prepaid technology is relatively new it is important to stock enough parts that are not readily available in the country.Also ensure proper training of the caretakers and technicians to ensure enough capacity in available to maintain the systems.

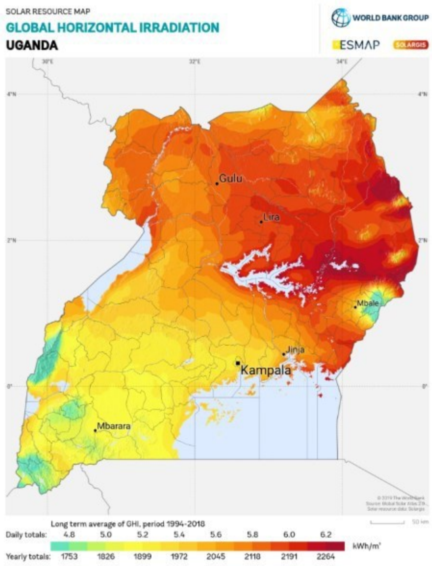
Photo: people extracting water at water kiosk, Liberia

9 DESIGN STEP 3: SIZING OF THE SYSTEM – AN EXAMPLE

In this chapter the overall sizing of the system - including pump selection - will be done based on the example data as discussed in the previous chapters.

9.1 GENERAL CALCULATIONS

The start of the calculations is to determine the peak sunshine hours. The location is in the north of Uganda – slightly north of Lira. The following map[17] shows the horizontal irradiation in Uganda.



For the location we can now see that the peak sunshine hours are about 6. The daily water need is 14 m^3/day. So as a first indication (14.000/6 =) we expect a maximum yield of about 2.300 liter per hour.

The pump yield states that the maximum yield of the well is 3m^3/hour. So the needed yield is technically feasible. The pump tests don't state the drawdown at this rate – so we stay safe and assume an approximate 28 meter drawdown. Which is de drawdown at a pumping rate of 3 m^3/hr. This results in a total depth of the water (drawdown plus static level = 28m + 12m) 40 meter.

[17] https://solargis.com/maps-and-gis-data/download/uganda © 2019 The World Bank,Source: Global Solar Atlas 2.0, Solar resource data: Solargis.

We know the length of the distribution pipe is 1682 meter. We choose PE pipe as it is locally available and easy to use. With this information we can calculate the approximate head loss in the pipe.

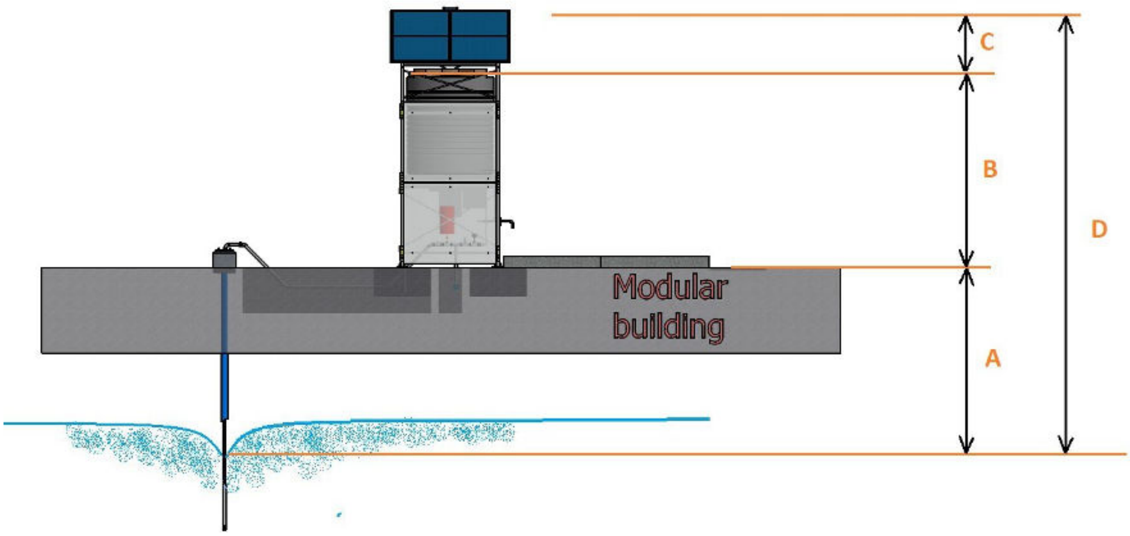
Internal diameter	Meter head loss per meter pipe*	Meter head loss per 1000 meter pipe	Speed of water in pipe (m/s)	Suitable	Total head loss (meter) in system
15 mm	1,05	1050	3,6	No	1766
20 mm	0,26	260	2	No	437
25 mm	0,088	88	1,3	No	148
30 mm	0,036	36	0,91	No	61
35 mm	0,017	17	0,67	Optional	29
40 mm	0,0089	8,9	0,51	Yes	15
50 mm	0,003	3	0,33	No	5

