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TRABAJO FIN DE MÁSTER

DEVELOPMENT OF A HIGH PERFORMANCE HYDROPOWERED PUMPING SYSTEM

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Madrid

Agosto de 2019

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MÁSTER UNIVERSITARIO EN INGENIERÍA
INDUSTRIAL (MII)

TRABAJO FIN DE MÁSTER

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Resumen

Esta tesis fue desarrollada en colaboración con la empresa holandesa aQysta, desarrolladora de bombas hidropropulsadas, que actualmente opera en varios países como: Colombia, España, Kenia, Zimbabwe, India, Nepal e Indonesia.

El porfolio de aQysta está formada actualmente por dos soluciones basadas en la combinación de una rueda hidráulica y una bomba en espiral, que tienen algunas limitaciones con respecto a sus valores de salida. Por lo tanto, aQysta decidió desarrollar un nuevo e innovador sistema de bombeo hidropropulsado, comenzando el proyecto MIT WW PCP.

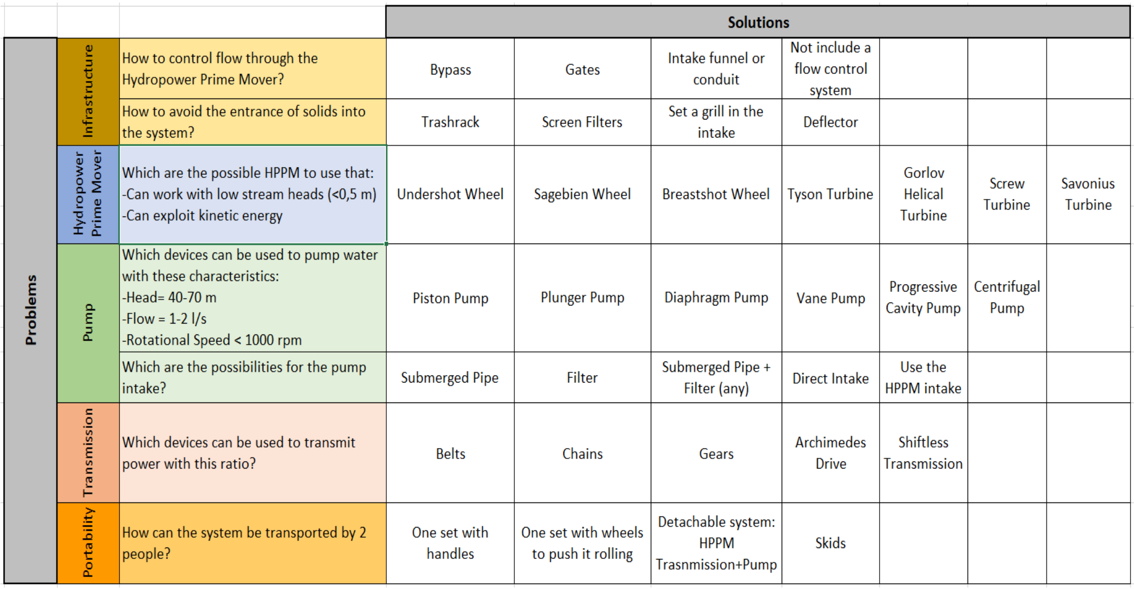
Esta tesis es la primera fase del proyecto MIT de aQysta B.V., y su objetivo principal es desarrollar conceptos e ideas innovadores para el diseño de este sistema de bombeo hidropropulsado. Por lo tanto, esta tesis es una investigación teórica sobre los sistemas de bombeo hidropropulsado.

El primer paso fue un estudio sobre el concepto de bombeo hidropropulsado con el objetivo de definir los subsistemas incluidos en él, los componentes que forman cada subsistema, para encontrar cuáles son las variables más relevantes y determinantes que afectan el rendimiento de un sistema de bombeo hidropropulsado, así como las interrelaciones existentes entre ellos. La siguiente tabla muestra los resultados obtenidos en este paso:

Subsystems	Components	Variables	
		Factors	Parameters
Context	-	-	Head Flow Rate Slurries and Solids Weather Conditions
Hydropower System	Weir Flow Control System Solids Rejection System Prime Mover	Hydraulic Head Flow Rate Infrastructure Necessary Cost	Rotational Speed Efficiency Maintenance
Transmission System	Transmission	Cost	Speed Ratio Torque Power Efficiency Maintenance
Pumping System	Intake Filter Valves Pump Outlet	Pumping Head Delivered Flow Rate Ability to Cope with Solids Cost	Pressure Rotational Speed Efficiency Maintenance

Posteriormente, se han estudiado diferentes tecnologías que podrían ser adecuadas para ser incluidas en el siguiente paso de la tesis. Además, se investigaron técnicas de innovación para generar conceptos creativos. El resultado de este paso es un cuadro morfológico que muestra los diferentes problemas a resolver para el diseño del sistema de bombeo hidropropulsado, así como varias posibles soluciones para cada uno de ellos. Es una herramienta útil para combinar

las diferentes soluciones para generar conceptos innovadores. El cuadro morfológico usado es el que se muestra a continuación:



			Solutions						
Problems	Infrastructure	How to control flow through the Hydropower Prime Mover?	Bypass	Gates	Intake funnel or conduit	Not include a flow control system			
		How to avoid the entrance of solids into the system?	Trashrack	Screen Filters	Set a grill in the intake	Deflector			
	Hydropower Prime Mover	Which are the possible HPPM to use that: -Can work with low stream heads (<0,5 m) -Can exploit kinetic energy	Undershot Wheel	Sagebien Wheel	Breastshot Wheel	Tyson Turbine	Gorlov Helical Turbine	Screw Turbine	Savonius Turbine
	Pump	Which devices can be used to pump water with these characteristics: -Head= 40-70 m -Flow = 1-2 l/s -Rotational Speed < 1000 rpm	Piston Pump	Plunger Pump	Diaphragm Pump	Vane Pump	Progressive Cavity Pump	Centrifugal Pump	
		Which are the possibilities for the pump intake?	Submerged Pipe	Filter	Submerged Pipe + Filter (any)	Direct Intake	Use the HPPM intake		
	Transmission	Which devices can be used to transmit power with this ratio?	Belts	Chains	Gears	Archimedes Drive	Shiftless Transmission		
	Portability	How can the system be transported by 2 people?	One set with handles	One set with wheels to push it rolling	Detachable system: HPPM Trasnmission+Pump	Skids			

Todas las soluciones se incorporaron en el Modelo de Evaluación, que es la parte final de la tesis, donde se evaluó la idoneidad de las tecnologías y los conceptos considerados generados en relación con las variables de salida hidráulicas, el costo y otros factores relevantes para el proyecto.

Por lo tanto, los resultados del proyecto son el estudio de conceptos, componentes y variables relacionados con el bombeo hidropropulsado, así como una investigación sobre el estado del arte, donde diferentes tecnologías de bombeo y transmisión de energía, así como soluciones ya implementadas, se describen. Sin embargo, el resultado más tangible de esta tesis es el Modelo de Evaluación, una herramienta de Excel utilizada para evaluar la viabilidad y la idoneidad de la combinación de las diferentes tecnologías consideradas.

Con él, se hicieron varias recomendaciones de configuraciones adecuadas del sistema de bombeo hidroeléctrico. Los trabajos futuros implican a los miembros de aQysta seleccionando una de estas configuraciones para diseñar un sistema de bombeo hidropropulsado basado en dicho concepto. Sin embargo, debe destacarse que esta tesis es puramente teórica, por lo que el proceso de diseño y generación de prototipos no se incluirá dentro de su alcance.

