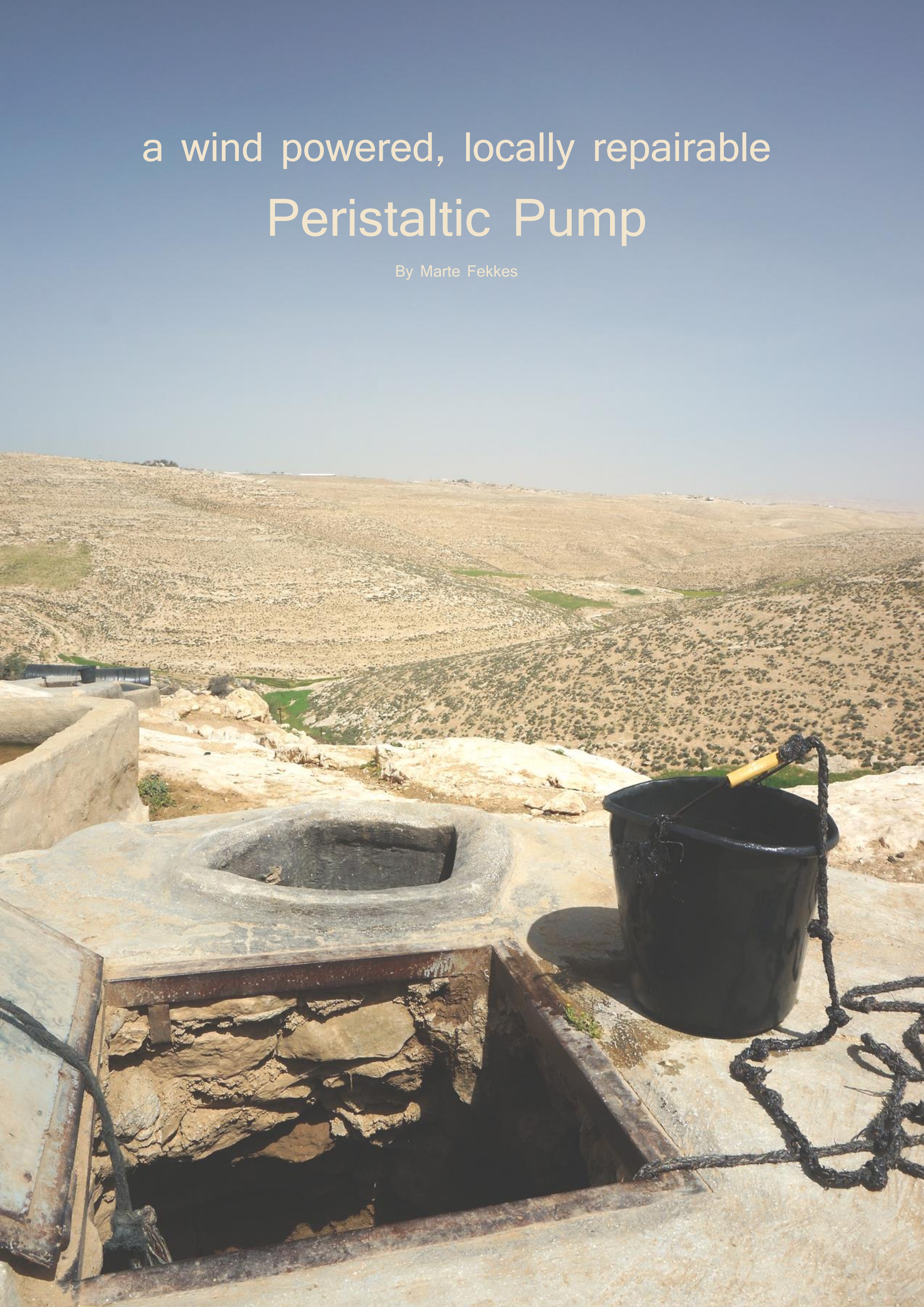
a wind powered, locally repairable

Peristaltic Pump

By Marte Fekkes



Marte Fekkes

Master Thesis:
"A sturdy wind-powered rotary displacement pump suitable to Developing Regions (field case Palestina)"

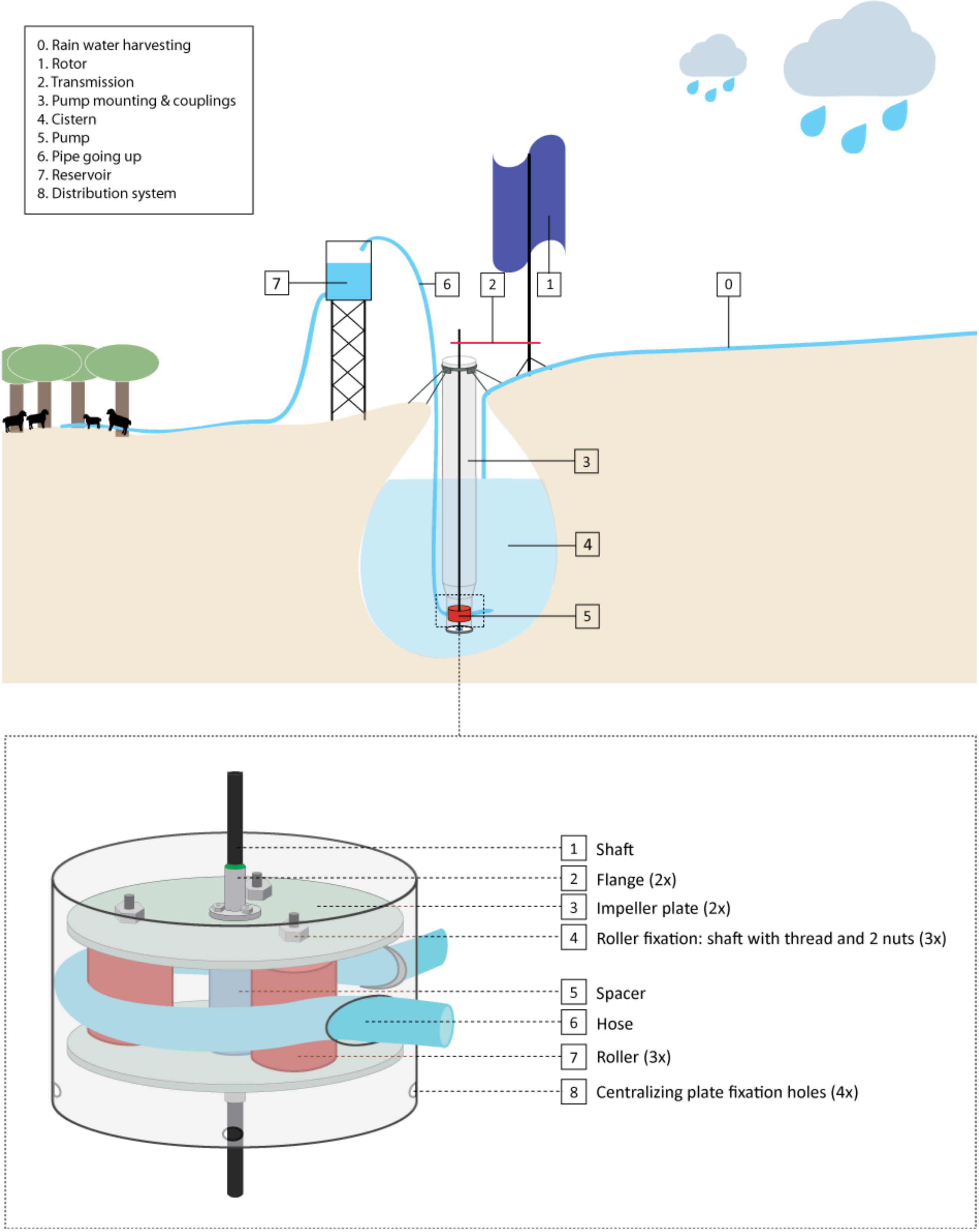
Master of Science "Integrated Product Design"
Faculty of Industrial Design Engineering
Delft University of Technology

December, 2015

Master Thesis Chair:
Dr. Ir. J.C. Diehl

Mentor:
Ir. Henk Kuiper

TU Delft


0. Rain water harvesting
1. Rotor
2. Transmission
3. Pump mounting & couplings
4. Cistern
5. Pump
6. Pipe going up
7. Reservoir
8. Distribution system
7
6
2
1
0
3
4
5
1 Shaft
2 Flange (2x)
3 Impeller plate (2x)
4 Roller fixation: shaft with thread and 2 nuts (3x)
5 Spacer
6 Hose
7 Roller (3x)
8 Centralizing plate fixation holes (4x)

I. Executive summary

This project describes a water distribution system that implements a peristaltic pump, for the Palestinian Communities in South Mount Hebron. These communities currently use buckets to transfer water from the wells to their homes, their herd or their fields. This labour intensive process effectively restricts the amount of wells they are able to access, and causes them to feed the herds close to the well. The herds' defecation consequently scatters in the wells area, polluting the water. Simultaneously, imported pumps have proven useless: their fuel is dispersed and expensive, and repair is beyond the local capabilities. The goal of this project was thus to design a *wind powered* and *locally repairable* pump that makes it *easier* for these communities to access water, and thus enables them to access *more* and *cleaner* water.

In situations similar to the Palestinian one, the rope pump is currently prevalent. The rope pump however requires a complex production process to ensure its life time. The peristaltic pump is simpler, because it implements a hose: this hose acts as an elastic seal and lowers the necessity for high production precisions. The peristaltic pump could thereby solve the rope pumps production issues.

To set the requirements for the pump and its mounting, the Pump Handbook (Karassik, 2008) and VLOM ("Village-level operation and maintenance") theory were used. VLOM theory states that the operation and maintenance of pumps can be performed on the village level. Such an approach reduces the dependency of villages on governments and donors (Coloru, Mgaya, & Taubert, 2012). This led, among others, to a manufacturing process that uses off-the-shelf tools and a pump that is repairable without the use of power tools. The Pump Handbook provided an overview of field conditions that influence the design of a pump. This led to a design that can withstand debris in the water, dry-running and corrosion.

A wind pump is a careful balance between rotor and pump operation. The pumps flow rate is dependent on the wind speed, but has to amount up to the water demand of the users. This implies that the rotor has to spin fast and often enough, while being held back by the torque that results from the water being pushed upwards. To optimize this balance between rotor speed and torque an algorithm was made, that iterates several torques to find the one that maximizes the rotors energy generation over time. The result of this method has rendered 35% more energy than the conventional method, which is designed to peak in energy generation at the average wind speed (Rijs & Smulders, 2006).

Using the found requirements, a range of pumps typically encountered in industrial projects (Grundfos, 2015; Karassik, 2008) and development projects (Fraenkel & Thake, 2006; Appropedia, 2015) was evaluated. This rendered four interesting pump types. The peristaltic pump was chosen to develop further, as it (as said) improves on the production precision issues that were discovered to limit the rope pumps implementation, and it was found more reliable than the rotary diaphragm and stationary vane pump.

The result of the design process is a water distribution system that uses the wind to pump water to a reservoir, from where it can be gravity-fed onwards. The system incorporates a three-roller peristaltic pump, with a 2mm thick hose and no add-ons. The pump is mounted at the bottom of the well by a pipe that is fixed to the terrain. Sleeves, that are used to connect the pipe pieces, incorporate centralizing plates that hold the shaft in place. As such, both the housing and the shaft of the pump are stable at the bottom of the well, and the complete installation can be (dis)mounted from the ground level.

A prototype of the pump was made and tested. It pumped 4,2L/min at a rotational velocity of 100RPM, with a 10m head and 2,2Nm torque. The prototype did not run stable yet; the hose would get dragged along by the rollers, creating a shock-like behaviour. This problem can be solved by implementing a thicker hose and connectors that push the hose against the housing. This would also improve the pumps flow rate.

In this stage the pump is not ready for implementation in Palestine. Continuation of the project would involve another design iteration, and consequently in-field prototyping and testing. Testing thereby involves its operation with a rotor, its life time, local production, and measurement of the impact on the lives of the Palestinian communities.

If successful, the peristaltic pump would be very promising to the developing world: the easiest to produce, with an excellent match to a wind rotor, and thus able to independently irrigate fields and fill water basins. From the basins users can use a siphon, rather than a bucket. Water could be accessible all day, close to homes and effortless.

II. Variables

General

ρ_{air}	The airs density	kg/m³
ρ_{water}	The waters density	kg/m³
g	The gravitational acceleration constant	m/s²
v_{wind}	The wind speed	m/s
n_{days}	The amount of days in the time interval	#

Cistern

$V_{cistern}$	The cistern size	m³
$V_{harvested}$	The volume of harvested rain per year	m³/year
$V_{outflow}$	The volume of water taken out of the system on a daily basis	m³/day
$A_{catchment\ area}$	The area of the catchment area	m²
$\eta_{catchment\ area}$	The catchment run-off coefficient	%
$h_{yearly\ rain}$	The height of rain that falls over the year	m
$Q_{daily,dry\ season}$	The summer daily flow rate	m³/day
$n_{drydays}$	The amount of subsequent dry days	#
$Q_{daily,wet\ season}$	The wet seasons daily flow rate	m³/day
$n_{wetdays}$	The amount of subsequent rainy days	#

Rotor

P_{rotor}	The rotors power output	J/s
A_{rotor}	The surface that the rotor covers	m²
Cp	The rotors power factor	%
$P_{rotor}(t)$	The rotors power output as a function of time	W
$P_{rotor}(v_{wind})$	The rotors power output over wind speeds	W
$\omega_{rotor}(v_{wind})$	The rotors rotational velocity as a function of the wind speed	rad/s
T_{design}	The optimized torque on the rotors shaft	Nm
$\eta_{\mathrm{system}}[i]$	The system efficiency of that iteration [i]	%
i	The transmission ratio	#/#

Pump

$Q_{pump}(t)$	The pumps flow rate over time	m³/s
$Q_{pump}(v_{wind})$	The pumps flow rate over wind speeds	m³/s
ω_{pump}	The pumps shaft speed	rad/s
T_{pump}	The torque on the pump shaft	Nm
$F_{pressure}$	The force required to push the water up	N
$F_{squeeze}$	The force required to move the squeeze forward	N
$T_{frictions}$	The torque lost in frictions on the shaft and roller axes	Nm
R_{pump}	The diameter of the pump	m
A_{pipe}	The cross-section surface of the pipe going to the reservoir	m²
H	The pumps head	m
P	The pressure in the pipe going to the reservoir	Pa

Hose

L_{path}	The length of the path that the hose follows within the pump	m
$L_{around\ roller}$	The length of the path where the hose wraps around the roller	m
$L_{between\ rollers}$	The length of the hose between rollers	m
OD_{roller}	The outer diameter of the rollers	m
A_{hose}	The hoses inner cross-section surface	m²
WT	The hoses wall thickness	m
ID	The hoses inner diameter	m

III. Table of contents

Introduction

Requirements

Water & Energy Flows

Pump Selection

Design

Tests & Evaluation

1. Introduction

Water is essential for health, food production and economic growth (UNESCAP, 2006), and therefore considered a fundamental human need that as a matter of right should be provided for all (UNCESC, 2002). Still, inadequate water access negatively affects the lives of four thousand farmers in South Mount Hebron, Palestine. This project, a graduation design thesis at TU Delft, shows a way to address their inadequate water access. In this chapter the problem statement is outlined, and the resulting project goal and approach are described.

1.1 Problem statement

1.1.1 Water harvesting and distribution

There is a water shortage in South Mount Hebron, Palestine. Water and fodder (grass for the herds) had in 2012 already become scarce to a point where families had to spend a third of their income to buy it. Many ended up impoverished and indebted; dependent on humanitarian aid (Hartman, 2012).

Studies in the region show that this water shortage can be addressed by improving the water infrastructure (Flatejord, 2012; Brand, 2013; Short & Thompson, 2003). Palestine features an annual rainfall similar to London, but it comes with a higher seasonality (World Bank Group, 2013) (UK Met Office, 2013). There is ample water, as long as enough of this rain is harvested and distributed. In Palestine a proper water infrastructure thus constitutes of water harvesting *and* distribution.

A distribution system is the missing link in this water infrastructure (Brand, 2013; Short & Thompson, 2003). The water harvesting system functions well. Troughs guide rain water from the hills into caves, where it is stored. These water storage caves are called cisterns. Distribution from the cistern to the users is done using buckets. Each cistern is supplied with a bucket on a rope to lift the water up, from where it is transferred by other buckets to the various usage points. This bucket distribution method is problematic, for two reasons.

1.1.2 The bucket system

The bucket system is first of all labour intensive, which effectively restrains the use of additional cisterns. The current bucket system takes so much time that using extra cisterns is beyond the communities reach. Yet, if more cisterns were to be used this would address the economic burden described in the first paragraph.

Figure 1 shows the Palestinian scenery, barren dry at the end of the dry season. The figure gives an overview of possible locations for extra cisterns that could be used if a more advanced distribution system than buckets was available. There are three possible places where a water distribution system is useful:

- In the hills, near the communities. A water distribution system is useful where the community lives higher than the cistern; the location of their homes and the cistern is decided by the location of existing caves. This would not provide extra water directly, but save time that can then be spent on accessing new water resources.

- On the more horizontal parts of the hills, extra cisterns could be used to irrigate the land. For irrigation one needs a small slant, so the water soaks in to the ground rather than running off it. Such a small slant cannot be irrigated using gravity, as the height difference does not provide enough pressure to distribute the water evenly. It thus requires a powered water distribution system. Rather than letting all the water flow to the valleys and into the soil immediately, less slanted parts of the hills could be kept green throughout the year. This would save the communities money that is now spent on fodder.

Figure 1: Possible locations for the pump

- In the valleys cisterns could be used to contain water that is now seeping into the ground too quickly. This would make water available for the herds, lowering their share in the community cistern, and making extra water available. This saves the communities money that is now spent on water.

The bucket system second problem is that it affects the water quality. An average herd drinks 200 buckets daily (Brand, 2013). To avoid water transport labour their drinking basin is usually within reach of the cistern (Figure 2). Due to this proximity of the herd to the cistern, defecation is scattered in the cistern area. When it rains it washes into the cistern, contaminating the water to a level where it poses a threat to human health. It is the primary reason for diarrhoea amongst children (Al-Salaymeh, Al-Khatib, & Arafat, 2011).

Figure 2: Fetching water to the herd, the herd surrounding the cistern.

1.1.3 Conclusion

To summarize the above an improved distribution system:

- Saves time spent on fetching water;
- Lowers or avoids contamination of water by the herds' poo;
- Increases the amount of water they can distribute, and with that opens access to more cisterns and thus more water.

To address these 3 goals, a distribution system should at least bring the water from the cistern to an elevated tank. From there, the water can be gravity-fed onwards to its usage point: the community, a separate drinking basin for the herd and/or a field of crops or fodder.

Figure 3: Woman carrying water to the community

1.1.4 Previous efforts

Efforts to improve the water distribution system were already made. These previous efforts included importation and installation of industrial pumps. They were however unsuccessful, due to two reasons. These will be explained below. These two reasons are this projects starting point, providing direction for the design.

The first reason the industrial pumps proved to be unsuccessful is the fact that they could not be repaired locally (Brand, 2013; Flatejord, 2012). When broken, they would be abandoned. There is thus a need for local repair possibilities: a design that matches the local skills and tools.

The second reason is that the imported pumps were powered by fuel, which is an expensive and dispersed energy source. The pumps would often stand still for months due to a lack of money and/or time to acquire the fuel. A pump should be able to work as a stand-alone, off-grid unit that does not require effort or money for operation. This implies using solar or wind energy to power the pump. These do not require fuels for operation and are thus free after the initial investment. Human interference with the installation can be downscaled to maintenance. There is thus a need for a distribution system implementing a renewable power source.

That renewable power source can be defined more precisely. Of wind and solar energy, the wind rotor requires a smaller investment. Solar panels require a production process and materials that are highly complex. A rotor can be manufactured and repaired with widely available tools and materials, in accordance with the need for local repair described above. Earlier work in the region thus concluded that "*Wind pumps could easily be assembled and maintained using the materials and skills available in the villages and cities, which makes them an attractive option for a truly sustainable solution*" (Short & Thompson, 2003).

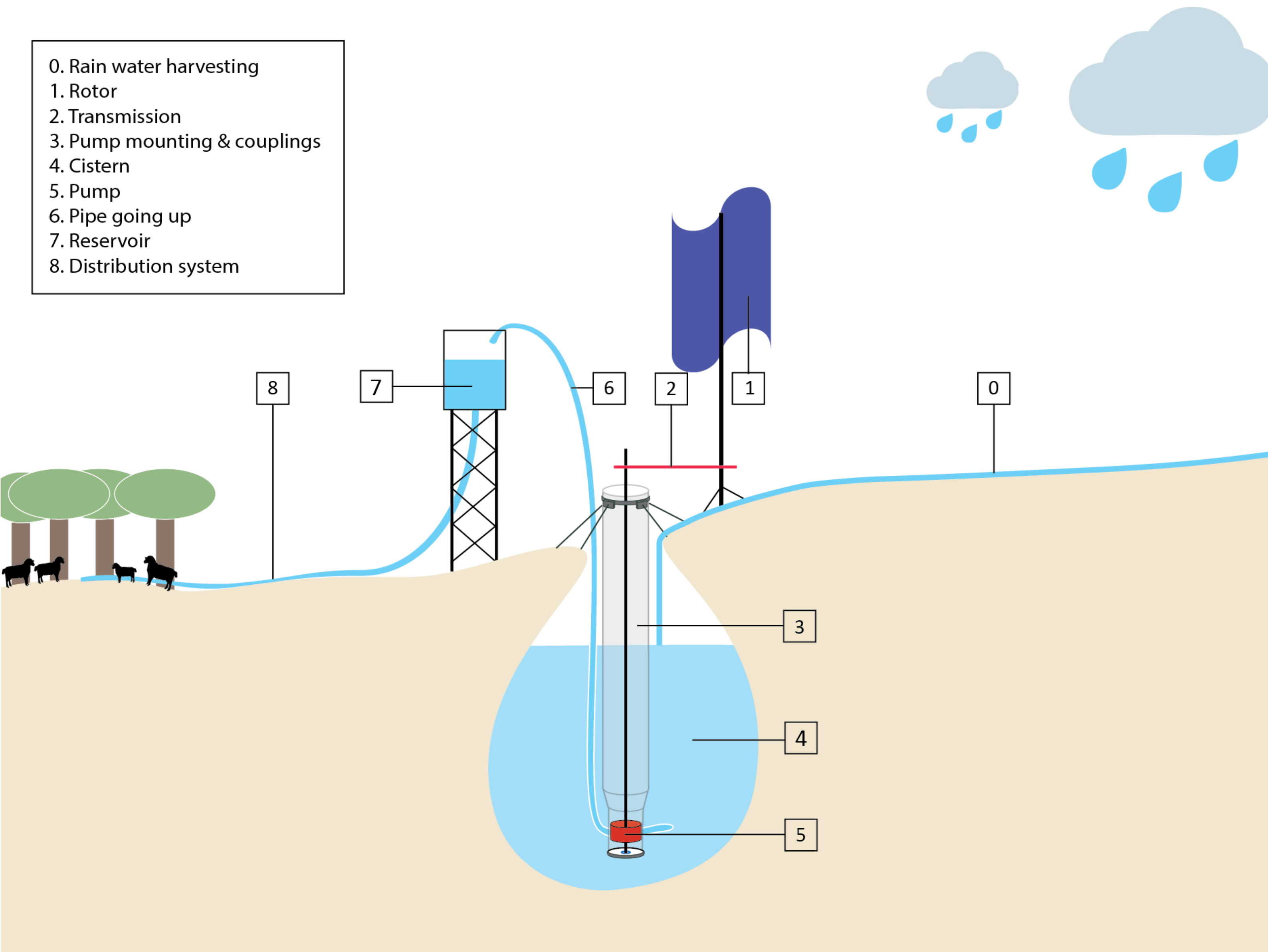
1.1.5 The envisioned system

Figure 4 depicts the envisioned water distribution system, resulting from the reflections above.

This water distribution system (Figure 4) consists of:

- The rotor, generating energy from the wind;
- A transmission, translating the rotation of the rotors shaft to that of the pumps shaft;
- The pump, translating the power in its shaft to pressure;
- The pipe or hose going up to the reservoir, bringing the water up;
- The reservoir, facilitating a match between irregular consumption (for herd, community and/or irrigation) and the wind-dependent flow rate from the pump;
- The gravity-fed distribution hoses or pipes; bringing the water whenever required to the community, herd or fields. This is where the communities can control the water flow: they can open and close the pipe or hose at their will, using e.g. taps or kinks in the hoses.
- One hose (not drawn in the figure) reaches from the top of the reservoir back into the cistern to avoid loss of water through spill overs.

Figure 4: System Overview



1.1.6 Scope

Within this system the highest design priority lies with the pump. Each of these components of course plays its part in the distribution, and all of them will have to be designed. Some elements are however so ubiquitously present in Palestine, that they can be acquired locally when the rest of the system has been defined. This includes the transmission, piping, hoses and reservoir. This project will not focus on them. Furthermore a partner was found interested in implementing their rotor. NGO Comet-ME is developing locally producible rotors. They have successfully implemented dozens of wind turbines, and are developing rotors for direct mechanical coupling (Comet-ME, 2015). The envisioned system will use one of their rotors. The focus of this project thus lies on designing the pump.

1.2 Project goal

The goal of this project is to design a wind powered and locally repairable pump that makes it *easier* for the communities of South Mount Hebron, Palestine to access water, and thus enables them to access *more* and *cleaner* water.

1.3 Project approach

To fulfil this goal the project is divided into four phases: (1) setting up the pumps requirements, (2) selecting a pump type, (3) developing its design to match the context, and (4) evaluating the resulting design to the initial project goal. These four phases are described here.

1.3.1 Pump requirements

A list of requirements is used for the pumps selection, design and evaluation. In accordance with the projects goal the requirements analysis considers the following three topics:

- Pump properties: How the pumps performance meets the communities' needs and context,
- Local repair: How can local repair be translated to requirements,
- Wind power: How can the pump-rotor combination be optimized.

In the report these requirements are split into requirements that do not require calculation, and the requirements that do require calculation. The report thus has a section on "Requirements", consisting of the pump properties and local repair requirements, and a section on "Water and Energy Flows", consisting of the calculations regarding the water and energy flows following the pump-rotor combination. After these two parts the full program of requirements is repeated.

1.3.2 Pump selection

According to a classification system of the Pump Handbook (Karassik, 2008), pumps can be classified in two phases: the first phase contains different working principles by which the pump translates energy to pressure and flow. The second phase contains pump types that depict different configurations by which this is done. A pump type is selected following these two phases, by comparing the various options of each phase to the requirements. After selection the pump type is developed further in the design chapters.

1.3.3 Design

The design chapter makes the pump type into a design. The chosen pump type is elaborated to a level of materials and dimensions.

As literature on the chosen pump types is scarce, this study combines literature with market research, expert interviews and rapid prototype experiments. A study of the various options within the pump type reveals the relation between design variables and performance. Together these render the required knowledge.

Consequently the studied performance – design relations are used to design the pump for the specific requirements of this project. This design is made tangible by a prototype.

1.3.4 Evaluation

The prototype is used to test the designs performance quantitatively and qualitatively. These tests evaluate the design to the requirements and its competitors. This provides a clear insight to the performance and promise of the design. Lastly, the evaluation and design chapter together render a set of recommendations for further improvement.

1.3.5 Project outcome

The result of this work will be the analysis and resulting first design of a pump for the Palestinian communities. Insight to the specific conditions and their influence on the design is gained. Which information is relevant to who is explained in the next section: the guide to readers.

1.4 Guide to readers

This project can be interesting for a number of people; (a) those that design water systems for the developing world, (b) those that make policy surrounding water in the developing world, (c) those interested in specifically wind pumping and (d) those interested in Do It Yourself pumping. Table 1 gives an overview of which chapters are interesting to whom.

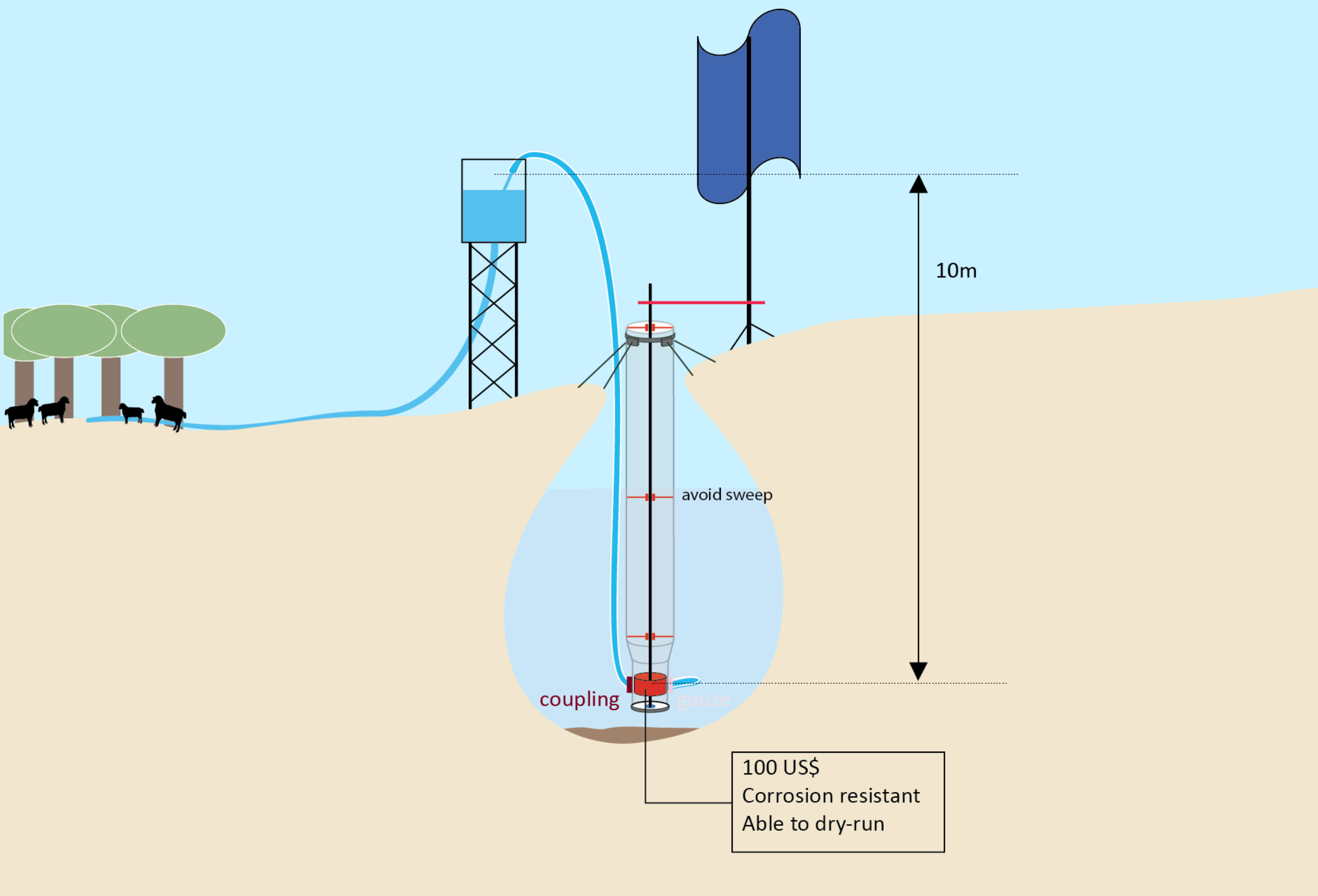
Table 1: Guide to readers

Phase	Section	Page	For Groups
Requirements	Pump Properties	p. 12	(a) (b) (c) (d)
	Local Repair	p. 16	(a) (b) (d)
Water & Energy Flows	Water Flow	p. 22	(a) (c) (d)
	Energy Flow	p. 28	(c)
	Water & Energy	p. 38	(a) (b) (c)
Pump Selection	Pump Selection	p. 46	(c) (d)
Design	Mounting Design	p. 62	(a) (c) (d)
	Pump Design	p. 74	(a) (d)
	Design Overview	p. 91	(a) (b) (c) (d)
Tests & Evaluation	Tests	p. 98	(c) (d)
	Evaluation	p. 119	(a) (b) (c) (d)

Requirements

The project approach (p. 7) showed that designing a wind powered, appropriate pump requires an analysis on three aspects: pump properties, local repair and wind power. The chapters here treat the pump properties and local repair aspects. Combined with the chapters on Water and Energy flows all necessary information for the pumps program of requirements is gathered. These requirements are used in later stages to choose the pump type, develop and evaluate it.

Figure 5: Overview of system with requirements



2 Pump Properties

The project approach (p. 7) showed that designing a wind powered, appropriate pump requires an analysis on three aspects: pump properties, local repair and wind power. This chapter treats the pump properties. Combined with the chapter on Local Repair and those on Water and Energy flows all necessary information for the pumps program of requirements is gathered.

2.1 Methodology

The pump properties and local repair aspects are quantified to the local context. Literature about the communities in Palestine is ample. These sources include (Brand, 2013), (Flatejord, 2012), (B't Selem, 2013), (Hartman, 2012) and (Comet-ME, 2011). Their experience relates to the social impact of water, what pump properties should be reached to affect impact and local production capacities.

2.2 Typical pump properties

The Pump Handbook is an authority when it comes to pump design and application (Barnes & Noble, 2007; Arora, 2011). It offers all properties one could keep in mind when designing a pump, including those for industrial purposes. To define the factors relevant in the developing world an interview with expert Adriaan Kragten was conducted. Adriaan Kragten is a developer of wind turbines and pumps for developing countries, previously at TU Eindhoven and now privately. This led to the following properties:

- <u>Head</u>: required pressure to transport the water, expressed as a height (in meters).
- <u>Flow rate</u>: amount of water transported per time period. This can be cubic meters per day, litres per minute, cubic meters per hour, et cetera. For communities it is common to assess how much water is used per day. The reservoir enables them to take water according to their preference, which on a daily basis totals to a stable, reliable amount. From the communities' point of view, the requirement for the pump is thus that enough water is available for them each day. From the viewpoint of pump designers it is however common to assess how much water it pumps per minute, dependent of its speed and/or head. A translation between these different ways of expressing the flow rates is required.
- <u>Suction head</u>: a pump is called self-priming when it can suck the water up from a certain depth. This depth is called the suction head and is expressed as a height in meters.
- <u>Debris</u>: presence of sand or little rocks in the water that cause abrasion.
- <u>Water quality</u>: water properties that might damage a pump or pipe, like corrosiveness.
- <u>Dry (empty) running</u>: if a pump is able to dry run it does not rely on the pumping fluid for lubrication.

- Intake and outlet configuration: how the pump is coupled to the rest of the water system.
- Shaft configuration: how the pump is coupled to the power source.

Besides these water transport properties the obvious limitation for any pumping system is:

- Available money / price of the installation

This excludes some properties from the Pump Handbook (Karassik, 2008). The excluded properties are: presence of entrained gases in the pumping fluid, hydraulic losses in the piping system, multiple modes of system operation, type of pump control, precise flow adjustment ability, necessity for design standards such as API and ISO, fluid characteristics such as viscosity, density et cetera, and required pump materials. These properties indeed seem irrelevant for a stand-alone system distributing water. They will be disregarded here.

2.3 Pump properties in the field case

Now that the pump properties are named, they can be translated to performance requirements for the field case. Each property is shortly introduced, followed by the relevant aspects of the field case and how it affects that property. This leads to a performance requirement for the pump. In later stages these are used to choose the pump type, optimize its design and evaluate the outcome.

The flow rate property is excluded from this chapter, but mentioned in the 'Water and Energy Flows' part of this report. The flow rate property directly relates to the calculations done on the pumps energy flow from the rotor. It was deemed more understandable if all these aspects were described together.

2.3.1 Head

The head is the pressure the pump provides expressed in meters height. As described in the problem statement (p. 7), water is pumped from the cistern to a reservoir. The minimum head is thus the distance between the cisterns bottom and the reservoir, plus a safeguard for friction losses.

The maximum cistern depth is 7m (Brand, 2013). The reservoir sits on a tower high enough to gravity-feed the water to the domestic space, herds or fields. A standard tower of 2m high is sufficient, as it can distribute water up to 30m far (Engineering Toolbox, 2015). Friction losses are estimated to 1m. The minimum pump head is thus 10m: 7m cistern depth, 2m reservoir tower and 1m friction losses.

2.3.2 Suction Head

A pump is called self-priming when it can suck up water from a certain depth: the suction head. Before water enters the pump, the pump would need to pump air to create enough under-pressure to suck the water up. As air is 830 times less dense than water, one can imagine how fast air leaks in relation to water. In other words: to pump air the pump will have to be produced many times more precise than when it only needs to pump water. As production precision is such an important factor (refer to local repair chapter, p.18), it was decided to submerse the pump in the water. This way the water will flow into the pump automatically. No suction head is required.

2.3.3 Debris

The debris property considers the amount and size of particles in the water that the pump can manage without being damaged through abrasion. In the field case the pumped water is rain harvested from the catchment area. As the environment is rocky and sandy, this debris will end up in the cistern. Though it sinks down, just after rainfall it will still revolve in the water (Brand, 2013). The pump should be able to manage small debris and sand, and include a gauze at its inlet for bigger particles, like rocks.

2.3.4 Water quality

The water quality for a pump describes water properties that can damage the pump, like corrosiveness. Corrosion of a pump weakens its metal components. A variety of different pumping fluids and the specific environment can induce corrosion of a pump. These include (Grundfos, 2015):

- pH
- Oxidising agents (such as oxygen)
- Temperature
- Concentration of solution constituents (such as chlorides)
- Biological activity
- Operating conditions (such as velocity, cleaning procedures and shutdowns)
- Chemicals.

Of the mentioned causes for corrosion, only the pH is relevant in the field case. Temperatures in Palestine are high, and the presence of herd poo creates some biological activity, but not to a relevant extend.

According to a study of 100 cisterns in the region, the water features pH values from 7.32 to 8.97 with a mean value of 8.16 (Al-Salaymeh, Al-Khatib, & Arafat, 2011). A pH of 8.97 would create ‘Moderate Scale Forming’ on metals that are constantly in contact with the water, and require water treatment or a protective coating (Oram, 2001). The pump should feature materials that are corrosion resistant or coated.

2.3.5 Dry running

If a pump is able to dry run it is independent on the pumping fluid for lubrication. For the field case where the pump is submersed in the cistern, dry running happens when the cistern runs empty. In the flow rate section it will be seen that a cistern is likely to run empty during the summer months (p. 25). The pump should be able to dry-run for the moments this happens.

2.3.6 Intake and outlet configuration

The intake and outlet of a pump depend on how it is coupled to the rest of the water system.
For the field case the pump will be submersed in the water. The debris section showed how it requires a gauze at its inlet to keep out larger rocks. Besides the gauze the inlet can be open, as there is no need to connect a pipe or hose there. The outlet however should provide a coupling to a hose or pipe going up towards the reservoir.

2.3.7 Shaft configuration

The shaft configuration depends on how the pump is coupled to its power source. The pump is submersed in the water, at the bottom off the well. The ingoing shaft from the rotor will thus be rotating, and long. Sweep is the ‘swinging’ of long rotating shafts and should be avoided.

2.3.8 Price

The price of the system should match the local circumstances and possible business models (Polak P. , 2011). The problem statement showed how the communities in the field case have to buy water, and how that has left them perpetually indebted (Hartman, 2012). Their water accessibility will not improve if the pump is more expensive than buying water. The pump lowers the amount of bought water; the next three paragraphs will translate this to a maximum price.

The flow rate section will show how a cistern can harvest more than two times its own volume (p. 23). A pump could optimize the water demand and water supply to harvest all of this water. The problem scope section furthermore showed a pump could be used to access a new cistern, where previously this was too time-consuming. These two scenarios combined make it safe to assume the pump could provide at least half of one cisterns volume extra per year. Half a cisterns volume amounts to 46 cubic meters (Brand, 2013).

This volume can be translated to the water costs the pump prevents. When the communities run out of water, they buy it from private contractors that import water using trucks. The price of water purchased from such private contractors is NIS 25 to 40 per cubic meter, depending on the distance from the water source to the village (B't Selem, 2013). Assuming the cheapest price off 25 NIS, half a cisterns volume in water thus costs at least 1150 NIS, or 300 US$ per year.

Assuming a return on investment period of one year seems probable in Palestine, due to the poverty of the communities and instability of the political situation. The 300 US$ that can be saved on a yearly basis should thus pay for the water distribution system. The rotor, transmission, filter, tank and pipes are estimated to cost 200US$ (Dotan, Wind rotor types and decision, 2013). This leaves a rough 100US$ for the pump.

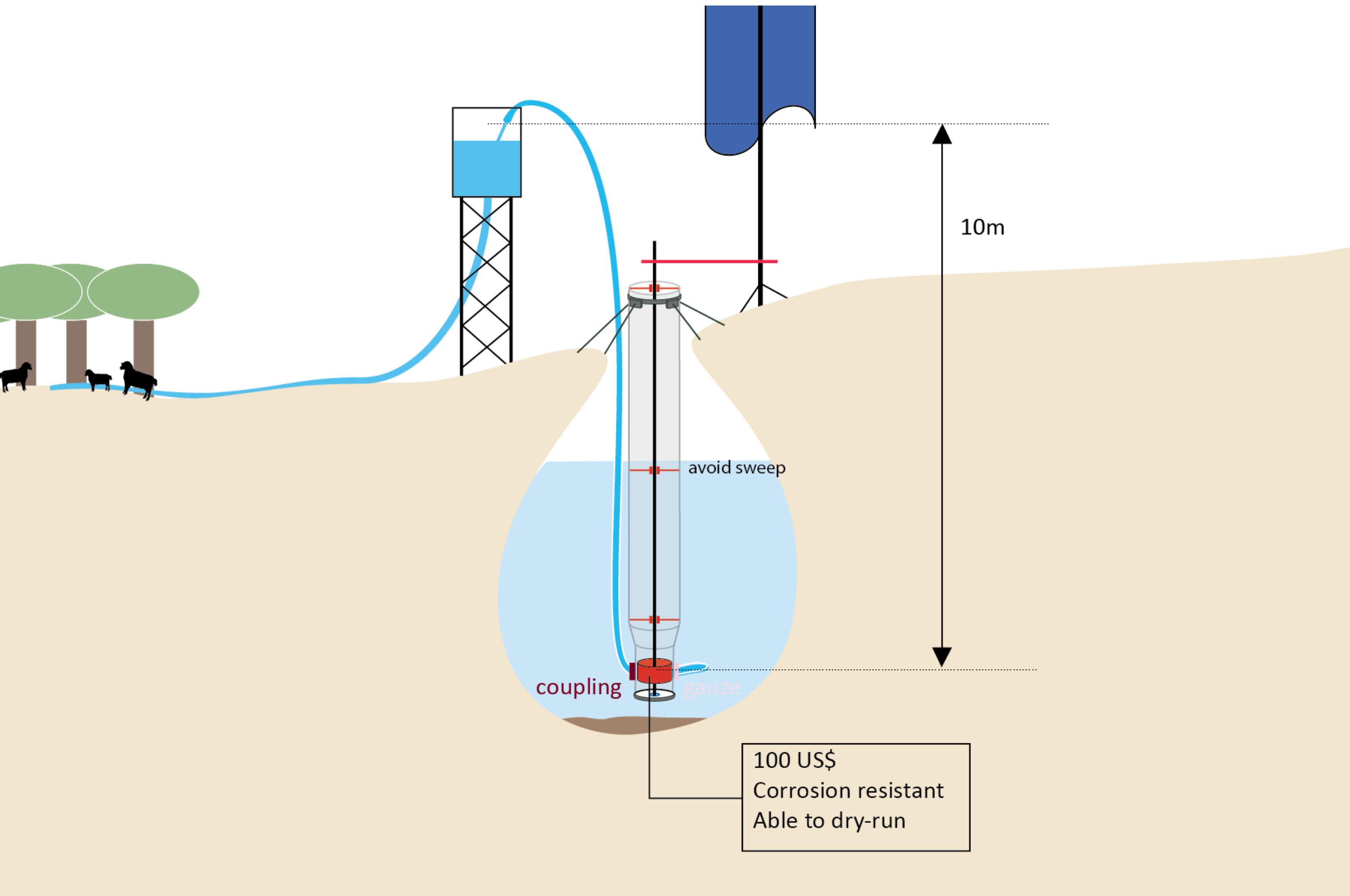
2.3.9 Overview

All pump properties are now quantified. Table 2 and Figure 6 give an overview.

Table 2: Pump properties required for the communities in South Mount Hebron, Palestine

Property	Field case
Head	10 meters
Suction head	0m, pump is submersed
Debris	Pump should withstand sand and little rocks
Water quality	Pump materials should withstand corrosion or be coated
Dry running	Pump should be able to dry run
Intake and outlet configuration	Open inlet with a gauze, coupling to a pipe or hose at the outlet
Shaft configuration	Ingoing shaft is rotating and long, sweep is to be avoided
Price	<= 100US$

Figure 6: System overview including requirements



3 Local repair

As described in the problem scope previous efforts to import industrial pumps were unsuccessful, as they could not be repaired locally (Short & Thompson, 2003). This chapter thus starts with an explanation of the approach to facilitate local repair, called Village Level Operation and Maintenance (VLOM). In the next section this theory will be translated to requirements for the field case.

3.1 VLOM theory

"Village-level operation and maintenance" (VLOM) theory states that operation and maintenance of pumps can be performed on the village level. Such an approach reduces the dependency of villages on governments and donors and relates directly to the local repair sought in the problem statement (p.1). A VLOM pump would need to be (Arlosoroff & al, 1987):

- Easily maintained by a village caretaker, requiring minimal skills and a few tools;
- Manufactured in-country, primarily to ensure the availability of spare parts;
- Robust and reliable under field conditions; and
- Cost effective.