*Assumed Hazen William constant: 140

To cover for the head loss in the elbows, T-pieces, no return valves and float valves we add an additional 5% to the friction losses of the pipe work.

In this example it is assumed that the pipes from the main distribution pipe to the water tanks are very short. Therefore we exclude the head losses in the secondary distribution pipes. If these secondary pipes are, however, long they should be included in the head loss calculation. They can be calculated with the same principles as described in this chapter.

Now we calculated the head loss in the pipe, we can calculate the total hydraulic head.

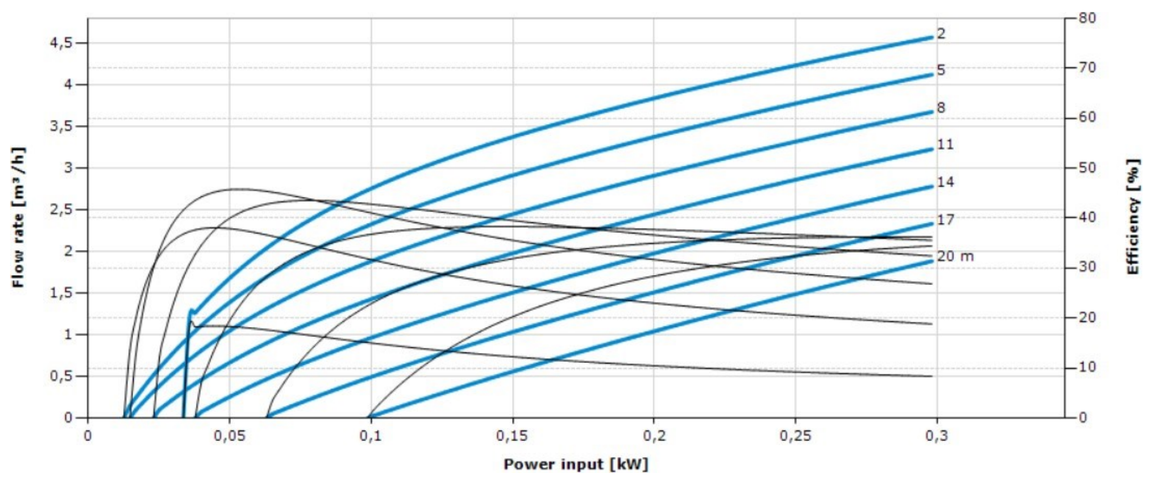


Factor	Description	Meter
A	Dynamic water level at well	40
B	Vertical height in landscape	14
C	Head loss due to friction in pipe and fitting work plus residual pressure	26 Being sum of -head loss in piping = 15 meter -additional 5% head loss elbows/T-pieces ≈ 1 meter -residual pressure: 10 meter
D	Total head	80

Note that the pump needs to supply about 8 bar to get the water to the highest part of the system. This means that the piping needs to be able to withstand at least 8 bar. For this we choose a pressure rating of the pipe of PN10 for the system as a whole to ensure simplicity in the design. Note that one could opt for lower pressure ratings after, for example, pipe work that starts from the well. The needed pressure to pump the water from the well to the highest point in the landscape is (14+26=) 40 meters. So about 4 bar.