Palabras clave:

Energía, sostenibilidad, innovación, energía hidroeléctrica, cuadro morfológico, riego, bombas, análisis, factibilidad, eficiente, económico, transmisión, hidráulica.

Abstract

This thesis was developed in collaboration with the Dutch company aQysta, a developer of hydropowered pumps, which currently operates in several countries such as: Colombia, Spain, Kenia, Zimbabwe, India, Nepal and Indonesia.

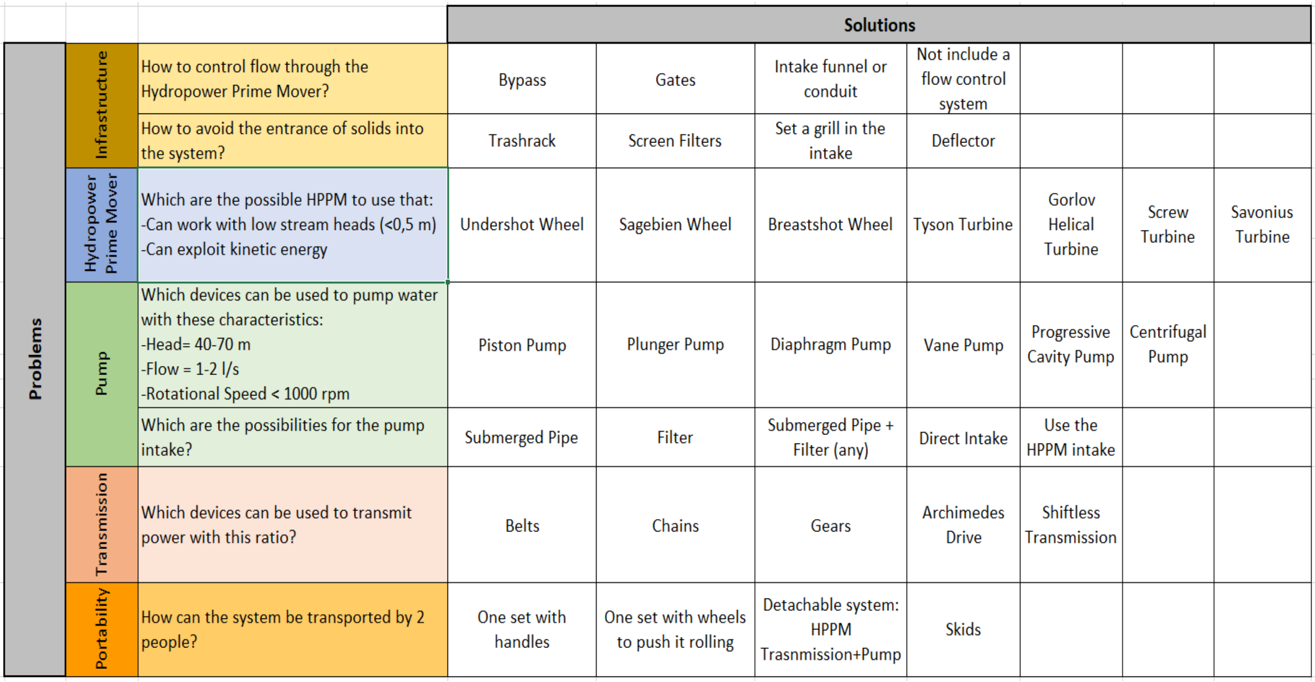
The portfolio of aQysta is currently formed by two solutions based in the combination of a waterwheel and a spiral pump, which have some limitations regarding their output values. Thus, aQysta decided to develop a new innovative hydropowered pumping system, starting the MIT WW PCP project.

This thesis is the first phase of MIT project of aQysta B.V., and its main objective is to develop innovative concepts and ideas for the design of this hydropowered pumping system. Thus, this thesis is a theoretical research about hydropowered pumping systems.

The first step was an study about the concept of hydropowered pumping with the objective of defining the subsystems included in it, the components that form each subsystem, to find which are the most relevant and determining variables that affect the performance of a hydropower pumping system as well as the interrelations existing between them. The following table shows the results obtained in this step:

Subsystems	Components	Variables	
		Factors	Parameters
Context	-	-	Head Flow Rate Slurries and Solids Weather Conditions
Hydropower System	Weir Flow Control System Solids Rejection System Prime Mover	Hydraulic Head Flow Rate Infrastructure Necessary Cost	Rotational Speed Efficiency Maintenance
Transmission System	Transmission	Cost	Speed Ratio Torque Power Efficiency Maintenance
Pumping System	Intake Filter Valves Pump Outlet	Pumping Head Delivered Flow Rate Ability to Cope with Solids Cost	Pressure Rotational Speed Efficiency Maintenance

Afterwards, different technologies have been studied that could be suitable to be included in the next step of the thesis. Furthermore, innovation techniques were researched in order to generate creative concepts. The result of this step is a morphological chart that displays the different problems to be solved for the design of the hydropowered pumping system, as well as several possible solutions for each of them. It is an useful tool in order to combine the different solutions to generate innovative concepts. This chart is displayed underneath:



			Solutions						
Problems	Infrastructure	How to control flow through the Hydropower Prime Mover?	Bypass	Gates	Intake funnel or conduit	Not include a flow control system			
		How to avoid the entrance of solids into the system?	Trashrack	Screen Filters	Set a grill in the intake	Deflector			
	Hydropower Prime Mover	Which are the possible HPPM to use that: -Can work with low stream heads (<0,5 m) -Can exploit kinetic energy	Undershot Wheel	Sagebien Wheel	Breastshot Wheel	Tyson Turbine	Gorlov Helical Turbine	Screw Turbine	Savonius Turbine
	Pump	Which devices can be used to pump water with these characteristics: -Head= 40-70 m -Flow = 1-2 l/s -Rotational Speed < 1000 rpm	Piston Pump	Plunger Pump	Diaphragm Pump	Vane Pump	Progressive Cavity Pump	Centrifugal Pump	
		Which are the possibilities for the pump intake?	Submerged Pipe	Filter	Submerged Pipe + Filter (any)	Direct Intake	Use the HPPM intake		
	Transmission	Which devices can be used to transmit power with this ratio?	Belts	Chains	Gears	Archimedes Drive	Shiftless Transmission		
	Portability	How can the system be transported by 2 people?	One set with handles	One set with wheels to push it rolling	Detachable system: HPPM Trasnmission+Pump	Skids			

All the solutions were incorporated in the Assessment Model, which is the final part of the thesis, where the suitability of the considered technologies and concepts generated was assessed regarding hydraulic performance, cost and other factors that are relevant for the project.

Hence, the results of the project are the study of concepts, components and variables related with hydropowered pumping, as well as a research about the state of the art, where different hydropower pumping and transmission technologies, as well as ready solutions that have been already implemented are described. However, the most tangible result of this thesis is the Assessment Model, an Excel tool used to evaluate the feasibility and suitability of the combination of the different technologies considered.

With it, several recommendations of suitable configurations of the hydropowered pumping system were made. The future works involve the members of aQysta selecting one of these configuration to design a hydropowered pumping system based on its concept. However, it should be stressed that this thesis is purely theoretical, so the process of design and generation of prototypes will not be included within its scope.