Years of experience consequently revealed that communities still rely on outside support for major repairs and spare parts. Thus, pump standardisation and privatisation of spare parts supply networks are currently considered pivotal issues (Coloru, Mgaya, & Taubert, 2012).

3.2 Local Repair in the field case

This section analyses how the above translates to the field case. This is done by the criteria found above. Cost effectiveness, robustness and reliability were treated in the pump properties section and will not be repeated here.

3.2.1 In- country manufacture

In-country manufacture relates to materials, parts, and production. Palestine is a land where not much grows. 'Local materials' are thus restricted to locally imported materials. These are sold in cities like Hebron. Though buying materials or parts would benefit these sellers, a higher importance is given to production labor on the village level, to boost the local economy. If beneficial for e.g. a products life time or effectiveness one should utilize imported materials and parts.

Field analysis performed by Brand (Brand, 2013) shows that the communities know how to work with cement, molding, painting, and simple tools like drills, saws etc. The average production facility in the nearest town (Hebron) features one or two machines (mill, standing drill, etc.), and an operator who can work with a precision up to 0.5mm. In Nablus an OEM market furthermore exists for car parts. There they are able to make surfaces flat with a precision of up to 0,05mm (Noursi, 2013).

3.2.2 Maintenance

To maintain the system the village caretaker has to be able to both do the maintenance, and when to do it. The problem scope showed how the pump will be a stand-alone, off-grid unit. It should be dismountable and repairable without the use of powered tools. Thus parts can be replaced when they break, without having to bring an electricity generator. The pump properties section consequently described how the pump will be placed down in the well. It should be clear when maintenance is necessary without dismounting the pump, for instance by creating wear indicators that are visible from above. What indicates wear varies per pump. This indicator is thus defined as a requirement that should be a part of the design.

3.2.3 Robust & reliable under field conditions, and cost effective

These items were discussed in the previous chapter, and thus not repeated here.

3.3 Conclusion

This chapter has shown the various considerations to take into account when designing a locally repairable pump. Combined with the chapter on Pump Properties and those on Water and Energy Flows all necessary information is gathered. The product requirements that sprout from this analysis provide the boundary conditions under which it will work.

3.3.1 Overview of requirements regarding Local Repair

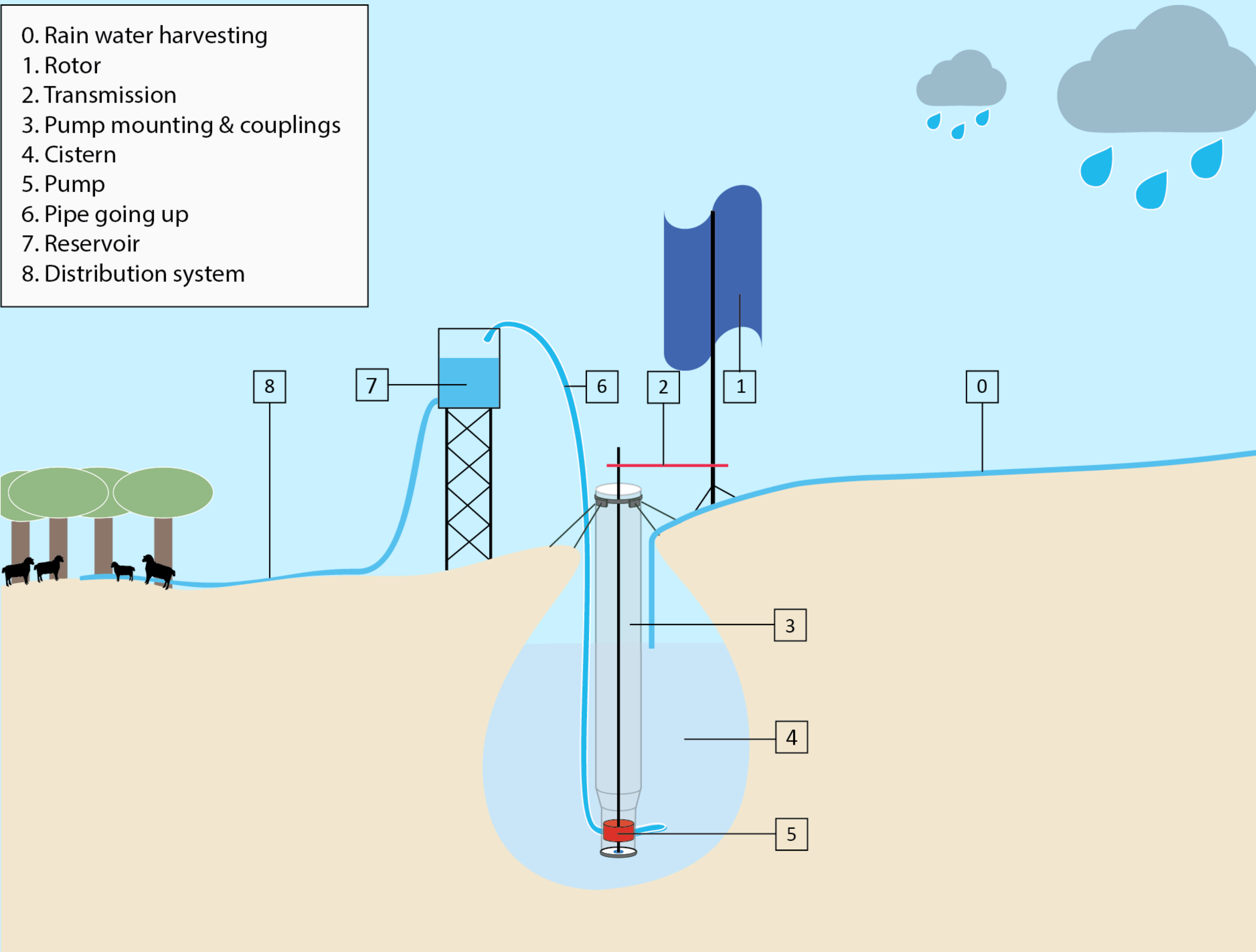
Summarizing the above the pump should be produced locally, be repairable by a local operator and both of these steps should use tools, materials and parts that can be acquired locally. Production should be as such that parts can be imported if required, but preferably manual labor is provided. This is done by optimizing the design for low precision production (≥ 0,5mm) and simple manufacturing steps. Repair and replacement of parts should be possible without power tools, and knowing when to repair it should be possible without dismounting the installation.

Water & Energy Flows

The goal of this project is to design a wind powered water pump for the communities in South Mount Hebron, Palestine (Figure 7). The water flow from the users view is how much water is available on a daily basis, but from the designers view it is a wind-dependent flow rate requirement for the pump. The water and energy flows thus come together in the pump. Completing the pumps requirements involves calculating these two flows through the system.

The water flow therein shows how much water has to be available each day. The energy flow shows how much energy the rotor can generate depending on the wind speed. In the third chapter these two are combined, which renders the pumps wind-dependent flow rate.

Figure 7: Overview of system with water containers and water flows

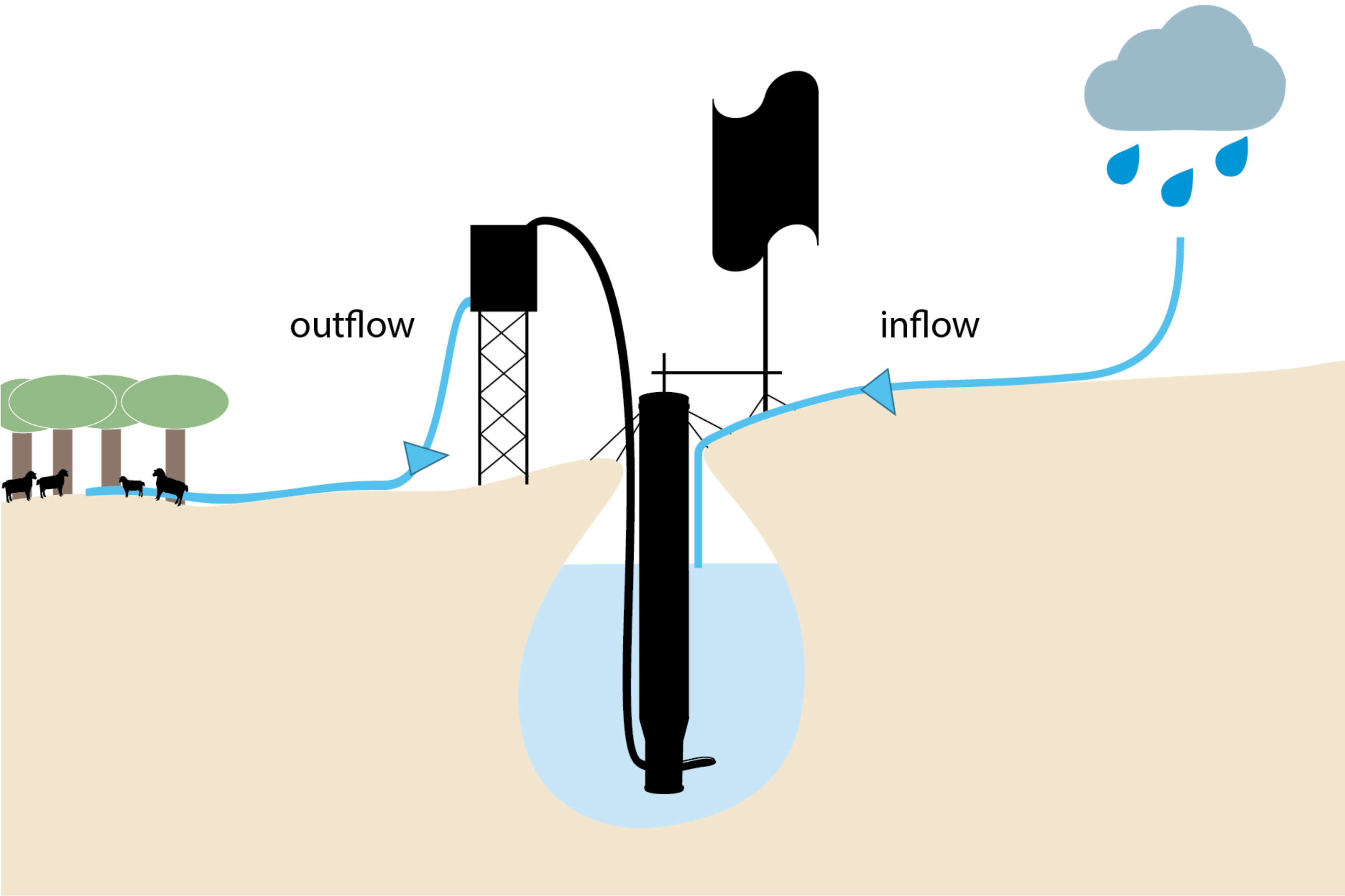


4 Water flow

In this chapter the water flow is calculated on a system level, to investigate how much water has to be available on a daily basis, per system. The Palestinian communities often use several cisterns to supply their demand (Brand, 2013). The flow per system is thus a balance between water use and the available harvested rain water per cistern. This chapter calculates that balance, resulting in the water flow per system.

Combining this flow per system with the energy flow found in the next chapter renders the water flow inside the system in the third chapter. For now the design of the system itself can be seen as a black box, creating a balance between the rains inflow and the uses outflow (Figure 8).

Figure 8: Balancing inflow and outflow



4.1 Water outflow

The water outflow from the system is managed by the communities. They use water for three purposes: (1) the community, (2) the herd and (3) irrigation. This section will quantify these purposes, after which the water inflow from the rain is assessed, and how many cisterns are thus required to satisfy these usage purposes. This then renders the water flow per system.

1 A community uses about 40L/person/day (Brand, 2013). Field analysis reveals that community size varies as people migrate between the cities and the hills. On average a community consists of about 10 persons (Brand, 2013). This implies a water outflow of 400L/day for domestic use.

2 The water used for the herds is to let them drink. How much they drink varies per season: in the dry season the heightened temperature increases the herds need for water. A herd of 270 sheep requires a water outflow of 2000 litres per day during the dry season and 570L per day during the wet season (Brand, 2013).

3 Irrigation is used to maintain the lands fodder production: to keep the hills green longer, so that the herd can eat. Increasing desertification renders the 'green' period shorter each year. The amount of lands to keep green is thus as large as possible. Rather than matching the water availability to the irrigations outflow, the irrigations outflow is matched to the availability of the water from the cistern. Each cistern used for irrigation purposes is completely emptied throughout the dry season.

4.2 Water inflow

As the water outflow is mapped for the different purposes water it is used for, it is possible to verify how many cisterns are required to fulfil each purpose. Each purpose requires one or more cisterns: the final flow per system is thus dependent of both the water demand per purpose, and what a single cistern can supply. To find the flow per system, the water supply per cistern is calculated here.

The water inflow to the system is harvested rain. Palestine features a dry and wet season (Figure 9). The cistern bridges these seasons: it fills throughout the wet season and empties during the dry season. This means that how much water a cistern can supply varies over the seasons.

4.2.1 Yearly inflow of rain

The rainwater inflow is determined by the rainfall, and the terrain from which this rain is harvested. In formal terms it is dependent on the rainfall depth, the size of the catchment area, and the run-off coefficient (Equation 1). The rainfall depth is the amount of fallen rain expressed in meters height. The catchment area is the area situated above the cistern, from which water flows to the cistern. The run-off coefficient describes the percentage of the fallen water that 'runs off' and into the cistern, as opposed to the water going into the ground.

$$V_{harvested} = h_{yearly\ rain} * A_{catchment\ area} * \eta_{catchment\ area}$$

Equation 1

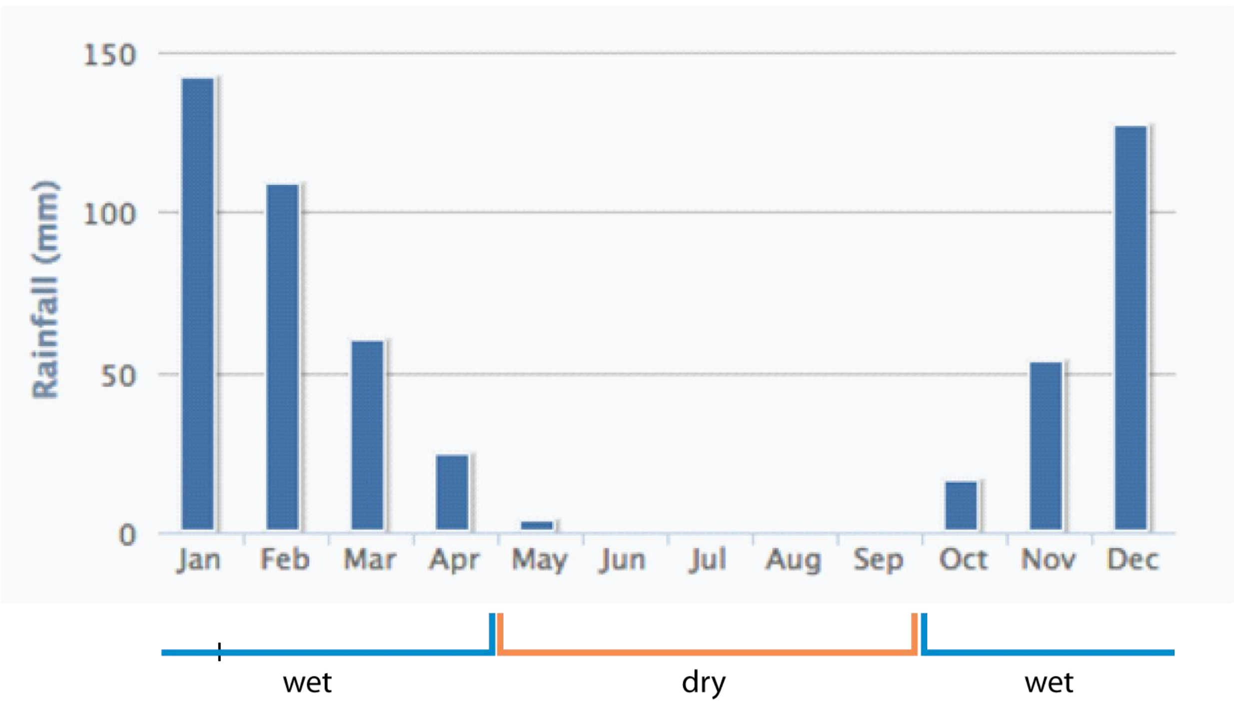
Data is available for these variables. Field analysis showed that the average catchment area is 750 square meters per cistern. The run-off coefficient for arid areas in the region is 50% to 60% (Kapur, Eswaran, & Blum, 2011). Annual rainfall is 550mm (World Bank Group, 2013) (Figure 1). The total annual volume of water that in theory can be harvested is thus 200 cubic meters a year per cistern.

$$V_{harvested} = 0{,}550m * 750m^2 * 50\% = 200m^3$$

4.2.2 Water supply capacity per season

The introduction explained how the cistern is filled in the wet season, and emptied in the dry season. This leads to two different formulae for the water supply capacity of the cistern.

Figure 9: Average monthly rainfall in South Mount Hebron, Palestine (coordinates 31.44; 35.16) from 1990-2009 (World Bank, 2013)



n the dry season water is used but no rain water is harvested: the cistern starts full but ends empty. The daily water outflow capacity is thus the cisterns volume divided by the amount of dry days (Equation 2).

The cisterns have an average size of 91.4 cubic meters (Brand, 2013). The amount of water that the cistern can supply in the dry season is thus 600 L/day.

$$Q_{daily,dry\ season} = \frac{\mathrm{V}_{\mathrm{cistern}}}{n_{dry\ days}} = \frac{91.4\ m^3}{5\ dry\ months = 153\ days} = 600L/day$$

Equation 2

In the wet season the cistern starts empty, and ends full. Simultaneously water might be used. As the rainwater inflow is bigger than the cistern, a surplus of harvested water remains available for consumption (Equation 3). This results in a flow rate of 550L/day.

$$Q_{daily,wet\ season} = \frac{V_{harvested} - V_{cistern}}{n_{wetdays}} = \frac{200m^3 - 91.4m^3}{7\ wet\ months = 212\ days} = 550L/day$$

Equation 3

4.3 Conclusion: matching inflow and outflow

How much water the cistern can supply per season can now be matched to how much water is required for the different usage purposes. This leads to the water flow per system.

Figure 10 gives an overview of the flow per system for different purposes, during the dry and wet season. Each purpose is treated separately, as their cisterns are in different locations. The herd drinks water at the bottom of the valley, irrigation happens in the less slanted parts of the hills, and the communities are scattered throughout the hills. Each thus depends on a separate distribution system.

- For a 10 person community, using 400L/day, a single cistern is sufficient throughout the year. The community demand is lower than both the wet season and dry season supply.

- For the herd the amount of required cisterns varies per season.
- During the dry season the herd drinks 2 cubic meters a day and thus requires 3,14 cisterns. Opting for 3 cisterns and using a bit from the community cistern is a likely option. The herd, though roaming around during the day, sleeps with the community. As the community cistern has spare water (see above), they

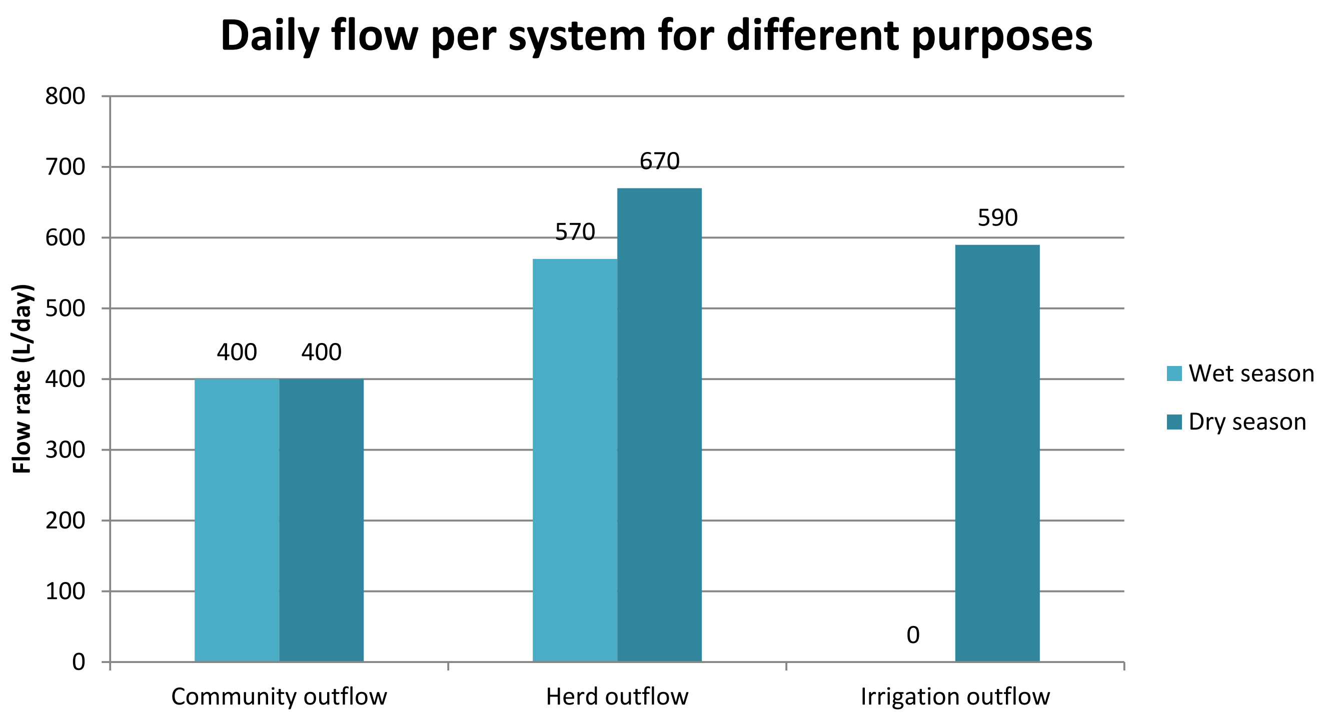
can have an evening or morning drink there. This implies that each water system used for the herd has a daily flow of $2000L\ /\ 3\ cisterns\ \ =\ 670$ litres in the dry season.

- During the wet season, the required 570L/day is 4% more than a single cisterns supply of 550L/day. Again it is likely that the herd drinks a bit from the community cistern besides using one own cistern. A system used for the herds during the wet season thus features a flow of 570L/day.

- Irrigation was seen to not be necessary during the wet season. During the dry season the cistern is emptied. Irrigation thus requires the dry season supply flow calculated above, which is 590L/day.

Figure 10 provides an overview of all water purposes described above. A system that can match the highest flow demand is able to serve all purposes; if more is pumped than used, spill-over from the reservoir can be fed back to the cistern. This leads to a daily flow of 670 litres per system.

Figure 10: Required flow rates per day in the dry and wet season



5 Energy flow

The previous chapter described 670L of water flows out of a single system on a daily basis. The pump that facilitates that water transport behaves dynamic: for each wind speed the rotor and pump behave differently. The energy flow from the rotor to the pump facilitates the systems water outflow. Over the course of the day the water flow of the pump to the reservoir should sum up to the water outflow by the communities. How the energy flow can match this requirement is treated in this chapter.

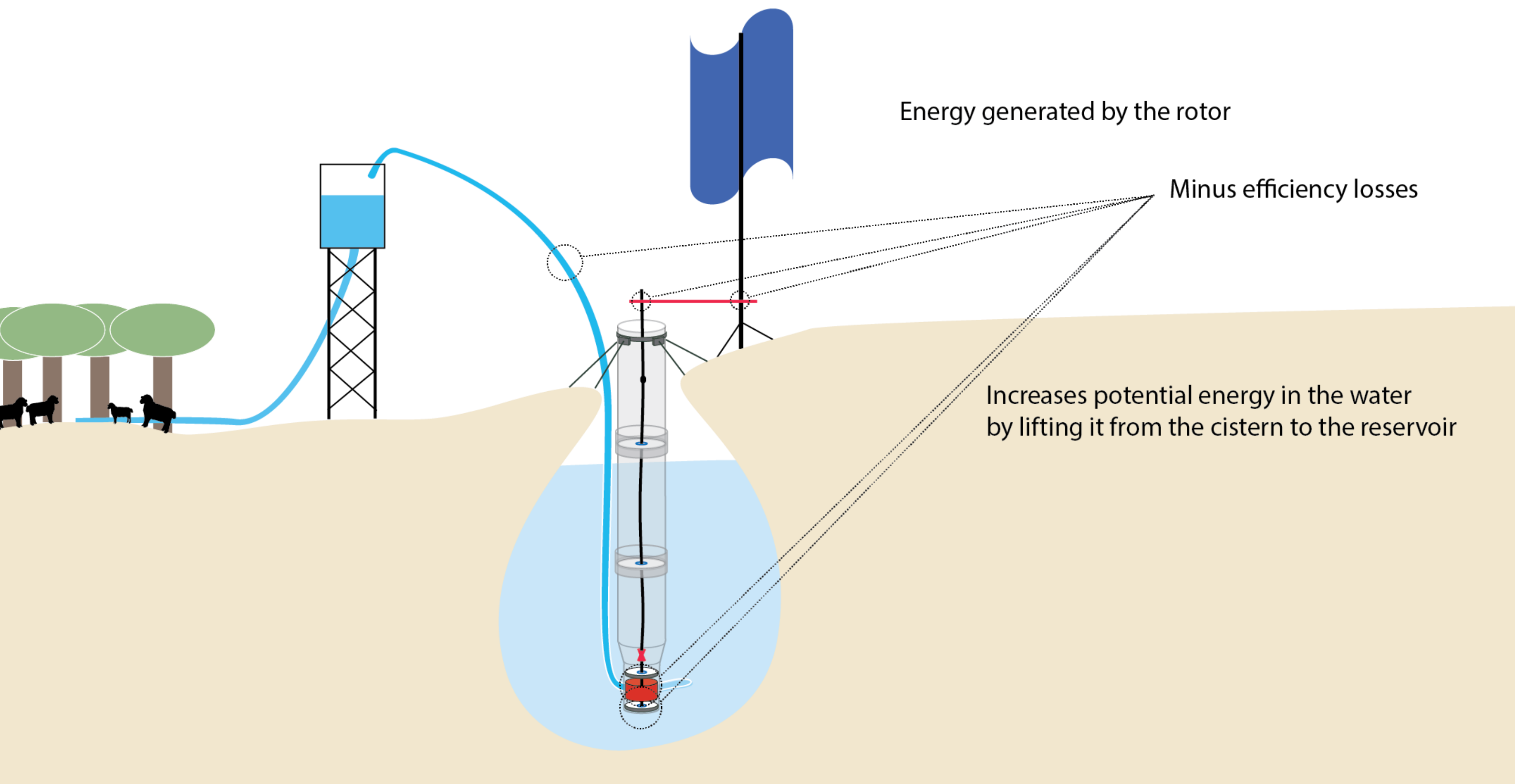
The rotor generates energy from the wind. This energy is transmitted through the transmission to the pump. The pump uses that energy, minus efficiency losses, to elevate water. For the project to be successful, the energy generated minus the energy losses have to be enough to elevate the required amount of water (Figure 11).

$$E_{generated} - E_{losses} = E_{water}$$

The energy losses in the system are unknown, as it is still to be designed. The rotor is given as it is provided in the field (p. 33). Maximizing the rotors energy output increases the chance that enough water is elevated.

In this chapter the rotors power output is thus maximized, and consequently quantified. In the next chapter, the resulting energy output is combined with the required water flow to calculate the wind dependent water and energy flow in the pump.

Figure 11: Overview of the energy in the system

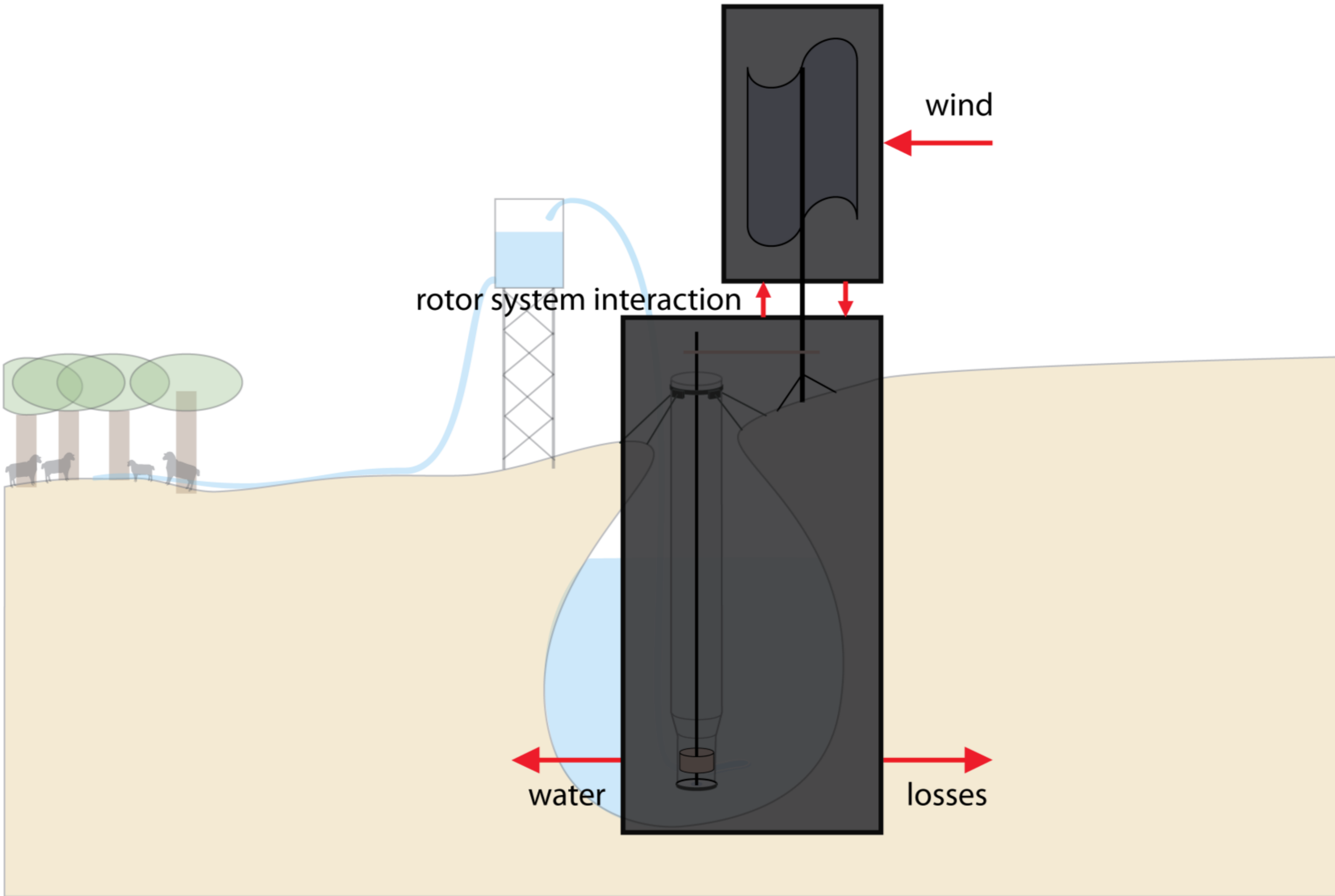


Maximizing the rotor output involves looking at the interaction between rotor and system (Figure 12). A strategy exists to do so. Literature however suggests it could be more effective: more energy could be generated (Smulders & Rijs, 2006). An innovation is thus proposed. The proposed innovation was modelled and verified using real life data, and renders 35% more energy generation over time than its predecessor.

This chapter thus contains the following sections:

- Maximizing the rotors energy output: the interaction between rotor and system
- The existing strategy to optimize that interaction
- The proposed innovation to optimize that interaction
- Executing the innovated strategy: used data and rotor
- Results: the energy flows from the rotor to the pump over time and wind speeds

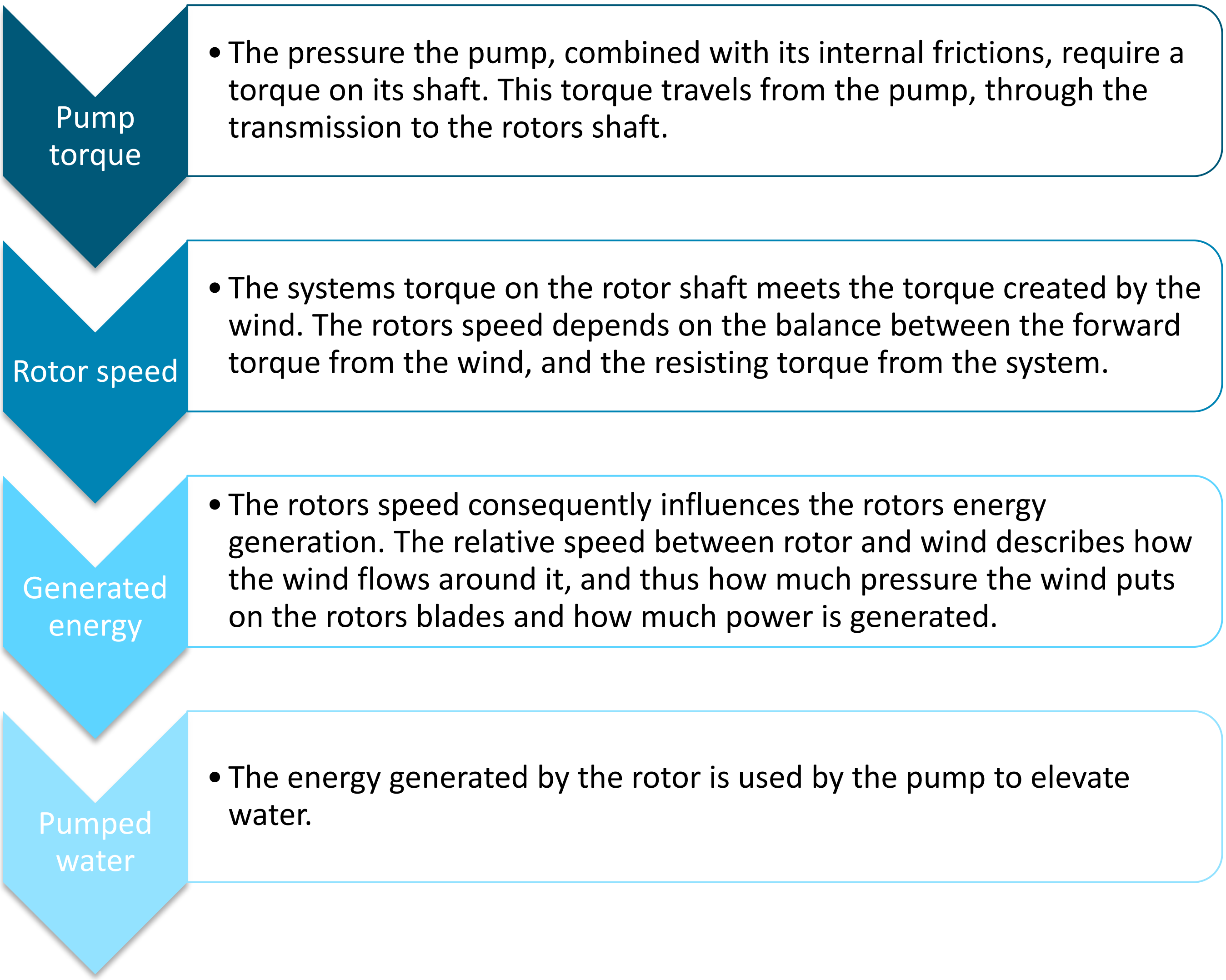
Figure 12: The role of the rotor system interaction in the system



5.1 Introduction: maximizing the rotors energy output

The rotors energy output is dependent of the system.
 describes this interaction. To summarize: the systems reaction torque works on the rotors shaft and thus influences its speed and generated energy. The interaction is explained in more detail in appendix [1].

Figure 13: How the pumps torque influences its flow.



5.2 Current optimization strategy

Maximizing the rotors energy output over time can be done in multiple ways. The current strategy uses a chosen wind speed: the average wind speed, the mean wind speed (probability weighted average wind speed), or the modal wind speed (most occurring wind speed). The pumps torque is designed to make the rotor peak in efficiency at the chosen wind speed. Literature however suggests this strategy is not adequate (Rijs & Smulders, 2006).

5.2.1 Why the current strategy is not adequate

Looking at local wind speed data (Figure 14), deciding which wind speed to design for is not instantly obvious. The wind speed varies each day, but also varies among days. If one optimizes the rotor shaft torque equilibrium to peak in efficiency at 2m/s wind speed (the bright red line in Figure 14), the rotor is less efficient at for instance 4m/s wind speed (the dark red line in Figure 14). Yet, the 4m/s wind speed occurs regularly too.

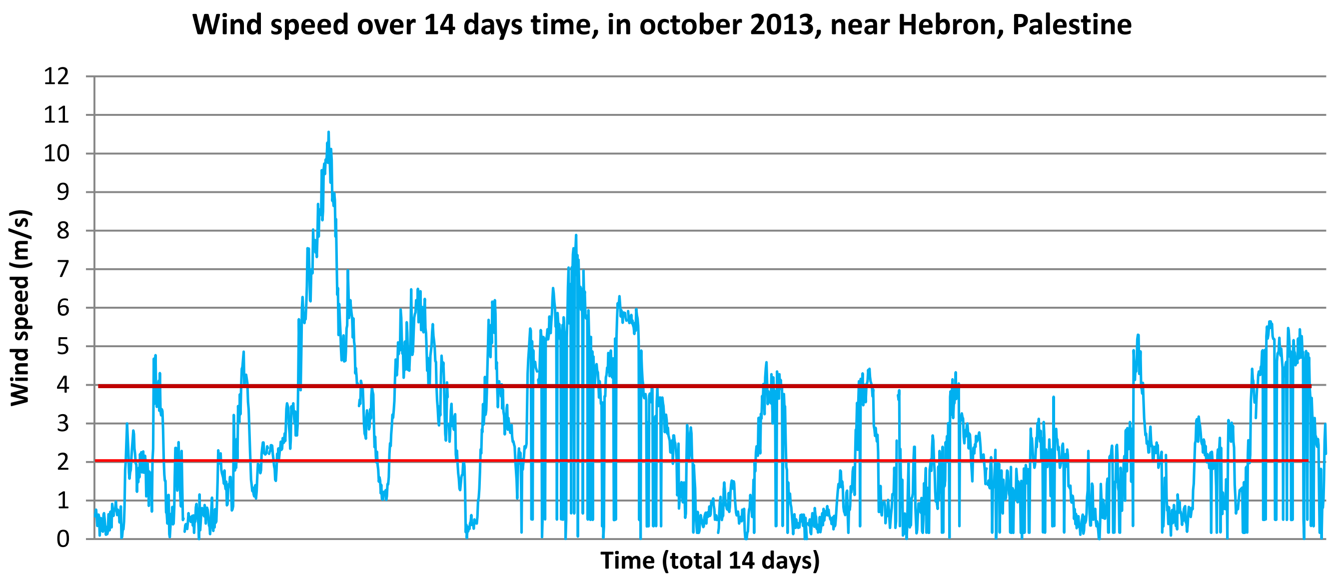


Figure 14: Local wind speed data

The wind speed influences the energy generation more than the efficiency. This makes it complex to choose a wind speed to optimize towards. Equation 4 describes the energy generation of a rotor. The efficiency is therein relevant to the first power, where the wind speed is raised to the third power. Figure 15 shows how the rotors power output varies for different system torques, that correspond to different chosen wind speeds one might optimize towards.

$$P_{rotor} = \frac{1}{2} * \rho_{air} * A_{rotor} * Cp * v_{wind}^{3}$$

Equation 4

That the wind speed has a bigger influence on the rotors power than its efficiency indeed renders it more complex to decide for which wind speed the system should be optimized. Rather than the average, mean or modal wind speed, a higher wind speed offers more energy when evaluated over time: though a higher wind speed may occur less often, it generates more energy.

The wind speed for which the system should be designed should thus be higher than the average, mean or modal wind speed. How much higher, depends on the local wind speeds, and how often they occur. This is difficult to estimate beforehand.

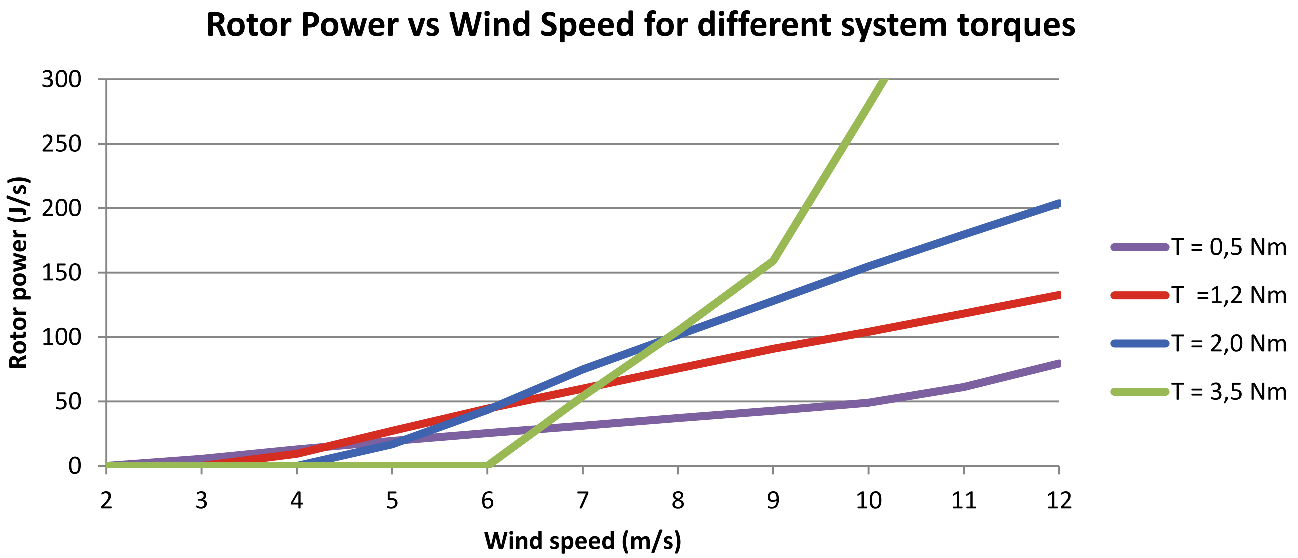


Figure 15: Rotor output versus wind speed for various system torques, that correspond to various chosen wind speeds.

5.3 Proposed optimization strategy

The proposed strategy works different than the current strategy: not from one chosen wind speed to system design, but from system design to generated energy over a time period of wind speed data. This way the rotors energy generation can be verified over a time period of recorded wind speeds, for any given resisting torque created by the system. Several torques are tried to find the one that renders the highest rotor energy output over time.

5.3.1 Description of the strategy

As said the strategy goes from the systems torque, to generated energy output over time. Several system torques are tried to find the one that yields the highest energy output. This process follows the following steps:

1. Data of the rotor is used to calculate the rotors torque and power output for several combinations of wind speeds and rotor speeds;

2. A set of system torques is assumed, and used to calculate the generated energy over time. This follows two steps:

a) The rotor speed and power generation is found for each occurring wind speed. This is done using the found relation between torque, wind speed and rotor speed. The rotor speed for that wind speed, is that rotor speed where system torque is equal to the torque the wind speed.

b) The power output – wind speed relation is combined with local wind speed data to calculate the power output over time. The integrated sum of the rotor power output over time is the total generated energy over time.

3. Find the system torque for which the generated energy is highest. This is the system torque that corresponds to the maximized rotor energy output.

At that point the optimization is finished: the system torque for which most energy is generated is found. The described iteration is developed to an algorithm code. This algorithms code, and its validation, can be found in respectively appendices [x] and [x].

5.4 Executing the strategy

Now that the strategy is defined it can be executed. The written algorithm needs to be sourced with data: the rotor data and the wind speed data. In this section both are chosen and described.

5.4.1 Rotor data

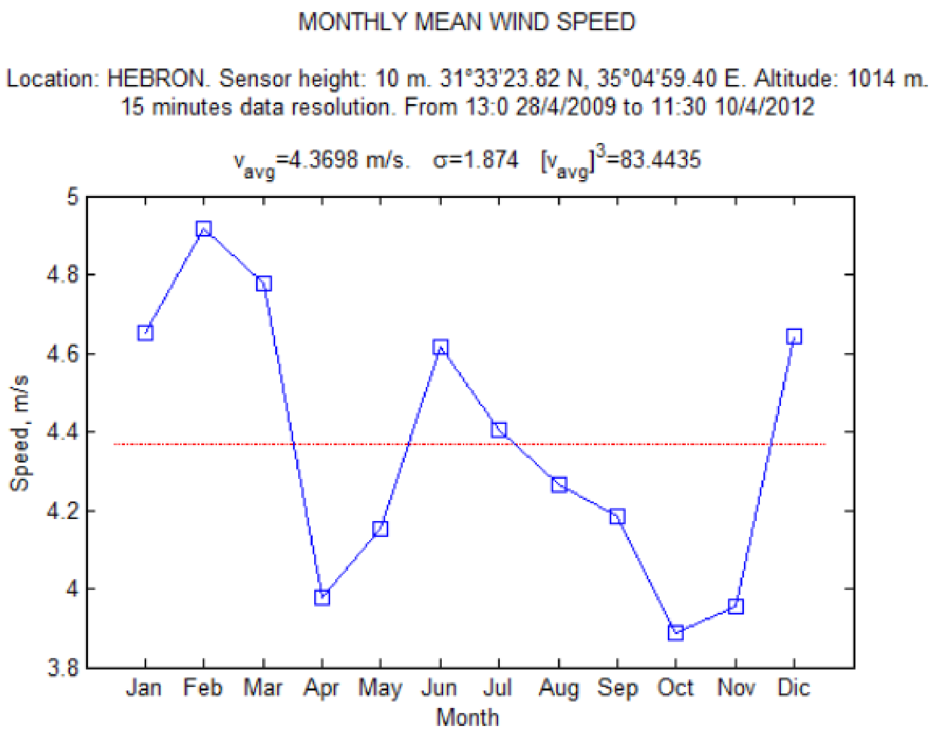
Rotor data varies per rotor type. For this project the Savonius helical rotor was chosen as it offers high torque at low wind speeds, it doesn't require a system to position itself in the right direction and it can be made relatively simple from waste materials (Hayek & Kahwaji, 2013)(Figure 16). The size is maximized towards installation possibilities (Dotan, Production possibilities in Palestine, 2013)(Figure 17). Its data was measured by NGO Comet-ME and can be found with the model in appendix [2]. The data mentioned here is the Cp-TSR curve of the rotor, its size and radius. The Cp-TSR curve lays a relation between the percentage of power the rotor takes from the wind, and the relative speed between rotor and wind. This is the data used in step 1 of the strategy.