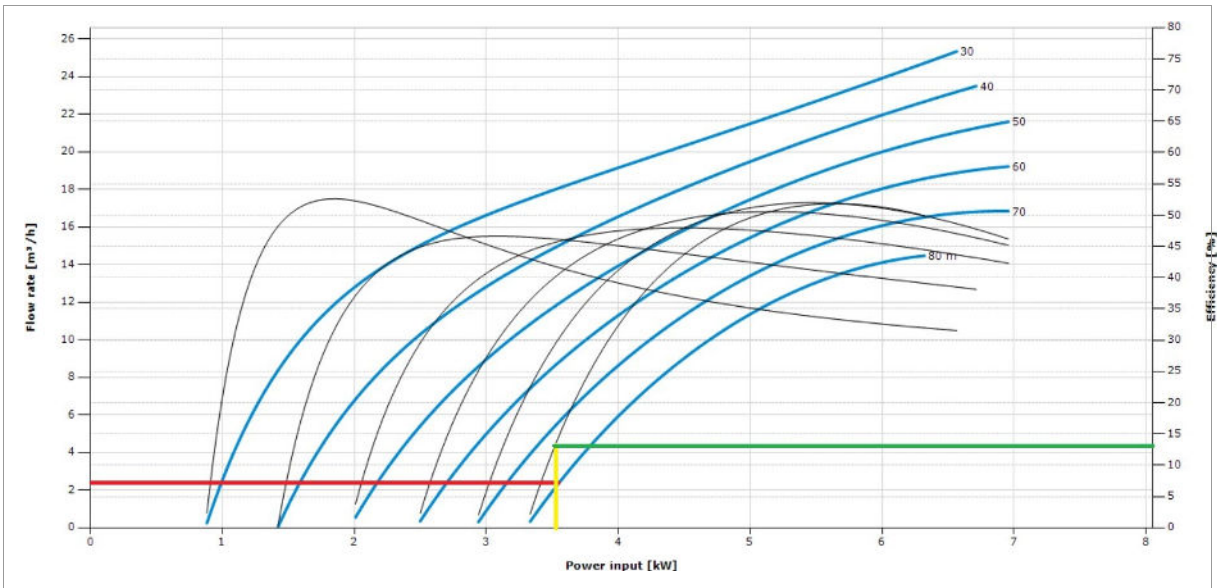
9.2 PUMP SELECTION AND SOLAR PANELS – THE MANUAL WAY

We now know (1) how much water the pump needs to pump and (2) how high the pump needs to pump the water. With this information we are able to select a suitable pump. In our example we have 3 pumps[18] available. The right column provides the pump charts and the left column provides the observations of this pump chart, related to our situation.

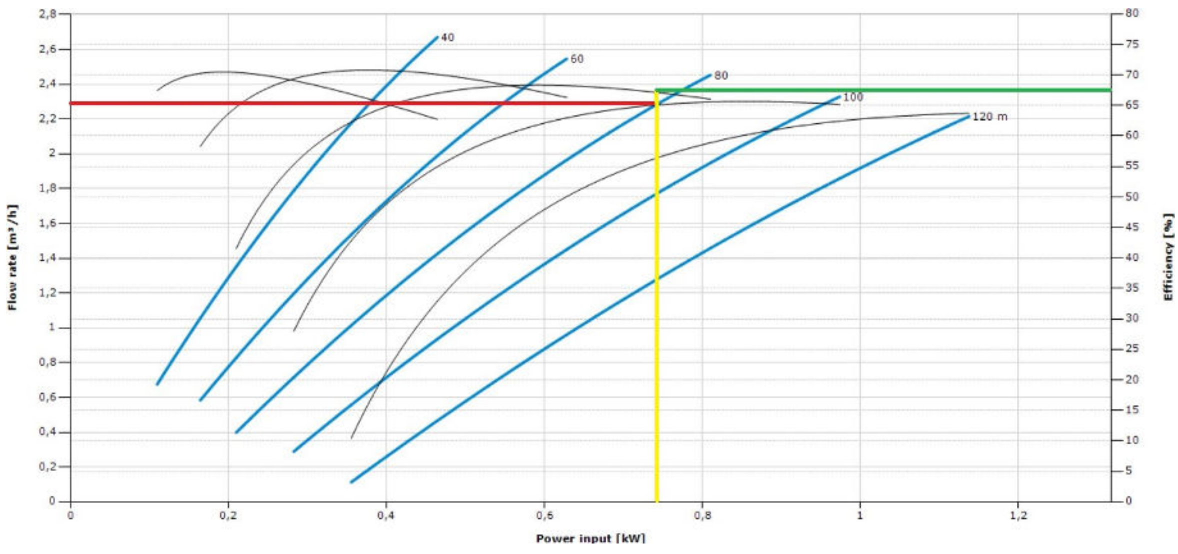
<table>
<tr><th>Name of pump</th><th>Pump chart and observation</th></tr>
<tr><td>Lorentz PS2 C-Cj5-8</td><td>This pump provides the correct yield – in the range of 2 m³/hr. However, one can see that the total head that the pump can deliver is about 20 meter. For this reason the pump is not suitable.</td></tr>
<tr><td colspan="2">