Key Words:

Energy, sustainability, innovation, hydropower, morphological chart, irrigation, pumps, analysis, feasibility, efficient, economic, transmission, hydraulics

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1. Introduction

aQysta B.V. is a company established in 2013 in Delft, The Netherlands that works in the sector of hydropowered pumping systems dedicated to irrigation. Currently, aQysta provides solutions such as Barsha Pump and HyPump based on a combination of waterwheels and spiral pumps.

Barsha Pump is the most recognized product of aQysta, it consists of an undershot waterwheel that has a spiral pump at both sides of the scoops. This design is considerably creative, because the spiral pumps act at the same time as pumps and as connecting element for the scoops. Furthermore, the shaft of the device has a hose inside it that collects water from the spiral pumps and delivers it to the outlet.

This device has also the advantage of its simplicity, being considerably light, it can be easily carried by four persons, and the installation process is straight forward, as it can be installed either fixed to the riverbed or floating. A Barsha pump working in a river in Nepal is depicted in Figure 1.

Figure 1. Barsha Pump operating

It has been awarded by the Empowering People Awards because of its innovation and with regards to the possibility that it implies for farmers of underdeveloped countries worldwide to water their crops without depending on rainwater.

Barsha Pump was the first hydropowered pump developed by aQysta, and the objective of this device was to be applicable to the majority of contexts possible. Thus, it was designed to be able to work in a wide range of conditions, and as a consequence it operates with a low efficiency. This fact, linked to the low head the pump provided led aQysta to design another device that could provide higher output head and flowrate as well as a higher efficiency.

The idea was to scale the concept used for Barsha Pump to increase the pumping head and flowrate delivered. Thus, HyPump was created based on this idea. The problem was that the simplicity and ease to install that Barsha Pump presented was not achievable at the scale of HyPump. Furthermore, the costs of production increase at a higher rate than expected, so there was a thought that some other configurations could lead to a better performance.

Regarding the limitations that both systems have, which make them convenient for a reduced number of scenarios, aQysta started project MIT WWPCP with the aim of developing an innovative hydropowered pumping system that can achieve a good performance in terms of head and flow rate, easy to install and that does not involve a great cost increase.

This thesis will be the first part of project MIT WWPCP, and it will be divided in three phases:

- An analysis of the concept of a hydropowered pumping systems, a study of the variables that determine its performance, to then define which of them should be considered as critical in the design of the system and determine the requirements for the resulting product, with regards to the needs in the market.
- An ideation phase which will involve a study into possible techniques to generate innovative ideas and to use current concepts and techniques to develop novel products, as well as a research of the state of the art. After this, ideas for the system that aQysta wants to develop will be proposed.
- Generation of a model to assess the feasibility and suitability of the different ideas proposed. This model will be a tool that will be used to make a recommendation with regards to what would be the best choices for the hydropowered pumping system, that aQysta wants to develop.

Thus, the result of the thesis will be a set of recommended systems to develop by aQysta. Then, the team of aQysta will analyze these proposals, assessing the chances of fitting in the current markets that aQysta works in and their ability to tap into new market opportunities. If the result of this assessment is positive, the next steps will be the design, prototyping and testing of the system.

It must be emphasized that the design and the development of a physical prototype is not in the scope of the current thesis, that, as it was before mentioned, will end with the conclusions and recommendations of the best hydropowered pumping systems to develop by aQysta.

2. Definition of the Goals to Achieve in the Development of the System

Despite it was not the first task done it is important to start this report defining which will be the objectives of the hydropowered pumping system to be develop in the MIT WW PCP project, the requirements for the devices that will form it and the conditions of the contexts where it will work.

To do so, the first step is to analyze deeply what is the objective and the approach of aQysta for the resulting product of MIT WWPCP project. In order to know this, a series of personal interviews were done to some members of the board of aQysta, in particular the managing and marketing director, the business development manager, the chief technology officer and the lead fluid dynamic engineer, to consider the approach of each of them for the project.

Each of this persons works in a different field at aQysta, so their requirements, desires and overview of the project may be different. Thus, the goal of the interviews is to, once they are all done, analyze them to find the common ideas they share about the results of MIT WWPCP project, as well as the particular desires of each of them.

The second step of this phase will be a meeting with aQysta's stakeholders that have relevant information about the preferences, complaints and desires of customers in the markets where aQysta is currently present. This meeting is as, or even more important that the interviews performed to aQysta's board, because it involves information about the characteristics of the hydropowered pump that customers have in mind and for which they would pay an extra price.

This process will result in a set of proposed objectives to achieve in MIT WWPCP project. Despite the fact that these objectives will be the ones approached by the board of aQysta and the customers, they should be later assessed to determine if they are feasible to achieve by aQysta and suitable to develop an innovative system.

2.1. Interviews

The interviews had a duration around thirty minutes each, and an outline was developed to guide the interview, despite the answer to the questions was free to be as expounded as the interviewee considers. Thus, the outline of the interview consisted of the following questions:

- Regarding at the global market of hydropower, what do you think are the problems or possibilities to improve that the current systems have?
- Where will the hydropowered pumping system work? In which context will it be set?
- Will it need facilities for adapting to the context (dam or weir)?
- Is there any geographical localized zone of interest?
- What estimated conditions will have these context?
- Regarding at the function of the system, which is the purpose of the system? Is there any opportunity for new markets?
- Who will be the customer of the resulting system?

- How will it harvest power from water?
- Which advantages should it provide with respect to other options (Barsha/HyPump/solar…)

2.1.1. Interviews Summary

The main advantage of hydropowered pumps is that they are available 24/7, and unlike fuel and electric pumps they do not have operational costs. The principal challenges of the current portfolio of aQysta are the low power that the waterwheel is able to extract from the stream and the low head the spiral pump is able to provide.

The purpose of the system will be to provide water for minor and medium size irrigation, being the targeted customers farmers with lands around 5 or 10 hectares, irrigation communities with lands smaller than 700 hectares and the governments of underdeveloped countries trying to provide sustainable ways of irrigation to farmers.

Despite electricity generation could be an interesting additional purpose for this device, the feasibility of including electricity as an output is low, as it would involve connecting the device to the grid, which may be not accessible in the location where the device will work, as well as paying the licenses and fees related with the grid service, so definitely, electricity generation will be not the purpose of the device.

Other fact that should be mentioned is the importance of head in comparison with flow rate. Head is a critical parameter with regards to irrigation, if the height or pressure that the pump provides is not enough to reach the point where water is needed or does not reach the pressure necessary for the irrigation system, the hydropowered pumping system will not be able to work in that scenario.

Therefore, head is the parameter that must take preference in the design of the pump, while flow rate developed is a secondary objective, and it can be regulated to meet the irrigation requirements by changing the rotational speed of the pump.

In this sense, positive displacement pumps emerge as great candidates to be considered as pumping device, because they commonly have a narrow range of pumping head, and the change in rotational speed just affects to the flow rate that the machine delivers. This fact supposes a great advantage with regards to velocity pumps, where the change of rotational speed affects both to head developed and flow rate delivered.

The contexts where the resulting device is planned to be installed will be canals, streams and rivers, with low head conditions, because they suppose the majority of the locations where hydropower can be harvested and irrigation is needed. Given these low head conditions of the targeted context, the potential energy available in the stream will be scarce, being the kinetic energy generated by the speed of the flow the main source of power. Thus, the hydropower prime mover selected must be able to take advantage of the kinetic energy of the river.