Figure 16 (left): Production of the Savonius Helical rotor using barrels and a metal frame.
Figure 17 (right): Installation of the Savonius helical rotor

5.4.2 Wind speed data

The wind speeds vary over the course of the year and day. Fourteen days of local wind speed data are available from October 2013, which is a month of exceptionally low wind speeds (Figure 18). This is thus deemed representative data: it is taken as a worst case scenario.

Figure 18: Monthly mean wind speeds in Hebron, Palestine. Source: (Juandeaburre, 2013)

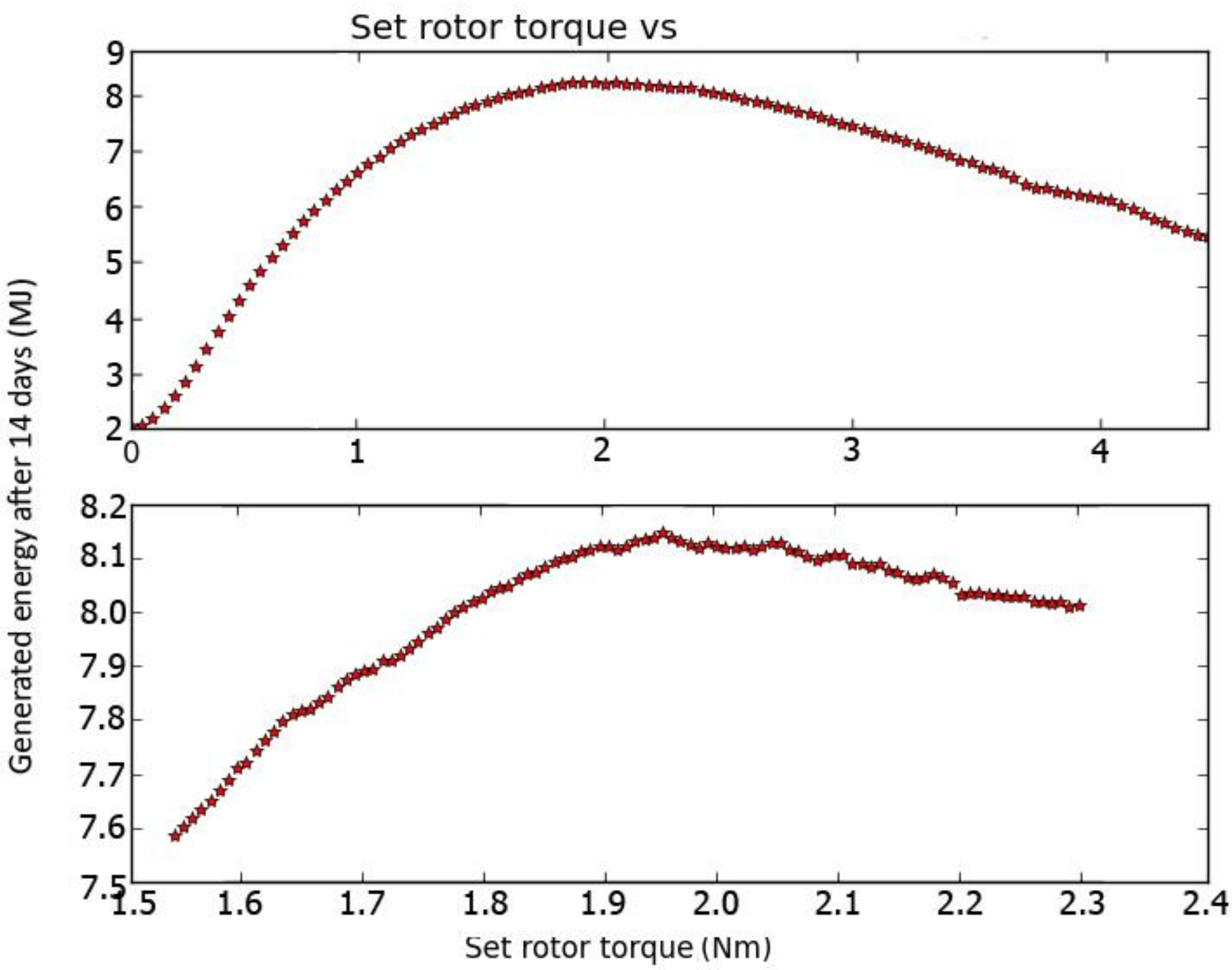


5.5 Results and conclusion

The model in comparison to the current optimization strategy renders the following results:

- Designing the system for the average wind speed renders 6MJ over the wind speed data set, at a torque of 1.1 Nm (corresponds to a chosen wind speed of 2.5 m/s)
- Designing the system for a time period of wind speeds renders 8MJ over the wind speed data set, at a torque of 1.9 Nm (corresponds to a chosen wind speed of 3.5m/s)
- This means that the optimized method generates 35% more energy.
- Figure 19 shows how the system torque relates to the generated energy over the 14 days of wind speed.

Figure 19: The calculated rotor energy output versus system torque. The bottom diagram is a zoom in of the top diagram.



The system torque, combined with the available data renders the rotor output of power and speed versus wind speed, and the rotor power output over time (Figure 20, Figure 21, Figure 22). How these calculations are made goes too far for this chapter, but can be found in appendix [2]. The rotor power output as a function of wind speed is combined with the required daily water flow in the next chapter, to find the flow rate within the pump.

Deviations from the system torque, caused by for instance irregular flow or changing frictions, cost efficiency. The rotor speed will vary with the torque, and with that its energy generation. Besides knowing the torque requirement, the pumps torque should thus also be as stable as possible.

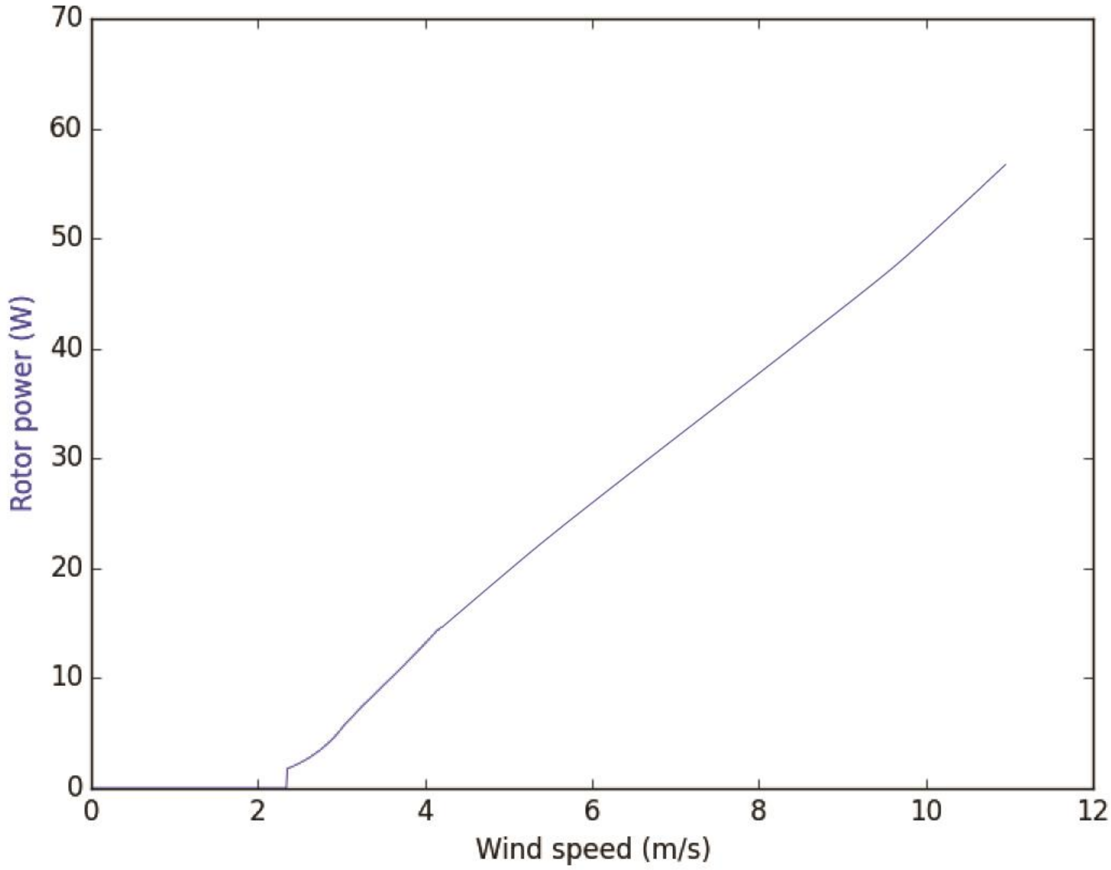


Figure 20: The calculated rotor power versus wind speed

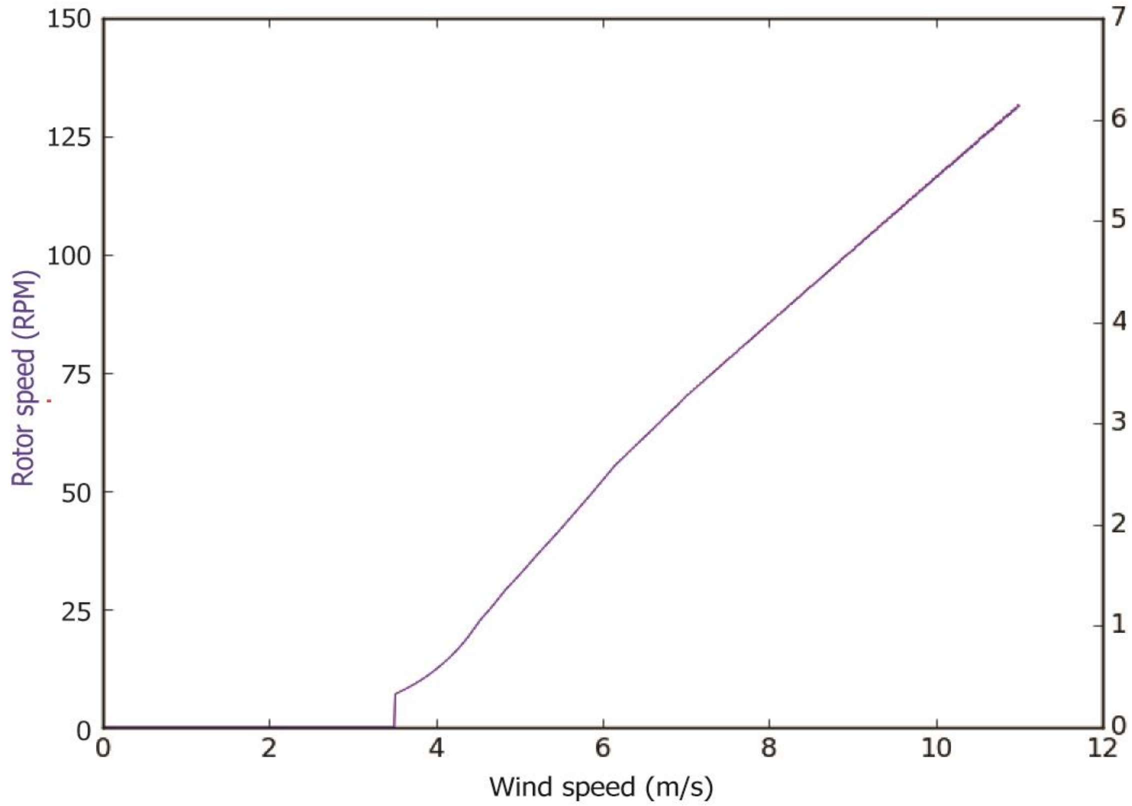


Figure 21: The calculated rotor speed versus wind speed

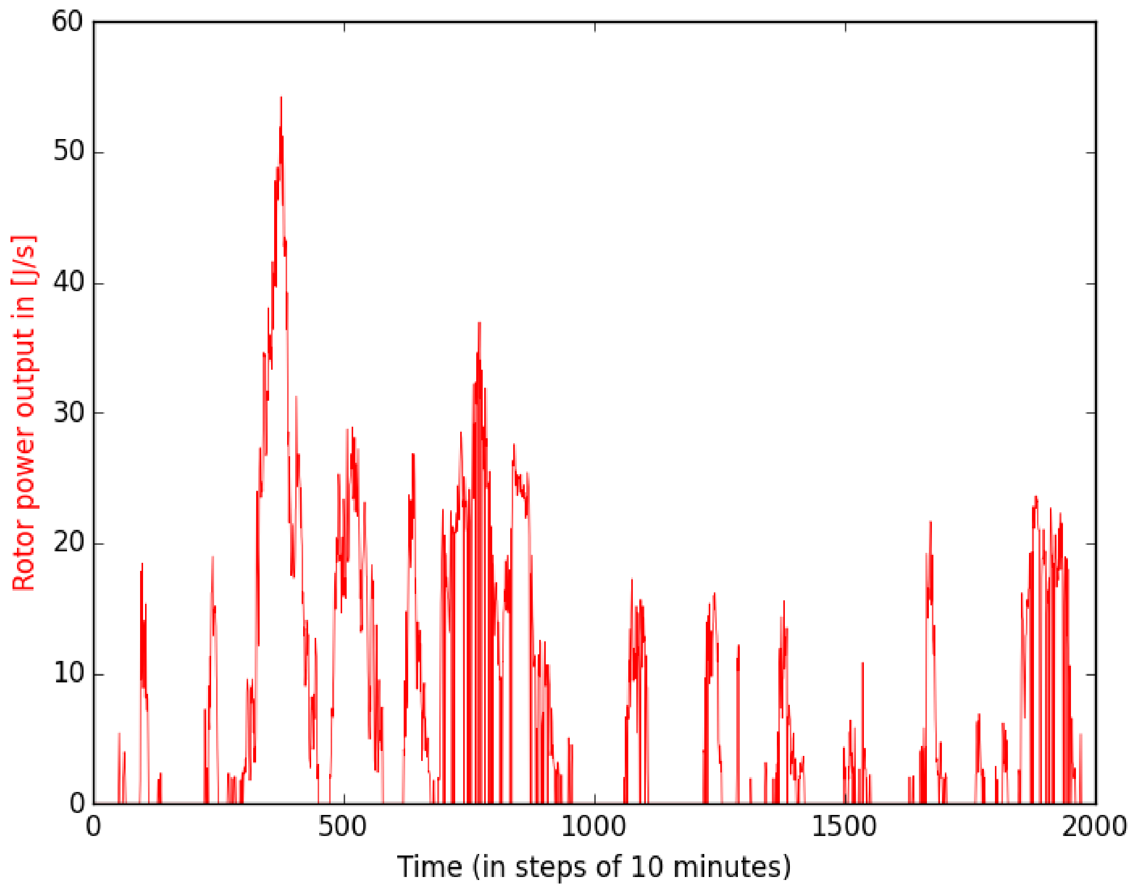


Figure 22: Rotor power over 14 days of wind speed samples

6 Combining water and energy flows

The availability of energy as a function of the wind speed is now known, as well as how much water is to be pumped using that energy.

These two combined render the criteria for the pump on both the water flow and energy flow. The full results comprise:

- T_{system}: the torque from the system on the rotors shaft. This creates the right torque balance in the rotor, maximizing its energy generation.
- $Q(v_{wind})$ and $Q(RPM)$: the pumps flow rate as a function of wind speed and the rotors RPM. The flow rate as a function of wind speed can be used to assess the performance of a wind pump. The flow rate as a function of RPM can be used to assess the performance of any pump. It will be used to dimension and evaluate the pump in later stages.
- η_{system}: The minimum allowed system efficiency: this has to be high enough to provide enough water with the optimized rotor performance.
- $V_{reservoir}$: the required size of the reservoir to overcome periods of low wind speeds.

The system torque was found in the previous chapter: to maximize rotor energy output it should be 1.9Nm. The other requirements are discussed here.

6.1 System efficiency

The system efficiency is calculated using iteration: for a range of efficiencies the flow rate over time is calculated and compared to the users water need. Calculating the flow rate over time (Equation 5) uses the rotor power output over time. The water outflow was found in chapter 4. Combining flow rate with outflow (Equation 6) results in a system efficiency of 40%.

$$Q_{pump}(t) = \frac{P_{rotor}(t) * \eta_{pump}[i]}{g * H * \rho_{water}}$$

Equation 5

$$\int_{t1}^{t2} Q_{pump}(t)\, dt = \int_{t1}^{t2} V_{outflow} * n_{days}\, dt$$

Equation 6

With that efficiency, the water volume in the reservoir fluctuates as in Figure 23. It shows the inflow from the pump to the reservoir over time, and the water taken out by the consumers once a day. The volume at the end of the time period is higher than its starting volume for both the wet and dry season. This indicates that enough water is pumped to fulfill the users need.

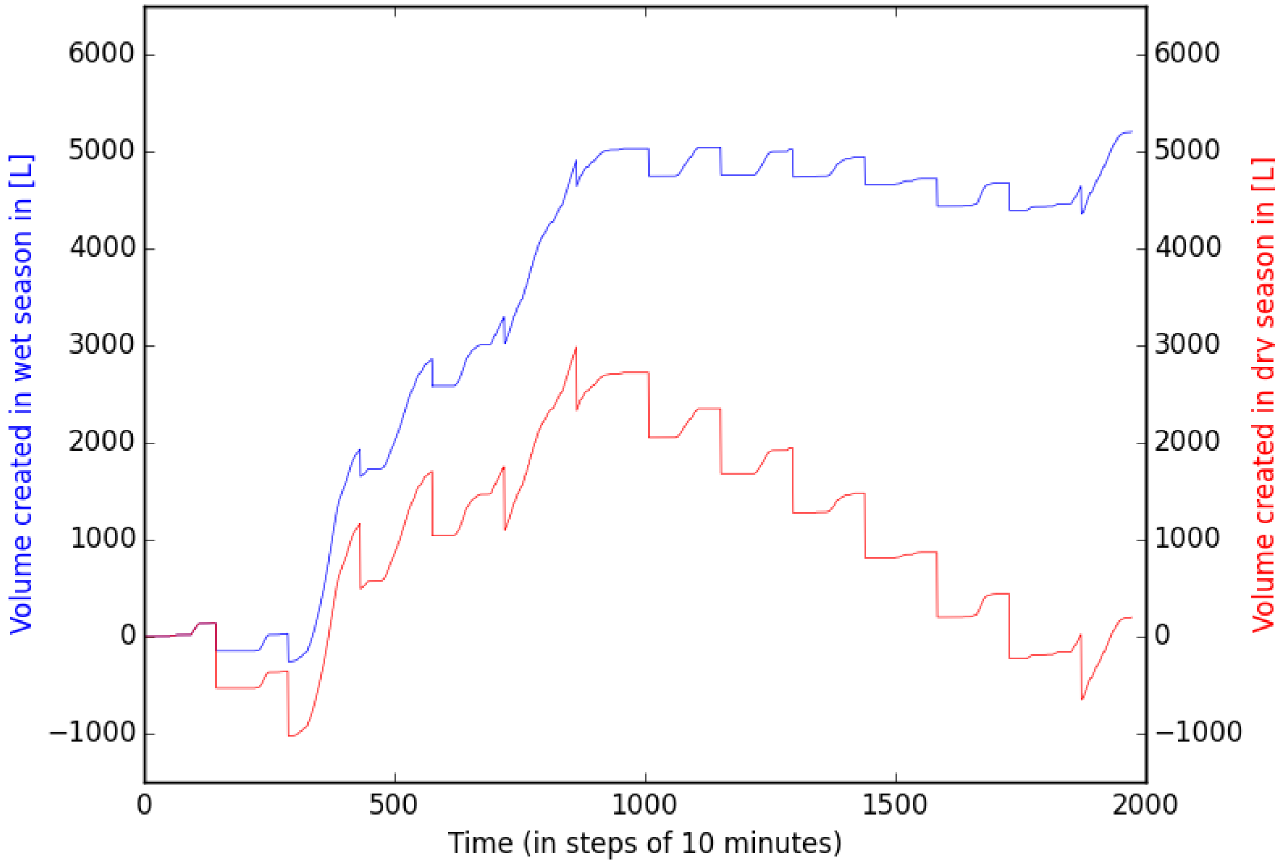


Figure 23: Volume in the reservoir over time

6.2 Reservoir size

Figure 23 also renders the required reservoir size: to overcome the days of low wind speeds in time samples ~900 to ~1800 the reservoir has to be big enough to hold the water provided by the high wind speeds before. The difference between the highest and lowest reservoir volume in Figure 23 renders the required reservoir size (Equation 7): 5,5 m^3.

$$V_{reservoir} = V_{reservoir,max} - V_{reservoir,min} = 5{,}5m^3$$

Equation 7

6.3 Pump flow rate

Calculating the efficiency also renders the flow rate (Equation 8). The rotor power is available as a function of time and as a function of the wind speed. To calculate the efficiency we used the rotor power as a function of time. To find the flow rate as a function of wind speed, we use the rotor power as a function of wind speed.

$$Q_{pump}(v_{wind}) = \frac{P_{rotor}(v_{wind}) * \eta_{pump}}{g * H * \rho_{water}}$$

Equation 8

To complete the requirements the relation between flow rate and rotor RPM is sought. This is done using the rotors power and rotational velocity (Equation 9). This renders the relation between flow rate and RPM (Figure 25).

$$P_{rotor}(v_{wind}) = T_{design} * \omega_{rotor}(v_{wind})$$

Equation 9

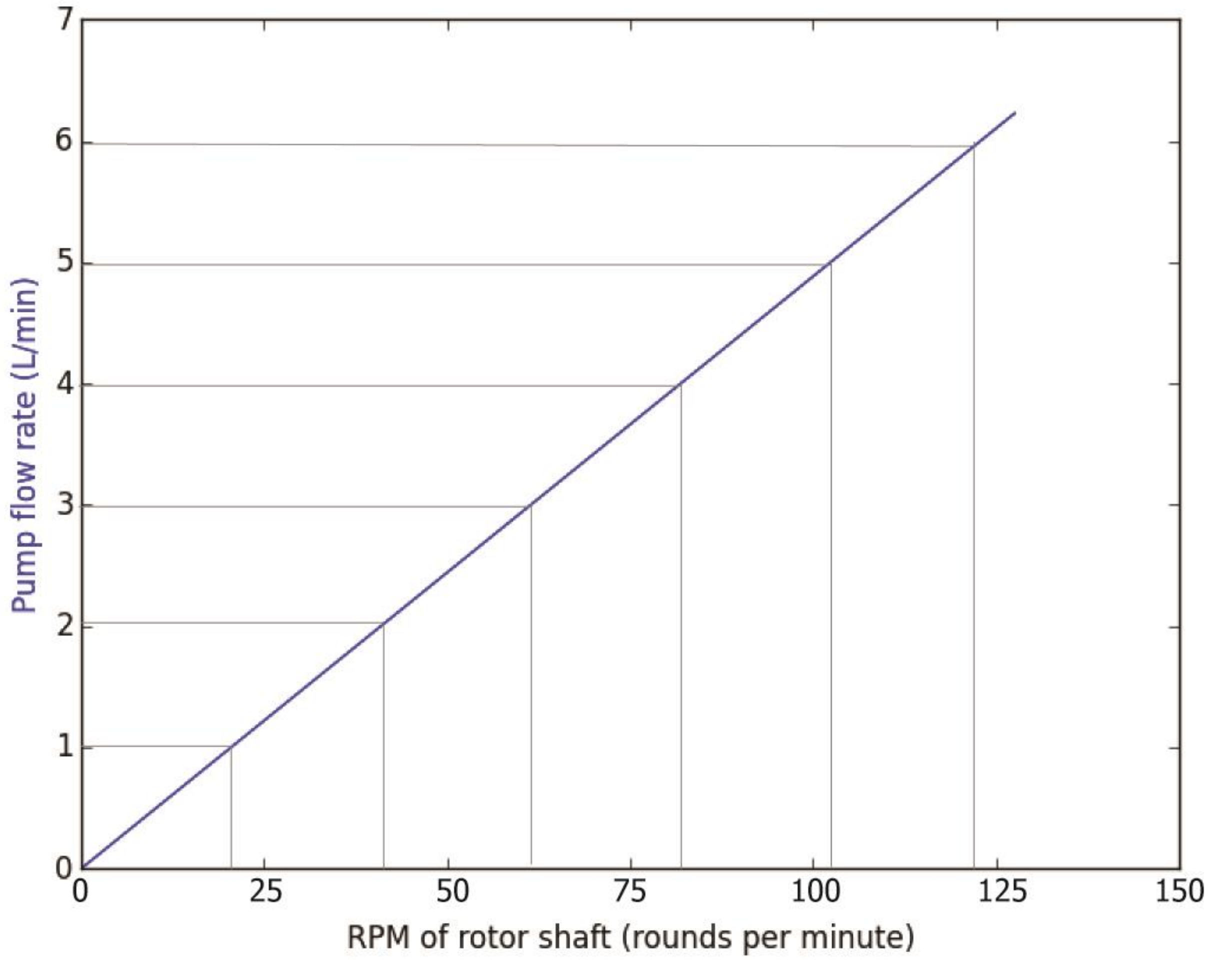


Figure 24: Flow rate - RPM relation

6.3.1 Transmission

Implementing a transmission could alter the pumps torque and angular velocity from that of the rotor (Equation 10 & Equation 11). This is important when evaluating the pump: the flow rate – RPM relation of the pump is the flow rate – i*RPM relation of the rotor. The torque at the pump shaft is the torque at the rotor shaft divided by i.

$$T_{pump} = i * T_{rotor}$$

Equation 10

$$\omega_{pump} = \frac{\omega_{rotor}}{i}$$

Equation 11

6.4 Conclusion

In the chapters above the water and energy flows through the system were quantified. This led to the energy and water flows through the pump: its flow rate, the system efficiency, the torque with which it can create pressure, the size of the reservoir to overcome periods of low wind speeds. In later stages, these can be used to dimension and evaluate the pump.

$$T_{pump} = 1.9Nm * i$$

$$\eta_{system} = 40\%$$

$$V_{reservoir} = 5{,}5\ m^3$$

$$Q_{pump} = \frac{\text{Figure 24}}{i}$$

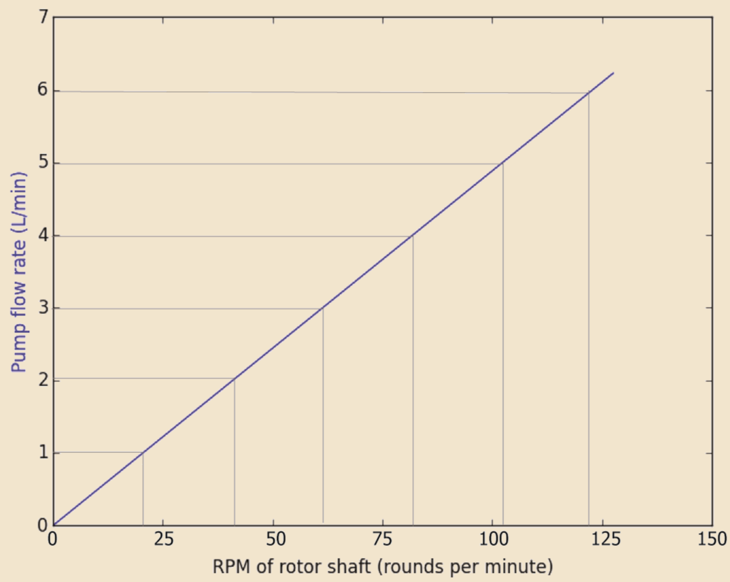
The next page summarizes the now completed program of requirements. After it the design of the pump starts: choosing a pump type, designing the pump and its mounting, and to conclude the project an evaluation of the design.

7 Program of Requirements

1. Pump specs
   1.1. Pumping head of 10m
   1.2. No suction head; the pump is submersed in the water
   1.3. The pump can handle small debris and sand in the water
   1.4. Pump can withstand corrosion
   1.5. Pump is able to dry run when cistern runs empty
   1.6. Pump outlet allows for connection to a hose or pipe, pump inlet includes a gauze
   1.7. Pump couples to a long vertically rotating shaft and avoids sweep
   1.8. Price is 100US$ or less

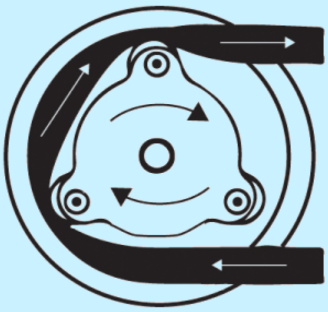
2. Local Repair
   2.1. Production should be such that parts are imported if required, but preferably manual labor is provided.
   2.2. Production precision is at maximum 0,5mm, or 0,05mm for the flatness of surfaces
   2.3. Simple manufacturing steps
   2.4. Maintenance costs and frequency are as low as possible
   2.5. Necessity for maintenance can be verified without dismounting the pump
   2.6. Parts can be replaced and repaired without the use of power tools

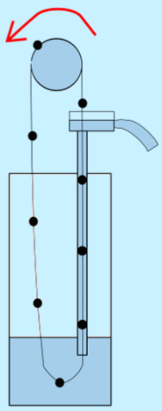
3. Water and Energy Flows
   3.1. The torque is 1,9Nm * transmission ratio *i*, and as stable as possible
   3.2. System efficiency is at least 40%
   3.3. Reservoir volume is at least 5,5 m^3
   3.4. Flow rate – RPM relation is as follows: (Figure 24)

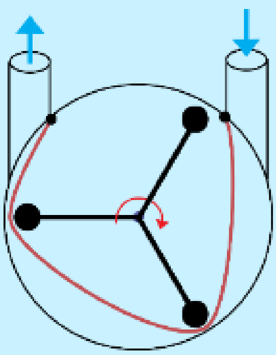


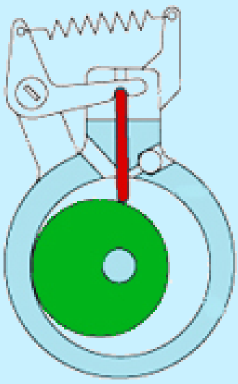
Pump Selection

The world of pumps is extensive. Classification systems facilitate the selection of the most suitable pump for a specific situation. The Pump Handbook (Karassik, 2008) offers such classification system, and is recommended for its completeness and clearness (Arora, 2011). The Handbooks classification system first defines the principle by which energy is added to the fluid (working principle), goes on to identify the means by which this principle is implemented (pump types), and finally delineates specific geometries commonly employed (pumps) (Karassik, 2008). Using the program of requirements as a guideline, this chapter will proceed through the working principles and pump types. The selected pump type will be elaborated further in the next chapter, resulting in this projects' design.









8 Pump selection

8.1 Working principles

The first layer of the Handbooks classification system regards the pumps working principle, or means by which energy is added to the fluid. All pumps may be divided into two major working principles:
(1) Dynamic, in which energy is continuously added to increase the fluid velocities within the machine to values greater than those occurring at the discharge, so subsequent velocity reduction within or beyond the pump produces a pressure increase (kinetic energy transfers to potential energy).
(2) Displacement, in which energy is periodically added by application of force to movable boundaries of enclosed, fluid-containing volumes, resulting in a direct increase in pressure up to the value required to move the fluid through valves or ports into the discharge line (literarily pushing the water forward). The displacement principle can be subdivided into linear and rotary motion.

Each of these principles is described and verified with the program of requirements (refer to p.43), after which the most promising one is selected and pursued in the Handbooks second layer of classification: pump types.

8.1.1 Linear displacement pumps

The linear displacement principle pushes the water forward, by a piston in a pipe. As the piston moves, the water is pushed onwards. As the piston moves backwards, new water is sucked into the pipe. One way valves ensure that the water that was just pushed forward can return into the pipe, and that the water in the pipe cannot be pushed back to where it was sucked from (Figure 18). The pipe-piston-valve combination can function single-action (pumping on one side of the piston) or dual-action (pumping on both sides of the piston) (Figure 18).

Figure 25: Single action linear displacement pump (left) and dual action linear displacement pump (right). Retrieved on 19-05-2015 from http://hawsepipe.net/chiefhelp/pumps/positive_displacment/reciprocating.htm

Linear displacement pumps have proven to be apt for local repair: "*About 3 million [locally repairable] treadle pumps have been sold to $2-a-day customers*" (Polak P. , 2011).

This working principle can match the water needs, as proven by Kickstart, who has built pumps fit for irrigating 2 acres of land (9 times the requirements' reach) with a head of 14m (Kickstart International, 2009).

When combining a piston pump with wind power, start-up torque however proves to be a barrier: the peak torque is π times as high as the average torque (Jongh & Rijs, 2004). This implies the rotor will start when it can overcome the peak torque, while it is most efficient at the average torque. As wind regimes that shortly feature high wind speeds to continue with average winds are uncommon, the piston pump – rotor combination has proven ineffective (Kragten, 2013).

Further developments on this issue have not received research priority. Several ways to overcome these issues have been summarized in 2004 (Jongh & Rijs, 2004). Development of these suggestions did not reach a prototype level to date. It was overruled by the development of solar powered pumps, electrical wind pumps and rope pumps (Gopal, Mohanraj, Chandramohan, & Chandrasekar, 2013).

8.1.2 Rotary displacement pumps

The rotary displacement principle uses a surface to push the water forward, and this surface is powered by a rotary motion. This allows for all kind of pumps: from gear pumps (where the teeth of two gears hook into each other in the middle, to move water along the pump rim)(Figure 26), to the Archimedes screw (Figure 27), to the flexible impeller (an axis with rubber flanges that spin in an eccentric house so that more water flows forward than backward) (Figure 28), to the rope pump (Figure 29) et cetera.

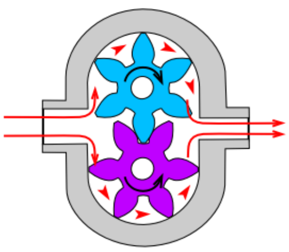
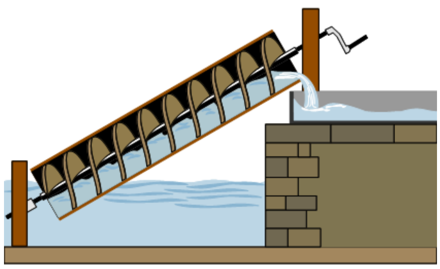
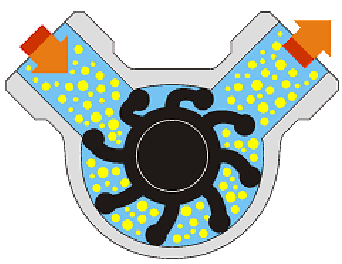
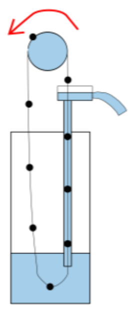





Figure 26 (left): Gear pump. Retrieved on 1-7-2015 from https://en.wiki2.org/wiki/Hydraulic_pump
Figure 27 (second left): Archimedes screw. Retrieved on 1-7-2015 from http://exchange.smarttech.com/search.html?q=%22archimedes%22
Figure 28 (second right): Flexible impeller pump. Retrieved on 1-7-2015 from http://www.lobe.dk/00002/00181/
Figure 29 (right): The rope pump. Retrieved on 3-7-2015 from https://www.youtube.com/watch?v=c6gwU7IHtlo

For the wind rotor this rotary displacement principle is perfect; a rotary motion has low peak torques and does not need a rotary-linear transmission. Since diversity is big, it is assumed that at least one type will be suitable for the communities' water demand and local production. The rope pump and Archimedes' screw are examples of rotary displacement pumps that have successfully been produced and implemented in the developing world (Fraenkel & Thake, 2006).

8.1.3 Velocity pumps

This class consists of centrifugal pumps. They 'swing' the water onwards, transferring a rotary motion to a linear one (Figure 22).

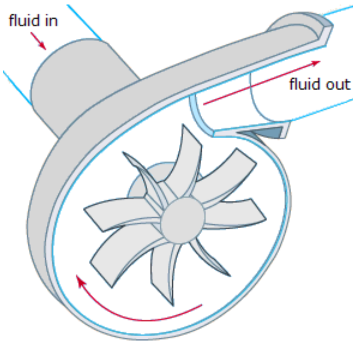


Figure 30: A centrifugal pump swings the water onwards. Retrieved on 19-5-2015 from http://www.wermac.org/equipment/pumps_centrifugal.html

Homemade variations are ample, which implies they can be produced with simple tools and little skill, and be suitable for local repair.

Though velocity pumps feature a low start-up torque, they do not match well with the rotor. The speed at which they need to spin is for a 10m head is not feasible for a rotor, even with a transmission (Kragten, 2013; Appropedia, 2015). It is thus doubtable that centrifugal pumps will be able to meet the water demands with a wind rotor.

8.1.4 Evaluating the working principles

Summarizing the paragraphs above, Table 1 shows that only the displacement pumps apply and that from these two, the rotary principle has a higher chance of matching the rotor torque.

Table 3: Evaluating the working principles to the Program of Requirements.

Working principle	Water Needs	Rotor Match	Local Repair
Linear displacement	Achievable	Doubtable	Achievable
Rotary displacement	Achievable	Achievable	Achievable
Velocity	Achievable	Not achievable	Achievable

8.2 Pump types

With the rotary displacement as a working principle for this project, a search to available pump types and their expected performance is the next step.

This is done for both pumps that are typically found in industrial purposes, and pumps that are typically found among development projects. Development project pumps were found in 'FAO Irrigation And Drainage Paper' (Fraenkel P. , 1986), and Fraenkels more recent book 'Water Lifting Devices, A Handbook' (Fraenkel & Thake, 2006). Industrial pumps were found through the Pump Handbook (Karassik, 2008), the World Pumps journal (Burrows) and by searching for specific types (e.g. searching for "gear pump" renders several pump types that use gears but function completely different).

Figure 26 provides an overview of pump types that work by the rotary displacement principle. The next paragraphs quickly evaluate these pump types, revealing most to be unable to meet the requirements. The remaining types are compared in more detail using a Harris Profile and risk management (Boeijen, Daalhuizen, Schoor, & Zijlstra, 2013). This leads to the conclusion of this chapter: the pump type most promising to meet the requirements for wind power, water needs and local repair.

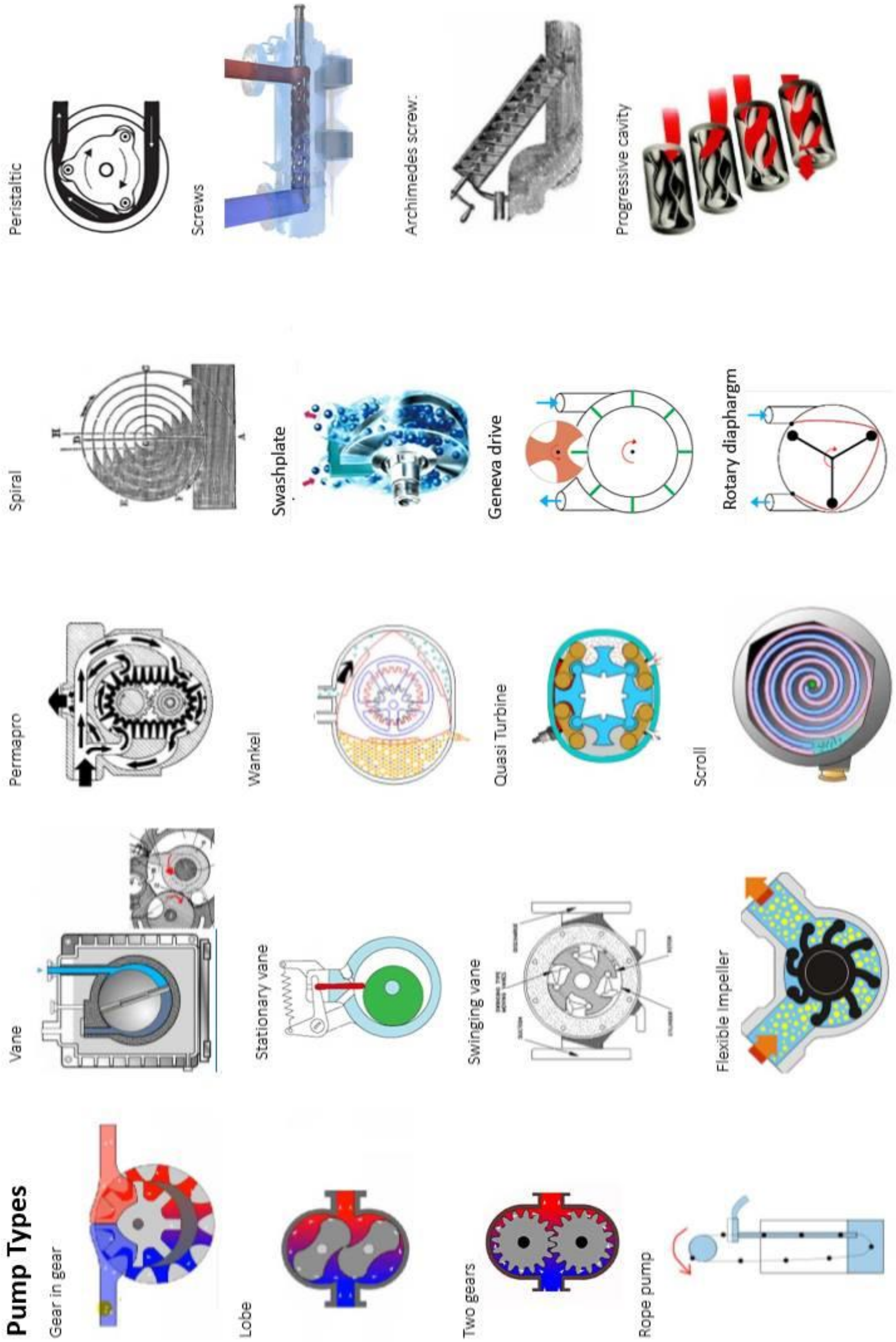


Figure 31: Overview of available pump types. Sources stated at their respective descriptions.

8.2.1 Description of pump types & evaluation of their performance in the field case

Each pump type of Figure 31 is described and evaluated shortly. The most promising types are compared in more depth.

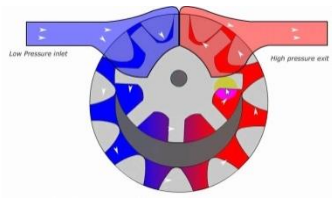
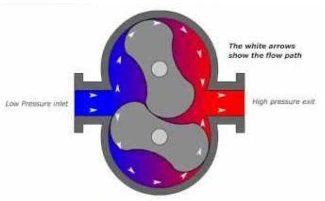


Figure 32: Internal gear pump type. Retrieved on 2-7-2015 from https://www.youtube.com/watch?v=MYvbDaHoxRg

The gear in gear pump (also referred to as internal gear pump) can be described as a smaller gear rotating inside a larger gear; both gears rotate (Figure 32). Their centres are not aligned, but the smaller gear rotates close to the rim of the bigger gear, with their teeth intertwined. At the inlet the gears unmesh and water is sucked into both of the gears teethes openings. At the outlet these openings close again and the water is forced out. The half-moon seen in the image is stationary and acts as a seal between inlet and outlet.

This pump is deemed not suitable for the Palestinian environments, as it cannot dry-run when the cistern runs empty. The interaction of the two gears causes friction and develops heat, generating expansion of the gear materials and ultimately pump failure (Pump School, 2014).



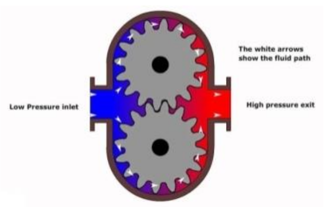


Figure 33 (top): Lobe pump type. Retrieved on 2-7-2015 from https://www.youtube.com/watch?v=_-fwWrFLiyY

Figure 34 (bottom): Two gear pump type. Retrieved on 2-7-2015 from https://www.youtube.com/watch?v=c6gwU7IHtlo

The lobe pump (also referred to as the Roots pump, Figure 33) and two gears pump (also referred to as external gear pump, Figure 34) function similar to each other. As the lobes/gears un-mesh on the intake side, they suck in the water. Water is taken along until the lobes/gears mesh again on the discharge side, and force the fluid through the outlet port under heightened pressure.

These two pump types are deemed not suitable for the field case, as they require high precision manufacturing. The parts have to fit tightly to prevent leakage from the high pressure side to the low pressure side. This increases manufacturing costs and requires a certain level of technology in order to facilitate production and repair.

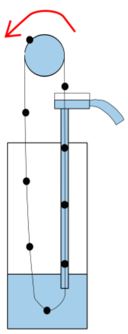


Figure 35: Rope pump type. Retrieved on 18-11-2015 from https://en.wikipedia.org/wiki/Rope_pump

The rope pump functions by having a rope with pistons enter the well and go up the well inside a pipe, lifting the water up (**Fout! Verwijzingsbron niet gevonden.**). This is a suitable pump for the field case. It is a mechanically powered pump widely spread across the developing world (Polak P. , Building a better mousetrap is only the beginning, 2011), often even wind powered. It is a locally repairable option (Fraenkel & Thake, 2006) that could meet the water demands of the Palestinian communities.