</td></tr>
<tr><td>Lorentz PSk2-7 – C-SJ17-9</td><td>This pump can provide the head as needed (appr. 80 meter). And it can also provide the needed yield. Yet at 2 m³/hr the pump would only have an efficiency of 13%. This would result in a very large solar array. Technically it is possible – but it would be an illogical choice. Moreover, the pump in not able to provide more than the 8 bar needed. Ideally – one chooses a pump that is able to provide a bit more than the design specifications of the piped systems to allow some room for unforeseen circumstances.</td></tr>
</table>

[18] Source: compass 3.1 Lorentz – including graphs showing performance of pumps



PS2-1800 HR-14H	This pump can provide a yield of 2.3 m³/hr at 80 meter hydraulic head. And can provide even more pressure if needed. The efficiency is about 63% at that working point. This is considered good. Given these characteristics – this pump seems to be the most logical pump of the 3.



Given the analysis above we opt for pump 3. The graph shows that the pump needs about 0.75 kW of power to operate. In order to determine the total need of solar panels we need to take into account the losses of the different parts in the system. In our calculation we assume:

- Electric loss: 5%. Equals 95% efficiency.
- Dust loss: 5% Equals 95% efficiency.
- Heat loss: 10%. Equals 90% efficiency.
- Control box loss: 2%. Equals 98% efficiency.

The total efficiency off the system therefore becomes: 0.95*0.95*0.90*0.98= 79%. The total array of the solar panels therefore need 750W/0.79= 950Wp.

As the location is north of the equator, the panels will need to face south. As the latitude is less than 15 degrees, the panels will need to be in an angle of 15 degrees.

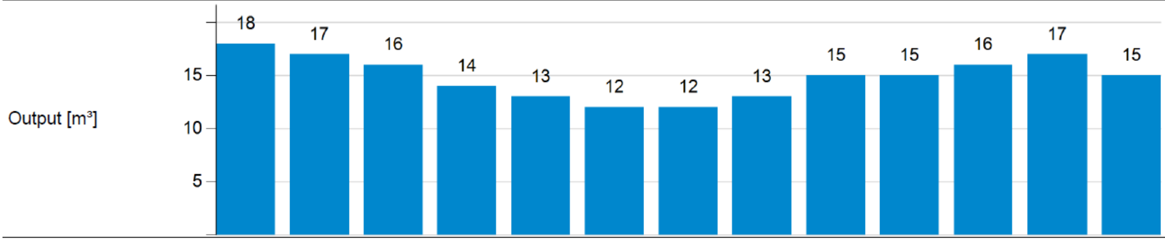
9.3 PUMP SELECTION AND SOLAR PANELS - USING SOFTWARE

By far, the easiest way to select a pump is using software from the pump suppliers. It, however, will need a basic understanding of the calculations behind it in order to select the right pump.