According to this, one probable method to be used to harvest power from the stream will be waterwheels, because they are easily scalable, cheap and they can take advantage of kinetic energy of water besides they can work in many different conditions. Furthermore, aQysta has experience in designing waterwheels. However, other type of prime movers that can work with low head conditions will be also considered.

In addition, there is an important issue related to the applicability of the devices, and it is that each scenario is different of the others, both regarding the hydropower conditions and the pumping requirements. Thus, Barsha pump was designed to fit the most scenarios possible, not achieving a high performance in any of them.

In this case, the approach for the device product of MIT WWPCP project will be different. The objective should be to design the hydropower pumping system for a specific context where it will work efficiently, ensuring that the system is scalable, so if the conditions or requirements in other possible locations are different the system can be scaled to fit those conditions and work efficiently there too.

2.2. Meeting with Stakeholders

During the first week of April, several regional managers of aQysta B.V. came to aQysta headquarters in Delft, to give their vision of the current situation of the market and to provide relevant information they gathered from customers. In particular, these managers work in the regions of Nepal, Indonesia and Colombia, that are together with Kenia, the main countries where aQysta is present.

This event was taken advantage to find out the usual comments that aQysta's customers report to these managers as well as the main complaints that Barsha pump has, the desires and preferences for future devices and the opportunities for new markets that may be covered by aQysta's portfolio.

This session was leveraged to gather information about the characteristics that the resulting device from MIT WWPCP should display, due to perspective of customers.

2.2.1. Meeting with Stakeholders Summary

The first step of the session had the purpose of ranking different configurations for the pump in order to give priority to some characteristics towards others. The configurations proposed were the following:

- Slow river
- Higher pumping height
- Small river (regarding the discharge)
- More water output
- Smaller pump
- Higher power
- Cheaper pump
- Storage
- Lighter pump
- Permanent installation
- Floating pump
- Non-floating pump

From these possible configurations there was a clear preference for a pump with a higher height and water output that also involves a decrease in the price. Furthermore, to ensure the preference of managers they were ask to decide between two of these configurations.

The result of this selection was that a higher height was doubtlessly the preference of all managers. They placed the higher pumping height considerably before the other two options.

Then, between a pump that delivers a greater flowrate and a cheaper pump, they preferred more water output rather than a decrease in the price. To sum up, regional managers have a clear priority for a pump with a height of at least 40 meters, that was the principal requirement they asked for.

The second part of this session involved the ranking of different features for the pump. The features considered are the following:

- Price: it is referred to the total cost of the device once it is installed and ready to operate, so it includes the price of the machine and the installation costs.
- Performance: it includes characteristic before mentioned, as the pumping height, flowrate delivered and power capacity.
- Usability: this feature refers to the ease to use the device once it is acquired. It involves the difficulty to install and uninstall it as well as the ease of using the water it provides for the irrigation of land.
- Applicability: this feature implies that the pump can be used in different contexts without making any change to it, further than a different installation.
- Durability: it refers to the lifetime that the device has.
- Reliability: this feature is referred to the real operation of the device, considering the maintenance that should be done and possible failure of the machine.
- Portability: it means the simplicity or ease of the devices to be carried by people to the context where it will operate.

Table 1 shows the assessment of the importance of the different features by the managers participating in the session. Each features is given a number of points that indicates its importance, the higher the number is the more important it is.

	Manager Indonesia	**Manager Nepal**	**Manager Colombia**	**Business Development Manager**	**Managing and Marketing Director**	**TOTAL**	**Importance**
Price	5	4	3	5	5	22	3
Performance	7	7	7	7	4	32	1
Usability	4	5,5	6	1	7	23,5	2
Applicability	6	3	1	6	3	19	5
Durability	2	1	4	2	1	10	7
Reliability	3	2	5	4	6	20	4
Portability	1	5,5	2	3	2	13,5	6

Table 1. Stakeholders features preferences

Other important comment that was made in this meeting was the fact that the device should be designed to operate in rivers as well as in canals, making no distinction between them at the time of deciding the parameters of the design.

Finally, the last part of the session was a dynamic where the participants were asked for their opinion about what should be the value of each of the following output parameters:

- Pumping Height
- Flowrate Delivered
- Price of the Device Installed
- Dimensions
- Weight
- Input Head

The results are displayed in the Table 2:

	Manager Indonesia	Manager Nepal	Manager Colombia	Business Development Manager	Managing and Marketing Director
Flow Rate (l/s)	1	0,8-1	0,5	1	0,5-0,75
Height (m)	>20	40	40-50	40	40
Installed Price (€)	1500	500	1700	2000	1500
Dimensions (m)	-	1,5x1,5x1	Truck	People can carry it	Pallet
Weight (kg)	-	50	50-60	60	50-60
Input Head (m)	0-0,5	-	-	0-0,5	0-0,5

Table 2. Performance values proposed by stakeholders

Another insightful comment that was brought up in this meeting was that pumping height, as it was before mentioned, is the most determinant parameter for the pump. Thus, despite the pumping height proposed by participants of the meeting was around 40 meters in all the cases, it could be considered to develop a device that delivers water at a height considerably greater than 40 meters.

Considering this scenario, the device could be used by communities to pump water to pools, and thus the price they would pay for this pump would be much higher. For instance, the possibility of developing a pump with a head of 120-150 meters with a price around 10.000€ was seen positively by all participants.

2.3. Survey for the Quantitative Definition of Performance Values and Context Conditions

The information gathered in the interviews and in the meeting was high insightful for defining a clear vision about the scope and objectives of the system, helping to discard options to consider in the further steps. However, it is important to define what are the expectations of the aQysta's founders and customers about the performance values for the system that will be developed.

Other important task in this section will be to define the conditions of the context for which the system will be designed. By defining a quantitative range for the main conditions of the context, i.e. head and flow rate, studies about infrastructure components and variables to consider will be significantly simplified.

In order to obtain a clear vision about the performance values expectations and about the context conditions to considered a survey with multiple options was developed. This survey will be completed by the board of aQysta and the before mentioned stakeholders, and later on the results will be analyzed to set a clear set of requirements. The questions included in the survey will be multiple predefined answer questions, and some of them will have the option for the survey respondents to write their own answer if none of the predefined answers approaches their thoughts.

Annex I contains the questions that were formulated in this survey, as well as the answers of respondents displayed in graphs with a brief analysis of theses answers.

2.3.1. Survey Summary

2.3.1.1. Context Definition

Regarding the definition of the context the survey provided some insights about the conditions of the available locations where the hydropowered pumping system can be implemented. These are the main characteristics defined in the survey:

- The static input head of the context will be between 0 and 0,5 meters.
- The water speed of the stream, canal or river where the system will be installed ranges from 1 to 2 meters/second.
- The flow rate of the stream canal or river where the system will be installed ranges from 200 to 2000 liters/second. It could operate in contexts with flow rates higher than 2000 liters/second, always that the flow rate that goes through the system is limited to 2000 liters/second.
- The context will have an assumed variability in its flow between 40 and 60%, so along the year the flow rate may vary up or down between a 40 and a 60% with regards to its nominal value.

2.3.1.2. Requirements Definition

The main performance values for the system that will be developed have also been defined in this survey. They are listed below:

- The system will be designed as a “higher cost-higher performance system”, meaning by this that it will be given more importance to achieve good output values than to reduce the cost of the system.
- The system will be able to pump water to a height between 40 and 70 meters, which means that it is not designed for pumping heads lower than 40 meters and higher than 70 meters and thus, its efficiency could decrease under those circumstances.
- The flow rate delivered by the system will range between 1 and 2 liters/second. If it works with values out of this interval, its efficiency may decrease.
- The system will be portable. Thus every solution that involves introducing any elements fixed to the riverbed will be discarded. Furthermore, the system should be able to be carried by to people.