It still faces some issues today, which could be improved. Imprecise pistons or rope knots cause either leakage or abrasion (Bombas de Mecate, 1998; Arrakis, 2006). A second issue regards the horizontal rotating axis of the pump, that influences the safety mechanism protecting the rotor from too high wind speeds (Kragten, 2013).

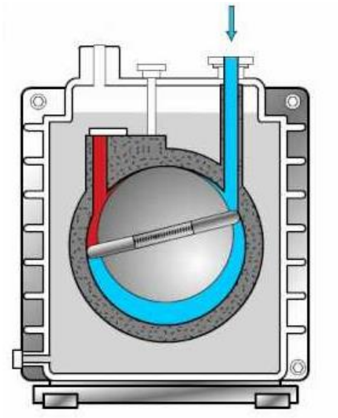


Figure 36: Vane pump type. Retrieved on 3-7-2015 from http://i.ytimg.com/vi/AFHogF-9eGA/hqdefault.jpg

The vane pump features an eccentric rotor with vanes that extend and contract to follow the rim (Figure 36). The rotor is located close to the pump rim so a crescent-shaped cavity is formed. Vanes or blades fit within slots in the rotor, and are pushed against the pumps house. As the rotor rotates fluid flows through the pump.

This pump type is unsuitable for the field case, as it cannot dry run. To keep the contact between vane and pump house smooth, it depends on the fluid for lubrication.

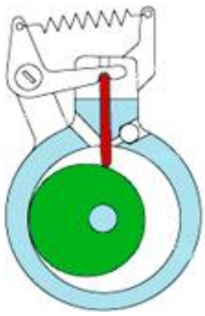


Figure 37: Stationary vane pump. Retrieved on 3-7-2015 from http://woligovabe.xlx.pl/negative-impingement-sign-wikipedia.php and adapted.

The stationary vane pump features an eccentric, cylindrical rotor that rotates around the pumps house (Figure 37). The part of its wall that touches the pumps house pushes the water forward. The stationary vane stops the water from flowing between inlet and outlet. It slides up and down as the rotors wall moves closer and further.

This pump is deemed promising for the Palestinian communities. As the rotor is a cylinder, its contact with the pumps house can be a rolling one. This makes it more suitable for dry running. Local production is possible due to the absence of complex shapes. Lastly it promises a good match with the rotor, as it has no high peak torques and pumps at any speed.

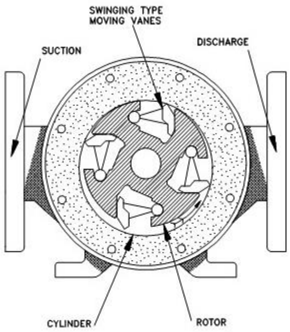


Figure 38: Swinging vane pump type. Retrieved on 3-7-2015 from http://fx.damasgate.com/wp-content/uploads/Rotary-Moving-Vane-Pump.jpg

The swinging vane pump type is similar to the normal vane pump type, except for the fact that it uses centrifugal forces to push the vanes against the rim (Figure 38). It is deemed unsuitable for the Palestinian communities, as utilization of centrifugal forces is unreliable with a wind rotor. Whether or not it achieves adequate closure at the occurring wind speeds is doubtable.

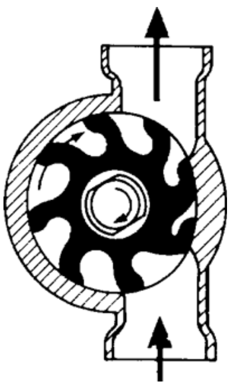


Figure 39: Fexible impeller pump type. Retrieved on 3-7-2015 from http://www.fao.org/docrep/010/ah810e/ah810e06.htm

The flexible impeller is also similar to the vane pump type, except for the fact that the vanes do not move in and out of the rotor, but bend (Figure 39).

It is deemed unsuitable for the field case, as a local production facility will be difficult to achieve. This is mainly due to the absence of such a flexible material, and the tools to shape it (p. 18).

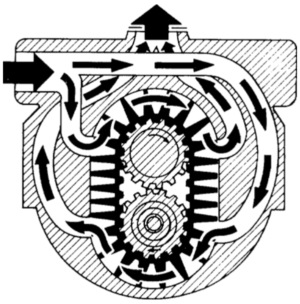


Figure 40: Permapro pump type. Retrieved on 3-7-2015 from http://www.fao.org/docrep/010/ah810e/ah810e06.htm

The Permapro has an endless rubber toothed belt which is driven around two pulleys (Figure 40). As the belt curves around a pulley, the teeth on the belt spread apart and increase the volume between them, thereby drawing in water. The diagram shows how both sides of the chamber simultaneously pump, and how channels in the casing direct the water.

This pump type is deemed less suitable for the Palestinian communities. The casing has to be cast, which is possible but overly expensive. Acquiring the belt provides similar problems as the flexible impellers' flexible part.

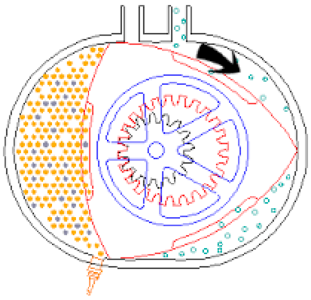


Figure 41: Wankel pump type. Retrieved on 3-7-2015 from http://www.animatedengines.com/wankel.html

The Wankel pump is a derivation of the Wankel engine (Figure 41). The trochoid (curved triangle) makes a movement within the pumps house that is both rotational and translational. The pumps house is at all times in contact with the trochoid at several points. The gaps between the house and trochoid vary in size as it is rotated, compressing and expanding the pumping medium.

It is an unsuitable pump type for the field case. Compression and/or expansion is perfect for pumping gases, but with water it creates a hindrance. Water hardly expands or contracts under pressure, forcing leakage across the trochoids corners. Besides this downside the trochoid shape and gears are difficult to produce.

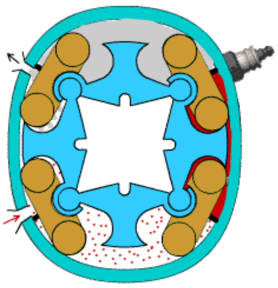


Figure 42: Quasi turbine pump type. Retrieved on 3-7-2015 from http://ecogeek.org/category/ecogeek/automobiles/page/90/

The quasi turbine (Figure 42) is similar to the Wankel engine in the sense that the chambers change their size along the cycle. The pivoting 'vanes' and complex house shape make it complex to produce. It is unsuitable to the Palestinian communities.

Figure 43: Scroll pump type. Retrieved on 3-7-2015 from https://www.youtube.com/watch?v=s3xulCRrjos

The scroll pump uses two spirals to trap the fluid (Figure 43). Often, one of the scrolls is fixed, while the other orbits eccentrically without rotating, thereby trapping pockets of fluid between the scrolls. Another method for producing the motion is co-rotating the scrolls, in synchronous motion, but with offset centres of rotation. The relative motion is the same as if one were orbiting.

This pump type is unsuitable for the Palestinian communities. The surfaces of the spirals create friction when the pump is dry, making it unfit for dry running. The spirals are thereby complex to produce with the required precision, making it unfit for local production.

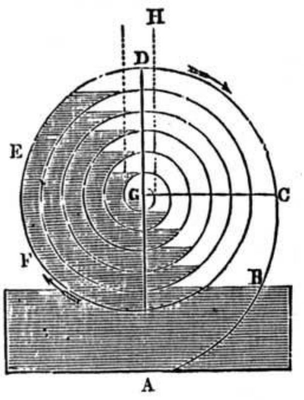


Figure 44: Spiral pump. Retrieved on 6-7-2015 from http://lurkertech.com/water/pump/tailer/

The spiral pump (Figure 44) lifts the water through its rotation. With each revolution of the spiral, the scoop collects half the volume of the outer coil. As water is taken into the coils, each column of water transmits pressure through the air to the preceding column of water. In this way the water in each coil is displaced to provide a pressure head. A cumulative head is built up at the inner coils and conveyed to an ascending delivery pipe.

It is a pump type unsuitable for the field case, as it is too big. The spiral pump has to be twice as high as the intended head (Fraenkel & Thake, 2006). This requires the cisterns entry to be modified, and such a big structure costs unnecessary amounts of money.

Figure 45: Swashplate pump type. Retrieved on 3-7-2015 from http://www.reitze.com/tradepro/shop/artikel/newsletterarchiv/3C29603C50B141A09D4B7E3D291A253D.htm

The swashplate functions by rotating a curved disk that traps the fluid between itself and the pump houses' sides (Figure 45). A plate element with a crevice embraces the disks cross-section, preventing flow from outlet to inlet.

It is unsuitable for the field case. Due to the frictions between the disk and pump house this is a pump unable to dry-run.

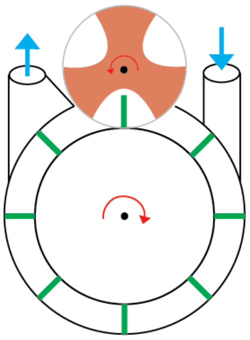


Figure 46: Geneva drive pump type.

The Geneva drive is a vane pump, but the vanes do not have to move inwards and outwards (Figure 46). It's the drive on top that creates the closure between out- and inlet. This drive has grooves that the vanes fall into, and rotates along with the drive.

This pump type is unsuitable to the field case. As the vanes are in continuous contact with the pumps rim and sides, it is unable to dry run.

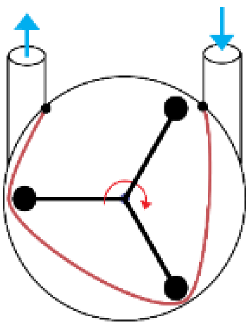


Figure 47: Rotary diaphragm pump type.

The rotary diaphragm traps the fluid between the rim and a flexible diaphragm (Figure 47). Vanes press the diaphragm against the wall, pushing the water forward as the vanes progress. The vanes can have little rollers on their ends that lower their friction with the diaphragm.

This pump is deemed suitable for the Palestinian communities. This pump diaphragm protects it from the Palestinian circumstances, like dry running, debris, high pH, et cetera. All materials can be locally available, including leather for the diaphragm. Local production is also possible due to the absence of complex shapes. Lastly it promises an excellent match with the rotor, as it has no high peak torques and pumps at any speed.

Figure 48: Peristaltic pump type. Retrieved on 3-7-2015 from http://www.pmdcorp.com/news/articles/html/precision_fluid_handling_deep_dive.html

The peristaltic pump squeezes a hose, and is used to pump in high hygiene environments or for abrasive fluids (such as cement). By moving the part of the hose that is squeezed, the water in front of it moves along. Rollers make sure the contact is low-friction.

It is deemed very promising for the field case. Though no publications of peristaltic pumps in the developing world exist, it was recommended as a very simple type of pump that can readily be improvised (Fraenkel & Thake, 2006). The match with the rotor seems promising. The hose does not cost efficiency by being squeezed, as it acts as a spring. The opening up of the hose behind the squeeze pushes the rollers forward as much as they are held back in front of them.

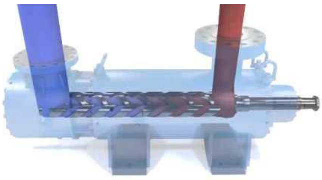


Figure 49: Screw pump type. Retrieved on 3-7-2015 from https://www.youtube.com/watch?v=BM-vUd9fAbc

The screws pump consists of multiple screws that trap the water between them and their casing (Figure 49). As they rotate the cavities move forward.

This pump type is deemed unsuitable for the field case. The screws are difficult to produce and depend on the fluid for lubrication.

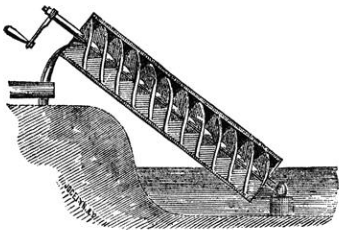


Figure 50: Archimedes screw type. Retrieved on 3-7-2015 from https://en.wikipedia.org/wiki/Archimedes'_screw

The Archimedes screw is a very old device, today still used in Egypt (Figure 50). It contains a screw in an enclosed container that lifts the water up as it rotates. It needs to be under an angle of maximum 45 degrees to achieve this (Fraenkel & Thake, 2006).

It is an unsuitable pump type for the field case, as its size is unnecessarily expensive and requires the cistern to be changed.

Figure 51: Mono pump type. Retrieved on 3-7-2015 from http://gutmbh.de/Exzenterschnecken.htm

The progressive cavity pump type (also referred to as mono pump type, Figure 51) exist of a helical rod that traps water between itself and the curved pump house. As the rod spins the cavities move forward.

The pump type is unsuitable for the Palestinian communities. The house needs to fit exact and has a complex shape. It is usually casted. The precisions required to cast a leakage free mono water pump are too high for the field case.

8.2.2 Pump type decision

All of the found pump types have been introduced shortly. Many of the pumps were hereby eliminated immediately; refer to Table 4 for an overview. This leaves the rope, stationary vane, rotary diaphragm and peristaltic pump types (Figure 29).

Table 4: Pump types evaluation overview

Pump type	Suitable?	Reason
Gear in Gear	No	Unable to dry run
Lobe	No	Unable to dry run
Two gears	No	Unable to dry run
Rope	Yes	
Vane	No	Unable to dry run
Stationary vane	Yes	
Swinging vane	No	Not reliable at all wind speeds
Flexible impeller	No	Unsuitable for local production
Permapro	No	Expensive and unsuitable for local production
Wankel	No	Unsuitable for local production and unsuitable for water
Quasi Turbine	No	Unsuitable for local production and unsuitable for water
Scroll	No	Unable to dry run
Spiral	No	Unnecessarily big & expensive, requires modification of cistern
Swashplate	No	Unable to dry run
Geneva drive	No	Unable to dry run
Rotary diaphragm	Yes	
Peristaltic	Yes	
Screws	No	Unable to dry run
Archimedes screw	No	Unnecessarily big & expensive, requires modification of cistern
Progressive cavity	No	Unable to dry run

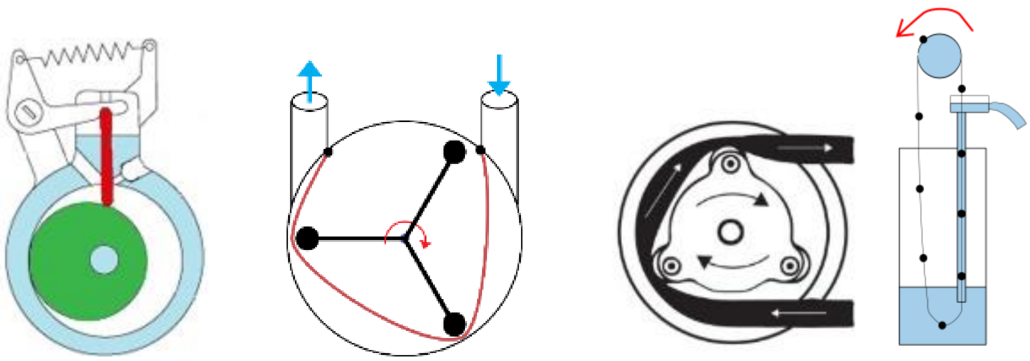


Figure 52: Pump types up for comparison. Left: the stationary vane pump. Second left: the rotary diaphragm pump. Second right: the Peristaltic pump. Right: the rope pump.

The remaining pump types are compared using a Harris profile and risk management (Boeijen, Daalhuizen, Schoor, & Zijlstra, 2013). A short summary is provided here, for the full report refer to appendix [3].

The stationary vane pump is in relation to the others a more complex and expensive pump. This is primarily due to the pump housing and rolling rotor. The pumps housing is complex to produce locally, or expensive to import. It has to hold a sliding vane vibration-free. This implies it requires a cast or high-precision machining. A waterproof cast is made of a resin, machining happens in plastic or stainless steel. Resins have to be imported internationally and are expensive in comparison to the other pump types that utilize local materials. Machining too is for this pump relatively difficult and expensive.
The pumps rolling rotor (the green element in Figure 52) should provide a rolling contact with the (blue depicted) rim. As drawn the rotor is powered by its shaft. To make the contact with the rim a rolling one the outer bound of the rotor should be a bearing, or the power mechanism should be changed to something more complex. Both add to the concepts costs.

The diaphragm pump features a relatively high uncertainty as to if the pump will work or not. The leather diaphragm should provide a closure between both of the pumps sides, and will move along these sides as the rotor rotates. The contact between diaphragm and side should thus be leakage free, but also relatively friction free to avoid constant reshaping or bending of the diaphragm. Several solutions come to mind to solve this issue, like having a very thick diaphragm, adding 'wings' to its side that stick to the pumps sides, et cetera. It is doubtable if these would work.

The peristaltic pump provides many benefits. The flexible hose makes precision production ranges more broad, and saves the life time of other elements while being replaceable itself. It however does need squeezing, which costs efficiency and heightens start-up torque. The opening up of the hose behind the roller lowers this effect. The hose itself will most likely have to be imported, unless it features similar dimensions as for instance the hoses used in cars. Though having some difficulties, the peristaltic pump seems able to work and offers various advantages.

The rope pump is a simple concept that has proven to work, though problems were found in production. If produced imprecise the pistons malfunction due to abrasion or leakage. The ideal outcome of VLOM methodology would be a pump design that can easily be copy-pasted by independent producers, so that impact can continue and expand independent from the initial organization (Polak P. , 2013). The production issues of the rope pump however keep occurring when new agents start production (Bombas de Mecate, 1998; Arrakis, 2006).

8.3 Conclusion

This chapter has worked its way through pumping working principles and available pump types to select the most promising pump type for the field case. Of the 20 pump types reviewed, 4 seemed able to meet the requirements. These four pump types were evaluated in more depth, revealing the stationary vane pump type to be more complex and expensive, the diaphragm pump type to feature a high outcome uncertainty and the peristaltic and rope pump types to be very promising.

Of these two, the rope pump type has been tested extensively in circumstances similar to the field case, and the peristaltic pump type is new but considered promising by experts in the field (Fraenkel & Thake, 2006). The peristaltic pump furthermore seems able to improve exactly on the production precision issues that were discovered to limit the rope pump types' implementation. The peristaltic pump types' performs better on production precision as it incorporates an elastic hose. If this project is successful, the peristaltic pump promises to be a better solution then the rope pump. This work will thus develop a peristaltic pump. The next chapter develop and evaluate the peristaltic pump type for the Palestinian communities: wind powered and locally repairable.

Design

This project describes the design of a locally repairable, wind powered water distribution system for the Palestinian communities, with a peristaltic pump at its core (Figure 53). The peristaltic pump therein offers various advantages: (1) less manufacturing precision, (2) easy replacement of the pumps most fragile part, and (3) rotary, any-speed motion and associated high efficiency for rotary power sources.

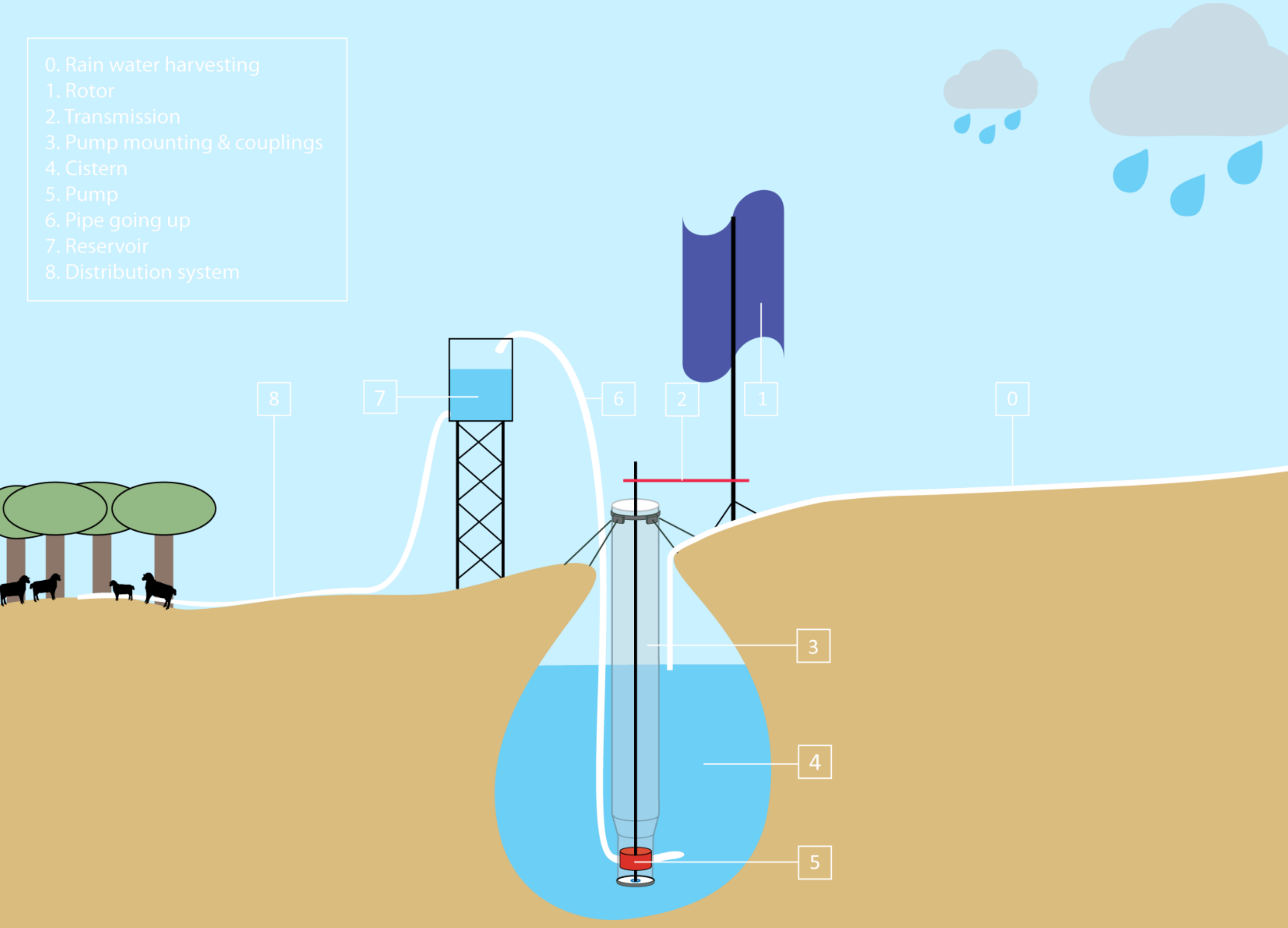
Scope

Besides the pump and its mounting, all system elements are locally available. The peristaltic pump is thereby the innovative part of the envisioned water distribution system. Its mounting is important for the local repair requirements: it has to be dismountable from the cistern. For its mounting configuration one working solution is thus developed. The peristaltic pump is consequently developed in more depth.

Design intention

Literature research did not reveal any previous designs for a peristaltic pump that can be locally repaired. Thus being the first effort to design a peristaltic pump for application in the developing world, the design will be kept as simple as possible. A minimalistic design is deemed most producible and repairable.

Figure 53: System overview

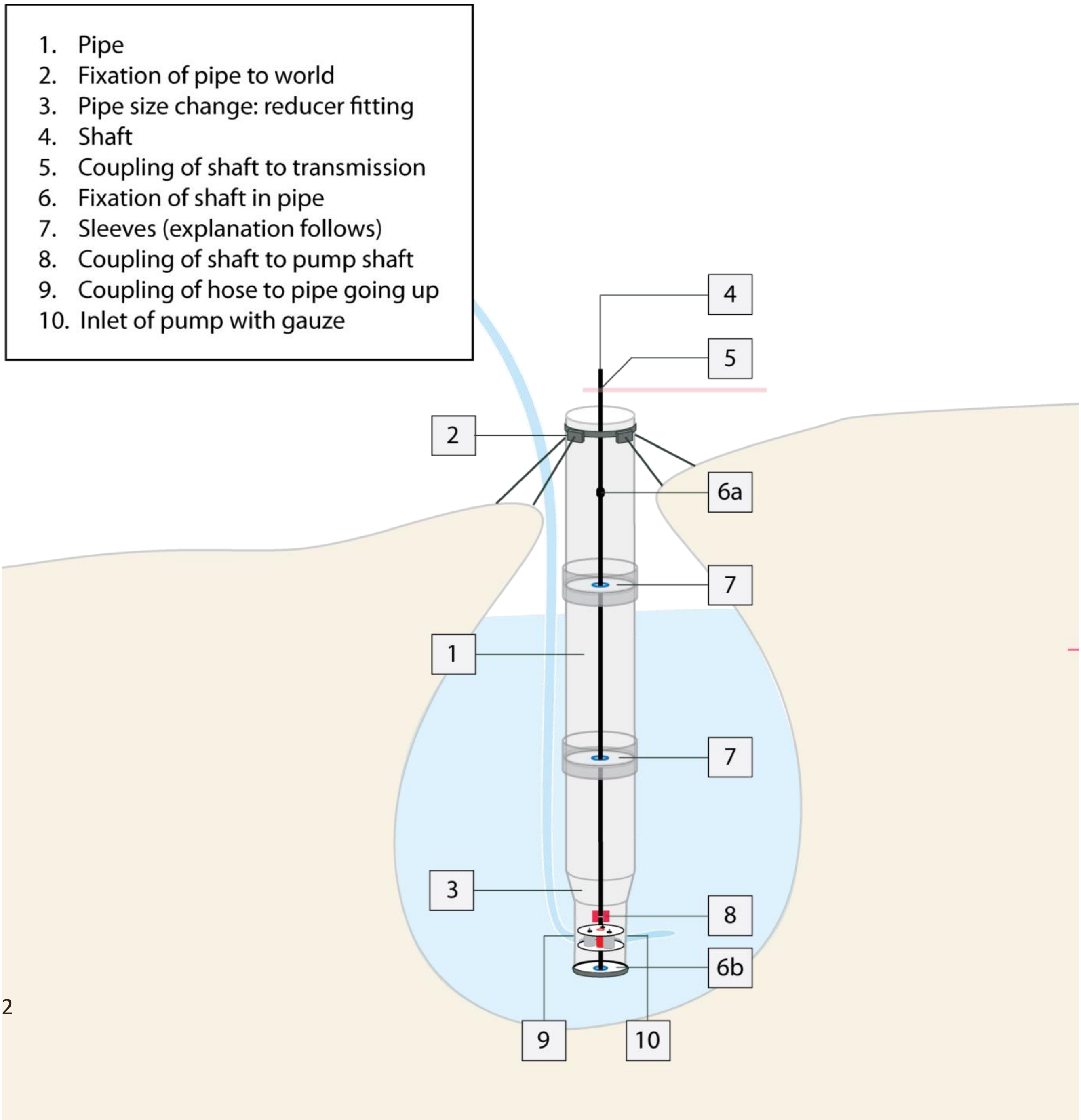


9 Pump mounting

This chapter describes a configuration for mounting the pump. Figure 54 names the parts in this pump mounting system; they are described below. In accordance with the requirements the mounting design features the following advantages:

- Dismountable without power tools
- Portable by two people
- The necessity for repair is visible from above
- Avoids sweep of the shaft and includes shaft centralization inside the pump
- Features a gauze to keep out debris
- All non-corrosive materials
- Combines standardized parts and simple manufacturing steps

Figure 54: Pump with part numbers



9.1 The pipe

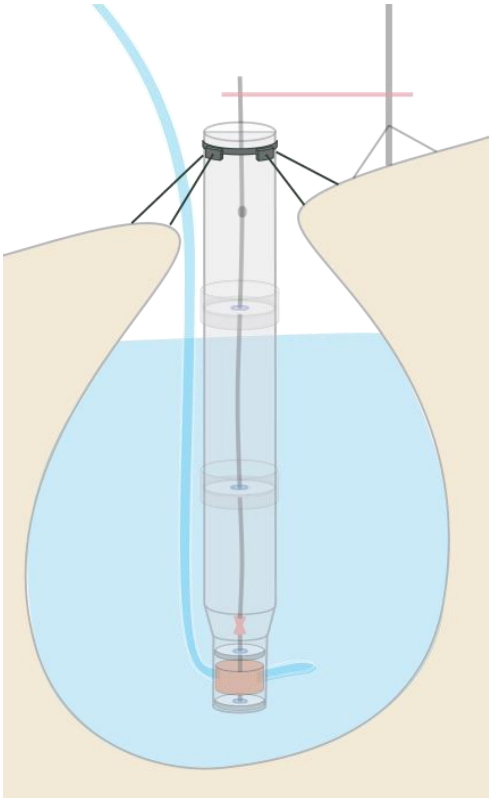
The pipe is number 1 in the part overview on page 62. It holds the pumps housing, that, in contrast to the pumps shaft, should not rotate. Holding the housing thus implies fixating it to the terrain: either inside or outside the cistern. As it is more complex to dismount a pump fixed at the bottom, a top fixation is chosen.

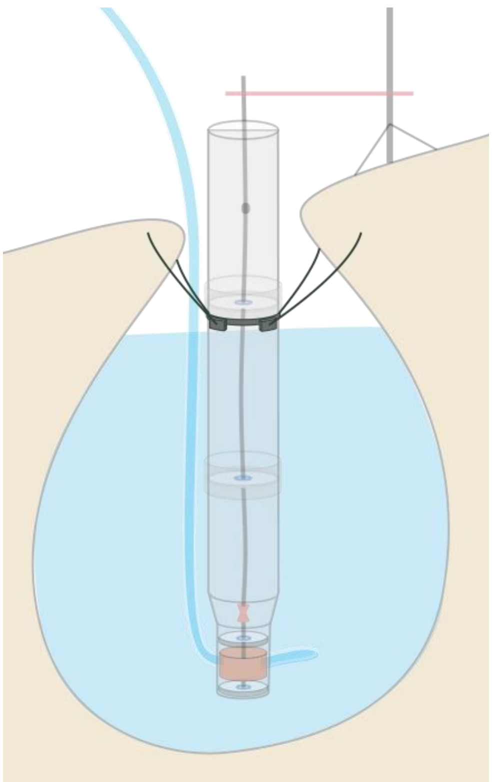
Between this top fixation and the pumps housing some material is necessary to bridge the distance. Rather than using a couple of rods to hold the pump it is chosen to hold the housing using a pipe. The pumps housing is also a pipe (refer to p. 91). It is practical to connect a pipe to a pipe, as this can be done using standardized sleeves (refer to number 3). These sleeves also facilitate bridging the 7 meters down in a simple manner: no welding or coupling is required, and the construction stays light-weighted. It is chosen to mount the pump using a standardized PVC pipe.

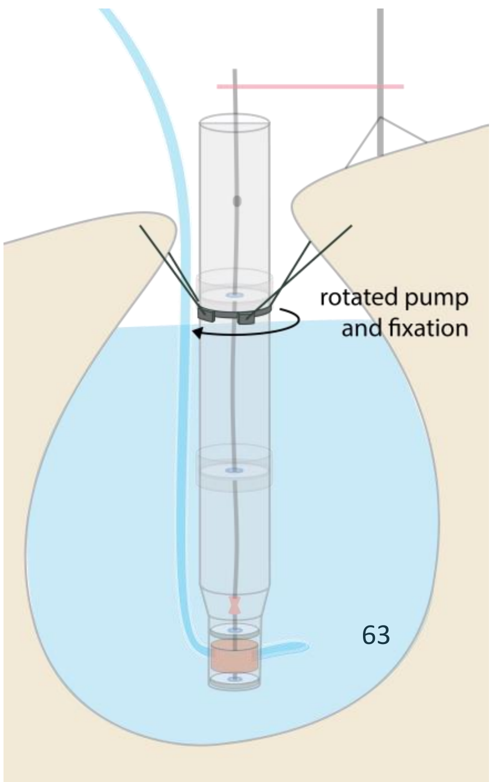
9.2 The fixation of the mounting pipe to the world

The fixation is number 2 in the part overview on page 62. The pump has to be mounted and dismounted, as said preferably without having to enter the cistern. It was thus decided that the pipe is fixed to the top of the cistern. This can be done using cables (Figure 56) or rods (Figure 55). The cables have the advantage that they allow a bit of movement, facilitating for instance vibrations or movements in the cisterns water. The cables however do need to hold the pump still as its shaft rotates: the pump might rotate along until it cannot reach further (Figure 57). This creates an unstable equilibrium where the pump winds up when working, and unwinds again when the wind is low. The fixation is thus done with rods.

Figure 55 (left): Fixation with rods
Figure 56 (middle): Fixation with cables
Figure 57 (right): Fixation with cables when the pump is working, rotating the pump until the cables are stretched







The fixation with rods may look as follows: at the top of the pipe, a ring is slid around it. Bolts hold the pipe to the ring. The ring is fixed to the ground using anchor plates fixed to the ground (e.g. using concrete). Figure 58 gives an overview of the described set-up.

To dismount the pump, the shaft must be detached from the transmission (refer to number 5), the bolts in the anchors are loosened and then the full configuration can be lifted out of the cistern.

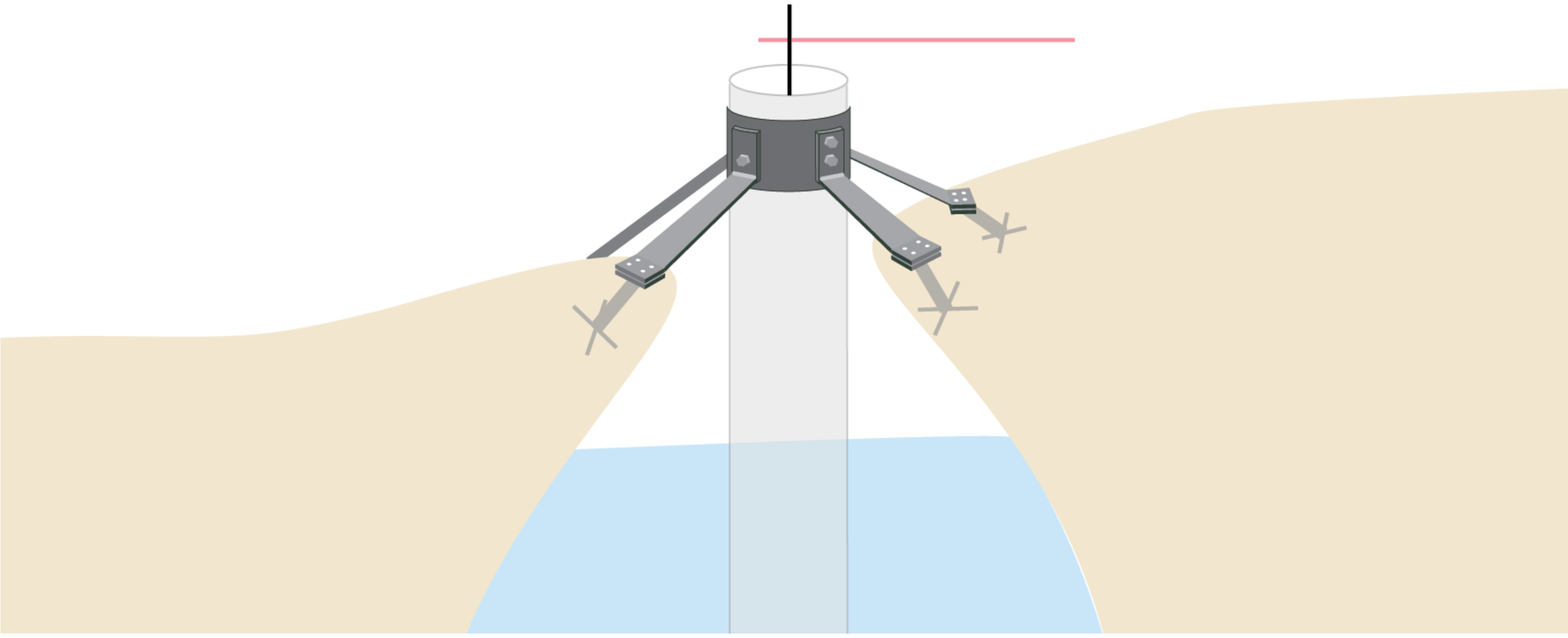


Figure 58: Fixation of the pump to the ground

To install the pump into the cistern an extra entrance needs to be drilled. Hatches are already present for the bucket system, but are 50x50cm square. This will probably not be big enough. By drilling a second entrance the hatch can be used to verify if there is still water in the cistern. If there is water and wind, and the pump is not lifting any water, the pump needs repair.

9.3 The size change in the pipe

The size change in the pipe is number 3 in the part overview on page 62. The pump housing is as large as the pump. The mounting pipes diameter depends on local availability and pricing of PVC pipes. If the mounting pipe diameter differs from that of the pump housing, a reducer fitting can connect both diameters. Note that these do not always align both sizes centres (Figure 59), so the design of the centralizing plates (refer to number 7) depend on this.

Figure 59: Pipe reducer fitting

9.4 The shaft

The shaft is number 4 in the part overview on page 62. The shaft transfers power from the transmission to the pump. It has to be connected to the transmission, guided downwards, coupled to the pump and held from sliding down. Construction elements that do this are described in numbers 5 to 8. The fixation of the pump (red cylinder) onto the shaft is described here. Fixing the pump to the shaft is done using flanges (Figure 60), that feature various advantages:

- Strong;
- Widely available;
- No machining of the shaft is required and;
- It is flexible to varying pump designs.

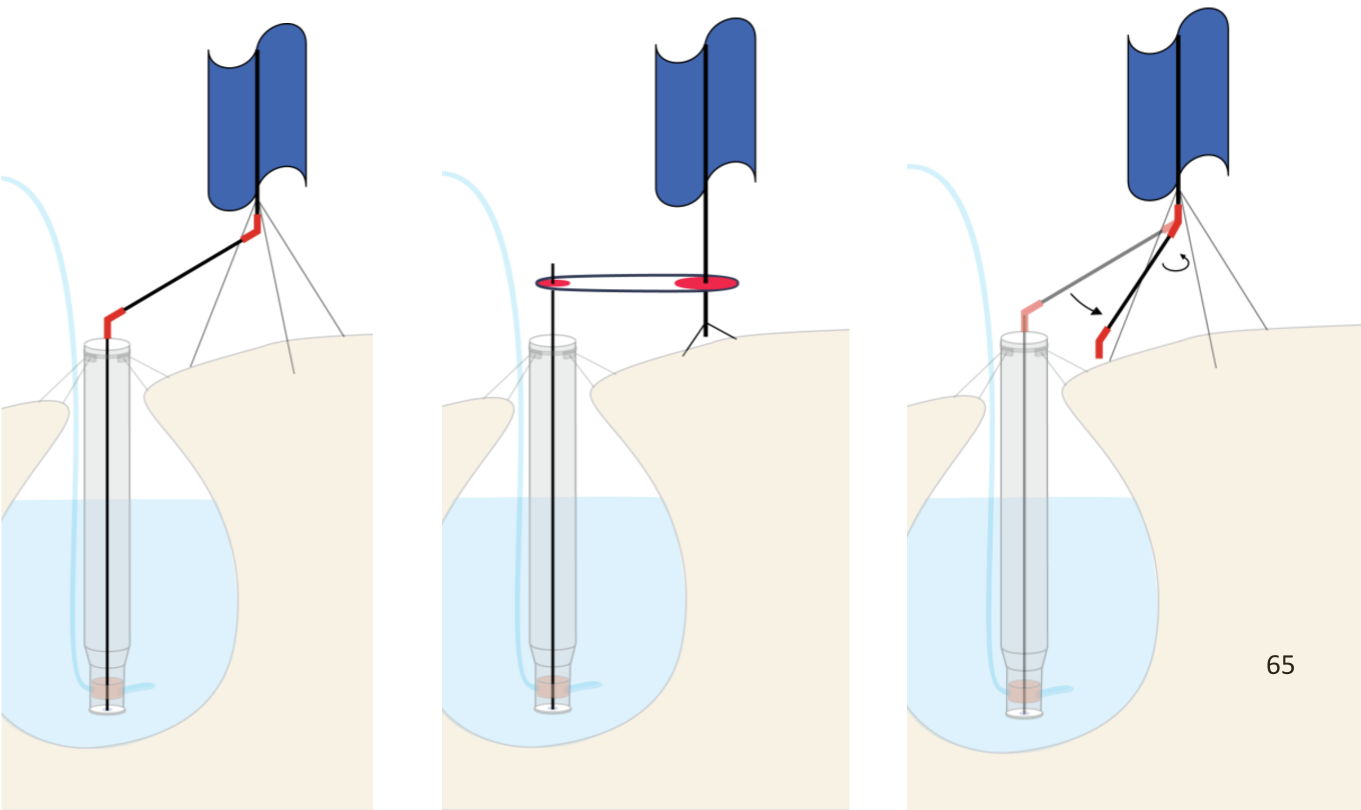
Two flanges keep the pump aligned with the shaft: one on top, the other at the bottom of the pump. The top flange can be welded to the shaft to fix the pump at a certain height, while keeping the pump dismountable through the bottom flange.

Figure 60: Flange

9.5 Coupling of the shaft to the transmission

The shaft coupling to the transmission is number 5 in the part overview on page 62. The shaft has to be connected to the transmission. It is likely that the transmission will either use cardanic couplings or a belt system, as these are common solutions (Figure 61). In both cases the pump and shaft have to be dismountable, so that the pump can be taken out of the well. This can be achieved in two ways: either the left part of the transmission is fixed to the top of the pipe and moves out with it, or it is not fixed on the left side at all and is free to be moved aside to let the pump out (Figure 62). The first option best suited for the belt transmission, the latter for the cardanic coupling transmission. Couplings that can be dismounted are available and can be obtained according to local preferences.

Figure 61: Two couplings between rotor and pump shafts. On the left cardanic couplings, on the right a belt system. Figure 62: The left part of the transmission is not fixed to the pipe or terrain, and is thus free to be moved aside. Here this happens by rotation from the rotors shaft.



9.6 Fixation of the shaft inside the pipe

The fixation is number 6 in the part overview on page 62. During operation the shaft may not move in vertical direction, and will thus need to be fixed vertically. Simultaneously it does need to move in vertical direction when dismounting the pump. One solution to achieve this is to hold it at the bottom of the pipe. Holding a vertical shaft can be done by a tapered bearing (Figure 63). The bearing is embedded in a thick round plate fixed in near the bottom of the pipe using screws (number 6a)(Figure 64). Remove the screws, take out the plate and the shaft is free to move down, exposing the pump. To avoid the shaft sliding down inside the pipe, a small (welded) thickening on the shaft near its top (number 6b) can refrain it from moving through the sleeves (number 7) (Figure 65). Note that the bearing has to be waterproof.

Figure 63: Tapered bearing.