In this paragraph the results of the modelling software of Lorentz will be used. This software generally provides a list of possible pumps that can be used in the system. In this case the PS2-1800 HR-14H – that is also listed as a good candidate - was selected to show the differences in outcome.

The modelling software shows the following expected output[19] of the pump.

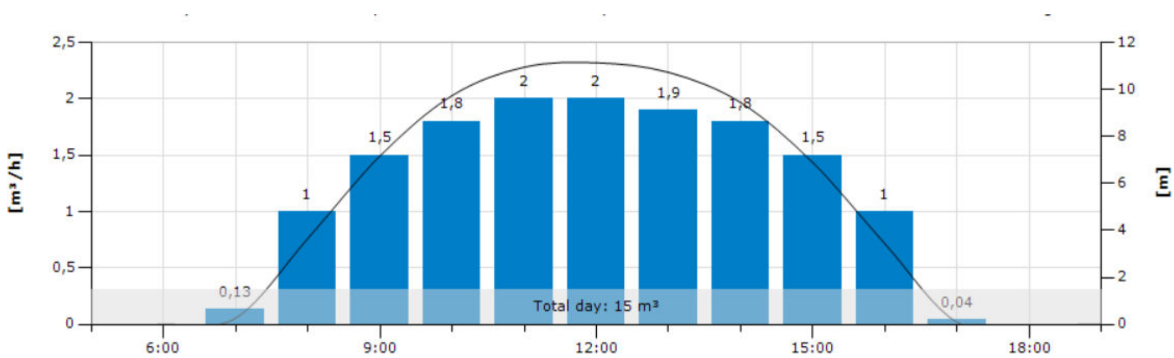
Daily output in average month **15 m³**



Daily values	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Av.
Energy [kWh]	5,7	5,7	5,1	4,6	4,3	3,9	3,7	4,0	4,7	4,8	5,1	5,5	4,7
Irradiation [kWh/m²]	6,8	6,8	6,0	5,4	5,0	4,5	4,2	4,6	5,4	5,5	5,9	6,5	5,6
Rainfall [mm]	0,37	0,90	2,1	4,2	4,7	4,5	5,0	5,8	5,1	4,7	2,5	0,83	3,4
Ambient temp. [°C]	27	28	26	24	23	23	23	22	22	23	24	26	24

As can be seen from the graph, the expected pump yield is slightly higher than the design data. An average 15 m³/day water production will result in less water during the wet season and a higher pump yield in the dry season.

The average daily water production (2 m³/hr) is close to the expected 2.3m³/hr water production during noon. Due to the lower flow, the head loss in the piping (right axis) is also less than our calculations.



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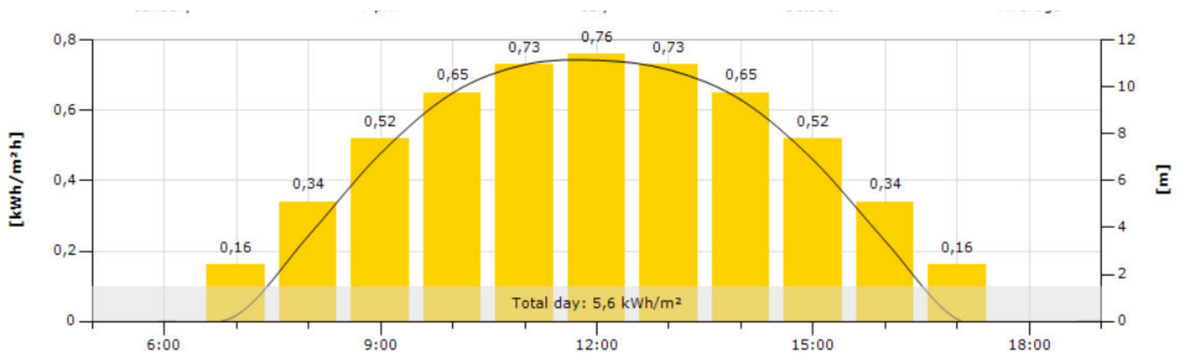
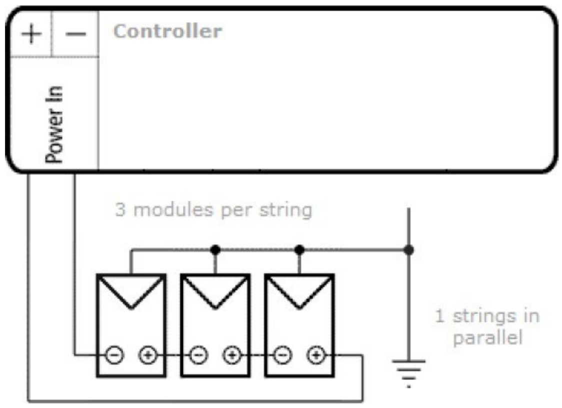
[19] Compass 3.1 of Lorentz