- The estimated price for the system is targeted to be between 1500 and 2500 €. However, it may increase during the design phase, due to the inclusion of components that increase the costs.

3. Analysis of a Hydropowered Pumping System

Once the requirements for the product have been stated and the context targeted has been quantitatively defined, by determining the range of values that parameters of the context will take, the next step is to analyze the concept of hydropowered pumping system within the scope of this project.

To do so it is important to set the boundary of the system to define the elements included in the system as well as the ones that should not be considered in the study. Later on, the study will focus on which are the variables that are considered critical or at least relevant for the performance of the system.

The hydropowered pumping system will be split into subsystems to acquire a clearer vision of the influence of each of them in the system overall. Then, each of the subsystems will be analyzed with the aim of finding subproblems to solve in order to achieve a high performance of the system.

Once the hydropowered pumping system is defined, the next phase will be to identify the physical components that constitute each of the subsystems as well as the variables that are involved in their functioning. Subsequently, it will be decided which of the mentioned variables are most relevant for being studied, while the ones that are not influential will not be brought into further study.

First, it is important to clarify that variables involved in the functioning of the different subsystems will be differentiated into parameters and factors. Factors are the variables with degrees of freedom, that can be adjusted to achieve different performances of the system, while parameters are variables that are fixed or can be defined by the interactions and relations of other factors. Thus, the most relevant variables for the current study will be factors, as they are the ones that affect to the design decisions and will determine the performance of the system.

The study of the variables will consist of defining the relations that the variables of each subsystem have with other variables of that subsystem and also with the ones involved in the other subsystems. This task will be done in order to construct a sequence of causality between them that can explain to what extent the rest of variables are affected when changing the value of one.

Regarding the relations between variables that have been discovered in the previous step, the final stage of the analysis will be to define the objectives to achieve with the hydropowered pumping system that will be developed during the course of the project.

To sum up, these are the objectives of the research that will be done on hydropowered pumping systems:

- Split the systems into subsystems that are more manageable and reduce complexity
- Describe physical components of each of the subsystems
- Identify the variables involved in the performance of each of the subsystems
- Classify these variables as factors or parameters, depending on the role they play
- Find relations for the factors and parameters

- Define the objectives to achieve by the hydropowered pumping system resulting from MIT WWPCP project.

3.1. Definition of Hydropowered Pumping System. Identification of Variables Involved

Once the steps of the analysis phase have been described, the start of the process will be to establish a definition for a hydropowered pumping system. To do this, it is necessary to differentiate the subsystems that comprise it, and define them in order to later develop a definition for the whole system. Therefore, a hydropowered pumping system will be divided into three different subsystems: the hydropowered system, the pumping system and the transmission system, plus the context where the system will be implemented. These will be defined and analyzed below.

From a strict point of view, a transmission system is not necessary, because hydropower prime movers and pumps can just rotate at the same speed, however forcing them to rotate at the same speed would make them work in non-optimal conditions and the process could be inefficient. For instance, waterwheels operate optimally under 30 rpm while the pumps considered operate optimally over 200 rpm [1]. Thus, it is necessary to consider the transmission system in this project.

As it was before commented, it is important to define the boundary of the system, in order to determine which components are considered as part of the system and to dismiss the ones that are not. Figure 2 shows a scheme of the hydropowered pumping system, its generic components and its boundary.

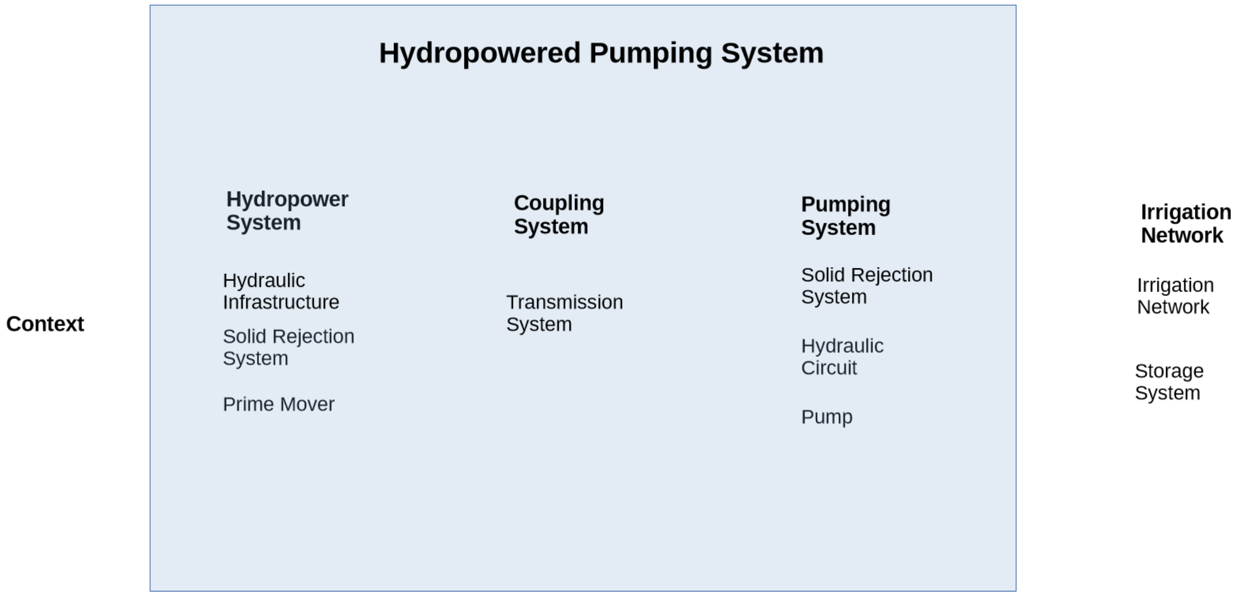


Figure 2. Hydropowered Pumping System Boundary

The context is the physical place where the system is installed, the environment, in this case it would be a river, a stream or a canal. It is not considered as part of the system because the variables that define it cannot be modified, so there are not degrees of freedom to change the conditions of the context. Despite it is not considered as part of the system, it is important to define its parameters, because they affect directly to the values of the variables of the system, so context will be later explained in more detail.

Regarding the hydropower system the generic components included in it are the hydraulic infrastructure, the solid rejection system and the prime mover. Despite the context parameters cannot be modified, it is possible to adjust the input values for the system. In the case of the hydropower system, a possible option is to build some infrastructure to alter the head and flow rate that will be the input of the hydropower system. For instance, some options would be building a weir can determine the input static head and the flow rate that enters the system, or making a bypass in the stream to regulate the flow rate. The solid rejection system is an important component to consider because it avoid the entrance of debris and solid particles to the system, that could damage it. In the case of the prime mover, it is the essential component of this subsystem, as it is the one that harvest hydropower from the stream.

The coupling system will be only composed by the transmission system that will be in charge of transferring the hydropower harvested in the hydropower prime mover to the pump.

The pumping system includes a solid rejection system, and in this case it is even more important to limit the entrance of solid particles than in the hydropower system, because pump are usually more sensitive to wear by solids that hydropower prime movers. A hydraulic circuit is also an important generic component, including pipes valves and other elements that make possible the water to go from the intake of the pumping system in the stream to the outlet. Finally, the pump is the main component of the pumping system, the one that uses the power harvested to lift water.