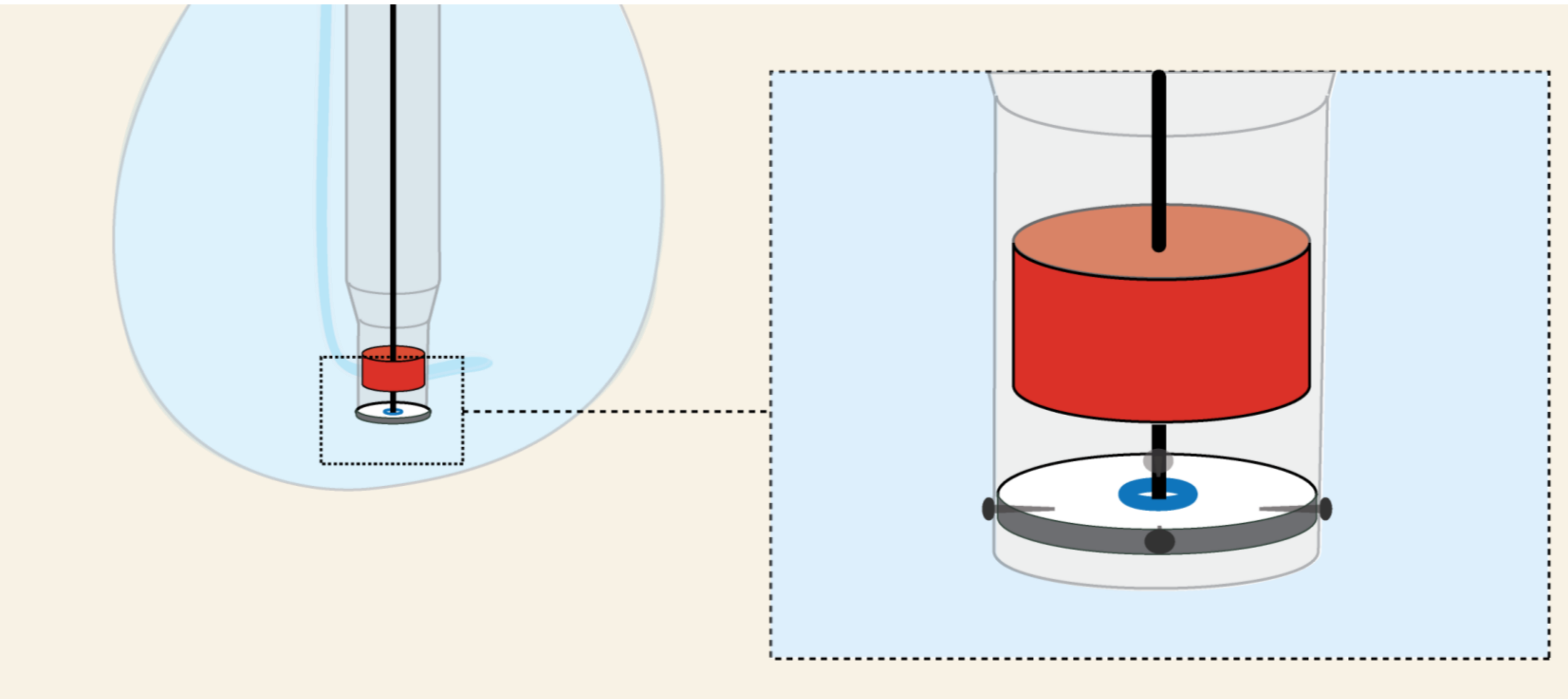
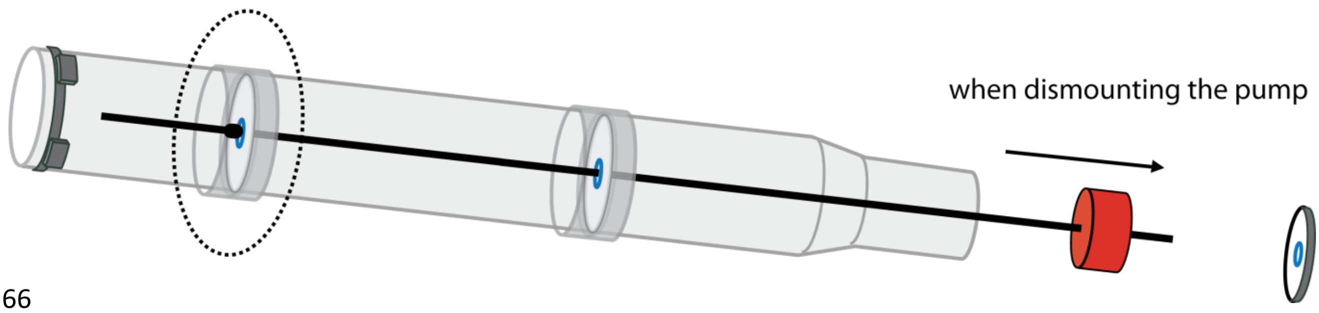


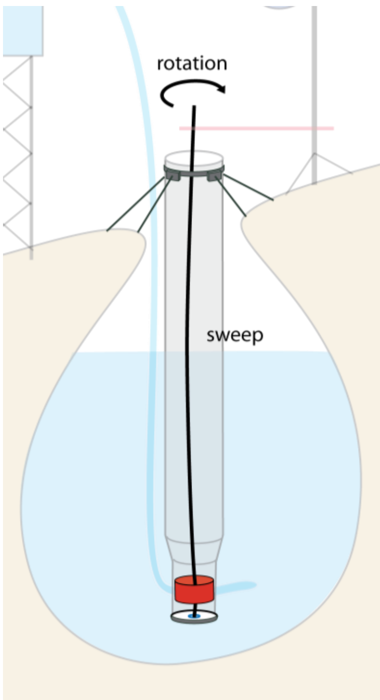
Figure 64 (above): Exploded view of shaft fixation. The blue ring depicts the tapered bearing
Figure 65 (below): Thickening on shaft prevents it from sliding down into the pump

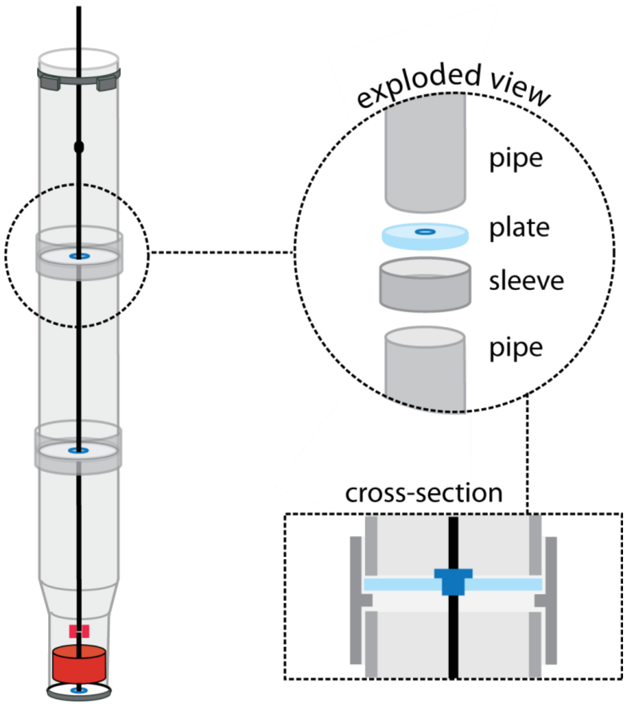


9.7 Sleeves

The sleeves are number 7 in the part overview on page 62. The sleeves connect the pipes to form one long piece of maximum 7m, depending on the cisterns depth. Pipes come in lengths of 1, 2 and 4m. Depending on local availability of pipe lengths there will be 1 to 7 sleeves required. These sleeves can be used to insert a guidance element (plate) for the shaft (Figure 67). The guidance elements are required to avoid the shaft from sweeping: a rotating vertical shaft starts to swing if it is unbalanced (
Figure 66). How many centralizing plates are required depends on the straightness and uniformity of the shaft. One might start with as many plates as the sleeves cater, to add more sleeves and plates if so required. The plates can feature a plain bearing to further smoothen the contact with the shaft.

Note that the reducer fitting (number 3) might not align the pumps housing with the pipe going up (p. 64). In that case the centralizing plates would have their shaft passage off-centered (Figure 68).





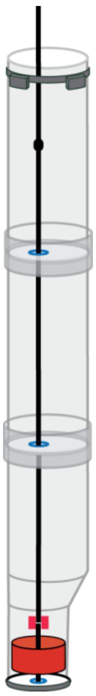


Figure 66 (left): Sweep in a long rotating shaft
Figure 67 (middle): Guidance element (plate) for the shaft combined with the pipe sleeves
Figure 68: Centralizing plates if the reducer fitting does not align both pipes

The deflection caused by sweep does not cause a height change that endangers the coupling of the shaft to either the transmission or the pump. A deflection of 10cm in a 7m long shaft causes a shaft longitude change of 3mm, which is considered negligible.

Sleeves are commonly glued to the pipes they are connected, which makes it relatively difficult to repair the shaft, centralizing plates or pipe. The pipe has to be sawed open and after repair reassembled by a new sleeve. One might also stretch lines from the top fixation ring to the bottom of the pipe. These lines have to be fixed tightly to avoid rotation of the pumps housing. This implies using nylon or stainless steel, both of which are a much more expensive investment in comparison to buying extra ‘repair’ PVC sleeves. It was thus chosen to glue the sleeves together: to provide a cheap, robust construction to hold the pump.

9.8 Shaft alignment in the pump

The coupling of the shaft to the pump is number 8 in the part overview on page 62. The sweep effect of the shaft described above should not affect the shaft inside the pump, as precision is important there. Pump shaft alignment can be achieved by (Figure 69) a combination of centralizing plates above and below the pump and a cardanic coupling (Figure 70). Cardanic couplings are available in Palestines vehicle repair industry. The lower centralizing plate is the one at the bottom of the pipe, holding the shaft (number 6b). The plate above the pump is a thick plate mounted with screws like the lower one. This way it can be dismounted from outside when the pump has been taken from the well. It is then possible to take the pump out of the pipe.

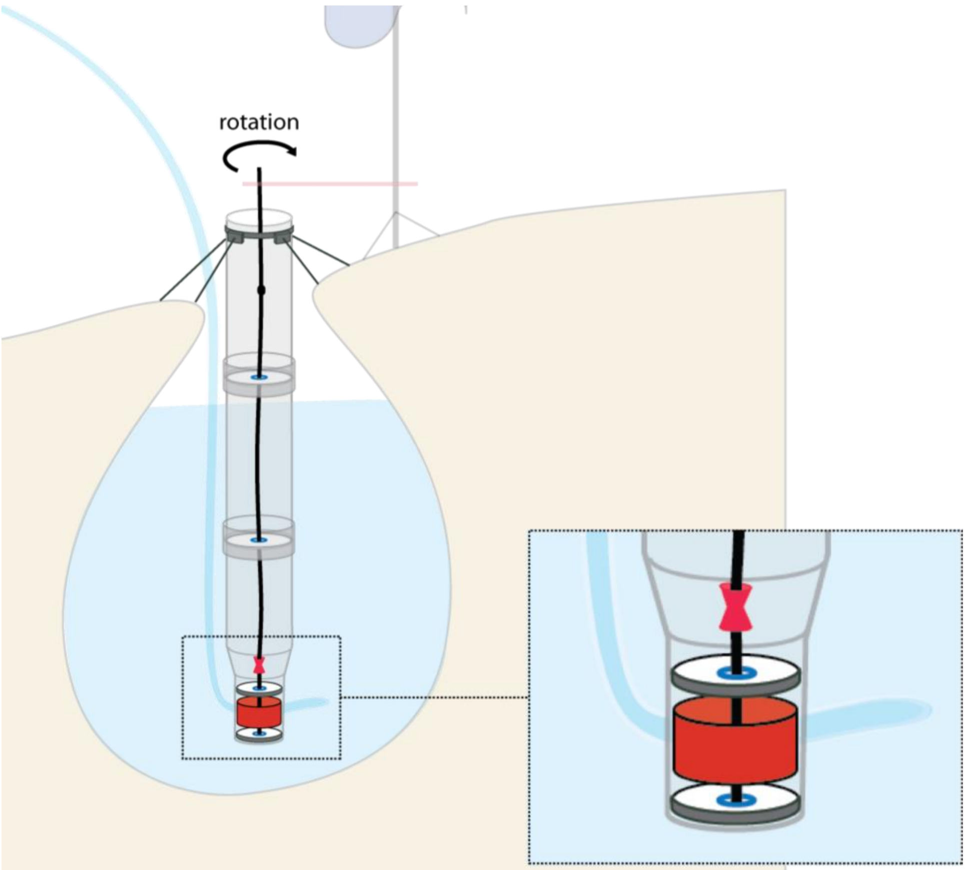


Figure 69: Sweep in a rotating shaft. On the left the sweep if no sleeves and shaft coupling is used. The situation on the right is the suggested design.

Figure 70 (left): Two types of cardanic couplings

9.9 Coupling of the pumps hose at the outlet

The hose coupling is number 9 in the part overview on page 62. A coupler is required between the hose inside the pump and the outlet pipe or hose. The outlet pipe going up the cistern could be anything: from a PVC pipe to a garden hose. The diameter of the outlet pipe influences the amount of torque on the pumps shaft: a large diameter creates a lot of surface to put pressure unto and thus corresponds to large torques (Equation 12). The diameter of the pipe or hose thus depends on the torque requirement as described in the wind power chapter. A coupler provides the match between the pipe or hose going up and the diameter of the hose inside the pump. Such coupling elements are typical for water, air and gas systems in for instance cars and houses (Figure 71), and can be acquired according to local preferences.

$$T_{pump} = F * R = P * A_{pipe} * R_{pump}$$

Equation 12

Figure 71: Examples of hose-pipe and hose-hose couplers

9.10 Inlet of the pump with a gauze

The inlet is number 10 in the part overview on page 62. The gauze at the inlet has to be big enough to not get clogged – hose gauzes are assumed to be too small. One solution is combining one of Figure 71 couplers with a larger gauze (Figure 72).

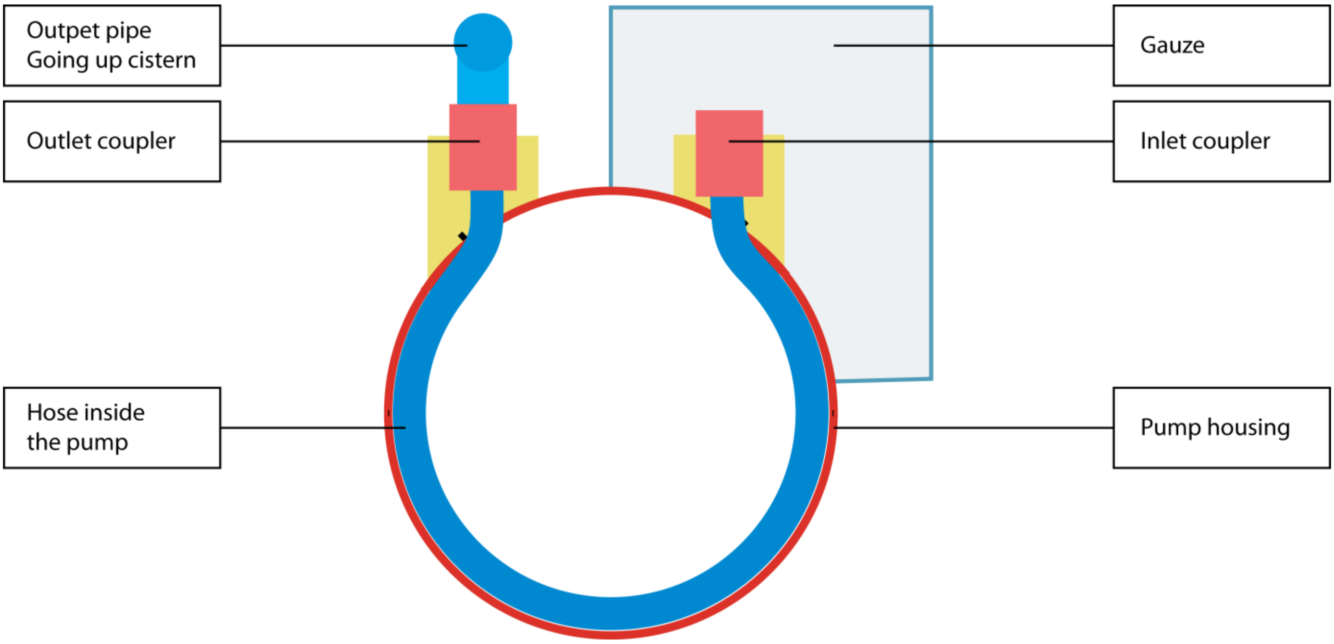


Figure 72: Configuration of outlet and inlet as seen from above

(Overview of the pump mounting is displayed on the next spread)

9.11 Overview of pump mounting

This section provides a summary of the considerations stated above. The pump mounting as designed provides a repairable construction to couple the pump to the rest of the system.

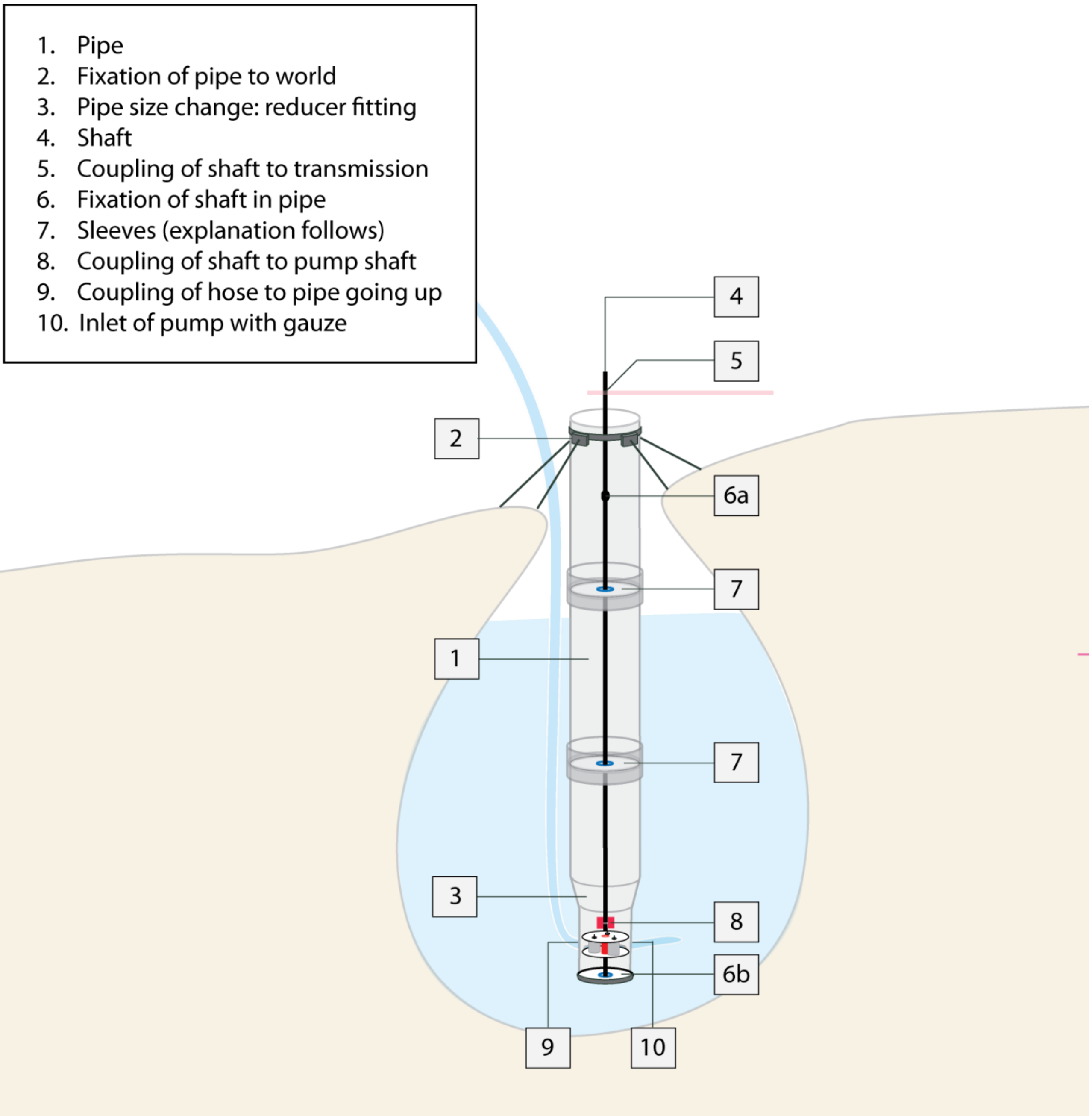


Figure 73: Pump with part numbers

The mounting of the pump is designed to hold the pump at the bottom of the well, while still being able to dismount it from the cistern. This is done by fixing the pump, whose housing is a standardized PVC pipe, to a pipe going up the cistern (number 1 in Figure 73). At the top of the well the pipe is held by a ring , that is bolted to rods that are anchored to the terrain (number 2 in Figure 73). This ring and pipe combination ensure that the pumps housing at the bottom of the well is still, while the shaft and pump rotate inside it.

The fact that it is a pipe going down the well furthermore makes it easy to stretch the required 7 meters down (a cistern is 7m deep). PVC pipes are connected using standardized sleeves, which are light weight and cheap. Centralizing plates are inserted into these sleeves, ensuring that the shaft goes down aligned and straight, as the shaft too stretches over 7m (number 7 in Figure 73).

The shaft is at the bottom fixed to the pump using a cardanic coupling, correcting any angle differences between the shaft going up and the shaft inside the pump (number 8 in Figure 73). After this coupling the shaft is centralized in the heart of the pumps housing using two centralizing plates: one above the pump and one below (number 6b in Figure 73). The bottom centralizing plate features a tapered bearing that carries the shaft. It can be dismounted by removing screws. To prevent the shaft from sliding into the pump when dismounting it a thickening on the shaft near the pipes top refrains it from sliding past the first centralizing plate (number 6a in Figure 73).

If the shaft, centralizing plates or pipe requires repair, the pipe is sawed open and after repair reassembled by a new sleeve. This is assumed cheaper than keeping the pipe together using for instance lines stretching from the top to the bottom of the pipe. Though such lines could be disassembled without breaking them, they would have to be very tight to refrain rotation of the pumps housing. This implies using nylon or stainless steel, both of which are a much more expensive investment in comparison to buying extra 'repair' PVC sleeves.

The pump is fixed unto the shaft at a set distance from its bottom by flanges, of which the top one is welded unto the shaft (number 8 in Figure 73). The bottom flange can be dismounted from the shaft, allowing repair of the pumps parts. The pump is connected to the hose going up the cistern by a standardized hose coupling (number 9 in Figure 73). At the inlet side of the pump the hose is coupled with a standardized hose coupling to the open water, surrounded by gauze that keeps out rocks (number 10 in Figure 73).

This summarized the mounting of the pump into the cistern, and coupling to the rest of the system. In the next two chapters the pump itself is designed. First the design of the peristaltic pump is discussed, then decisions are made to the peristaltic pump most appropriate for the Palestinian communities.

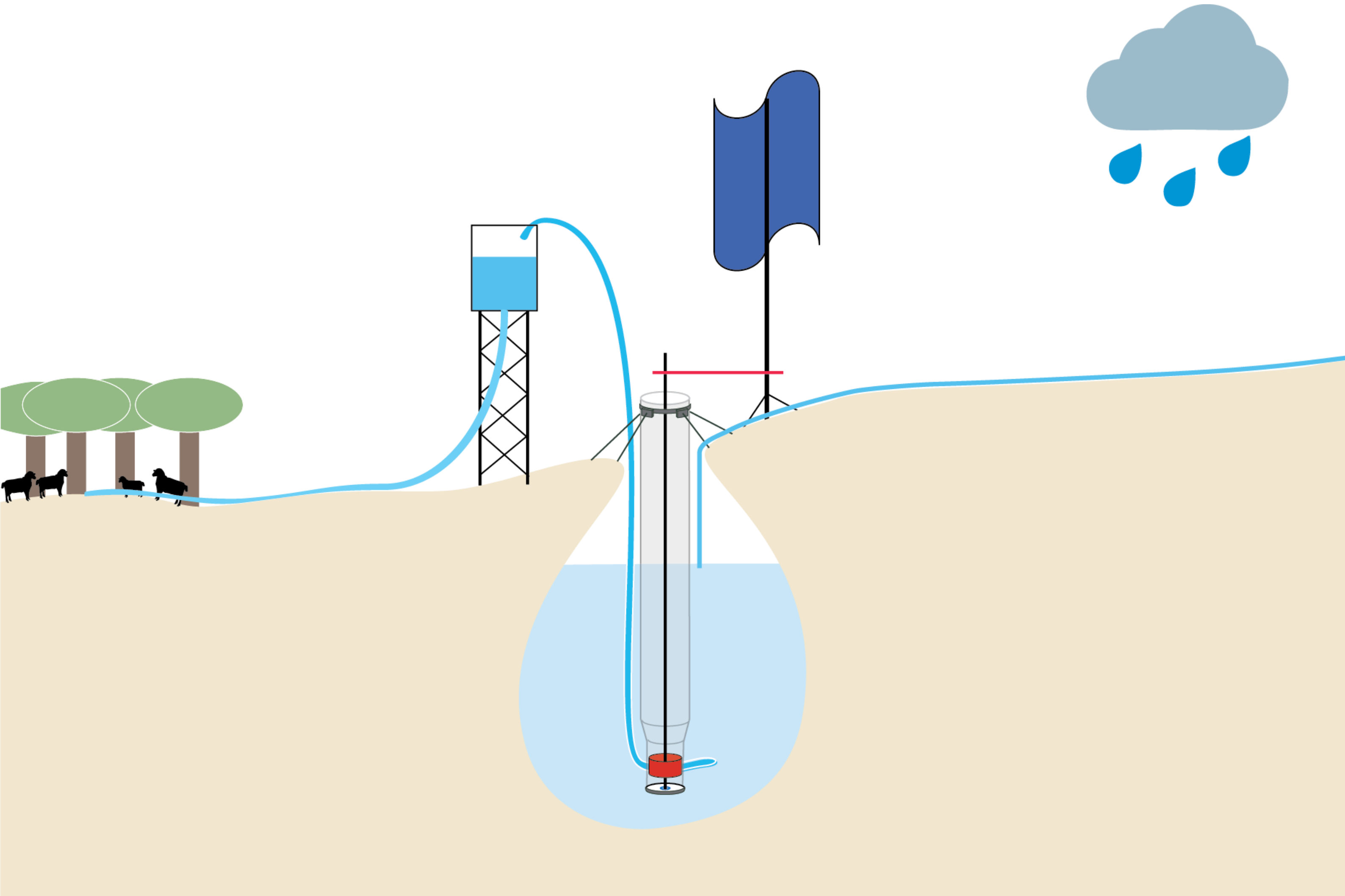
10 Peristaltic pump design considerations

The peristaltic pump itself is part of the system described above, and the key focus of this project. Within the system described above (
Figure 74), it is the red cylinder. This chapter describes the peristaltic pump and what one has to pay attention to when designing it. The next chapter describes the resulting design decisions.

Information on pump design is primarily found in the market place. Literature is limited to the World Pump Journals showcase of new products and several publications from the micro pump sector, both of which are irrelevant to the field case situation. The first does not provide the reasons for the made design decisions, the latter is a design optimized for precision performance: contrary to the design sought here. Knowledge on peristaltic pump design it thus gained by investigating the different ways parts are implemented for different circumstances in the commercial world.

The research section first explains the pumps most common parts and their function. Consequently it describes attention points: found as differences among peristaltic pumps, or design decisions that seem universal but contradictory to what would be beneficial to the context. The full report of the market research includes all design variables, and can be found in appendix [4].

Figure 74: System overview



10.1 Common configuration of parts

Figure 75 shows the peristaltic pumps common parts. It shows the hose, being squeezed between the pumps rim and the rollers. The distance between the rollers and rim is referred to as occlusion. The rollers are free to rotate around their respective shafts, lowering the friction between roller and hose. The impeller holds the rollers, and connects their movement to the pumps shaft. As the shaft rotates the impeller pushes the roller along the rim, pushing the water in the hose forward

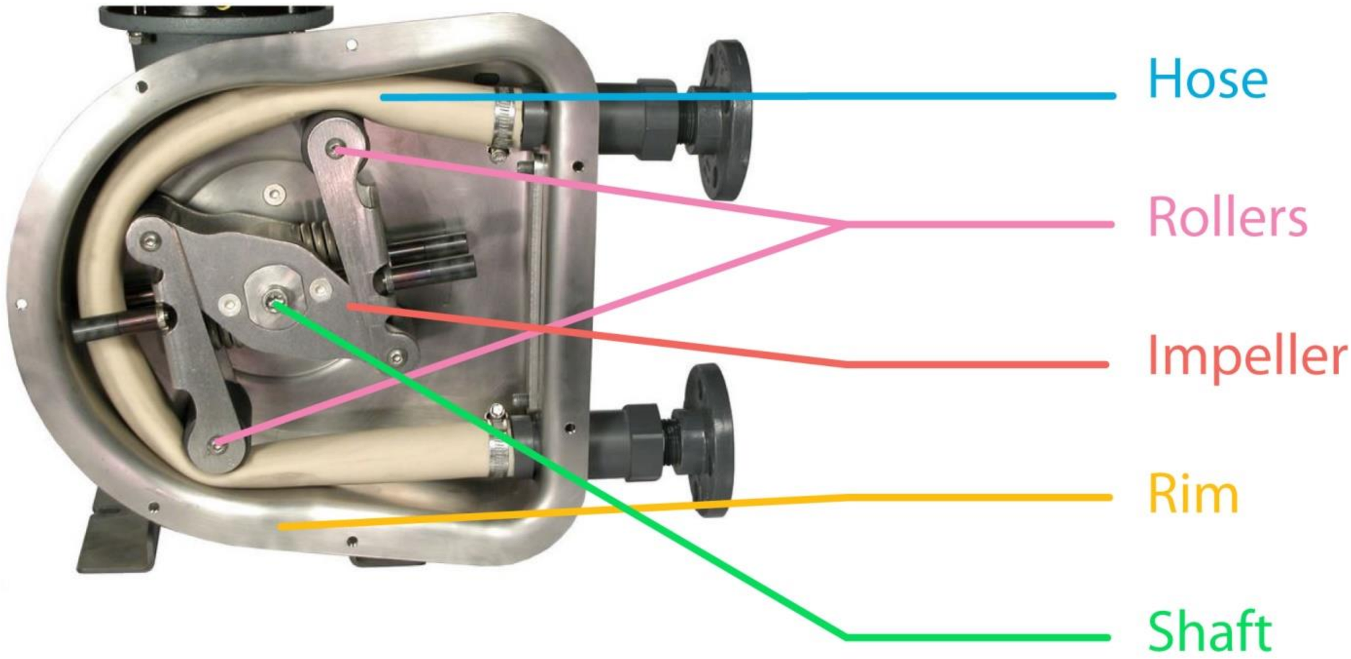
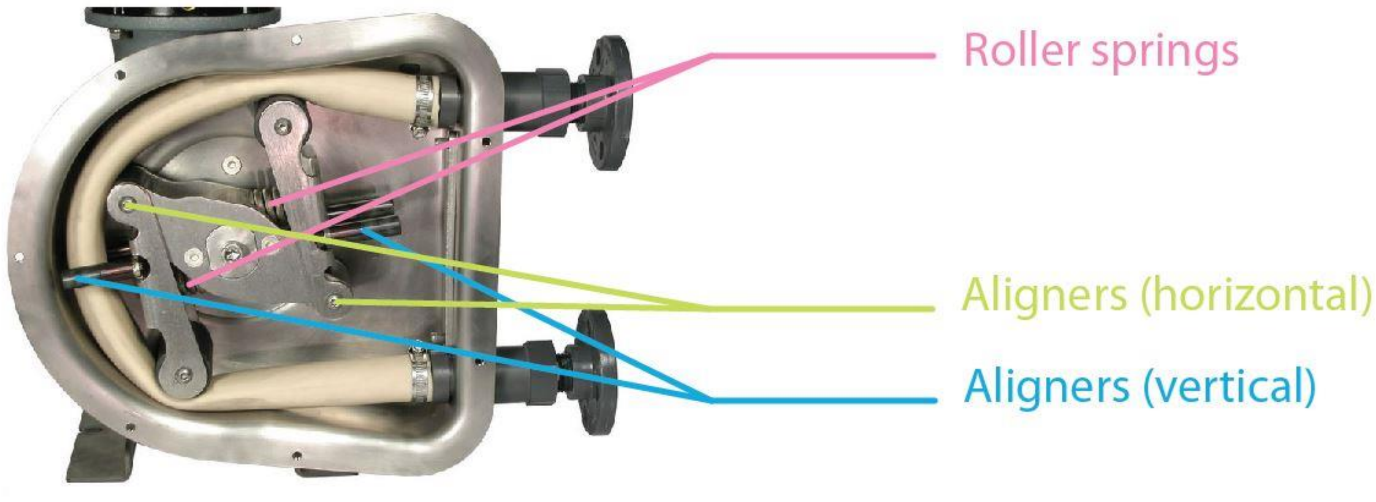


Figure 75: Depiction of hose, rollers, impeller, rim and shaft in the peristaltic pump.

Figure 76 shows additions that can optimize the pumps performance: springs on the rollers and aligners. The springs cater for irregularities in the hose, fluid or occlusion, the aligners keep the hose in place. The horizontal aligners herein keep the hose close to the rim; the vertical aligners refrain the hose from creeping upwards or downwards beyond the rollers reach. The difference between horizontal aligners and rollers is that aligners do not squeeze the hose; they merely keep it in place.

Figure 76: Depiction of roller springs and aligners in the peristaltic pump



10.2 Life time of the hose

The life time of the hose is the peristaltic pumps most precarious limitation, and therefore the first attention point. Most peristaltic pumps are designed for single hose use, especially those in high-hygiene environments. The hoses life time is however vital to the pumps performance: the hose fatigues slowly, making the pumps performance fade out slowly. Its repair planning is thus hard to define, which could cause pump abandonment. This section will thus explain the governing influences on hose life time, and how one can assess and lengthen life time.

Hose life time: an explanation

The wear in the hose consists of stress and strain rate. Stress indicates how intensely the hose is changed from its natural shape; it is a function of the hoses elasticity and displacements. Strain rate is the change of stress over time and influences how well stress is 'remembered', or in other words: the amount of wear each passing of stress induces.

Stress on the hose in a peristaltic pump has multiple sources: occlusion presses it from a circle to a flat, elongation happens when the hose moves along with the rollers, the hose is bended along the pump rim, and expanded by the water head. Strain rate is dependent of the change of stress over time: the speed with which the rollers move, and how they engage with the hose.
Besides this 'ideal' calculation, local peaks of stress and strain rate can be created by particles in the water (debris), imperfections in the hose material or hose wall thickness, and imperfection in the rim and driver dimensions.

Optimizing the design

Considering these wear influencers, one can design the pump such that it minimizes them. The following design variables impact hose life time:

- The occlusion (the distance into which the hose is squeezed, between roller and rim) defines the strongest stress put on the hose. Looking at the hoses squeezed-flat cross-section
- (), stress from occlusion occurs especially at the edges of the hose; that is where the bend is strongest. Ideally the stresses are only created by the sharp bends in the flat shape, but when occlusion is too narrow the driver will also compress the edges unnecessarily. To optimize life time the occlusion should thus rather be too big than too narrow. A roller or rim with a customized profile furthermore aids to put less stress on the hoses edges while still closing the hose completely.
- The pumps speed influences the strain rate induced when the rollers move forward over the hose, and the amount of wear-inducing roller passes per time interval. The pumps speed together with the hoses' internal volume defines the flow rate. For a set flow rate optimization towards a small amount of passes thus results in a large pump. A slow big pump lives longer than a fast small pump.
- The amount of rollers defines how much stress is induced each cycle; if three rollers pass the hose it creates stress more often than if only two rollers pass by. Fewer rollers are beneficial for hose life time.

- The roller diameter influences the strain rate as squeezing the hose happens more or less gradually. The rollers should be as large as possible.
- Springs on the rollers aid in minimizing the impact of local peak stresses created by debris et cetera.

The next section describes if and how the designs hose life time can be predicted, to verify if and how hose life time can be guaranteed.

How to predict hose life time

The hoses life time is considered complex to model or calculate, as it requires a dynamic fluid-structure interaction analysis, where the structure is elastic. The most recent model (Elabassi, Bergstrom, & Brown, 2011) has succeeded in calculating stress and strain rate at the location where the roller is engaged with the hose, but how consequently life time is affected cannot be predicted to date (correspondence with dr. Elabassi: july '15). Dr. Elabassi is still working on it: future efforts might include his work.

Producers' data cannot be used to estimate the hoses life time. Hose life time data provided by producers sparingly describe the test circumstances, limiting the possibility to translate the test results. Data among producers can vary up to ten times, for a hose of the same material and dimensions. To predict hose life time, a test is required with similar circumstances as the final situation.

Which circumstances should be similar can be explained using the wear causes as described above. Reliable tests incorporate the same hose, fluid, head, speed, occlusion, rim and rollers' size and shape, and time period as the intended situation.
Doing such tests at this stage is not feasible. The required life time of a year is beyond the span of this project.

As the hose is the most vulnerable element in the peristaltic pump, one can use it to plan maintenance. Flow rate drops if the hose wears, so regular flow rate measurements (note that the wind speed has to be the same for each measurement) can indicate the necessity for maintenance. For flow rate measurements the pump will not need to be taken out of the cistern.

Conclusion

Hose life time is the primary cause of pump failure and possibly abandonment. Maintenance may be scheduled to match the wear in the hose, which can be measured by keeping track of the pumps flow rate. Life time of the hose however remains difficult to predict. The best that can be done at this stage is to design the pump to lengthen hose life time, as described above. These design aspects will be used as attention points to guide the design process. Life time tests are recommended for a later stage.

10.3 Number of rollers

The amount of rollers varies enormously among the pumping world, where it was just seen that it should be as small as possible to cater for long life times. This renders it an attention point: why would you use more rollers?

A good reason to go with more rollers appears to be exact flow rate control: dosage pumps come with up to 6 rollers, where for instance slurry pumps feature only one roller.

Multiple rollers furthermore aid in keeping the hose close to the rim. In some pumps the hose 'wraps' around the rollers, rather than following the rim (Figure 77). In such cases the point where the roller engages with the hose near the inlet creates a torque peak (Figure 78).

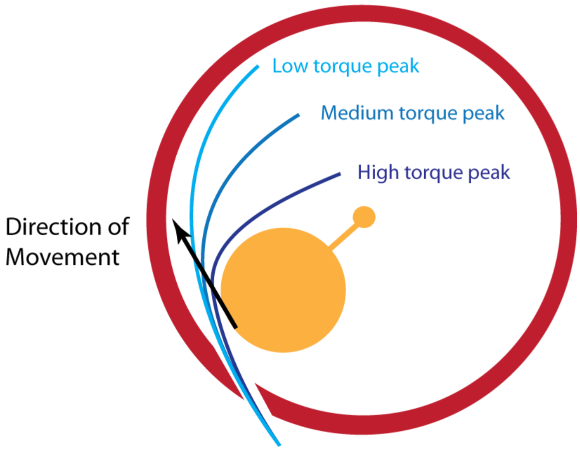


Figure 77 (left): Peristaltic pump where the hose 'wraps' around the rollers. Retrieved on 10-6-2015 from http://www.lambda-instruments.com/?pages=francais-pompes-peristaltiques
Figure 78 (right): Torque peak heightens as the hose is further away from the rim.

Every roller also creates an extra 'barrier' for leakage. Leakage is commonly expressed as a backwards flow rate that happens across a gap. In the case of the peristaltic pump, water inside the hose might flow past the squeeze provided by the roller: the opening in the hose when squeezed is in this case the gap. The leakage flow rate is proportional to the gaps cross-sectional surface and the pressure difference across this gap (Zhao, Billdal, Nielsen, & Brekke, 2012). A proportional relation between gap surface and leakage flow rate implies that if the gap becomes twice as big, leakage flow rate becomes twice as big. The pressure difference proportionality implies that if pressure difference across the roller is twice as high, leakage will be twice as high. More rollers divide the total pressure difference over more 'gaps', thus lowering the total leakage.

If there is a single roller it has to be noted that the hose then passes by itself, as otherwise water would flow from outlet to inlet when the roller does not engage with the hose (Figure 79). The hose passing by itself requires a more complex track or guidance for the hose, so that it does not move from behind the roller (TheFlyingBeer, 2011).

Figure 79: Peristaltic pump with a single roller. The hose passes by itself to avoid leakage. Retrieved on 14-7-2015 from http://empoweringpumps.com/water-scarcity-issues-may-solved-better-selection-pumping-technologies/

The amount of rollers is thus a precarious issue: while avoiding unnecessary stress on the hose one does want to keep torque peak and leakage low. This attention points' design question is thus: how many rollers are minimally required to function well in the field case?

10.4 Pump speed and dimensions of the rim and hose

The pumps speed and dimensions of the rim and hose together define the pumps flow rate. A larger rim implies a larger pumped volume per cycle, as does a larger hose. To optimize hose life time the pump speed needs to be as slow as possible, implying a bigger pump. This is thus an attention point: how big can the rim and hose be within the cost and torque requirements?

10.5 Thickness of the hose

Most commercial peristaltic pumps feature a very thick hose. This broadens the span of proper occlusion (more elastic material to accommodate displacements), aids in the hose opening back up as the roller has passed (higher cross-sectional stiffness keeps the hose open) and keeps the hose closer to the rim (higher lengthwise stiffness keeps the hose straighter). A thicker hose also costs more torque, which matters less in engine powered pumps, but can create difficulties when the pump is combined with a wind rotor. This makes it an attention point: does the pump for the Palestinian communities need a thick hose, or could it be more efficient with a thin one?

10.6 Springs on the rollers

Springs are very prevalent; almost every peristaltic pump features springs on the rollers. These allow the rollers to move inward and outward (lowering stress peaks and broadening the spectrum of proper occlusion), and often to slow the roller down as it engages with the hose (lowering torque peak at the hoses inlet). Many different configurations are found to combine these two directions. This makes it an attention point: would springs be required, and how should they then be configured?

10.7 Aligners

Aligners keep the hose in place. They can function in two directions: to keep the hose close to the rim and to keep the hose at the same height as the rollers. Keeping the hose close to the rim lowers the torque when the roller engages with the rim near the pumps inlet (Figure 78). Keeping the hose at the same height as the rollers is necessary when it 'creeps' away from the rollers. That aligners are prevalent but not ubiquitously present make it an attention point: are they required for the Palestinian communities?

10.8 Rim & Roller profile

The roller squeezes the hose against the rim. To optimize the hoses life time one would apply a profile to the rim, roller or both. This is however rarely seen in commercial pumps. It is thus too an attention point, to verify its necessity for the field case.

10.9 Impeller & Shaft

The impeller transports the shafts rotation to the rollers' movement. The impeller keeps the rollers vertical and centralized at a set distance from the rim.

10.10 Hose material

As life time was seen to be important, the hose material is an attention point. Natural rubbers, chemical rubbers (NBR), silicones and specifically made elastomers are typical hose materials. This section gives a short introduction on these materials.

Natural rubber (€25/m) is harvested as latex from the Pará rubber tree, which mainly grows in South East Asia. Globally it is readily available anywhere and highly standardized. A risk is that it deteriorates faster in the sun and heat: exposure to temperatures above 30^{o}C creates 'stains' of oxidized rubber within hours (Transport Information Service, 2015).

Chemical rubbers (€5/m) can be mixed with a solar protector, but they are toxic to humans, animals and plants. Letting them carry water is a health risk. Worldwide the chemical rubber market features cheap, low quality alternatives that are unreliable both in dimensions and material uniformity.

Silicone hoses (€40/m) exist in many different dimensions, but are commonly enforced with steel wire. Soft hoses are not available worldwide yet. A few dozen producers exist, and hold up their quality.

Elastomers like Tygoprene or Verderprene (≥ €80/m) are specifically made for peristaltic pumps and feature the highest reliability. They are specified in detail and can feature: chemical resistance, high softness, heat resistance, vacuum resistance, high pressure resistance, UV resistance, high dimensional precisions and long life time (Saint-Gobain Corporation, 2013). Both Tygoprene and Verderprene have a single production facility worldwide.

10.11 Summary

The market research showed how pumps are commonly designed and focussed the design process. The design will concentrate on: the number of rollers, the balance between pump speed and dimensions of the rim and hose, hose thickness, springs on the rollers, aligners, rim and roller profiles, the impeller and shaft and the hose material. Their impact on the design is repeated in the design chapter; here they are just stated as the conclusion of the sections above.

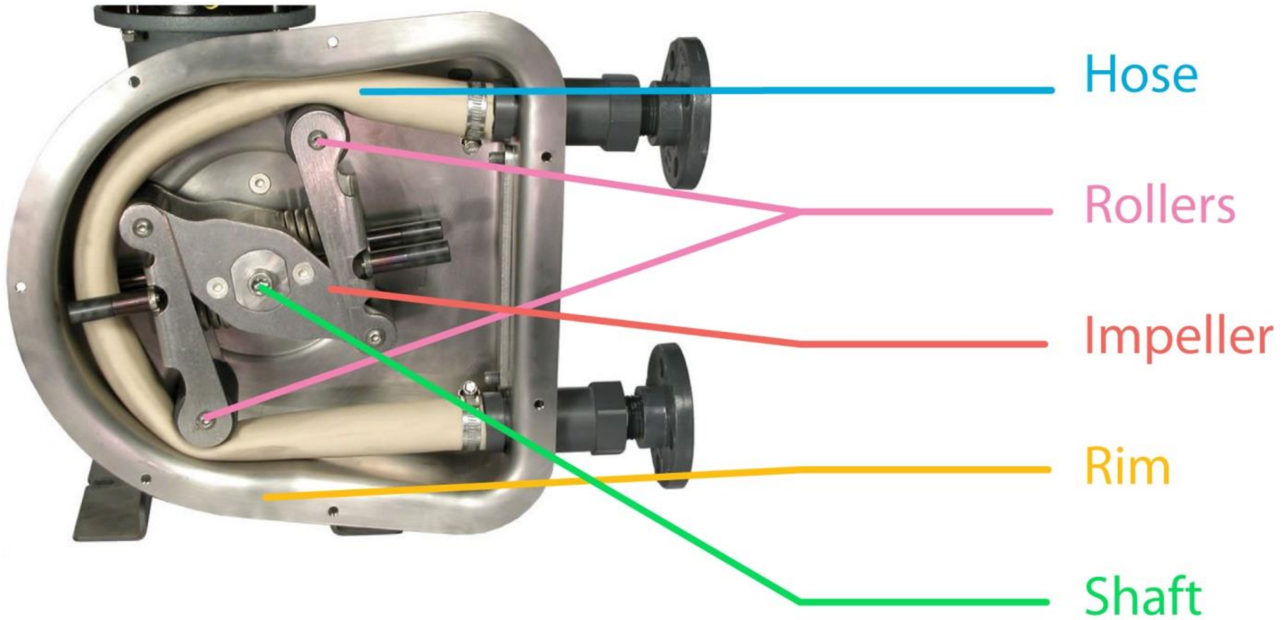


Figure 80: Depiction of hose, rollers, impeller, rim and shaft in the peristaltic pump.

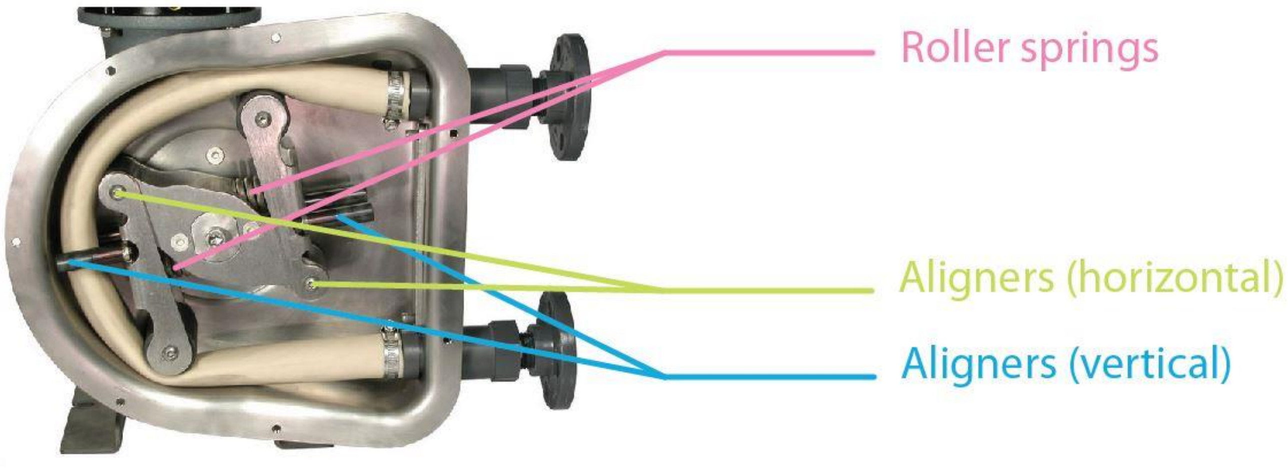


Figure 81: Depiction of roller springs and aligners in the peristaltic pump

11 Design

The previous chapter rendered the basic design of the peristaltic pump, and the attention points for the field case specific design. These are now elaborated upon to design a peristaltic pump for optimum field case performance.