The reason that the water production is lower at noon is because the program expects less irradiation during this time of day. In our calculation we assumed 1 kWh/m2 with a 6 peak sunshine hours. The program expects on average 5.6 peak sunshine hours with that peak at around 0.76 kWh/m2. Here it becomes clear that the peak sunshine hour approach is handy and forms a good starting point. Yet it lacks the (assumed) accuracy of the software.

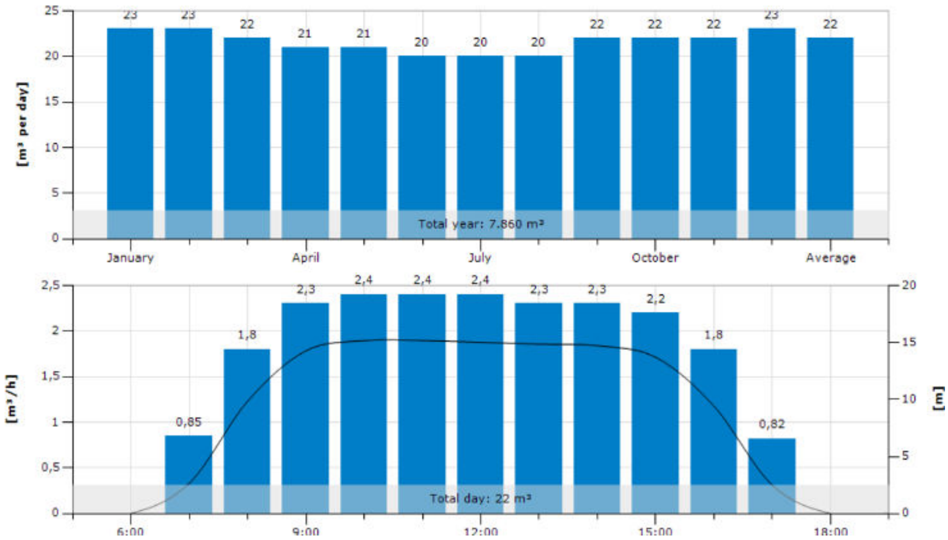


The program suggests 990 Wp of solar panels in series. The cable from the controller is suggested to be 6 mm2 3 phase cable



As can be seen from the modeling, the data changes slightly but not significantly. And the differences can be explained. By being able to understand what the software is modeling one gets a good grip on the outcomes.

The interesting part of using software to model the pump is that one can easily change parameters to see the effect. For example, if the water demand grows overtime one can simulate what will happen if one increases the number of solar panels. In this case, the amount of solar panels is increased to 1800 wp.



On can see that the pump yield in the afternoon hardly increases. The solar array is then overpowered. Yet this additional power allows the pump to provide more water during the early morning and late afternoon. Boosting the pump to supply about 20 m³/day.

9.4 TANK SIZING

The last step is the sizing of the tanks. This determines the design of the tower. The structural consequences (larger tanks need stronger and larger towers) can be found in the technical drawings.

The following table shows a way of estimating the needed volume of a storage tank. The assumed buffer is based on the consumer behaviour.