Finally, the water lifted will be used for irrigation. To do so it is necessary whether a piping network or a storage like a pool or a pond that feeds an irrigation system. These irrigation system will not be within the scope of the system, it will be the responsibility of the customer to provide the necessary infrastructure to use the water lifted by the system for irrigation or any other purpose considered. Thus the hydropower pumping system will end in the outlet of the pump.

Once the boundary of the system has been clearly defined and the different generic components have been listed, the three subsystems and the context will be described, explaining the variables that influence the performance of the systems and the particular components of each subsystem.

3.1.1. Context

Within the scope of the report, the context is the physical place where the system is located. There are some requirements for a location to be the context of implementation of a hydropowered system, the main one being that the chosen location can provide a stable water flow.

3.1.1.1. Parameters of the Context

The variables that determine if a location is suitable for hydropower are all parameters because as it was explained before, the context is an environment which conditions are more or less constant, but fixed, so there are no degrees of freedom in them. According to some sources such as articles by S.P. Adhau et al.[2], C.S. Yi et al. [3] and the website of the company Renewables First[4], these are the main parameters to assess the suitability of a location for hydropower:

- Head
- Flow Rate
- Simple layout
- Grid connection
- Site Access
- Single Ownership
- Environmental Sensitivities

From these, simple layout and grid connection will not be considered as relevant parameters, because a simple layout is a parameter determined by the design of the system, and the grid connection is only relevant if the goal of the hydropower system is to produce electricity and deliver it to the grid, which is not the target of aQysta. In the case that aQysta aimed to generate electricity with the hydropower system, its aim would be to consume it in that location. Besides, site access and single ownership of the land are not essential to be considered in this study, because they are focused to big size systems, that are not the target of this project.

Due to the experience acquired by aQysta in past project, there are three more parameters that are considered as highly relevant when determining the conditions of a context. These parameters, that will be included in the study are the following:

- Slurries and Solids
- Weather Conditions
- Terrain

The considered parameters will be described below.

Head

Head is the most relevant characteristic for determining the aptitude of a location for hydropower, taking into account that the power generated by the facility is proportional to head, according to Equation 1.

$$P = \rho \cdot g \cdot Q \cdot h$$

Equation 1. Hydropower Equation

where P is the available hydropower, ρ , the density of the fluid, g, the force of gravity, Q, the flow and h the head. As the density of water and the force of gravity are constants, the parameters determining the hydropower of a scenario are head and flow.

Head is defined as the height difference between the point where the water enters into the system and the point where it leaves it, and it is measured in meters. Usually the more head a location has, the more suitable it is for the installation of a hydro system, as it is translated into more power. In the case of hydropower used for irrigation the power needs are lower than, for instance the power needs of a hydroelectric plant. This also affects the head of the stream, that can be very reduced or even null, in the case that the kinetic energy is efficiently used.

Head is also a critical parameter for the costs of hydro systems, as they are related to the physical size of the civil engineering structures, being higher for low head high flow than for high head and low flow.

Flow Rate

Flow rate is the other crucial parameter when assessing the suitability of a location for hydropower, as it can be observed in Equation 1. Flow is defined as the volume of water that passes through the system in a determined time, the common units to measure it being cubic meters per hour, liters per second or gallons per minute in the American standards.

Flow usually refers to the average flow that the stream delivers, being subject to natural variability due to rain or floods and droughts seasons. It is important that the variability of the site is minimized because if a high variable flow location is dimensioned for its average flow, it will happen that in flood and intense rain season, there will be more flow than the required, being the excess missed, and in extreme cases the excessive flow could result in damages for the system. On the other hand, in dry seasons the flow will be insufficient for the system to have an efficient performance.

A remarkable fact should be highlighted about flow regarding head, and it is that low head usually implies a high flow and vice versa. High flow streams are usually located in low lands having a large catchment upstream with a lot of tributaries, while locations with large head are usually places where land is steeper and the catchment is smaller, so the flow rate of the river is low.

Environmental Sensitivities

The more ecologically sensitive a location is, the more costly, long and expensive the process of consenting will be. Thus, when studying the feasibility of a hydropower system in a particular location, it should be taken into account the impact that the system will have for river fauna and vegetation as well as the alterations provoked to the course of the river, considering the environmental impacts that the river will suffer downstream.

Usually environmental sensitivity is not a factor that stops the development of a project, however it plays an important role to delay the deadlines.

Slurries and Solids

The presence of slurries and suspended solids in the water stream is one of the factors that may shorten the lifetime of the system, wearing away the prime mover and pump components if not taken into account. A stream with high presence of slurries and solids involves an increase in civil works costs due to filters that should be positioned before the intake of the system to avoid that debris and big particles get into the prime mover and the pump. Filters also imply another additional cost regarding at the maintenance necessary for the filter not to get obstructed with dirt.

Weather Conditions

In normal conditions weather is not a differential factor for the feasibility of a location, as it will not provoke major changes in the conditions of the system. However, it is necessary to consider two important factors: precipitations and temperature.

Tropical and monsoon environments where extreme conditions related to precipitations take place have to be cautiously studied, because the average flow will be a parameter hard to estimate due to the variability of the conditions, and also flood periods where massive volumes of water and slurries are delivered to the system, damaging it, supposing an emerging danger for the facilities.

Temperature is also crucial, because locations where cold season can deliver temperatures under 0ºC may be not suitable for the placement of a hydropower system, as the freezing of components can translate in serious damage for the system, provoking a malfunction or in worst case failure.

Terrain

This parameter takes into account both the river banks and the river bed. River banks refers to the land alongside a body of water, while river bed is the land where the river flows, the land immediately under the stream.

This parameter is important because depending on the characteristics of the terrain the civil works necessary to build the system will be more or less expensive. For instance, if the ground is too soft and sandy, the civil works will require more expense to make the ground stable.

To sum up, the mentioned parameters determine the suitability of a location for hosting a hydropower system, regarding at the objectives of this system. Thus, the objective is actually the most important factor to consider, because it will determine the range in which head and flow should be, for the context to have enough hydropower available to meet the requirements of this objective.

However, the objective of a hydropower system is at the same time determined by the conditions of the location where it is planned to be installed. For instance, if the conditions of the location provide certainty about a reasonable amount of hydropower, the objective of the system can be to pump water to a pool to be then distributed in any case, or even to produce electricity to be consumed in the location. If the hydropower available is not high enough and on the other hand the location is surrounded by crops, the objective of the system could lead the hydropower to be used to pump water directly to crops.