11.1 Number of rollers

The peristaltic pump uses rollers to squeeze a hose: moving the squeeze forward along with the rollers is how the water is pumped. The amount of rollers with which this is done is an important design decision. The research section showed how more rollers create:

- Less leakage
- Less peak torques
- Faster hose wear
- (And that a one roller design would require a more complex hose path).

Hose wear was seen to be the first part to need repair, that thus needs to be kept whole as long as possible. Simultaneously the pump has to function within the flow rate and torque limits found in the requirements. To evaluate how many rollers are at least required to provide a leakage free, low peak torque design a test was done. This test consisted of two prototypes: one with 2 rollers, and one with 3 rollers (Figure 82, Figure 83).

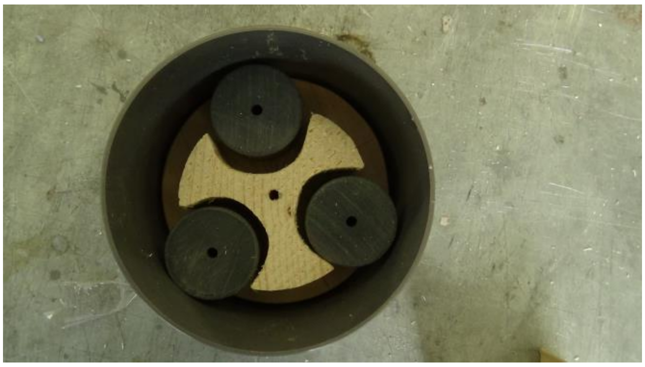
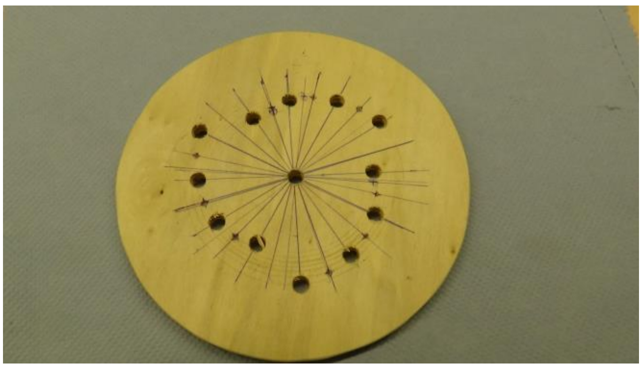
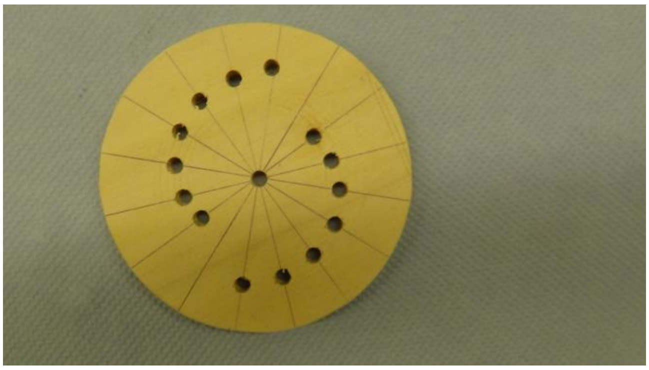


Figure 82 (left): two roller prototype
Figure 83 (right): three roller prototype

The test included several connection points for the rollers, so that the occlusion could be optimized within precision steps of 0,5mm (Figure 84, Figure 85).

Figure 84 (left): Plate to hold three rollers, with different settings for the occlusion.
Figure 85 (right): Plate to hold two rollers, with different settings for the occlusion.





While testing the prototypes it appeared that the two roller design does not provide stable operation: torque peaks were too high. The test with three rollers proved stable.
The impact of the amount of rollers was seen first in the deformation of the rim. In the test with two rollers the pump rim deformed to a rotating oval, where the 3 roller prototype remained more circular. The optimal occlusion for two rollers was measured to 1/3^{d} of 2 times the wall thickness (the thickness of a hose pressed flat); implying the rest of the space the flat hose needs is created by the deforming pump rim. For three rollers occlusion was best at 5/6th of 2 times the wall thickness. Constant deformation of the rim results in both an unnecessarily high torque and a higher pump rim wear. Rim deformation could however also function to facilitate debris passing through or varying hose thickness. A bit of deformation is thus desirable, but as much as with the current two-roller prototype is unreliable. Besides using more rollers, deformation could be avoided by taking a stiffer rim; either a non-standard thicker PVC tube or a stiffer material like stainless steel. Besides being harder to find, such stiff rims would also be more expensive.

Secondly, the two roller design moved shock-wise and broke often due to the peak torques, where the three roller design proved stable. The hose in the 2 roller prototype moved both along its length and perpendicular to it (up and down across the roller). This resulted in the thinnest hose tearing multiple times (Figure 50) and the rollers running so hard against the washers that they would dissolve (Figure 87). Besides this, the bolts holding the driver plates would loosen frequently, or the drill used as the motor would go over its maximum torque. Aligner would aid to avoid this, but still allow rim deformation.

What was seen considering pump rim deformation and torque peak dictates the application of three rollers. Using more than three rollers was not deemed necessary.

Figure 86: Teared hose
Figure 87: Damaged rollers

11.2 Wall thickness of hose

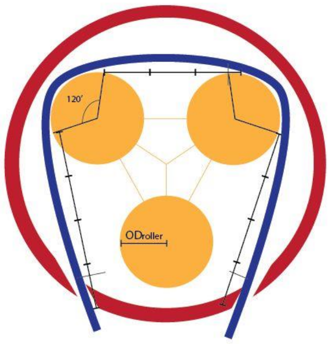
The research in the previous chapter showed that a higher wall thickness broadens the spectrum in which occlusion is adequate, improves the hoses' proximity to the rim and the opening up of the hose behind the roller (and with that the flow rate). It also heightens the required torque, which poses a threat to the match with the rotor. The wall thickness should be as small as possible, while still opening up behind the roller and being leakage-reliable within 0,5mm production precision.

A test with hoses of 22mm diameter and multiple thicknesses revealed that a 2mm thick hose suffices. A 1mm thick hose would regularly tear, a 1,5mm thick hose would be more reliable but not properly opening up, and 2 mm thick hose would open up and be reliable. Similarly, the 1,5mm thick hose would be difficult to match to an occlusion setting, where the 2mm thick hose provided a match without leakage or high torques. It was decided to go with a 2mm thick hose.

11.3 Pump speed, inner diameter of rim and hose

The pump has to provide enough flow rate to cater the Palestinian communities, which comes down to 5L/min at 100RPM rotor speed. The flow rate is a function of pumps rotational velocity and the amount of water it pumps per cycle.

A model was made to balance rotational velocity and the pumps dimensions. This model was designed to match the flow rates as seen in the test with the three rollers. This rendered that the pumped volume per cycle is a function of the hoses' path length when wrapped around the rollers (
, Equation 13), and the hoses inner cross-sectional surface when not completely opened up (Figure 89, Equation 14). The roller is herein assumed as large as possible while still fitting inside the rim.



$$L_{path} = L_{around\ roller} + L_{between\ rollers}$$
$$= \frac{1}{3} * \pi * OD_{roller} * 2 + 9 * \frac{1}{2} OD_{roller}$$

Equation 13

$$A_{hose} = \frac{2}{3} * A_{AB} + \frac{1}{3} * A_C = \frac{2}{3} * \left(WT * \pi * \frac{1}{2} ID \right) + \frac{1}{3} * \left(\pi * \left(\frac{1}{2} ID \right)^2 \right)$$
$$\approx ID(WT + \frac{1}{4} ID)$$

Equation 14

Figure 88: The hoses path length as modelled to calculate the volume pumped per cycle (Equation 13).

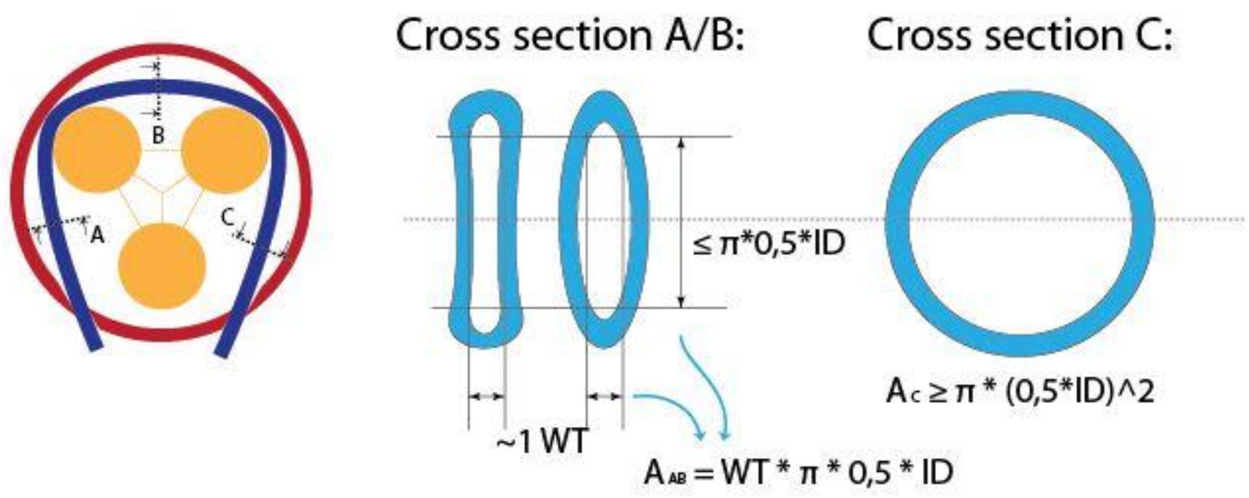


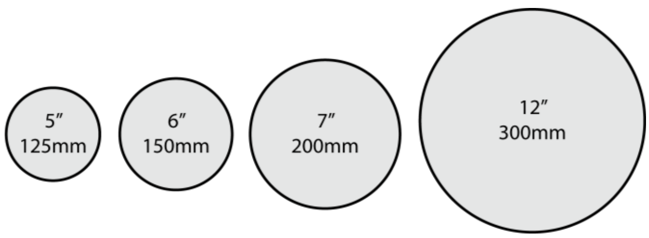
Figure 89: The hoses cross-sectional surface as modelled to calculate the volume pumped per cycle (Equation 14).

The optimization of the dimensions is depicted in Table 5. It shows how the RPM varies to acquire the demanded 5L/min for 4 different rim sizes. These 4 options feature rim sizes (Figure 90) that match standardized PVC pipes. They will be prototyped and tested with several hose diameters. This verifies the influence of hose size and rim size on the flow rate.

Table 5: Flow rate calculation as dependent on the inner diameter of hose and rim.ID stands for inner diameter, WT for wall thickness, OD for outer diameter and V_cycle for the volume pumped per cycle.

Pump variable	5" option		6" option		7” option		12” option	
ID hose	24	mm	28	mm	32	mm	36	mm
WT hose	2	mm	2	mm	2	mm	2	mm
Surface hose	192	mm^2	252	mm^2	256	mm^2	296	mm^2
Rim ID	125	mm	150	mm	200	mm	300	mm
Roller OD	40	mm	50	mm	65	mm	100	mm
Path length	264	mm	330	mm	429	mm	659	mm
V_cycle	5,1E+04	mm^3	8,3E+04	mm^3	1,1E+05	mm^3	2,6E+05	mm^3
RPM	99	RPM	60	RPM	46	RPM	19	RPM
Transmission	1	:1	0,6	:1	0,76	:1	0,32	:1
Flow rate	5	L/min	5	L/min	5	L/min	5	L/min

Figure 90: Rim sizes



11.4 Occlusion

Occlusion is the distance between the pump rim and the rollers: the distance between which the hose is squeezed. It influences hose life time, torque, leakage, and with the latter the pumps head and flow rate. One can calculate the optimum occlusion using the hoses wall thickness. Rim deformation and imprecise production however ask for multiple occlusion settings within one pump. Figure 91 shows an impeller that facilitates multiple settings. This allows optimization of the occlusion for each pump after its production.

Five positions are made for the rollers, one that leaves 5/6th of twice the hose wall thickness in distance between the rim and roller (refer to p. 78), and 4 other positions: two in steps of 0,5mm towards the rim and two in steps of 0,5mm away from the rim (in accordance with the 0,5mm precision requirement, refer to p. 18).

Figure 91: Impeller with multiple occlusion settings to install the rollers in.

11.5 Springs on the rollers

The connection of the roller could be spring-loaded. This would lower peak stresses caused by e.g. debris, broaden the range of proper occlusions and lower peak torque near the inlet. The following spring options were considered: rubber patches or bushings, a push spring (through various connections), and a feather spring (through various connections).

Though spring loads take care of a lot of uncertainties, they add many too. Now not only the position of the rollers axes has to be precise, but also the spring constant – and the spring constant over life. As the necessity for springs remains unsure and the added complexity is large, it was decided to first opt for a design without springs.

11.6 Aligners

Aligners are connected to the impeller to keep the hose in place. This is possible both vertically and horizontally: from creeping past the rollers reach, and to keep the hose close to the pumps rim. In the roller section it was decided to try a design with 3 rollers. As that runs stable, no rim aligners need to be added. It remains unsure if horizontal aligners are required: the pump being submersed stabilizes the hose, and as it has more than one roller the hose sits in one plane. There are no reasons it would move from that plane. It was decided to test a design without aligners.

11.7 Profile of rim and roller

A profile on the rim or roller influences the shape the hose is squeezed in. It could optimize the pressure profile on the hose, which lengthens its life time. They could also keep the hose from creeping, for instance by featuring a flange at the top and bottom of the roller. Figure 92 shows how a profile on the roller could be optimized towards optimal pressure profiles. Shaping the roller is easier than shaping the rim, as tools can easier access an outer profile than one within a shape. Such a profile has to match the hoses dimensions, and would thus be different for each hose.

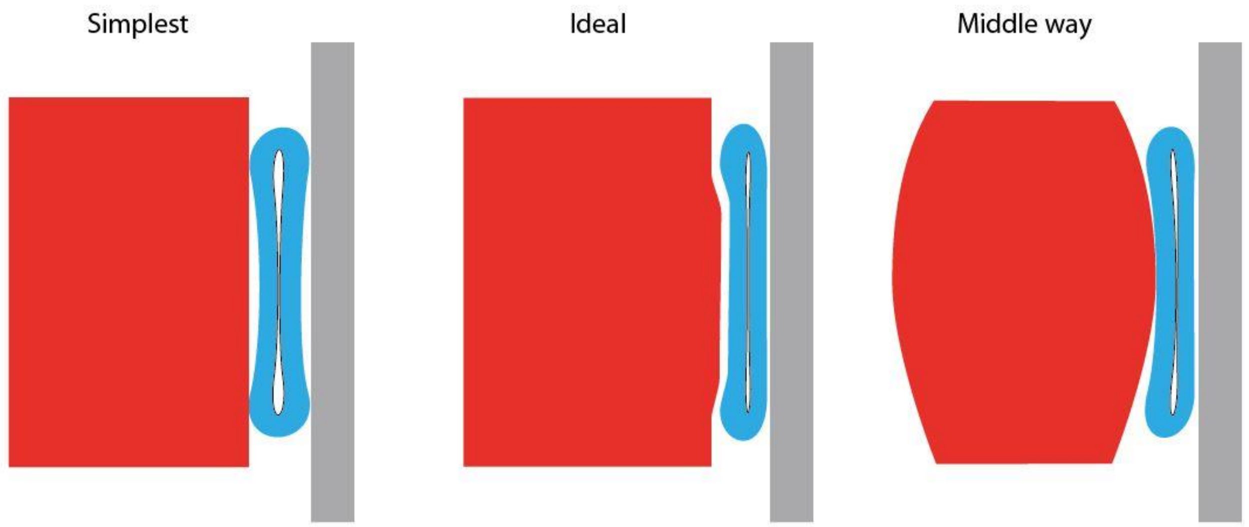


Figure 92: Roller profiles

Off-the-shelf rollers with such profiles are common. Figure 93 depicts considered options. Of these, only the skate wheels provide stability on its axis; all others can ‘wiggle’. A quick test showed a skate wheel (1cm thick) cannot close hoses with an ID of over 14mm, smaller than what is required (Table 5). None of the off-the-shelf rollers are apt for the Palestinian communities.

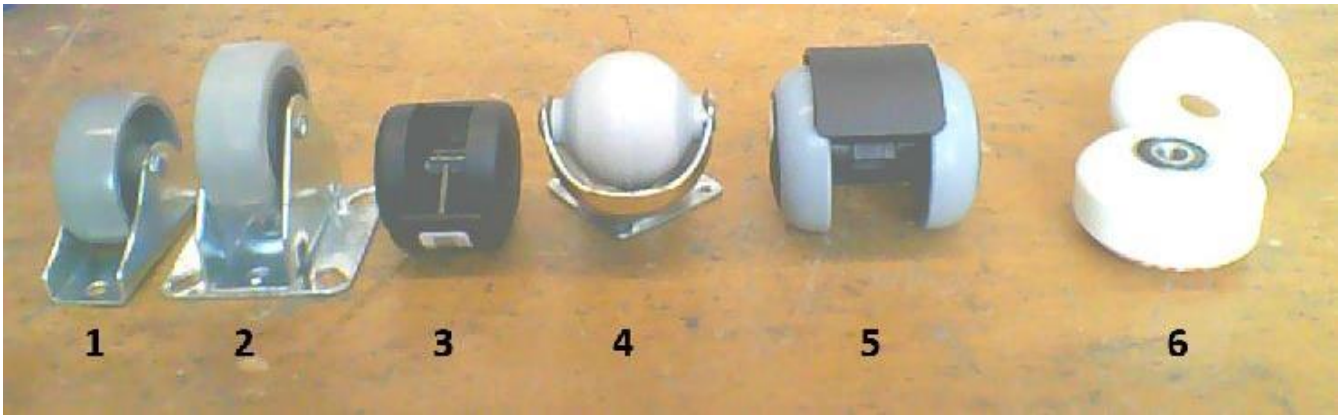


Figure 93: Off-the-shelf rollers. Number 1: cart wheel simple. Number 2: Cart wheel with sturdy base. Number 3: chair wheel. Number 4: soft cart wheel. Number 5: Chair wheel big. Number 6: Skate wheels with bearings.

This implies rollers will have to be made locally. Making a roller as a cylinder is relatively simple. Shaping a profile into it is more complex. It will not be done until life time tests show it is required.

11.8 Impeller & shaft

The impeller supports the movement of the rollers. It is the heart of the pump, connected to the shaft, keeping the rollers vertical and centralized at a set distance from the rim. A design was made to do this (Figure 94). It features two impeller plates with holes at different occlusions. The roller has an axis at its center which protrudes an impeller plate on each side of the roller and is fastened with a nut. The impeller plates are kept at a set distance and parallel by a spacer. This spacer sits around the pump shaft; the shaft protrudes through the entire impeller. Above and below the impeller sits a flange, of which the top one is welded onto the shaft. Bolts with nuts on each side protrude the flange, plates and spacer to tighten all together and fix it to the shaft.

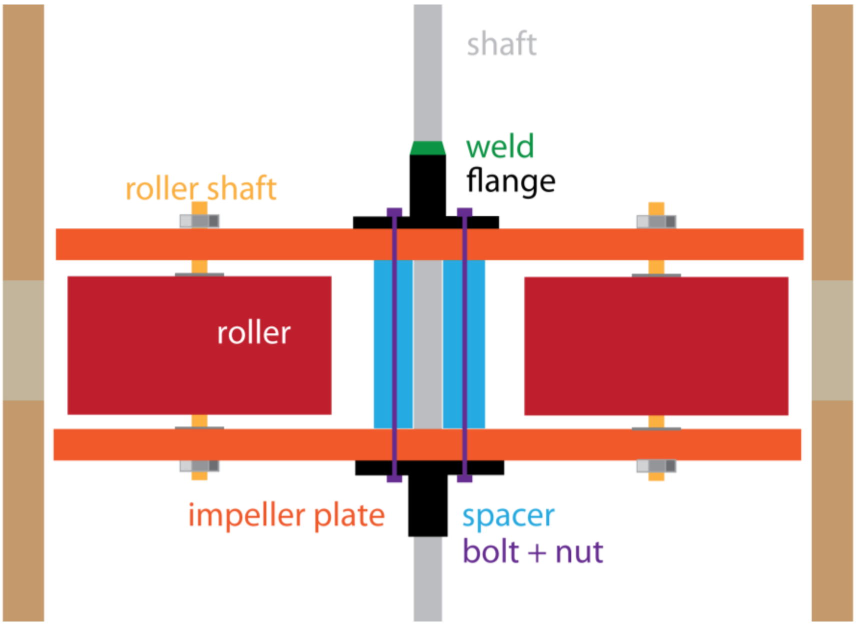


Figure 94: Impeller overview

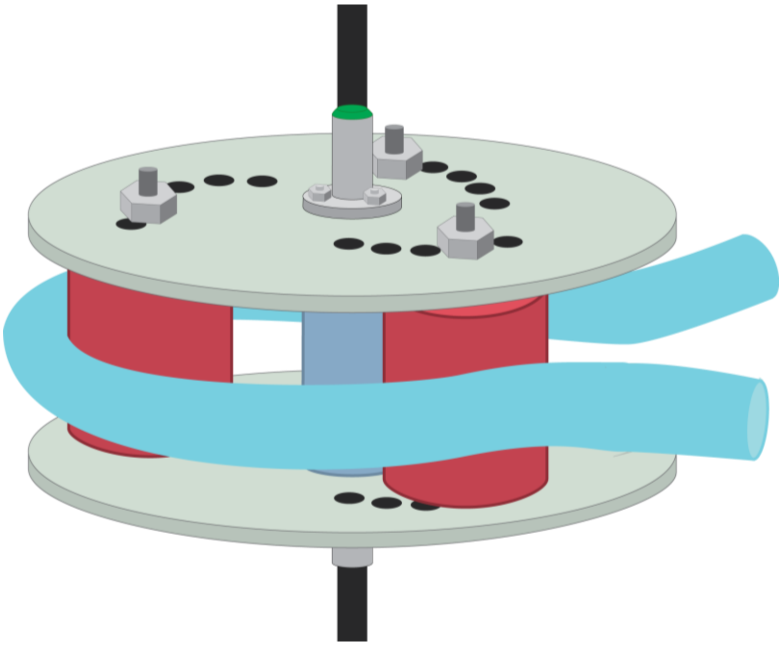


Figure 95: The impeller in 3D

11.9 Hose material

Table 6 provides an overview of the different materials and their properties as described on p. 80.

Table 6: Hose material overview

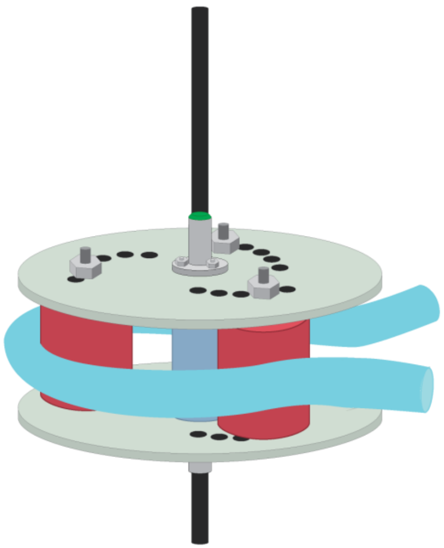
Material	Risks	Wear sensitivity	Local availability	Price/m
Natural Rubber	Deterioration by sun	High	High	€ 25
NBR	Toxicity & cheap alternatives	High	High	€ 5
Silicone	Import can be a strain	Middle	Middle	€ 40
Tygo/Verderprene	Very expensive	Low	Low	€ 80

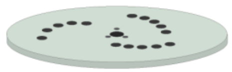
The silicone hose provides the most promising combination of characteristics. Hose quality and production professionalism are vital to avoid leakage and unexpected weak points, but the investment required to acquire Tygoprene/Verderprene was deemed too high. The rubbers are rejected for their wear sensitivity, which leaves silicone. It will have to be imported, but grants a safety in the sense of reliability both over life time as over different producers.

11.10 Dimensioning

The pumps rim size and hose size were decided in section 11.3 (p. 84). In this section, the dimensions of all other parts are deviated from them (Figure 96). The rollers are therein assumed as large as possible.

Figure 96: Dimensions of the designs' parts

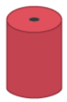




Impeller Plate
Diameter: Rim diameter - 6mm
Plate height: 6mm to avoid bending
Diameter of shaft passageway: Shaft diameter
Diameter of spacer bolt passageway: half of the Shaft diameter
Distance of spacer bolt passageway from centre: the Shaft diameter.
Angle between spacer bolt passageways: 120°

Occlusion settings: 3x 5 holes
Angle between holes: 25°
Distance holes from centre:
Radius of rim - 5/6th of twice the hoses wall thickness - Roller radius plus one at +1.0mm, one at +0,5mm, one at -0,5mm and one at -1,0mm.

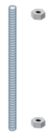
Spacer
Diameter: Thrice the shaft diameter
Spacer height: 4π * Hose radius + 30mm
Diameter of shaft passageway: Shaft diameter
Diameter of spacer bolt passageway: half of the Shaft diameter
Distance of spacer bolt passageway from centre: the Shaft diameter.



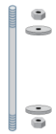
Roller
Diameter: (Rim diameter - Spacer diameter) /2 - 20mm
Roller height: 4π * Hose radius + 20mm
Diameter of axis passageway: Roller axis diameter

Shaft
Diameter: 12mm
Height: Spacer height + 2* Impeller plate height + 50mm
Flange welded on 20mm distance from top

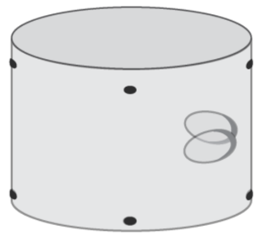
Flange
Height and diameter of thick and thin part: as available
Diameter of spacer bolt passageway: half of the Shaft diameter
Distance of spacer bolt passageway from centre: the Shaft diameter.
Angle between spacer bolt passageways: 120°



Spacer bolt and nuts
Diameter: Half of the shaft diameter
Spacer bolt height: Spacer height + 20mm
Spacer nut: M [spacer bolt diameter]



Roller axis, nuts and washers
Diameter: 8mm
Roller axis height: Spacer height + 2* Impeller plate height + 30mm
Roller axis thread height: Impeller plate height + 15mm
Roller axis nuts and washer: M8

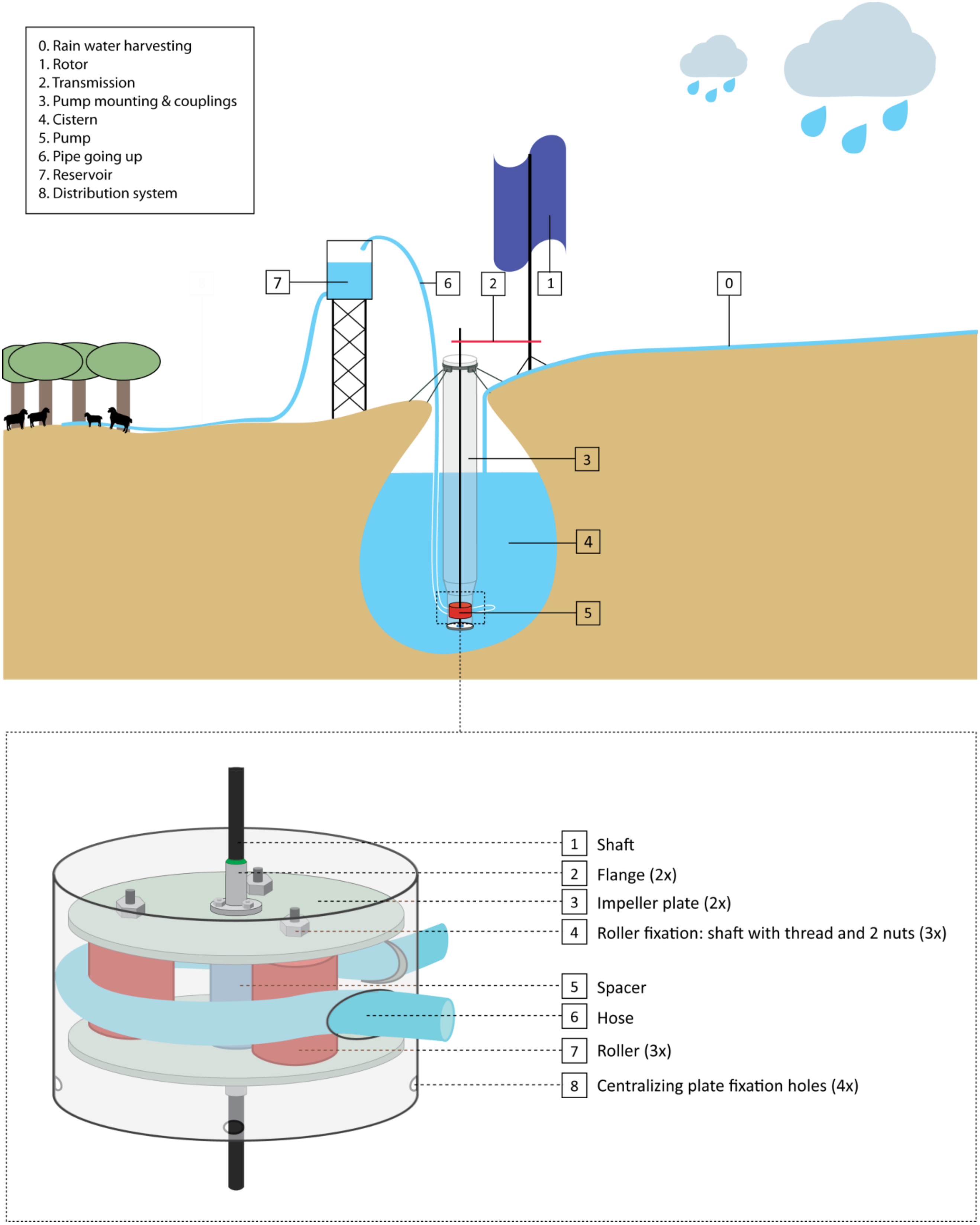


Rim
Diameter: Rim diameter as decided
Height: Spacer height + 2* Impeller plate height + 80mm
Hose passageway: ellips with breadth of twice the Hose diameter and height of once the Hose diameter
Hose passageway height: half of Rim height
Centralizing plate screw passageway diameter: 5mm
Centralizing plate screw passageway angle: 90°
Centralizing plate screw distance from rim edge: 15mm

12 Overview of the design

The design regards a locally repairable, wind powered peristaltic pump for the communities in South Mount Hebron, Palestine. That pump is part of a bigger system (Figure 97), including a rotor, transmission, mounting, pump, hose to the reservoir, reservoir, and gravity-fed distribution hoses to the users.

Figure 97: The complete system



Within this system the design focussed on the pump and its mounting. The mounting of the pump consists of a pipe, fixed with a ring to the terrain. This pipe consists of several standardized PVC pipes held together by sleeves, with shaft centralizing plates inserted to keep the shaft from sweeping. At the bottom of the cistern the pipe holds the pump. The pumps shaft is connected to the shaft going up with a cardanic coupling. Inside the pump the shaft is held in the centre and vertical by two centralizing plates. The bottom centralizing plate therein features a tapered bearing that carries the shaft and pump. That plate is fixed to the bottom of the pipe using screws. The hose inside the pump is coupled to the open water at the inlet, and to the hose going up at the outlet using standardized hose couplings. At the inlet a gauze is added to keep debris out of the pump.

The pump is as minimalistic as possible; a minimalistic design is deemed most producible and repairable. A peristaltic pump pushes water through a hose by squeezing it with rollers. These rollers can be spring loaded, or feature complex shapes. Aligners can be present to keep the hose in place. These options were decided against: it remains unsure if they are necessary and they do make the design more complex and more difficult to produce. The design is thus a three roller peristaltic pump with no additions.

The hose is a 2mm thick silicone hose, of which various diameters will be tried to verify the diameters impact on flow rate and torque. In combination with various rim sizes this will render insights to how one can achieve the desired flow rates within the torque requirement. The hose thickness is the result of an optimization between torque and production precision. The hose has to be thick enough to provide leakage free operation within the 0,5mm production precision limit. It should not be thicker than that, as that increases torque unnecessarily. The 2mm thickness was found to be sufficiently thick to be leakage free within the 0,5mm production limit.

The three roller design is a result of a test with both a three roller and a two roller prototype. One roller makes the hose 'cross itself', making it more prone to vertical movements. Adding more rollers however costs hose life time. In the tests the two roller design made the rim deform, but the three roller design proved stable.

To facilitate the movement of the rollers an impeller was made. This impeller connects to the pump shaft by flanges, holds the rollers vertical using a spacer and at a set distance from the rim: the occlusion. This is done using two impeller plates, between which the rollers are held. The rollers feature an axis with thread at its ends to be held by nuts, above and below the two impeller plates. A spacer around the pumps shaft keeps the plates parallel and at a distance that allows the rollers to spin freely.

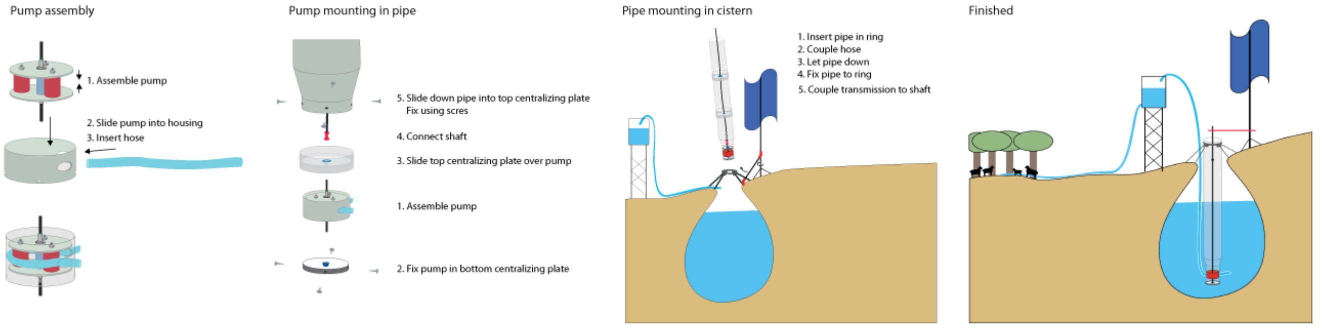
Occlusion was found to ideally be 5/6th of twice the hose thickness. In the prototype additional occlusion possibilities will be made in the impellers plates, to facilitate for imprecise production and so that leakage and torque can be verified with steps of the production limit of 0,5mm.

Page 93 shows how the pump can be mounted and dismounted into, or out of, the cistern. The necessity for repair can be assessed using the flow rate – RPM relation. If the flow rate starts to drop, while the rotors RPM is the same as during the last measurement, the hose has started to fatigue. The flow rate drops because the hose opens up less when it is worn, and thus transmits less water per cycle.

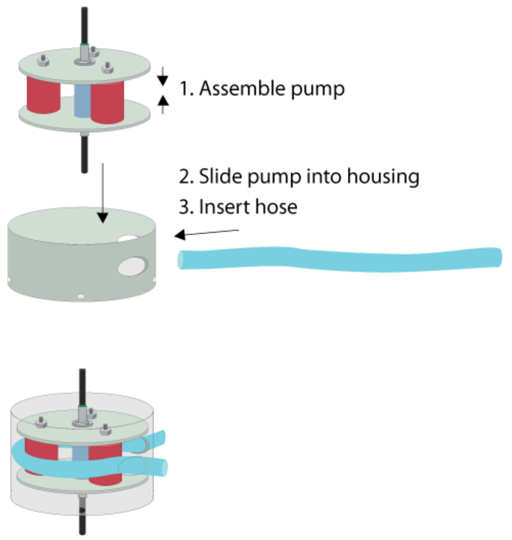
In accordance with the requirements the mounting and pump design feature the following advantages:

- Dismountable and repairable without power tools, by 2 people
- The necessity for repair is visible from above
- Avoids sweep of the shaft and includes shaft centralization inside the pump
- Features a gauze to keep out debris
- The pump itself can withstand sand and particles in the water, thanks to the hose
- The pump does not rely on the fluid for lubrication, and can thus dry-run
- Both pump and mounting feature all non-corrosive materials
- Combines standardized parts and simple manufacturing steps
- Production precision required to a maximum of 0,5mm

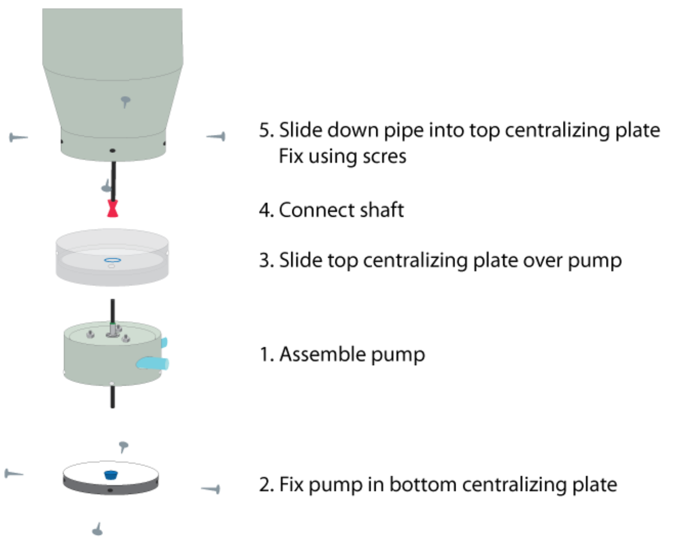
Overview



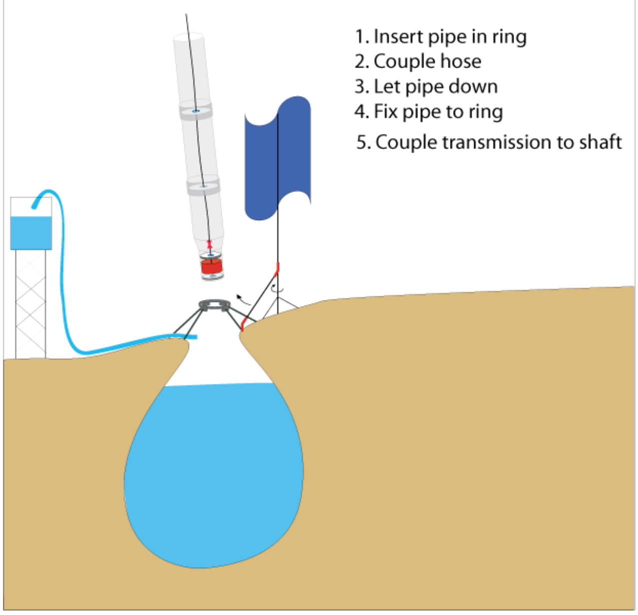
Pump assembly



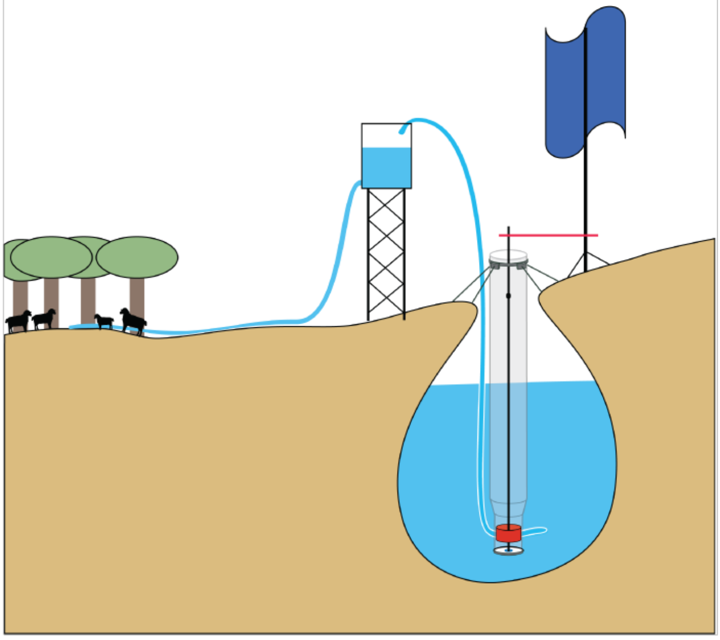
Pump mounting in pipe



Pipe mounting in cistern



Finished

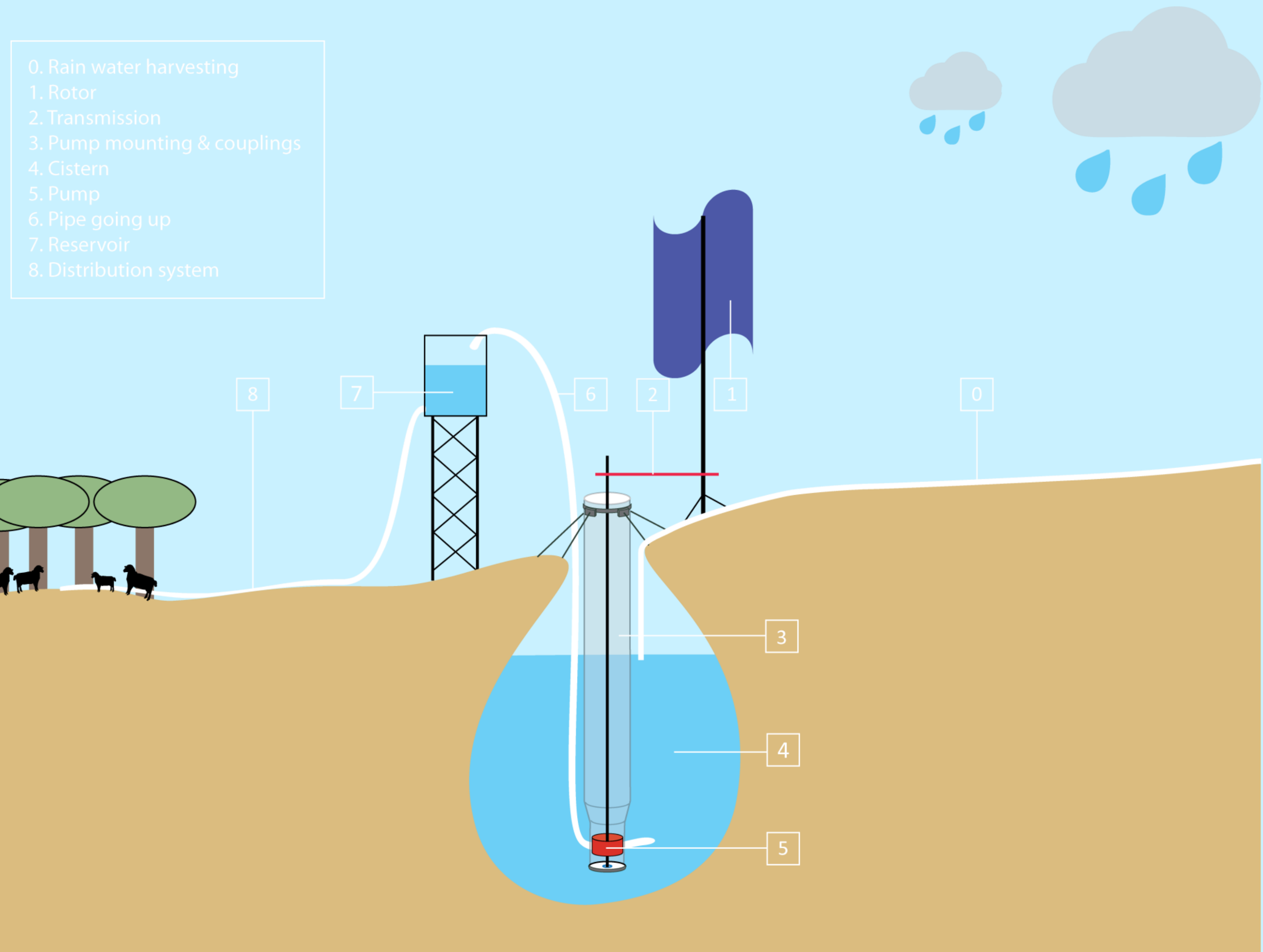


Tests & Evaluation

The design chapter resulted in a concept for a simple peristaltic pump. A three roller design with a 2mm thick hose and no other supplements (no spring loads on the rollers, no aligners, no rim or roller profiles) (Figure 95). This pump should be a locally repairable, wind powered alternative to the bucket system that the Palestinian communities use now. It is part of a bigger system (Figure 98), that includes a rotor, transmission, pump mounting, pump, hose to the reservoir, reservoir, spill-over hose back into the cistern and a gravity-fed distribution to the users.

In this part of the report the design is tested and evaluated. How the pump performs is revealed both for the Palestinian communities and the pumps main competitor: the rope pump. This reveals the pumps performance and promise both within the field case and beyond.