What	**Total consumption (peak – liters per day)**	**Consumption behavior**	**Assumed % of buffer needed**	**Calculated tank size/selected tank size (liters)**	**Closest tank size available**
Public point at well	3.000	Mostly during day	50%	1.500	2.000
School (students)	1500	During day	35%	525	1.000
Yard connections	375	Morning - evening	65%	240	300

Additional storage will increase the service level in terms of water availability as more water can be buffered for periods where the production is less than the consumption. This will however, also come with cost consequences as larger towers and tanks are more expensive.

10 COMMON MISTAKES – LESSONS LEARNED

To record some common pitfalls, we listed the following field experiences:

- **Mix of units**: a simple pump test had been done and it was recorded that the dynamic water table was 15 feet deep (about 4.5 meters). The pump was ordered based on that information. Once in the field the dynamic level proved not to be 15 feet deep but 15 meters deep! As a result, the pump provided considerable less water than intended.
    - **Lesson**: make sure to always work with the same units.
- **Safety**: a location for a water tower was picked next to a church under construction. Consumers started to complain a year after the construction of the church was finished that there was a lot of traffic causing safety issues.
    - **Lesson**: don't (only) assess the situation as it is now, but also take a future situation into account.
- **Location of tower:** the concept of the system was firmly explained to the head office of an NGO and the local crew set out to determine the location of the towers. In the end they placed the central tower inside the village and the second tower high up in the mountain. During the installation it was noted that the locations were not logical: the central tower was far away from the well and the second tower had no consumers nearby. When asked for the reasoning is became apparent the technicians wanted enough consumers for the central tower and use the second tower to serve as a buffer vessel that would feed the household connections by means of gravity.
    - **Lesson:** clearly, the technicians knew what they were doing and reasoned based on what they were used to do. However, this system works differently than conventional systems. Make sure all necessary information is transferred to the technicians in charge in the field. This includes: the central tower needs to be close (within 20m range) of the well to avoid cable losses. Furthermore, the system does not function with gravity to provide water to the households.
- **Theft:** fences with barbed wire were installed around the water tower. The tower was placed close to the compound of the caretaker. All to avoid theft of the solar panels. Within 5 months the panels were stolen.
    - **Lesson:** also take measures that people planning to steal the panels have to make considerable noise to do so. Weld the bots and nuts - that connect the solar panels to the frame – fixed. This ensures one needs a grinder of a hacksaw to steal the panels. Resulting in a lot of noise. Paint the name of the owner underneath the panels. One can also engrave your name in the aluminum frame.

- **Water price (1):** a tower was implemented at the moment the water price was not been determined based on expected cost. So ensure a good uptake the organization started with a low price with the option to increase the price once the population liked the system. That price increase never came as the population protested and threatened to vandalize the system.
    - **Lesson**: once you offer a service cheap, it is very hard to sell the same service more expensive at a later stage.
- **Water price (2):** a tower was implemented without upfront negotiation about the water price as this proved a taboo. The population was only informed it was a paid water service once the system was installed. In the end a very low water price was agreed upon and it became financially unsustainable.
    - **Lesson**: once a water system is installed, all the room for negotiation is gone. Do the negotiation upfront. If the population is not willing to pay a fair price, go to another location.
- **Orientation of solar panels:** solar panels were installed by a local contractor. They faced east. When asked why they faced east it was stated that all people come in the morning to drink. Therefore, the panels should face the sun in the morning. As a result, the pump didn’t produce the calculated amount of water during the day.
    - **Lesson:** on itself, the contractor had a valid point and gave it some good thought. However, the water tank should be sized as such that is buffers enough water for the consumption in the morning. By placing the panels in an optimal position, one assures the system as a whole functions in an optimized way, throughout the day. Ensuring that consumers have water in the morning as well as in the evening.
- **School**: a system was installed at a school compound. Once installed the problems started: there was no money and it was expected that the income of the water tower would pay for school events and latrine facilities. Resulting in a financial unsustainable situation.
    - **Lesson**: although the initial intentions might be good, clear and consistent communication upfront and written contracts need to be in place. Make sure that, although there might be a water need, the consumers are able and willing to pay for a service. In the case of the school, a reliable income was missing to pay for the water. And the school envisioned the water tower as a source of income rather than an expenditure.