3.1.2. Subsystem 2: Hydropower System

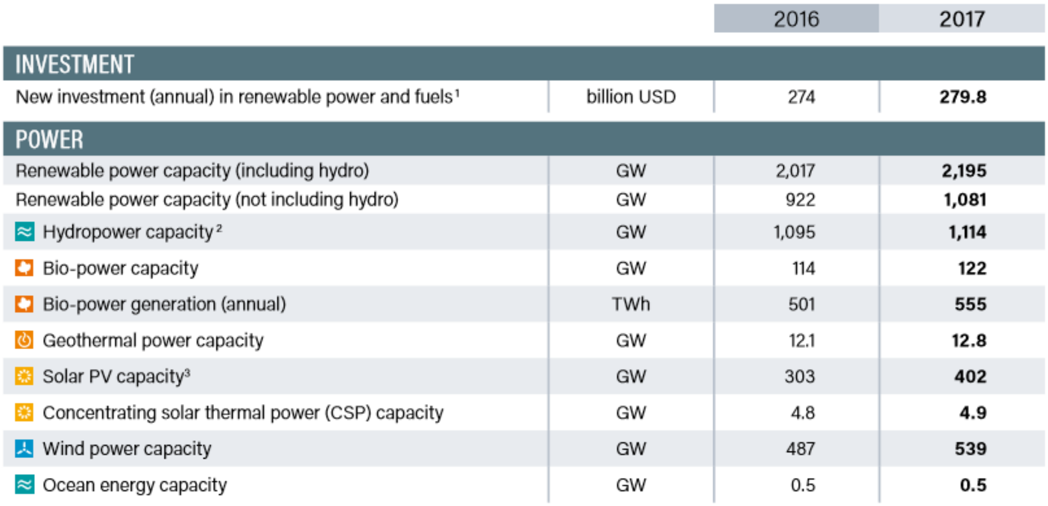
Hydropower is a term often confused with hydroelectricity. While hydroelectricity refers to the conversion of energy from a water flow into electricity, hydropower is the transformation of the energy from a water flow into mechanic power, that could then be used to produce electricity by an electric generator.

However, the concept hydropower does not necessarily involve electricity. In fact, hydropower has existed since the 4th century BC when the first waterwheels were used for moving millstones to grind grain in the Ancient Near East[5]. Figure 3 shows a waterwheel used by population of Syria in the Antiquity.

Figure 3. Noria of Hama, Syria, built in the 4th century BC

It was not until 1880 when the early hydroelectric plants emerged. By that time they were mainly used to build power arc and for incandescent lighting. Later in 1895 the electric motor was highly developed, and this supposed the rise of the hydroelectricity concept as it is understood currently.

Since this, hydropower has evolved accompanied by electricity to an important increase in the devices and techniques used for converting the energy in a water stream into electric power and the development of huge dams and hydroelectric plants to exploit the waterpower, to become one of the most important sources of energy worldwide and the most important renewable energy source as it can be observed in Figure 4[6].



		2016	2017
INVESTMENT			
New investment (annual) in renewable power and fuels[1]	billion USD	274	**279.8**
POWER			
Renewable power capacity (including hydro)	GW	2,017	**2,195**
Renewable power capacity (not including hydro)	GW	922	**1,081**
Hydropower capacity[2]	GW	1,095	**1,114**
Bio-power capacity	GW	114	**122**
Bio-power generation (annual)	TWh	501	**555**
Geothermal power capacity	GW	12.1	**12.8**
Solar PV capacity[3]	GW	303	**402**
Concentrating solar thermal power (CSP) capacity	GW	4.8	**4.9**
Wind power capacity	GW	487	**539**
Ocean energy capacity	GW	0.5	**0.5**

Figure 4. Renewable Energy Indicators 2017

3.1.2.1. Types of Hydropower Systems

First of all, it is important to define the types of hydropower systems, regarding the power capacity of the plant. Therefore, four types of hydropower systems can be distinguished, according to the article by D. Egré et al. [7]:

- Large hydro: this type includes systems with a power capacity higher than 10 GW.
- Small hydro: it includes the hydropower plants between 100 kW and 10 GW.
- Micro hydro: this refers to hydropower systems ranging from 100 kW to 5 kW.
- Pico hydro: this last type includes system under 5 kW.

From these types of hydropower, the most relevant for aQysta is pico hydropower, because the majority of the projects that aQysta works in up to now are for hydropower capacities up to 5 kW. However, it could be possible to scale systems to fit for a capacity power higher than 5 kW, so micro hydropower should be also taken into account.

Furthermore, another distinction can be done, due to the location and elements involved in it. Four main types of hydropower systems can be distinguished, according to the article by Yasser M. Ahmed et al. [8]:

- Dammed Reservoir
- Pumped Storage Facilities
- Run-of-River
- In-Stream

From these four types of hydropower systems the most relevant for the thesis are the in-stream facilities and small run-of-river projects, because the current aim of aQysta is to use hydropower for irrigation, minimizing the costs of the facilities. In consonance with this, dammed hydropower and pumped storage are not the target to focus on, as the civil works costs they involve are considerably high and their objective is the production of electricity to inject it in the grid, so these systems are out of the scope of the current project.

Despite dammed hydropower is not frequently used for irrigation, and in this project it would suppose considerable cost overrun, the possibility of using a small dam or a weir could enter in the cost scope of the project, being an interesting alternative to consider, that will be studied later on.

The most suitable systems to analyze are the in-stream systems that do not require serious civil works to adapt the water stream for hydropower harvesting. Other interesting option could be to scale down run-of-river systems in order to decrease the costs they involve and adapt them for the purpose of irrigation.

Thus run-of-river and in-stream systems will be described in more detail below. Figure 5 depicts the layout of the four systems listed before.