Figure 98: System overview



13 Tests

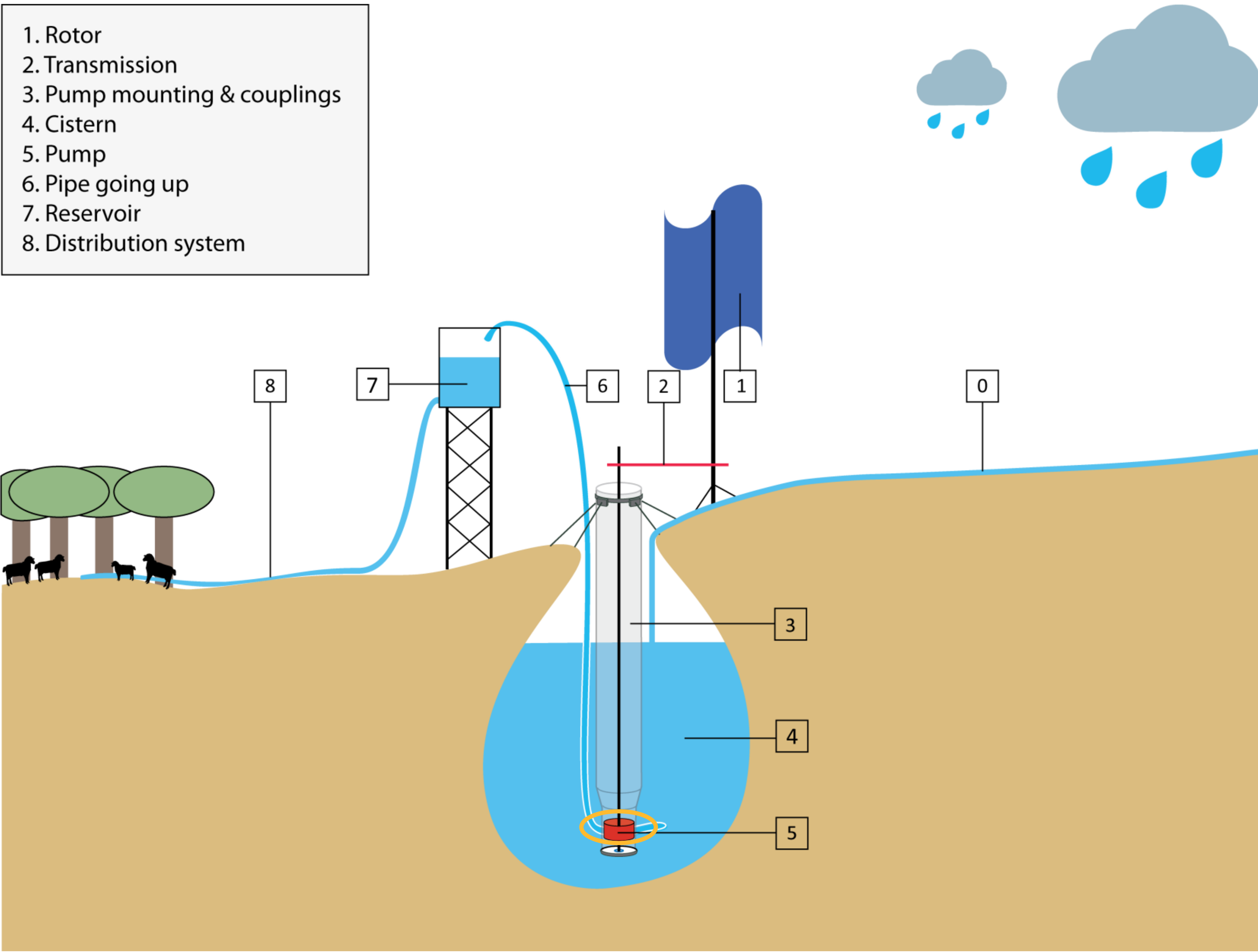
The design is verified in this chapter using prototypes. The design of the pump and its mounting were made to match the production capacities, repair requirements and field conditions of the Palestinian context. Other parts of the system can be assembled based on local preferences.

Some of the requirements are however not obviously met; these will be tested here. This regards specifically the flow rate and torque. The part of the system that will be tested is the pump (Figure 99).

During the design phase specific attention points for peristaltic pumps were acknowledged. These are used to verify the concepts ideas. Did decisions work out well, or should the design be changed?

In the next chapter the results shall be discussed and evaluated on the full program of requirements to verify if it is fit for the Palestinian communities.

Figure 99: System overview, with in the yellow circle what will be tested.



13.1 Goal of the test

The goal of the test is to verify if the concept:

1. Is able to provide enough flow rate at a suitable torque;
2. Features a well-made design.

For goal 2 the design chapter revealed the following attention points:

- Creep: if the hose moves up and down along the roller;
- Proximity to rim: if the hose stays close to the rim or 'wraps' around the rollers;
- Smooth operation around inlet: if torque increases as the roller engages with the hose at the inlet;
- Range of proper occlusions: if the production precision of 0,5mm allows for leakage-free operation;
- Opening up of hose: if the hose opens back up again behind the roller.

13.2 Method

To test the design, torque and flow rate a methodology was developed. This describes how prototypes were made and measured.

13.2.1 Hardware

The hardware facilitates testing the designs operation, torque and flow rate. The starting point of the tests is 4 prototypes, representative of the design. In agreement with the section on pump speed, rim and hose size (p. 84), four versions are made with different rim sizes: 5", 6", 7", 12". These will be combined with 2mm thick silicone hoses with an inner diameter of 6, 22, and 26mm. The combinations are from now on denoted as x"y, where x stands for the rim size and y the hoses inner diameter. For instance: 5"22 denotes the 5" rim with the 22mm hose. All models were built according to the program of requirements: with 0,5mm production precision and the possibility to replace parts.

Figure 100 and Figure 101 show the test set-up equipment. The test site is a 4 story high staircase, where the required 10m head is available. The pump was powered by a drill. Flow rate was measured with a 1L jug with indicators at each 100mL, and a timer. RPM was measured with a bicycle speedometer; torque with an electric spring balance. Furthermore each test was filmed and pictures were made of possible damage.

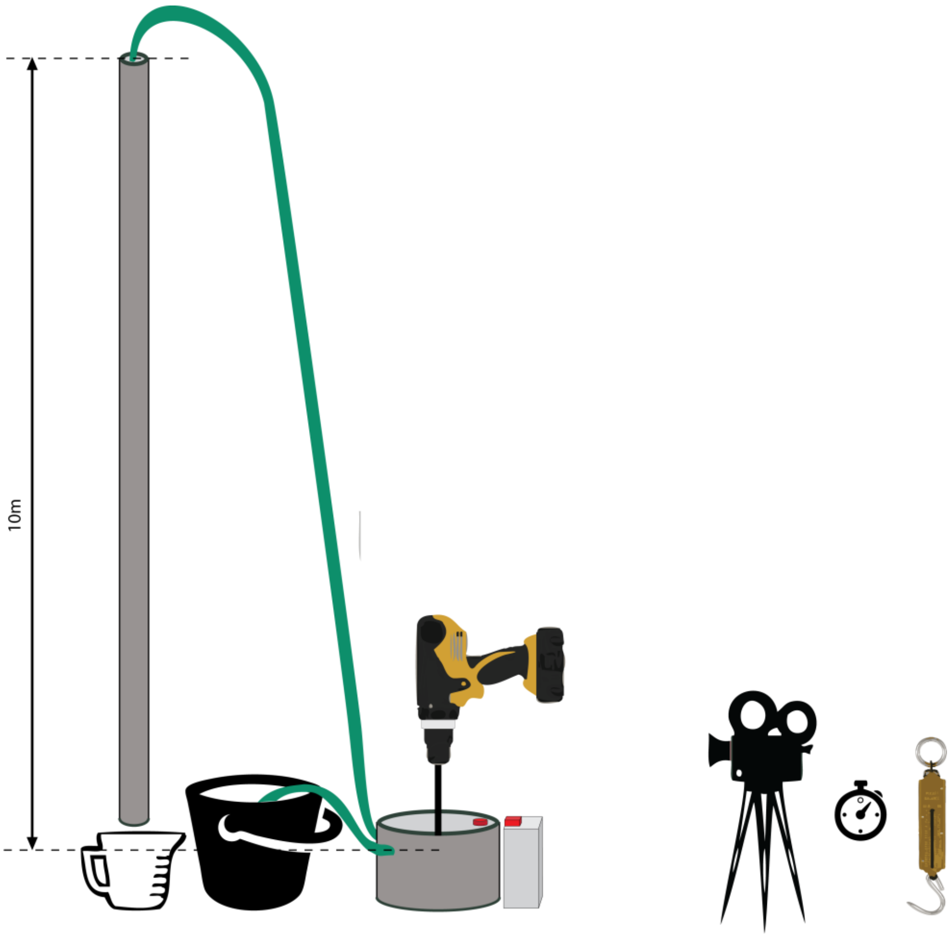
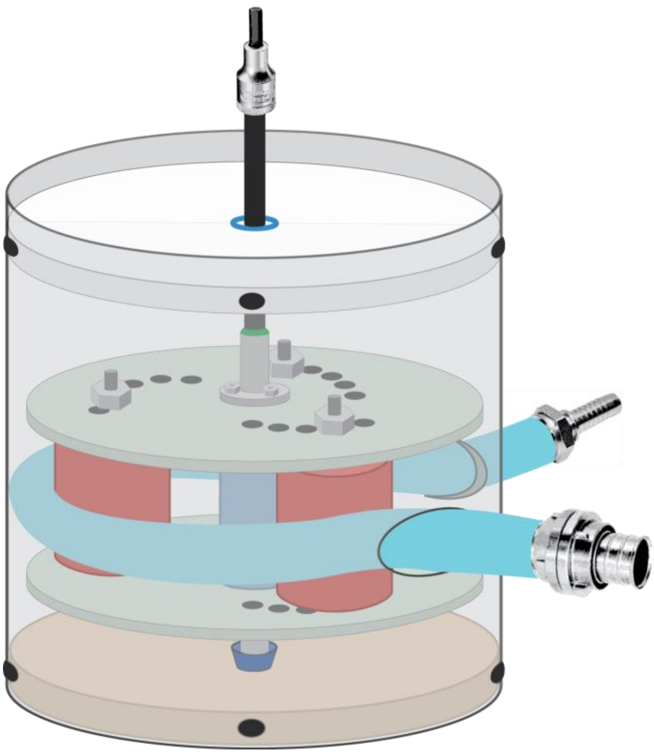


Figure 100 (above): Test set-up. On the left the primary installation with the 1L jug, bucket and drill-powered pump. The bicycle speedometer is herein depicted in red. On the right the supplementary equipment: camera, timer and spring scale.

Figure 101 (below): The pump prototype used in the test set-up



13.2.2 Process

Before each test the occlusion setting is optimized, to provide the best achievable occlusion for that rim-hose combination. Each prototype features impeller plates that allow occlusion to be set at 5 different positions, spaced 0,5mm from each other, as described on p. 86. Starting with the setting at 5/6th of twice the hoses wall thickness, the rim-hose combination is tried and, depending on its performance, the occlusion setting is optimized towards minimum leakage and torque.

After this occlusion optimization the second step is to couple the pump to the staircases' water system and the drill, to set-up the instruments and to measure for each combination:

- Static torque over the pumps cycle
- Flow rate at several RPMs

Besides the measurements, each test is filmed and observation notes are made on the behavior as described in goal 2.

13.3 Results

Results of the test are both the torque and flow rate data, and the observations on performance. These are described here, after which they are interpreted in the discussion section.

13.3.1 Flow rate and torque data

The data consists of flow rate versus RPM and torque data. Figure 102 reveals the measured flow rates for all the tested rim-hose combinations.

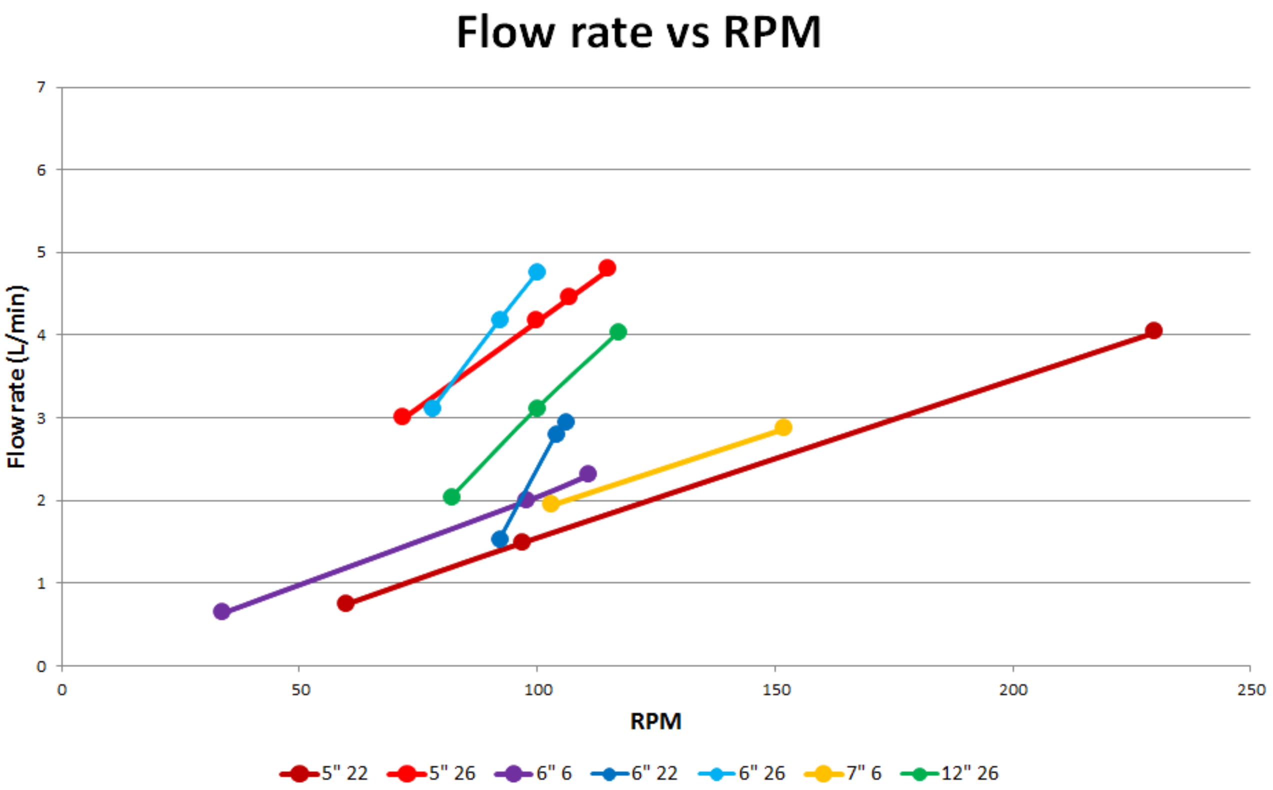


Figure 102: Flow rate vs RPM with data points and connecting lines.

Figure 103 reveals the torque over the pumps cycle. The rotor – load combination is optimized for one torque, so any variations in torque cost efficiency. Besides the absolute value, the variation in torque is thus important.

Most prototypes featured a cycle of 3 phases: one of the rollers is at the inlet (1), one where one of the rollers is just behind the inlet, one where one of the rollers is just behind the inlet (2), and (3) one where no roller is near the inlet. As the prototypes feature 3 rollers, the associated peak torque (1), minimum torque (2) and average torque (3) happen trice during one cycle. It has to be noted that the 12” rim featured not only a varying torque according to the separate phases, but a different torque across the phases for each roller. Each of the three rollers that passed rendered a different peak torque. The peak torque represented in the graph is the highest one encountered.

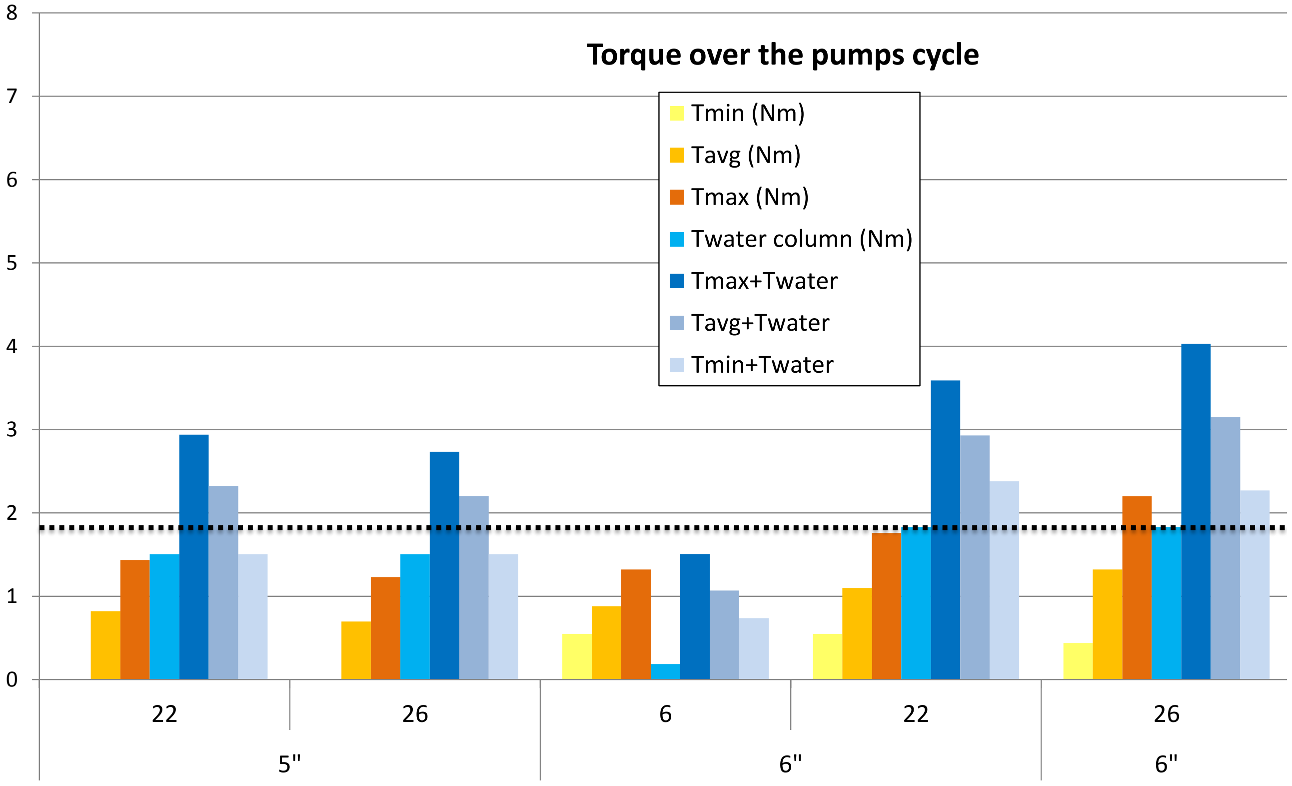


Figure 103: Torque over the pumps cycle. Tmax happens as a roller engages with a hose, Tmin right after that and Tavg happens when the high and low torques have passed. Twatercolumn indicates the extra torque that would be required when the water column is filled. The dotted line depicts the torque as ideally provided by the rotor.

13.3.2 Observations

The observations serve to verify the design and, as described in the project goal section, regard: creep, proximity of the hose to the rim, operation when a roller is near the inlet, the range of proper occlusions, and the opening up of the hose.

Smooth operation around inlet

Peak torques appeared for all prototypes when the roller engages with the hose at the inlet (Figure 103). These peak torques manifested as shocks: the impeller slowing down as the roller engages with the hose, and speeding up very quickly just afterwards. Though the intensity of the shocks varied with the measured peak torque, all prototypes showed this behaviour. These shocks have caused two types of damage to the impeller.

The first type of damage relates to the unloosening of rollers bolts. This caused their axes to shift upwards or downwards. On one side they release from the impeller plate, on the other side they run into the centralizing plate (Figure 105). Being released on one side caused the rollers to skew, damaging themselves and the impeller plates (Figure 104).


Figure 104: The rollers 'shave' into the impeller plates once their axis has released on one side.

The second type of damage is that the bearings jumped out of the centralizing plates (Figure 105), allowing the shaft and impeller to roam more freely. This allowed for skewing of the complete impeller within the rim, damaging the impeller plates and rim (Figure 106).

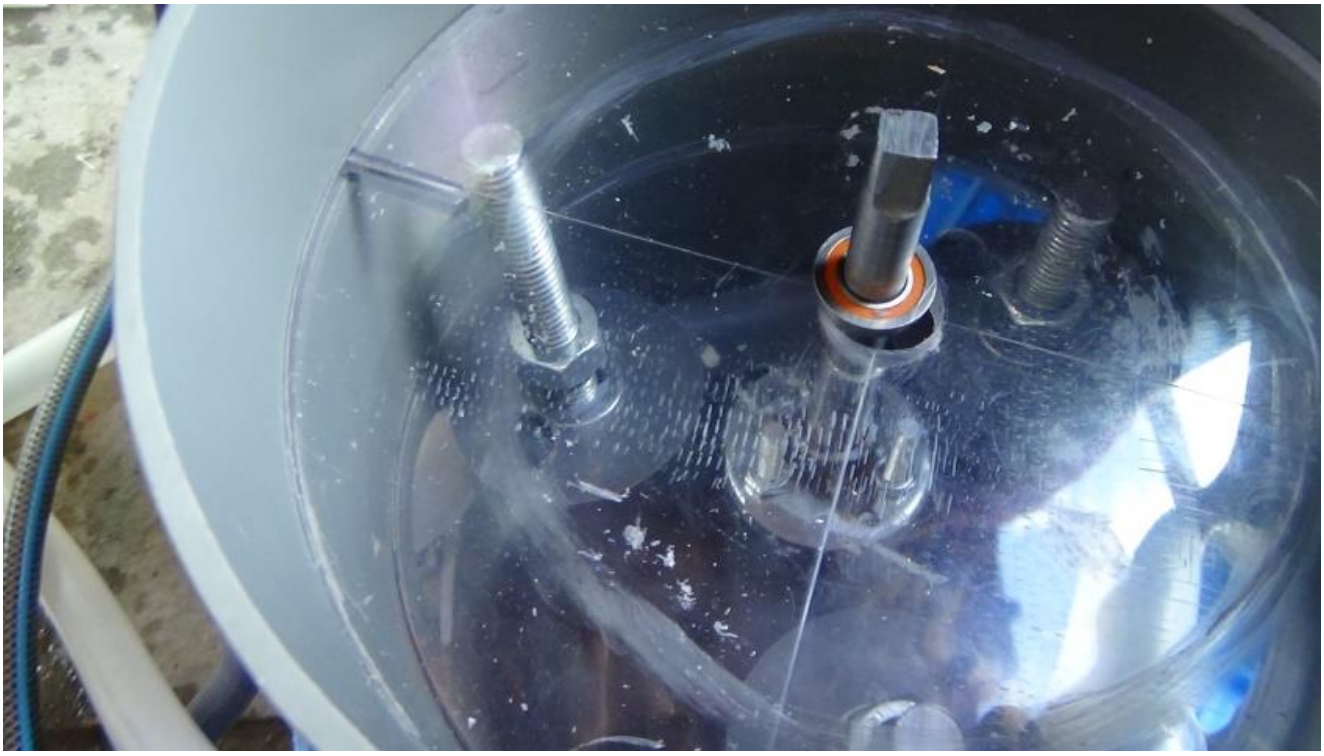


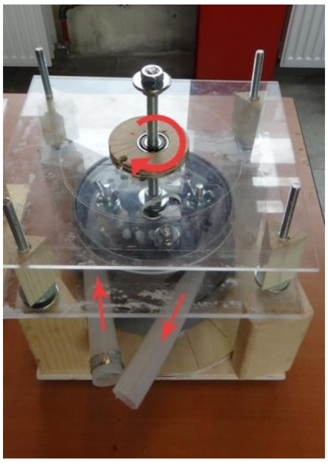
Figure 105: Two types of damage visible. The left roller axis has started shifting up, running into the centralizing plates. A circular track indicates the damage the axis has done on the centralization plate. The second impeller damage is caused by the bearing jumping out of the centralizing plate, as can be seen on the right half of this picture.

Figure 106: The impeller plate has 'cut' into the rim.

Creep

Creep implies the hose moving above or below the roller. This happened sparingly, but more frequently as peak torque and associated shocks increased. Creep caused the hose to get stuck between impeller plate and roller, damaging the hose (Figure 107) and stopping the pump.

Figure 107: Damaged hose after creep: the black stains are particles from the impeller plate.



Proximity of the hose to the rim

In most tests the hose wrapped around the rollers, rather than staying close to the rim. This was adjoined by elongation of the hose, and the hose being ‘dragged’ along with the rollers (Figure 108). The part of the hose outside the prototype shortened on the inlet side, and got longer on the outlet side.
The small, relatively thick hose did not show this behavior.

Figure 108: What is meant with the hose 'moving along with the rollers'

Opening up of the hose

The prototypes where the hose elongates showed a less circular cross-section than those prototypes where the hose is stable.

Range of proper occlusion

The occlusion was optimized in steps of 0,5mm. If the pump still leaked indicates if this was a proper occlusion. After each test, the backflow from the hose going up the 10m head through the pump was observed. This rendered the following results:

Rim hose combination	Leakage note
5”22	Visible backflow
5”26	No leakage
6”6	No leakage
6”22	Visible backflow
6”26	Visible backflow
7”6	No leakage
12”26	Visible backflow

13.4 Discussion

In this section the results are interpreted. Validity of the tests is discussed, both quantitatively and qualitatively. Though the observations reveal that this design does not run stable, its performance on flow rate and torque are promising.

13.4.1 Data versus expectations

To verify if the tests are representative they are compared to what they were expected to result in. This is done by:

- Explaining what the tests were expected to result in
- Linking deviations from the expectations to possible causes, and the designs attention points
- Reviewing the prototypes’ data in terms of the expectations and possible deviations
- The resulting conclusion on representativeness, performance and design

Expectations

The flow rate – RPM data can be compared to expectations both qualitatively and quantitatively. A model to calculate flow rates was presented on p. 84. It reveals flow rate should be proportional to RPM, and gives the expected outcomes of the tests. Both proportionality and outcomes will be discussed.

The torque data can be compared qualitatively to the expectations. Torque should increase as the hose stiffness or rim size increases. A stiffer hose increases torque, as it requires more force to squeeze closed. A larger rim size increases torque, as it enlarges the lever arm on the shaft (Equation 15).

$$T_{pump} = \left(F_{pressure} + F_{squeeze}\right) * R_{rim} + T_{frictions} = \left(P * A_{pipe} + F_{squeeze}\right) * R_{rim} + T_{frictions}$$

Equation 15

Furthermore it would be expected that the torque varies during the pumps cycle. The amount of rollers that is squeezing the hose varies, and with that the required squeezing torque. When one roller is between the inlet and outlet, 2 rather than 3 rollers squeeze the hose.

Results in light of the expectations

Figure 109 shows the found flow rate - RPM results again, including proportionality indicators: lines that spring from the origin and continue proportional to RPM. It shows how three out of seven prototypes feature a steeper-than-proportional relation to RPM that does not spring from the graphs origin (the blue and green lines). The other combinations behave as expected (**Fout! Verwijzingsbron niet gevonden.**).

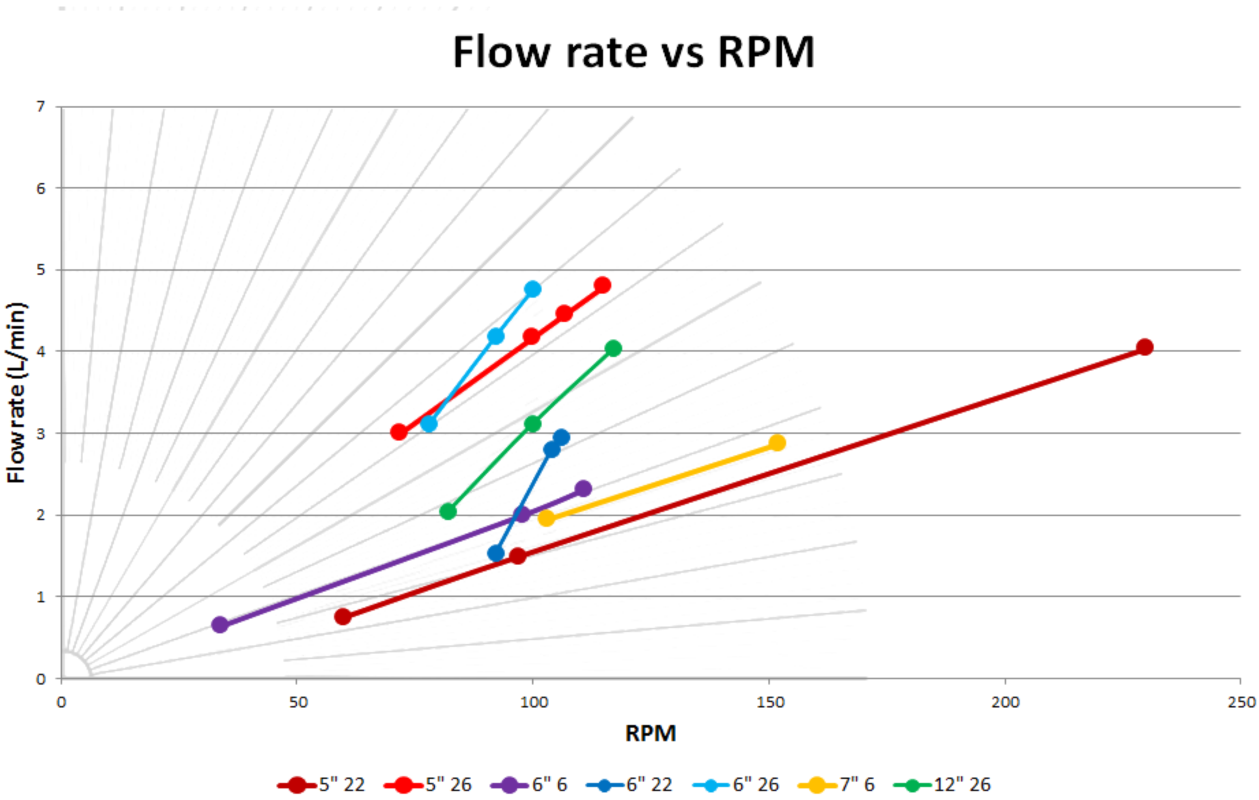


Figure 109: Flow rate vs RPM and lines that depict proportionality.

Fout! Verwijzingsbron niet gevonden. shows the found flow rate – RPM relation in comparison to those from the model. Comparing the data quantitatively to the expected results (**Fout! Verwijzingsbron niet gevonden.**) shows that:

- The 6mm hose performs better than expected, both in the 6” rim and the 7” rim.
- The 5” 26 combination performs almost as expected, in contrast to other combinations with similar rim or hose sizes.
- The 12” rim is further away from its expected results than the 5” and 6” rims.

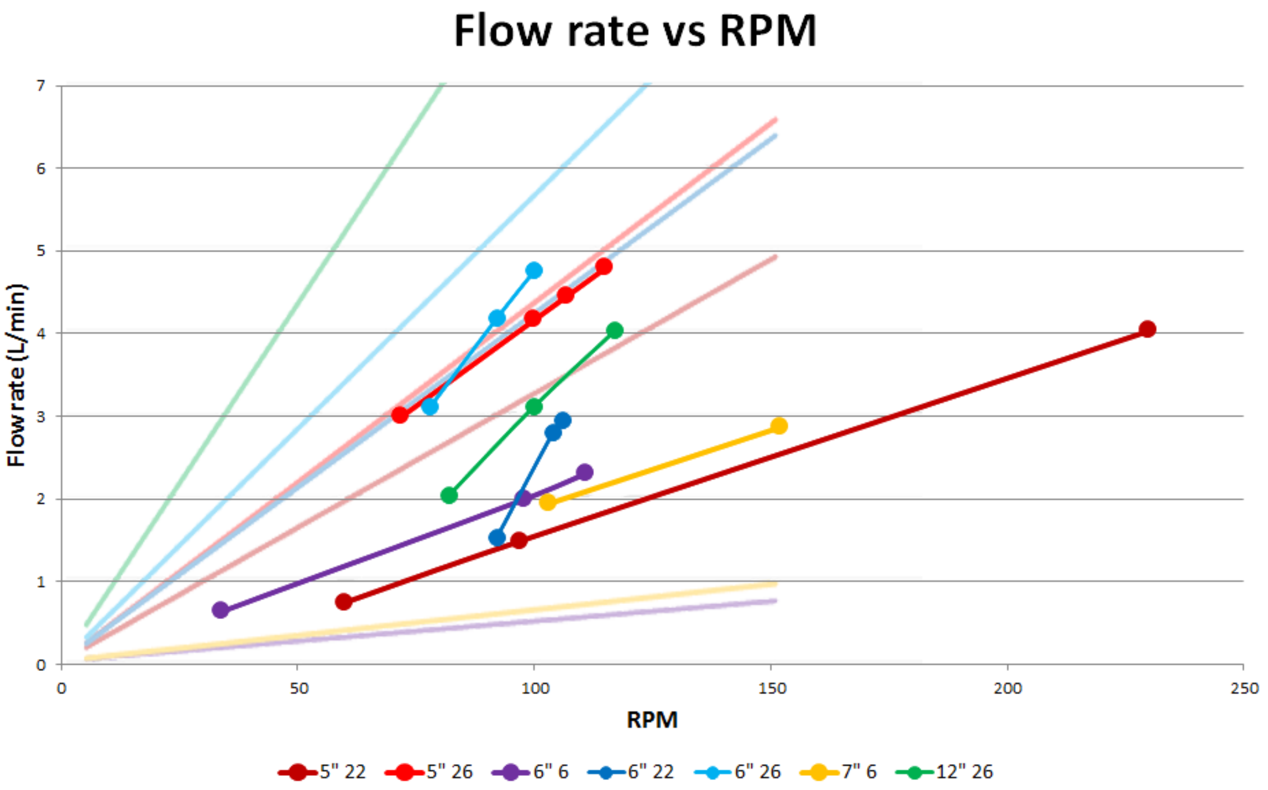
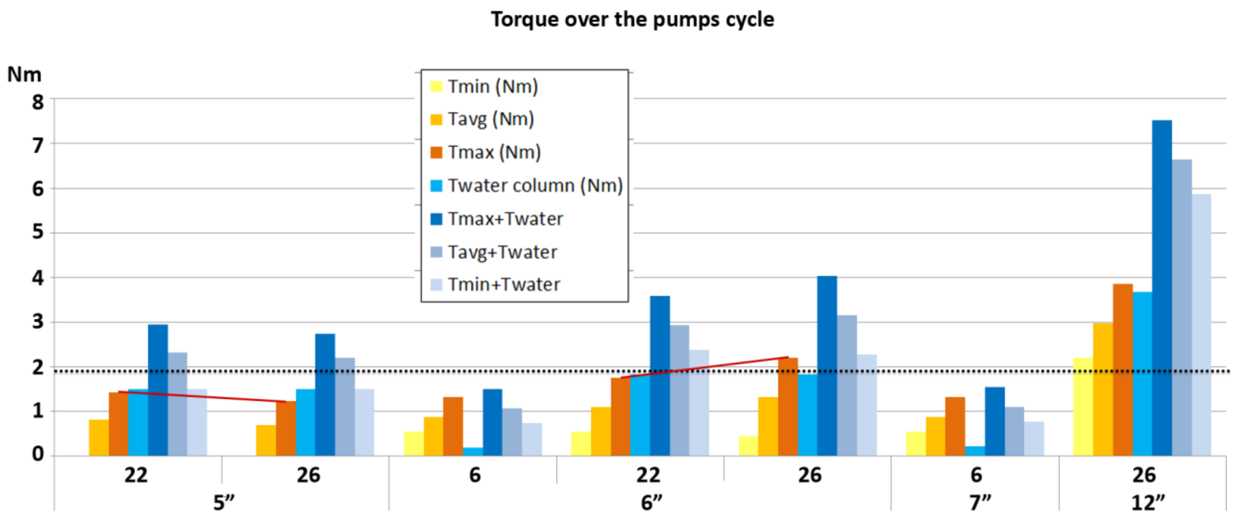
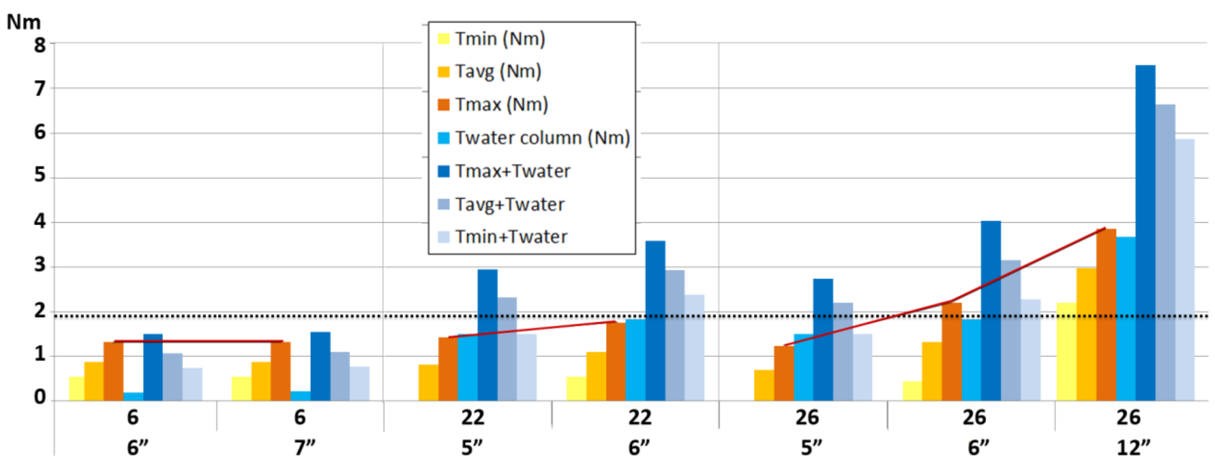


Figure 110: Flow rate vs RPM and the flow rate vs RPM of the model (slightly transparent).

Figure 111: Trends in torque data, with red lines indicating the trend between different hoses for similar rims (above) , and different rim sizes but similar hose (below).





The torque is reviewed, to assess the torque increase over rim or hose size changes, and the torque variation over the cycle. The torque data reveals the following unexpected behaviour:

- With the 6mm hose the torque does not increase when rim size increases
- The 5”26mm combination features a relatively low torque in comparison to the 5”22, 6”22 and 6”26 combination
- The 5” and 6” rims with 22mm and 26mm hoses feature an extreme torque change when by a roller passes the inlet: 77-100%.

Table 7: The torque change over the pumps cycle.

Combination	Torque drop as roller passes inlet	Torque increase as roller is near entrance
5”22	100%	+75%
5”26	100%	+76%
6”6	60%	+50%
6”22	70%	+60%
6”26	80%	+67%
7”6	60%	+50%
12”26	20%	+30%

Table 8 provides an overview of the found results. They shall be discussed in the next section.

Table 8: Summary of the found results in comparison to the expectations

Combination	Proportionality	Performance	Torque	Torque change
5”22	Slightly steeper	Less	Changes with size as expected	100%
5”26	As expected	As expected	Lower than expected	100%
6”6	As expected	Better	Not altering over rim size	Two third
6”22	Steeper	Less	Changes with size as expected	77%
6”26	Steeper	Slightly less	Changes with size as expected	80%
7”6	As expected	Better	Not altering over rim size	Two third
12”26	Steeper	Much less	Slightly lower than expected	One third

The cause for deviations

The attention points that were found during the design phase mention several causes that can create a different behaviour than was expected. These are treated here, and consequently compared to what was seen regarding the data’s’ behaviour. The attention point creep is skipped, as it caused the pump to stop and these results were omitted.

Leakage can alter the flow rate and torque behaviour. This would be seen by:

3 The flow rate – RPM relation being steeper than proportional. Leakage flow rate is proportional to gap size, but independent of RPM. For lower RPMS the leakage flow rate is thus a larger portion of the total flow rate than at higher RPMs. This results in a relation between flow rate and RPM that is steeper than proportional.

4 Less flow rate performance. If leakage occurs, the flow rate performance is less than modelled.
5 A different torque than expected. If the occlusion is not suitable and leakage occurs, the hose is not closed fully. The torque to squeeze the hose is then less. A broad occlusion also facilitates hose wrap, as the hose is less pressed against the rim and thus easily dragged along. This heightens the torque.
6 Visible backflow observed. During the observations if was noted if backflow through the pump was visible after the experiment. If backflow was observed, this indicates that there is room for leakage during the experiment.

Cause	Proportionality	Performance	Torque	Torque change
Leakage	Steeper	Less	Lower or higher	Can be as in hose wrap

Hose wrap alters the flow rates performance and torque behaviour. This would be seen by:

1 Less flow rate performance. A different inner volume of the hose influences the results quantitatively, but not its proportionality (steepness). If the inner volume of the hose is different than expected, this results in a different pumped volume per rotation and thus a different flow rate. Its flow rate – RPM relation would still spring from the origin, but perform different than the model. This happens not only when the hose wrap influences the hoses path, but also when the hoses' cross section is different than in the model.
2 High torque, and a large variation in torque
If the hose is 'dragged' along with the rollers this influences the torque. This primarily happens because the hose then stretches as a new roller engages near the pumps inlet. If this happens, it is thus visible in a large variation of torque over the prototypes cycle and a high torque in general.
3 Shock-like behaviour and hose elongation are observed. During the observations it was noted that most pumps show shock-like behaviour, and feature a hose that wraps around the rollers and elongates on the outlet side. This is a clear indication that the hose wrapped around the rollers. The 6mm hose was the only exclusion to these observations.

Cause	Proportionality	Performance	Torque	Torque change
Hose wrap	As expected	Less	Higher	High

If the hose does not open up this influences the flow rate performance, and can be related to hose wrap. This would be seen by:
1. Less flow rate performance: If the hose does not completely open up, it transmits less water per cycle and thus lowers flow rate.
2. Hose wrap: If the hose is wrapped around the rollers and elongated, this stretches the hose, pulling it more to an oval.

Cause	Proportionality	Performance	Torque	Torque change
Hose not opening up	As expected	Less	Can be as in hose wrap	Can be as in hose wrap

The prototypes' data in terms of the expectations and possible deviations

In this section the seen deviations from the expectations are coupled to their causes (Table 9).

Table 9: The observed deviations from the expected behaviour, and the causes that might create this combined

Combination	Proportionality	Performance	Torque	Torque change
5"22	Slightly steeper	Less	Changes with size as expected	100%
5"26	As expected	As expected	Lower than expected	100%
6"22	Steeper	Less	Changes with size as expected	100%
6"26	Steeper	Slightly less	Changes with size as expected	100%
6"6	As expected	Better	Not altering over rim size	Two third
7"6	As expected	Better	Not altering over rim size	Two third
12"26	Steeper	Much less	Slightly lower than expected	One third
Cause	Proportionality	Performance	Torque	Torque change
Leakage	Steeper	Less	Lower	-
Hose wrap	As expected	Less	Higher	High
Hose not opening up	As expected	Less	Can be as in hose wrap	Can be as in hose wrap

In the group of the 5"and 6" rim with the 22mm and 26mm hoses, all combinations feature the leakage indicators but for the 5"22 one. That this behavior is linked to leakage is confirmed by the observations on backflow (p. 107). The fact that most, but not all, combinations performed worse than expected render it safe to conclude that the production precision of 0,5mm has relevant influence on the performance. The occlusion could be set in steps of 0,5mm, and the most optimized setting was found for all combinations. Still, 3 out of 4 combinations performed worse than expected.
Interesting is that the non-leaking one also features a lower torque, in comparison with its counterparts. Hose wrap might thus be less for a properly closing hose, as it is pressed tightly against the rim.

The 6mm hose performed better than expected in both the 6" and 7" rim and had a relatively high torque. This behaviour can be explained by the larger stiffness of the 6mm hose: the 2mm wall thickness creates a relatively larger amount of material versus its inner volume of water. The section 'Wall thickness of hose' on p.84 revealed that a larger hose stiffness both pushes it straight (keeping it close to the rim) and back to its circular shape (keeping it opening up after the roller). It is safe to conclude that a thicker hose would perform better.

The 12" rim leaked heavily, but also showed a relatively low torque variation. Apparently, here a more spacious occlusion does not result in more hose wrap. The per roller varying peak torque furthermore indicates that occlusion varied over the three rollers. Varying occlusions can be explained by the fact that production precision is less tight for larger pipes. The inner diameter can deviate up to 1mm in 6” pipes, but up to 3.6mm in 12” pipes (Water Regulations Advisory Scheme, 2012). A deviation of 3.6mm is relevant within the production precision of 5mm, implying that the 12” rim has a higher chance of having a point where leakage and/or torque increases.

Conclusion

Leakage and hose wrap influence the results relevantly. These causes explain the found deviations between the data and the expectations.

In terms of goal 2 of these tests, the designs suitability, it was furthermore learned that the hoses wall should be thicker, and that the rim size and occlusion influence more than previously thought. Hose thickness should be high enough to provide enough stiffness for the hose to open up and remain close to the rim. The rim size has an effect on flow rate as thought, but cannot be increased without compromising on the occlusion. If the occlusion becomes flexible enough when a thicker hose is used remains unknown. Occlusion was found to not only influence leakage, but also hose wrap. The force with which the roller squeezes the hose against the rim keeps the hose from moving along with the roller, if was prone to do that.

To assess the first goal, the flow rate and torque requirement, the data has to be assessed in light of a transmission.

13.4.2 The data in light of a transmission

In the chapter on wind power it became clear that the rotor will provide a certain range of RPMs at a fixed torque, with which the pump has to create the desired flow rates. However, the RPM of the pump does not have to be the RPM of the rotor: a transmission can heighten or lower the RPM as seen fit (Equation 16). A transmission also influences torque (Equation 17). Could the flow rate and torque requirements be satisfied with a transmission?

$$RPM_{pump} = \frac{RPM_{rotor}}{i}$$

Equation 16

$$T_{pump} = T_{rotor} * i$$

Equation 17

Calculating the transmission follows 3 steps:

1. Selection of one point in the RPM-flow rate requirement to set the transmission to: 100RPM with 5L/min.
2. Interpolation of flow rate data to find each combinations’ flow rate at 100RPM
3. Calculation of transmission for each combination: $i = \frac{5L/min}{Q_{data\,@\,100RPM}}$

The calculated transmission renders the torque for each combination (Figure 112). None of the combinations manage 5L/min at 100RPM with a torque of 1,9Nm. The 5”26, 6”6, 6”26 and 7”6 combinations get close.

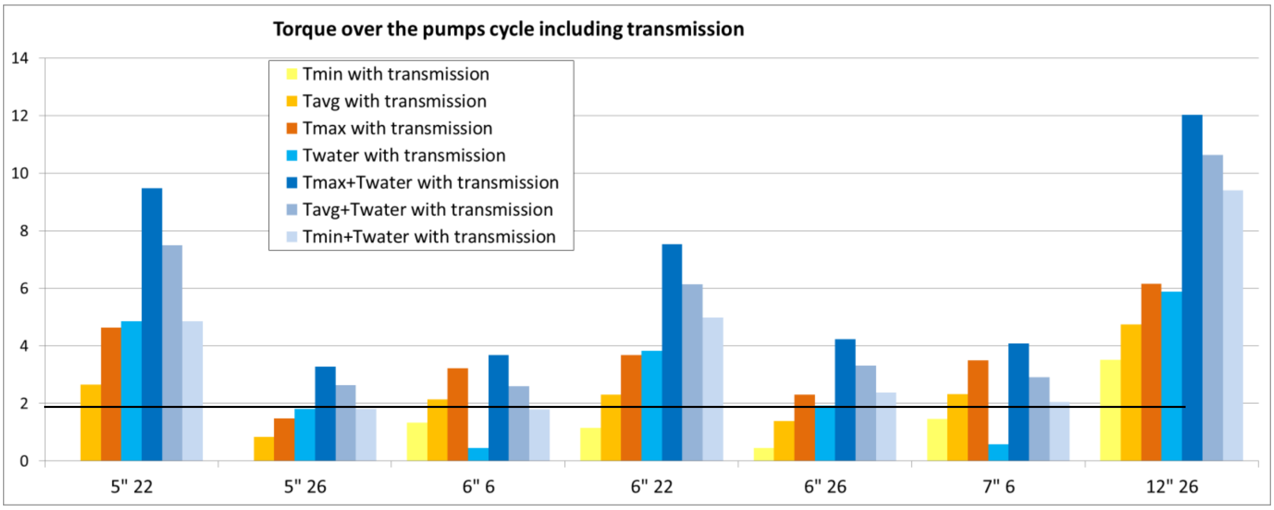


Figure 112: Torque along the pumps cycle including a transmission set to render the required flow rate

13.4.3 Other rim-hose combinations

The previous paragraphs revealed the results for the current rim-hose combinations. They currently almost suffice, and recommend a thicker hose. Is it possible to predict the performance of other combinations?

Though a larger rim creates a larger flow rate, the tests revealed that larger rims also increase the deviations in their inner diameter. A larger rim thus also risks higher torque peaks and more leakage. This was confirmed among the 6” and 7” rim with the 6mm hose: though torque peak was steady, flow rate was lower for the 7” rim. The maximum rim size advised in this report is thus the 6” rim (200mm outer diameter).

For the hose the tests revealed that more than inner diameter, the hoses stiffness dictates the prototypes performance. The 6mm hose performed exceptionally well, both in torque and flow rate. It stays closer to the rim and opens up more, creating a larger inner volume. Less stiff hoses, like the 22mm and 26mm ones, showed hose wrap and flat cross-sections. Could a larger hose with a thicker wall create sufficient flow rate, while keeping torque low?
There is not enough data available at this point to do any predictions. A test with several hoses of varying wall thicknesses is very interesting. Silicone hoses are available in several wall thicknesses for each inner diameter.

13.4.4 Validity of results

Validation of the results gives insight into the repeatability of the experiments. In the case of these tests, the primary questions that rise regard the scarcity of data and instable operation of the prototypes. Additionally the test set-up and method are scrutinized for possible unwanted influence on the results.

Scarcity of data points

The scarcity of data points is the first threat to repeatability. Several rim hose combinations are missing, and existing rim hose combinations feature two to three data points. The fact that data is missing does however not imply that the existing data is unreliable, as the reasons for missing data are practical (Table 9).

Table 10: Reason for absence of certain rim-hose combinations

Rim hose combination	Reason for absence
5” 6	Prototype got severely damaged before 6mm hose was tested
7” 22 and 7” 26	The rim turned out larger than indicated, causing the occlusion settings to be too wide for both the 22mm and 26mm hose. Production of new impeller plates was limited by budget and time.
12”6 and 12”22	The 6mm hose and 22mm hose proved too short for the rim. Acquisition of longer hoses was limited by budget and time.

Influence of instable operation to the results

Looking at the repeatability of the existing data, the damage done to the prototypes is the first consideration. Damage was indeed done to all prototypes. It included impeller plates running into the rim, rollers running into the top or bottom, the hose to creep above or below the plate. All of these influence occlusion and increase friction in the pumps operation. Experiments were however stopped when the ‘start signs’ of these damage types were noticed: loosening bolts, bearings, moving shafts, sudden increases in torque. Thus the resulting influences on occlusion and increased frictions were absent during the experiments. The *presence* of data is doubtable upon repetition as prototypes might break, but the results were found during stable operation.

Further examination of the data shows it is indeed reliable qualitatively for the current design. The data performs as expected, taking into account the observations. The hose wrap is for instance represented in the data: flow rates are lower than expected and torque increases with rim size. It is also clear that a production precision or occlusion range of 5mm is influential for the 22mm and 26mm hoses: flow rates and torque varied opposite to what was expected and leakage lessened performance.
On a quantitative level it remains unsure if the prototype would produce the found flow rates and torque upon repeated production and testing. The hose wrap and varying occlusion influence the results too much.

Test set-up evaluation

Looking at the test set-up and method, a few changes were made from the original (Figure 113). These regard the addition of a cardanic coupling between the prototype shaft and drill shaft, and the addition of a fixation to hold the pump. A cardanic coupling couples two shafts that meet under an angle. In this case, they

allow the power source (drill) to be held by a human: now it does not need to be kept perfectly aligned. The fixation was a metal ring, fixed to the base of the rim and a wooden block underneath the prototype. This facilitates keeping the prototype in place with the feet.
These additions were necessary to operate the prototypes solitarily. The additions do not change the original design; there too the pump shall be fixated to the well

and coupled to the up-going shaft.

Figure 113 (right): Revised set-up, including cardanic coupling and fixation.

Test methodology evaluation

Another shortcoming to the test is the 1L jug used to measure the flow rate. It had indicators at each 100mL, which allows for deviations op to 50mL from the full litre. This was combined with a timer that rounds to seconds, again allowing up to 0,5s deviations. Combined this adds up to 6% to 12% deviation from the measured value (Table 11, Figure 114). Flow rate data was thus verified using the film recordings, which allows for a much higher time precision. The results presented above thus show some deviation, but not the deviation possible with the original methodology.

Table 11: Possible deviations from a measured value. The second, third and fourth column depict the measured amount of seconds per litre that is associated with the flow rate.

Measured flow rate	s/L	s/L max	s/L min	Flow rate max	Flow rate min	Deviation
1 L/min	60	60,5	59,5	1,1	0,9	6%
2 L/min	30	30,5	29,5	2,1	1,9	7%
3 L/min	20	20,5	19,5	3,2	2,8	8%
4 L/min	15	15,5	14,5	4,3	3,7	9%
5 L/min	12	12,5	11,5	5,5	4,6	10%
6 L/min	10	10,5	9,5	6,6	5,4	11%
7 L/min	8,6	9,1	8,1	7,8	6,3	12%

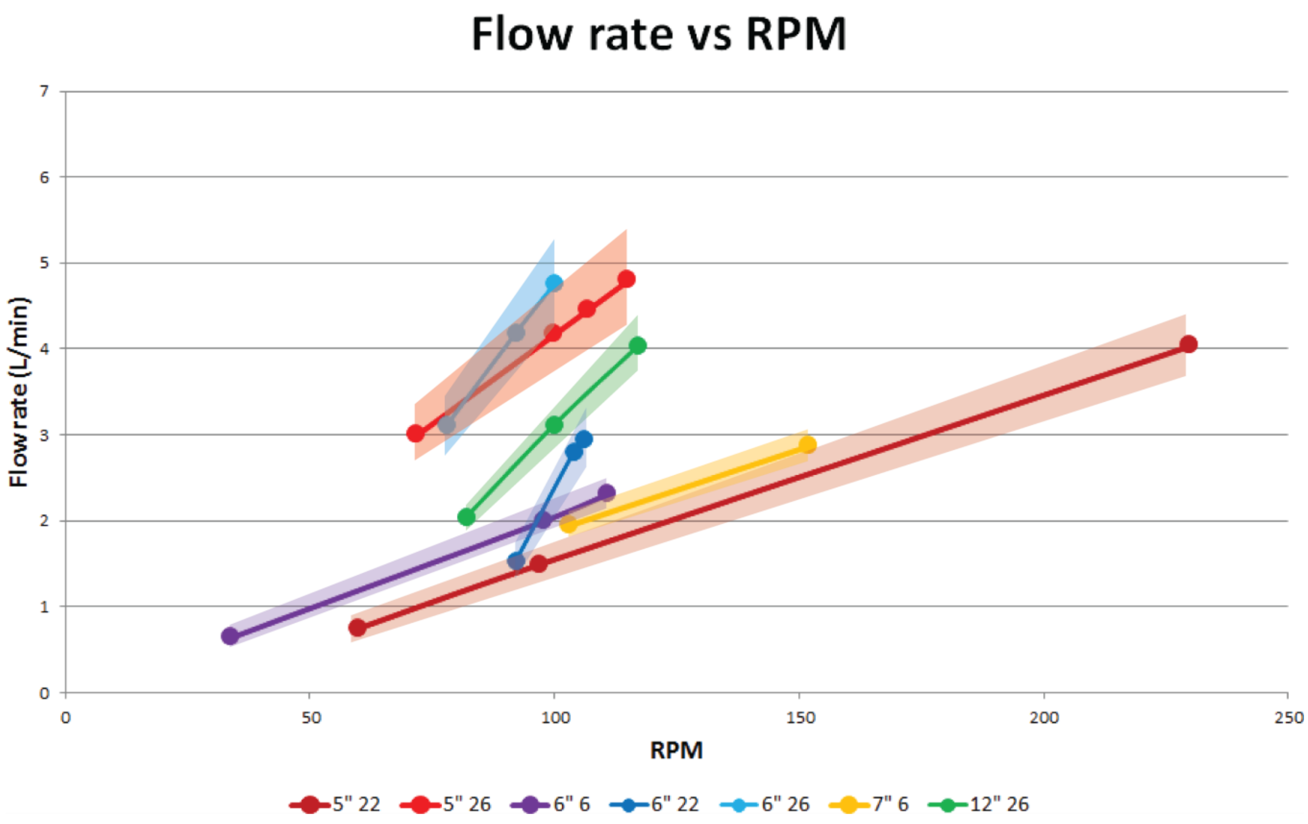


Figure 114: Possible deviations from the flow rate data

Conclusion

The test-set up and methodology were changed with last minute insights to operate the tests solitarily, and precise enough. Though data points are scarce, they do provide a qualitative insight to the functioning of the design. Quantitatively the results are not reliable, due to the influence of the occlusion range and hose wrap.

13.4.5 Conclusion: answers to the tests' goals

The data on flow rate and torque, combined with the observations have given valuable insights to the designs functioning, flow rate and torque. In short: some of the prototypes have nearly met the flow rate criterion within the torque criterion during the tests (Figure 112), though the results are quantitatively unreliable upon repetition. Leakage and hose wrap influenced the results relevantly, indicating future efforts might perform both better and worse.

The functioning of the design, and why it did not operate stable, were assessed by combining observations with the data. It revealed that the hose is at this moment too thin, and that the larger rims are less reliable. A hose with an inner diameter between 6 and 26 mm with a relatively thick wall in a 6" rim would perform better, both in terms of stable operation as in terms of flow rate and torque. How much better, cannot be estimated to date. Further recommendations will be treated in the recommendation section (p. 127).

14 Evaluation

The tests provided only a part of the evaluation of the full concept. In this section the full program of requirements will be treated, to evaluate if the design is fit for the Palestinian communities. Its performance will furthermore be compared to the performance of the rope pump: the currently prevalent pump for similar circumstances. This leads to the conclusion of this designs evaluation, indicating the pumps performance and promise both within the field case and beyond. Recommendations furthermore show what future work might focus upon.

14.1 Program of Requirements

The program of requirements resulted from the research phase on local repair, field conditions and water and energy flows, that match the pump and rotor to the water demand of the communities. The full program is listed in chapter 7, p. 43. In this section the prototypes performance on each requirement is discussed, sometimes combining several as they interfere with one another. The color with which the requirement is written indicates if the requirement is met: red is a 'no'; orange a 'probably not'; yellow a 'was not tested till date'; and green a 'yes'. A summary of this section is given in the conclusion, where the comparison of the prototypes to the program of requirements is combined with the comparison to the rope pump.

2.1 The torque is 1,9Nm * gear ratio *i*
3.3 Production precision maximum 0,5mm
2.3 Flow rate – RPM relation is as Figure 24
As described extensively in the discussion section, this combination of requirements was not met, though results were close. The torque required to acquire the demanded flow rate was 3,2Nm, rather than 1,9Nm. These results were furthermore unreliable upon repetition, as a proper hose closure could not be achieved reliably within 0,5mm production precision. A thicker hose could improve the performance.

1.2 Pumping head of 10m
All prototypes were capable of achieving the 10m head within the production precision limitation of 0,5mm.

1.3 The pump is submersed in the water

Submersing the pump in water will not damage it (refer to requirement 1.5), but can slow its start-up down. The water inside the pump adds inertia to the impellers rotation (Equation 18). This inertia takes up some energy upon speeding up (Equation 19). This amount of energy is however negligible in comparison to the total amount of energy required (≥8J/s). The pump is able to be submersed in water without changed behavior.

$$I_{water} = \frac{m * r^2}{2} = 0{,}01\ kg \cdot m^2$$

Equation 18

$$E_{water} = 0{,}5 * I_{water} * \omega^2 = 0{,}5J$$

Equation 19

1.4 The pump can handle small debris and sand in the water

1.7 Pump outlet allows connection to a hose or pipe, pump inlet includes a gauze

The hose is capable of handling small debris and sand, but the gauze at the inlet was not yet included in the prototypes, nor was the outlet connector. These can be added in accordance to the design (p. 70).

1.5 Pump can withstand corrosion

All the pumps elements are made of plastics or stainless steel. The bearings in the centralizing plates should either be water tight roller bearings, or plastic plain bearings.

1.6 Pump is able to dry run

The pump does not depend on lubrication.

1.8 Pump couples to a long rotating shaft and avoids sweep

The connections of the pump to the shaft, and upwards to the wells entry, were not yet included in the prototypes. These can be added in accordance to the design (p. 70).

1.9 Price is 100US$ or less

The bill of materials of the 5”and 6” pump remained below the 100US$ in the Netherlands ($85 and $98 respectively). The 7” pump almost made it ($114), but the 12” pump was much more expensive ($208). Local prices remain unknown.

2.2 Pump efficiency is 40%

The pumps efficiency can be calculated using dynamic frictions or input power; both were not measured till date. The pumps efficiency remains unknown.

3.1 Production should be such that parts are imported if required, but preferably manual labor is provided.
3.4 Simple manufacturing steps
3.5 Parts can be replaced and repaired without the use of power tools
All parts but the hose can be made locally. The most difficult production step is to make the circular plates for the impeller- and centralizing plates. They were now made from a plate material; for larger batch sizes manufacture could include cutting of a plate from a PVC rod or cylinder. Assembly does not require powered tools; it is done with the use of screw drives and a wrench.

3.2 Maintenance costs and frequency as low as possible
As described in the life time section of the hose, testing the life time takes a year and thus reaches beyond the span of this project.

14.1.1 Conclusion

The fulfillment of some requirements remains unknown, others are or can be achieved. The flow rate and torque might be achieved by using a thicker hose.

14.2 Rope pump

The rope pump is this concepts' primary competitor. It is locally repairable pump, widely spread across the developing world, often even wind powered. It however does face some production problems: 90% of pumps break down within a year due to imprecise manufacture of pistons and rope (Appropedia, 2015). This is exactly where the peristaltic concept could improve: due to the flexible hose production precision could be much lower. In situations similar to the Palestinian case, the peristaltic pump could, if successful, provide a easily producible alternative to the rope pump.
This section will thus evaluate the rope pump to the program of requirements, to compare both performances in the conclusion section.

1.1; 2.1; 2.3; 3.3: Torque, production precision and flow rate

Rope pumps feature varying pipe diameters, piston spacings and production precisions. These all impact both flow rate and torque. Rijs and Smulders (Smulders & Rijs, 2006) provide formulae for flow rate and torque. This renders a flow rate of 5,9L/min at 100 RPM, 14,5mm pipe diameter, 1m piston spacing and 0,5mm production precision (Table 12).

Table 12: Rope pump flow rate calculation

Input			
ρ	1000	kg/m^3	Density of water
g	9,81	m/s^2	Graviational constant
H	10	m	Head
D_{wheel}	0,23	m	Diameter of wheel driving the rope optimized to set Vrope to 1,2m/s, as recommended by (Williams, 2014)
t_{gap}	0,0005	m	Gap distance between pipe and piston, set to the maximum production precision of 0,5mm
D_{pipe}	0,0145	m	Diameter of pipe, set to yield Tpump=1,9Nm
$N_{pistons}$	1	$\#/m$	Number of pistons per meter as recommended by (Williams, 2014)
RPM	100	$\#/min$	
Output			
A_{pipe}	1,65E-04	m^2	$A_{pipe} = \pi\left(\frac{D_{pipe}}{2}\right)^2$ = surface of cross section of pipe
V_{rope}	1,2	m/s	$V_{rope} = \frac{RPM}{60} * 2\pi * \frac{D_{pipe}}{2}$ = velocity of the rope
T_{pump}	1,9	Nm	$T_{pump} = \rho * g * H * A * D_{wheel}/2$ = torque
$Q_{leakage}$	1,01E-04	m^3/s	$Q_{leakage} = \pi * t_{gap} * D_{pipe} * \sqrt{2g/N_{pistons}}$ = leakage flow rate
Q_{ideal}	1,99E-04	m^3/s	$Q_{ideal} = V_{rope} * A_{pipe}$ = ideal flow rate
Q_{real}	9,80E-05	m^3/s	$Q_{real} = Q_{ideal} - Q_{leakage}$ = real flow rate
$\boldsymbol{Q_{real}}$	5,9	$\boldsymbol{L/min}$	

1.2 Pumping head of 10m

Rope pumps are known to go as high as 50m (Bombas de Mecate, 1998).

1.3 The pump is submersed in the water
1.5 Pump can withstand corrosion
1.6 Pump is able to dry run
Rope pumps are always submersed into the well and can withstand corrosion and dry running.

1.4 The pump can handle small debris and sand in the water
1.7 Pump outlet allows connection to a hose or pipe, pump inlet includes a gauze
The spacing between piston and pipe allow for some debris and sand. The pipe is usually a material of a high hardness, implying damage done affects the pistons that can easily be replaced. The rope pumps design however does not allow for a gauze at the inlet, implying the rope pump should not be completely at the bottom of the well and/or utilized right after rainfall. The pumps outlet does allow for a connection to a hose or pipe easily.

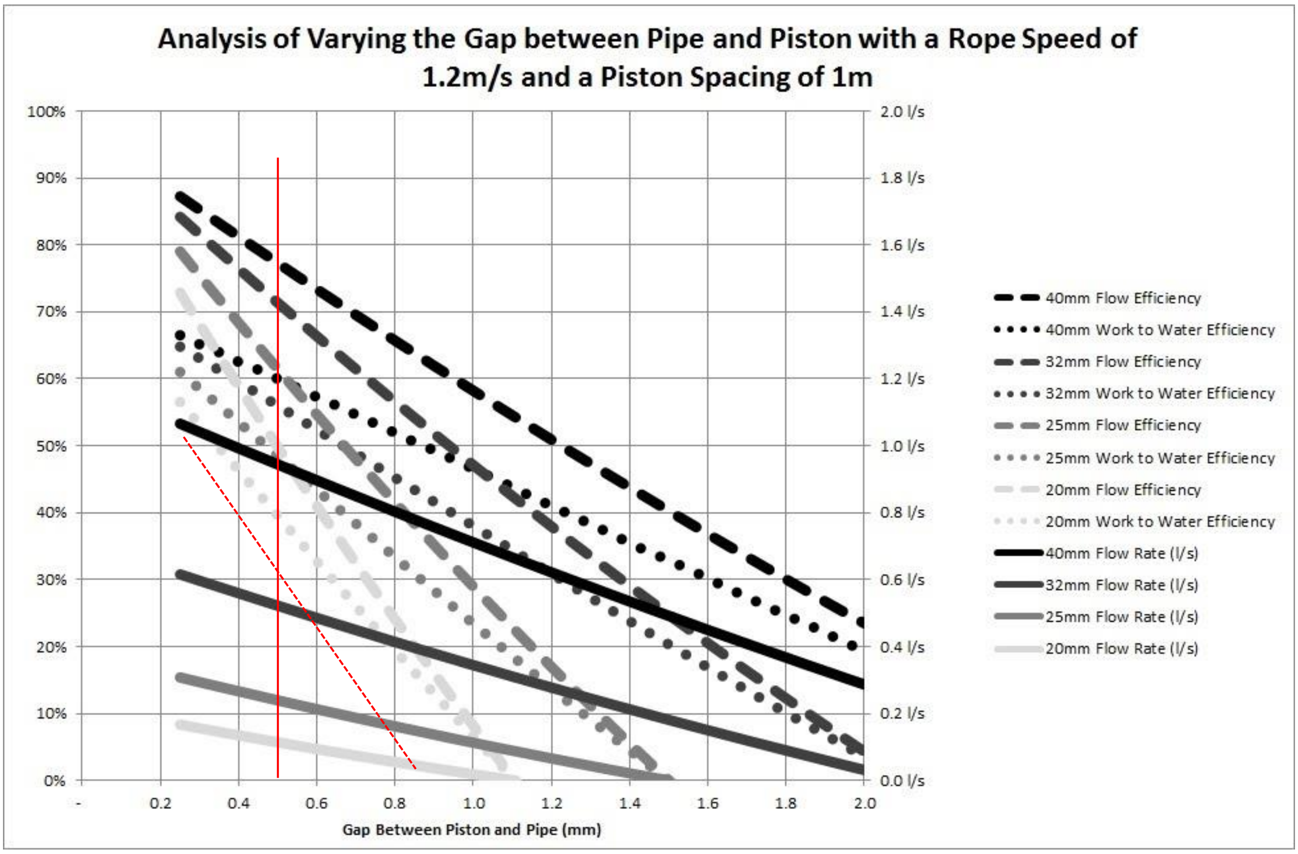
1.8 Pump couples to a long rotating shaft and avoids sweep
A transmission from the rope pumps horizontal shaft to the rotors vertical shaft is required.

1.9 Price is 100US$ or less
The Hand Rope pumps cost between US$ 30-150 depending on model, location of production, and local cost of materials and labor (Appropedia, 2015).

2.2 Pump efficiency is 40%

The rope pumps efficiency depends on its gap size, rope speed, piston spacing, and pipe diameter. It was just seen that for the Palestinian situation the pipe would be 14,5mm, the gap size 0,5mm, the rope speed 1,2m/s and the piston spacing 1m. This corresponds to a work to water efficiency below 40%. With the energy available in the wind, such efficiency will not suffice to lift enough water up. The rope pump will thus need a higher rotor power output to achieve the flow rates calculated above.

Figure 115: Rope pump efficiency versus gap size (Williams, 2014), including indicator (red) at 0,5mm gap and for the Work to Water Efficiency at 14,5mm pipe diameter.



3.1 Production should be such that parts are imported if required, but preferably manual labor is provided.

3.4 Simple manufacturing steps

3.5 Parts can be replaced and repaired without the use of power tools

Development of the rope pump has refined itself, making the production process more complex. To match the performances calculated above, production includes "*a variety of steps, such as plastic injection; hand making, dehydration and glazing of ceramic piece; metal work to make the wheel structure and pulley wheel; and other manual mechanical work*" (Bombas de Mecate, 2012). These steps are possible in Palestine, though not in the villages themselves. Assembly and replacement of parts is possible without the use of power tools.

3.2 Maintenance costs and frequency as low as possible

The rope pump needs frequent visit. After installation of a rope pump one has to return after a few weeks to adjust the tension in the rope. Maintenance consists of periodically lubricating the bushing, where the maintenance frequency depends on the local circumstances. In the Palestinian environment sand therein poses a threat and lubrication has to happen once a month. For other parts a yearly visit to repaint and check the equipment suffices. The rope pump should then last at least 3 years without replacement of parts. Rope pumps have been known to last up to 20 years when including part replacements (Bombas de Mecate, 2012). However, if produced badly 90% of rope pumps breaks within a year (Appropedia, 2015).

14.3 Conclusion

The peristaltic design until date does not perform as required. Its operation is unstable and gathered results do not satisfy the flow rate and RPM criterion. Upon improvement, it might satisfy the Palestinian needs.
When comparing the prototypes performance to the rope pump, the rope pump is thus more reliable. It achieves the desired flow rate, plus 18%. Its primary downside is that it requires a higher production precision to have a suitable efficiency. The gap between piston and pipe should be smaller than 0,4mm, or the rotor has to be provide more power to counteract the slacking efficiency. The production process is the second downside of the rope pump: it is much more complex, involving ceramics, injection molding and metal working.
If the peristaltic design is improved, and provides stable operation and higher flow rates, it is thus expected to provide a better solution for both the Palestinian case and other similar situations.
Table 13 provides an overview of the paragraphs above.

Table 13: Comparison of the Peristaltic design and rope pump on the requirements

Requirement	Peristaltic design	Rope pump
2.3 Flow rate – RPM	4,2 L/min	5,9L/min
3.3 Production precision	<0,5mm	<0,4mm
2.1 Torque	2,3 Nm	1,9 Nm
2.2 Efficiency	?	<40%
1.2 Head	>10m	<50m
1.3 Submersible	V	V
1.4 Debris	V	V
1.5 Corrosion	V	V
1.6 Dry-running	V	V
1.7 Gauze and outlet connector	V	Gauze impossible
1.8 Shaft connector and sweep	V	V
1.9 Price	$98 in NL	$30-150
3.1 Local parts	But for hose	But for polypropene rope and high-density polyethylene for the pistons
3.2 Maintenance	?	Monthly
3.4 Production steps	Simple	Injection moulding, ceramics, metal
3.5 Replacement and repair	V	V

14.4 Project conclusion

The current design does not function as required: it is unstable and nearly, but not fully, acquires enough flow rate within the torque requirement. If the pump operates stable, decreasing peak and average torque and increasing flow rates, it could improve on the rope pump and meet the requirements (Table 13). A thicker hose aids towards this goal: the results of the relatively thick 6mm hose indicates that a thicker hose might solve the stability problems and increase the flow rate within a manageable torque. This would make it a very promising pump to the developing world: the easiest to produce, excellent match with a wind rotor and thus able to independently irrigate fields and fill water basins. From the basins users can use a siphon, rather than a bucket. Water could be accessible all day, close to homes and effortless.
Especially for the field case, this would improve the daily water hassle of remote communities and open up new water resources and new economic windows.

14.5 Recommendations

The tests and design process rendered insights that are useful for further development of the peristaltic pump. These are described here, both for the product design as for the steps of a possible continuation of the project.

14.5.1 Product design

With the design chapter in mind, a relation between the instable operation and design is found.
A multitude of possible solutions come to mind:

1. Implementing a thicker hose
2. Implementing a connectors that not only couple the hose, but also push it against the rim
3. Implementing extra rollers / aligners
4. Implementing springs on the rollers / rim / shaft
5. Implementing a bearings on the roller axis

The simplest improvement would be a thicker hose. This would:

- Keep the hose closer to the rim, thus
  - Avoiding hose wrap and the associated peak torques and damage;
  - Increasing flow rate per cycle;
- Keep the hose opening up more, which increases flow rate;
- Render the occlusion range broader, making the pumps operation more reliable;
- Probably not cost extra torque, but keep the hose acting as a spring: pushing the roller forward after the squeeze as much as it was holding it back in front of the squeeze;
- Not add any extra parts to the pump;
- Not add relevant costs (Damen Rubber, 2015).

Tests would have to be done to verify.

Option 2, the connectors, are required to connect to the world outside the pump, but were not part of the prototypes until date. If made well they could not only connect the hose, but put the hose under a slight pressure inside the pump, ‘pressing’ it against the rim. This will keep it close to the rim. Once hose wrap happens it heightens torque peak, pulling the hose more, heightening torque peak, pulling more, et cetera. A risk is that *if* the hose elongates, it might start to fold near in the outlet, obstructing the rollers and breaking the pump. The question is thus if the pressure put on the hose by the connectors is enough to keep it from elongating to that extend.

If the result of using a thicker hose and proper connectors is not adequate (e.g. torque becomes too high, it still shocks), options 3 to 5 remain. Of these, an easy one to try out is the springs in the rim; this could for instance be a rubber strip, glued against the rim. A strip made of an elastic material against the rim has the same effect as springs on the rollers or shaft, but is much easier in production.

A last option is adding aligners, rollers or bearings on the roller axis: these increase the pumps complexity and price to a relevant extend. Extra rollers would only be required if leakage remains a problem within the production precision limits, after increasing hose wall thickness.

14.5.2 Project process

The pump is not ready for implementation at this point. Further prototyping and testing of separate solutions is required. If continuing with this project the following steps would be appropriate:

1. Iterative design until stable operation is met (refer for possible steps to product design recommendations)
   a. In future tests include measurements of input power or dynamic torque to verify efficiency. Measuring input power can be done with a motor with known efficiency to power the pump. Dynamic torque can be measured using a torque transducer. During the selection of a transducer note that both RPM and torques are relatively low.

2. Testing the other parts of the program of requirements allows to fully verify the concept in its context. This includes:
   a. Verification of the designs producibility and local price through in-field production.
      - Test the flow rate versus RPM relation and torques for the locally produced prototypes.
   b. Testing with the rotor to measure flow rate over the day and versus wind speed, to verify the rotor model and satisfaction of the communities' needs.
   c. Installation of the complete system within a community to assess social effects, appreciation, and influence of the system on water usage habits and -quantities.
   d. Life time tests, measuring (change in) flow rate, pressure and torque over time and/or establishing observation wear indicators for the hose. Change in flow rate, pressure and torque indicate that the hose is getting 'tired'; not opening up so well anymore, elongating and becoming thinner (changing the required occlusion, and torque). This test can be done in-field or in a lab.

Tests 2b to 2d can be combined in one field set-up. Such a set-up includes a stand-alone system of a rotor, pump, reservoir and piping to the end-users. A small electrical system is beneficial for data logging, and would include a battery, RPM sensor for the rotor, wind speed sensor, flow rate sensors to and from the reservoir, and water quality monitoring. Wireless data transfer can in addition inform the operators of malfunctioning and/or other interesting events (such as storms and celebrations (sudden rise of water use)). If the rotor-pump combination is not installed inside a community such wireless data transfer is highly recommended due to the local political situation.

3. Additional measurements could aid other organizations to dimension the pump and predict its behaviour for their circumstances. This includes:
    a. Measuring flow rates with different heads/pressures, creating the Head-Flow Rate graph typical to pumps. This will allow other organizations to estimate how the pump will behave with their respective water heads;
    b. Establishing a validated model between flow rate and rim size, and flow rate and hose size. This allows other organizations to choose their pumps diameters to acquire their desired flow rates.
    c. Creating an understandable calculation methodology, program, excel sheet or the like to tweak all these factors to different circumstances.
    d. Creating an understandable production and implementation manual.

Furthermore the wind rotor model is quite an improvement to the current modelling steps for wind pumps (refer to p.32). It could improve efficiency of any future rotor-pump combination, and be useful to organizations implementing such installations.

This leaves me to say that this has been a very interesting project, that I would gladly see continued. The rope pump has had to become complex in production to ensure its life time. I'm curious if the peristaltic pump could provide a truly sustainable design; cost effective, reliable and easy to copy by anyone interested. If it may be so that someone continues with it, I'm willing to share my insights. Feel welcome to contact me at martefekkes@gmail.com. The best of luck!

15 Acknowledgements

This report would not have been possible without the aid of my mentors, partner, family, friends, some professional health workers s and the friendly people of Palestine and Israel. I'd like to thank all of them warmly – for endless proof-reading, for support and for lay-out and structural advice.

JC Diehl
Henk Kuipers
Martine van de Velde
Elly & Evert Fekkes
Tom & Marieke
Sylvia Ham

Amber Leeman
Annette Voesenek
Maryse Karsten
Peter van der Linden
Martin Havranek
Anne Leeuw
Mike Bond
Renske Rothuizen
Raissa Ulbrich
Rienk Aalbers

Stephanie Meulemans
C Veldhuizen

Ahmad Almasry
Noam Dotan
Ezra Nawi
Waseem Jabari
Jalal Tamimi
Elad Orian
Imad Muna
Li Lorian

16 Bibliography

Allan Dagen, A. (2011). Pastorialism as a form of entrepeneurship - Marketing. In L. Dana, *World Encyclopedia of Entrepeneurship* (pp. 313-314). Cheltenham, UK: Edward Elgar Publishing Limited.

Al-Salaymeh, A., Al-Khatib, I., & Arafat, H. (2011). Towards Sustainable Water Quality: Management. *Water Resource Management 25(6)*, 1721-1736.

Appropedia. (2015). *Appropriate Technology*. Opgehaald van Appropedia: http://www.appropedia.org/Appropriate_technology

Arlosoroff, S., & al, e. (1987). *Community Water Supply: The Handpump Option.* World Bank.

Arora, M. (2011, 1 6). *Pump Handbook Fourth Edition – A Book Review*. Opgehaald van EK Westrel: http://ekwestrel.com/pump-handbook-fourth-edition-a-book-review/

Arrakis. (2006). *Training Manual Hand Rope Pump, Model Module 1: Production.* Zambia, India & Mozambique.

Barnes & Noble. (2007, 11 30). *Editorial Reviews*. Opgehaald van Barnes & Noble bookstore: http://www.barnesandnoble.com/w/pump-handbook-igor-j-karassik/1100554840?ean=9780071460446

Boeijen, A. v., Daalhuizen, J., Schoor, R. v., & Zijlstra, J. (2013). *Delft Design Guide.* Bis Publishers.

Bombas de Mecate. (1998). *Experiences and Tolerances in Rope Pump Production.* Managua, Nicaragua: Technology Transfer Division, Bombas de Mecate.

Bombas de Mecate. (2012). *Operation, Maintenance and Repair.* Nicaragua.

Bombas de Mecate. (2012). *Pistons*. Opgehaald van Rope Pumps: http://www.ropepump.com/

Bombas de Mecate. (2012). *The Production Process.* Nicaragua.

Boutilier, M. S., Lee, J., Chamers, V., Venkatesh, V., & Karnik, R. (2014). Water Filtration Using Plant Xylem. *PLOS One*.

Brand, R. (2013). *Graduation report.* Delft: TU Delft.

B't Selem. (2013). *Restrictions on access to water and non-development of water infrastructure in Area C.* B't Selem.

Burrows, A. (sd). World Pumps. *ISSN: 0262-1762*. Elsevier.

Chan, L., Chan, M., & Wang, J. (2009). *Design of water filters for third world countries.* Toronto: University of Toronto, Department of Mechanical and Industrial Engineering.

Coloru, B., Mgaya, S., & Taubert, R. (2012). *Appropriate technologies for rural water supply.* Fondazione ACRA-CCS.

Comet-ME. (2011). *2011 Annual Report.* Opgehaald van http://comet-me.org/publications/annual-reports

Comet-ME. (2015). *2014 Annual Report.* South Mount Hebron, Palestine: http://comet-me.org/publications/annual-reports/.

Comet-ME. (2015). *How we Work*. Opgehaald van Comet-ME : http://comet-me.org/about/#4

Damen Rubber. (2015, 5). *Prices of transparant silicone hoses*. Opgeroepen op 5 19, 2015, van Damen Rubber products: http://www.damenrubber.nl/collectie/siliconenslangen-en-toebehoren/transparante-slangen/

Dotan, N. (2013). Production possibilities in Palestine. (M. Fekkes, Interviewer)

Dotan, N. (2013). Wind rotor types and decision. (M. Fekkes, Interviewer)

Dotan, N. (2014, 3). Production possibilities in Palestine. (M. Fekkes, Interviewer)

Dunn, P. (1978). *Appropriate technology: technology with a human face.* Macmillian press.

Elabassi, N., Bergstrom, J., & Brown, S. (2011). Fluid-Structure Interaction Analysis of a Peristaltic Pump. *Excerpt from the proceedings of the 2011 COMSOL conference in Boston.* Boston.

ENA Yelkaplan. (2014). *New Generation Wind Pump Technology*. Opgehaald van ENA Windmill Technologies: http://www.ena.com.tr/english.htm

Engineering Toolbox. (2015, 06 16). *PVC Pipes - Friction Loss and Flow Velocity - Schedule 40*. Opgehaald van The Engineering Toolbox: http://www.engineeringtoolbox.com/pvc-pipes-friction-loss-d_802.html

Flatejord, M. (2012). *Water and Electricity Strategies for Bedouin in Area C, Palestine.* Agder: University of Agder, Faculty of Economics and Social Science, Department of Development Studies.

Fraenkel, P. (1986). *FAO IRRIGATION AND DRAINAGE PAPER 43.* Rome: FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS.

Fraenkel, P., & Thake, J. (2006). *Water Lifting Devices, A handbook, third edition.* Warwickshire, UK: UN-FAO.

Gopal, C., Mohanraj, M., Chandramohan, P., & Chandrasekar, P. (2013). Renewable energy source water pumping systems—A literature review. *Renewable and Sustainable Energy Reviews 25*, 351-370.

Grundfos. (2015). *Submersible and dry-installed pumps for aggressive environments.* Opgehaald van Grundfos Water Distribution:

Hartman, S. (2012). Like water for the thirsty. *Renewable Energy Systems in Palestinian Communities in the South Hebron Hills*.

Hayek, J., & Kahwaji, R. (2013). *Hydrolus: Design of a Savonius Wind Pump for Developing Regions.* Mc Gill University.

Jequier, N. (1979). Appropriate technology: Some criteria. In A. Bhalla, *Towards global action for appropriate technology* (pp. 1-22). Elmsford, USA: Pergamon Press.

Jongh, J. d., & Rijs, R. (2004). *Pump Design.* Arrakis.

Juandeaburre, I. (2013). *Software development for wind data quality control. An approach to case analysis: Weather analysis in stations in the West Bank (Palestine).* Pamplona: Dpto. de Proyectos e Ingeniería Rural.

Kapur, S., Eswaran, H., & Blum, W. E. (2011). 3.4 Relations Between Runoff and Rainfall. In S. Kapur, H. Eswaran, & W. E. Blum, *Sustainable Land Management* (p. 72). Berlin Heidelberg: Springer.

Karassik, I. J. (2008). *Pump handbook (4th edition).* McGraw-Hill.

Kickstart International. (2009). *B2B Brochure 01/09 of Moneymaker Irrigation Pumps.* Nairobi, Kenia: Kickstart.

Kragten, A. (2013, 10 2). Pump types that could work in the developing world using wind power. (M. Fekkes, Interviewer)

Lenntech Water Treatment Solutions. (2015). *Desalination with Reverse Osmosis modules*. Opgehaald van Membrane technology: http://www.lenntech.com/desalination-ro-modules.htm

Moore, K. (2008). Pumping water with the wind. *Home Power 122*.

NASA & SSE. (2004). *Annual 50m wind speed.*

Noursi, I. (2013). *Automotive Aftermarket Products.* USA: Export.gov.

Oram, B. B. (2001). *Drinking Water Issues Corrosive Water* . Opgehaald van Water Research Center: http://www.water-research.net/index.php/drinking-water-issues-corrosive-water-lead-copper-aluminum-zinc-and-more

Polak, P. (2011, 10 28). *Building a better mousetrap is only the beginning*. Opgeroepen op 5 1, 2015, van Paul Polak: http://www.paulpolak.com/building-a-better-mousetrap-is-only-the-beginning/

Polak, P. (2011, 11 7). *From Concept to Market: How to design for Impact*. Opgehaald van Paul Polak: http://www.paulpolak.com/from-concept-to-market-how-to-design-for-impact/

Polak, P. (2013). *The Business Solution to Poverty: Designing Products and Services for Three Billion New Customers.* San Francisco, USA: Berrett-Koehler

Publishers.

Pump School. (2014). *Internal Gear Pumps*. Opgehaald van Pumpschool.com: http://www.pumpschool.com/principles/internal.asp

Ragheb, M., & Ragheb, A. (2011). Wind Turbines Theory - The Betz Equation and Optimal Rotor Tip Speed Ratio. In R. Carriveau, *Fundamental and Advanced Topics in Wind Power* (p. Chapter 2). Intech.

Rijs, R., & Smulders, P. (2006, September 23). *A Hydrodynamic Model of the Rope Pump.* Netherlands: Arrakis.

Saint-Gobain Corporation. (2013). *A guide to Tygon tubing formulations.* Opgehaald van Thermoplastic Elastomers: http://www.processsystems.saint-gobain.com/uploadedFiles/SGPPL-PS/Documents/Flexible_Tubing/FT-TygonTubing-Brochure.pdf

Short, T., & Thompson, P. (2003). Breaking the mould: solar water pumping—the challenges and the reality. *Solar Energy 75*, 1-9.

Smulders, P., & Rijs, R. (2006). *A Hydrodynamic Model of the Rope Pump.* The Netherlands: Arrakis.

Sprinkler Warehouse. (2007). *How To Check Water Pressure*. Opgehaald van Sprinkler System And Irrigation Basics: http://www.sprinklerwarehouse.com/DIY-Determine-Pressure-and-Flow-s/6671.htm

TheFlyingBeer. (2011, 7 11). *Forum: Cake pan + skateboard wheel + bike brakes = homemade peristaltic pump??* Opgeroepen op 5 15, 2015, van Home Brew Talk.com: http://www.homebrewtalk.com/showthread.php?t=279120&page=3

Transport Information Service. (2015, 6 16). *Natural Rubber*. Opgehaald van Cargo Loss Prevention information from the German marine insurers

Turbex. (2014, 1 1). *Prices*. Opgeroepen op 5 1, 2015, van Turbex Wind Pump: http://www.turbex.co.za/images/Turbex_Pricelist_Jan2014.pdf

UK Met Office. (2013). *London Heathrow Rainfall, 1961-1990.* Opgehaald van Historic Station Data: www.metoffice.gov.uk/climate/uk/stationdata

UN Millenium Project. (2005). *Energy services for the MDGs.* New York, USA: The International Bank for Reconstruction and Development/The World Bank and the United Nations.

UNCESC. (2002). *ICESCR, General Comment 15, para.2.* Geneva.

UNESCAP. (2006). *Water Infrastructure.*

UNESCO. (1996). De´claration de Harare sur l'e´nergie solaire et le de´veloppement durable. *Sommet Solaire Mondial.* Harare.

UN-Water. (1977). *The 1977 United Nations 'Water Conference' at Mar del Plata .* Mar del Plata: United Nations.

Verderflex. (2013, 1). *Smart Tube Pumps.* Opgeroepen op 10 2013, van Verderflex Peristaltic Pumps: www.verder.com

Water Aid. (2013). *Hand-dug wells.* www.wateraid.org/~/media/Publications/Hand-dug-wells.pdf.

Water Regulations Advisory Scheme. (2012). *Certificate of Compliance BS EN 1401.* Sharjah, UAE: National Plastic & Building Material Industries L.L.C.

Weather Online. (2015, 6 7). *Ben Gurion Airport Wind Speed History*. Opgehaald van Climate of Israel: http://www.weatheronline.co.uk/weather/maps/city?FMM=1&FYY=2000&LMM=12&LYY=2015&WMO=40180&CONT=asie&REGION=0023&LAND=IS&ART=WST&R=0&NOREGION=1&LEVEL=162&LANG=en&MOD=tab

Westra, M. (2010, 1 19). *Why water pumps should be extremely repairable*. Opgehaald van Akvo: http://akvo.org/blog/why-water-pumps-should-be-extremely-repairable/

WHO & UNICEF. (2014). *Progress on sanitation and drinking water (JMP).* Geneva, Switserland: WHO Library Cataloguing-in-Publication Data.

Williams, C. (2014). *Pump Efficiency and Model Equations.* East Africa: MaWaMa.

Wolde-Ghiorgis, W. (2002). Renewable energy for rural development in Ethiopia: the case for new energy policies and institutional reform. *Energy Policy 30*, 1095-1105.

Wood, A. (1976). *Water lifters and pumps for the developing world.* Fort Collins, Colorado: Colorado State University.

World Bank. (2013). *SE4ALL Global Tracking Framework.* Vienna, Austria: World Bank.

World Bank Group. (2013, 8 2). *Climate Change Knowledge Portal.* Opgehaald van http://sdwebx.worldbank.org/climateportal/index.cfm?page=country_historical_climate&ThisRegion=Asia&ThisCCode=PSE/

World Health Organization. (2012). *Global analysis and assessment of sanitation and drinking-water (GLAAS)*. Opgehaald van Water supply, sanitation and hygiene development: http://www.who.int/water_sanitation_health/hygiene/en/

Zhao, W., Billdal, J., Nielsen, T., & Brekke, H. (2012). Study on the leakage flow through a clearance gap between two stationary walls. *Earth and Environmental Science 15*.