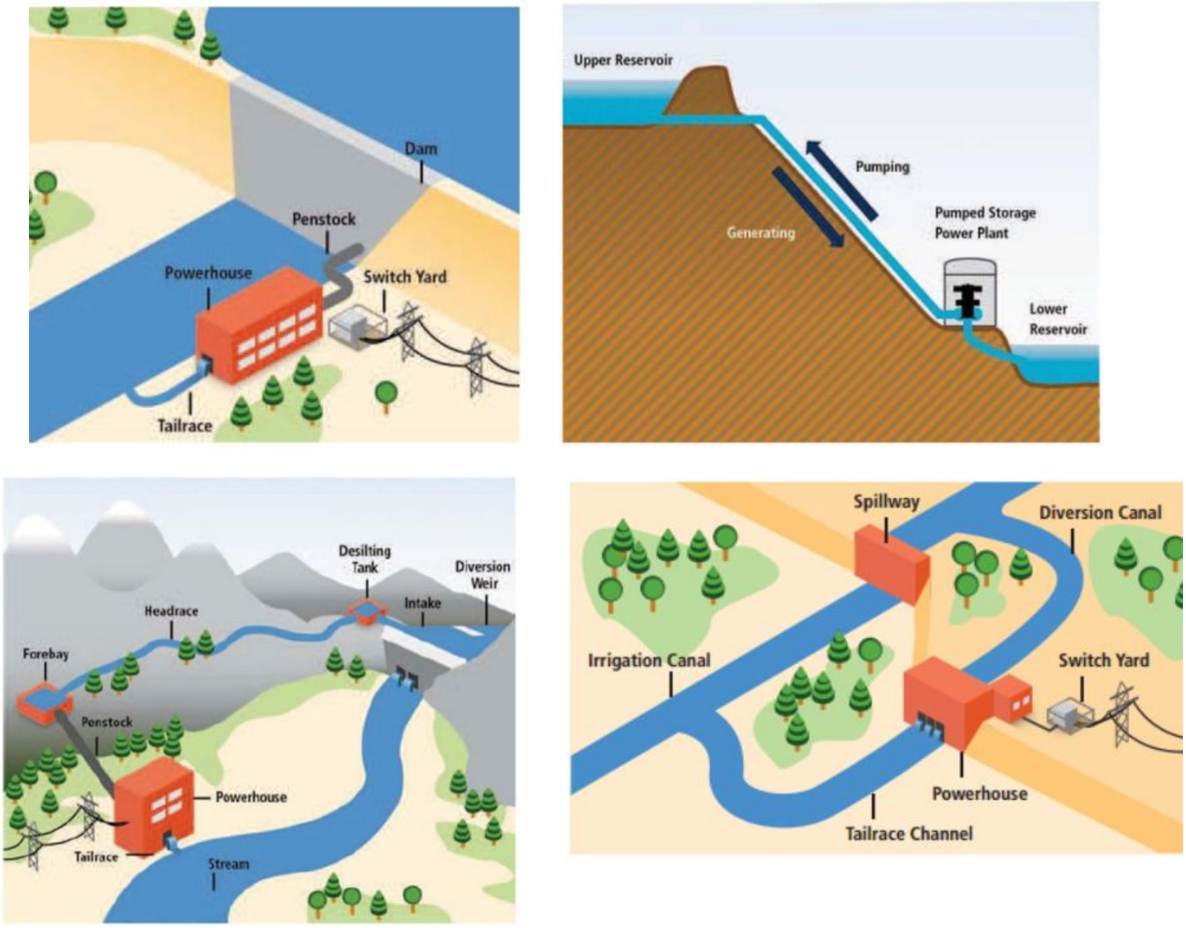


Figure 5. Types of Hydropower System, from left to right upside down: Dammed Reservoir, Pumped Storage, Run-of-river, In-Stream. Source: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation-Hydropower

Run-of-River

These facilities, are systems that depend on natural water flow rates, directing part of the water from the stream to the hydropower prime movers. They usually do not include a dam in the system. The main advantage of these systems is that the civil works and construction costs are significantly lower than the ones for the facilities that involve a dam. However, they have the drawbacks of a reduced energy production compared to the reservoir systems, and since the flow of stream is subject to natural water variability, the production of energy is more intermittent than in dammed hydropower.

In-Stream

In-Stream technologies usually involve the installation of hydrokinetic turbines in stream of rivers or canal to generate energy leveraging from scenarios with barrages or falls. Hydrokinetic prime movers are the ones that take advantage mainly of the kinetic energy of the river, produced by the speed of the water flow, unlike common turbines that use potential energy of hydraulic head to produce energy.

As mentioned, the most common type of prime movers used in these facilities are hydrokinetic turbines, however, all kind of hydropower technologies can be applied in them, provided that the requirements for their use are met. In-Stream systems have the main advantage of minimizing construction costs, despite the conditions for energy production are highly variable. Devices are installed directly in the streams having minimum facilities to regulate the flow rate or the head, so scenarios with a high variability of conditions are not suitable for the use of these technologies, unless some infrastructure for reducing variability of stream is included.

3.1.2.2. Components of Hydropower Systems

Below there will be listed the main specific components that a hydropower system usually has. It is important to clarify that the previously mentioned hydropower systems are formed by different components depending on the infrastructure necessary for their operation, regarding this, the list below will include the general components that every hydropower has. Hydroelectric power plants have the following components, according to the article by H. J. Wagner [9]:

- Storage Reservoir
- Dam or Weir
- Flow Control System
- Solids Rejection System
- Prime Movers
- Tailraces and Draft Tubes

With the exception of the storage reservoir that is targeted to small or large hydropower projects with aim to produce electricity, these are the elements relevant for the scope of the project. Tailraces and draft tubes are necessary depending on the type of hydropower prime mover chosen, so they will be included.

Dam or Weir

Dams and weirs have several functions in a hydropower system, the most important ones being to create artificial head and store water. Dams are the most expensive part of hydro projects as well as the most critical structure; a failure of a dam would provoke a flood that cause serious and expensive damages to surroundings, even endangering lives of people.

In minor hydropower projects instead of big dams, weirs are used. Weirs follow the same principle as dams at a smaller scale. They are barriers used to lift the water level of a stream and to conduct part of the flowrate to a canal, or to the intake of the hydropower system.

While dams are related to large and small hydropower projects, which is not the scope of MIT WWPCP project, weirs can be used in micro hydropower projects and thus, weirs are definitively more relevant than dams, because of the scale of the project and the associated costs that each of the two components have.

Flow Control System

It is quite frequent that in hydropower projects, some elements are included to control the water flow through the system. These elements are frequently gates and valves. Their main function is to control the flow that enters in the prime mover regarding at the load of the plant, and to shut it off when inspection or maintenance is necessary, or in case of emergency.

Low head plants just need gates at the entrance of the prime movers to control the flow, while medium and large head ones need additional butterfly or pivot valves.

Solids Rejection System

To avoid the entrance of debris and solid particles that may damage the system, it is frequent the use of trash racks and filters. The purpose of trash racks is to avoid the entrance of debris and major solids such as logs to the prime mover. Thus, racks are placed in the intake to enable the removal of the accumulated solids that may obstruct it. They are commonly flat bars set vertically with a space between them that depends on the flow that the prime mover holds.

Furthermore, if a higher degree of water cleaning is necessary, because the prime mover is especially sensitive to solid particles, a filter can be included in the system. It is also

Prime Movers

The prime mover of the system will be the device that will generate a rotary movement using the hydropower of the context, these devices will be the hydraulic turbines. Hydraulic turbines can be distinguished in two main categories on the basis of the type of energy at the turbine inlet according to T. Alam [10]:

- **Reaction Turbines**: these are a type of turbine that generates hydraulic power from the pressure or weight of a fluid. The fluid is introduced in the turbine with high velocity and low head, and changes the pressure while it moves through the rotor causing a reaction on the turbine blades, provoking the rotation of the rotor. Thus, the turbine needs to be encased in order to contain this water pressure.

  Reaction turbine are the most common turbines used in hydroelectric industries, being Kaplan and Francis turbines the best known ones and they usually work with low or medium head and medium or large flowrates. The main disadvantage that they have is the considerable infrastructure they require for their optimal functioning.

- **Impulse Turbines**: these turbines take advantage only of the kinetic energy of the fluid, as there is no pressure difference between the inlet and the outlet, and it is constant in its way through the impeller. Thus the most common impulse turbines are wheels, that take advantage of the speed or the weight of water for moving blades or buckets. Other important impulse turbines that are commonly used nowadays are Turgo turbine, Banki Turbine and screw turbine.

  Waterwheels have been used since old times in watermills to grind grain, until 19th century, when there was a huge development in hydraulic turbines motivated by the industrial revolution. In this period, wheels were improved, and the zenith of this development was the invention of the Pelton wheel, the best-known and most used impulse turbine.

One important fact to take into account regarding prime movers is the definition of the context conditions carried out in 2.3.1.1. The range of input head for the hydropowered prime mover is 0 – 0,5 meters. Furthermore, the only hydraulic infrastructure considered for varying the context conditions is a weir, and it does not change substantially the input head, so prime movers that cannot operate with low head conditions and taking advantage of kinetic energy of water will be not taken into account for further steps.

Tailrace and Draft Tubes

Tailrace is the outlet of the turbine, the element that returns the water to the stream after it has passed through the turbines.

In some plants water is just returned to the stream as it gets out of the turbines, because the outlet pressure is low enough to represent a considerable energy waste. However, in large and small plants, water leaves the turbine with a considerable pressure, that would be missed if it is returned to the stream, translating in energy loss.

To avoid this, draft tubes are located in the tailrace, to recover part of that missed energy by a suction effect, to do this it is built with the shape of a diffuser. Thus, draft tubes generate a negative pressure at the outlet of the turbine, that makes the head slightly higher so the turbine can use the maximum energy from the water flow. Figure 6 shows a scheme of the disposition of draft tubes and tailraces.

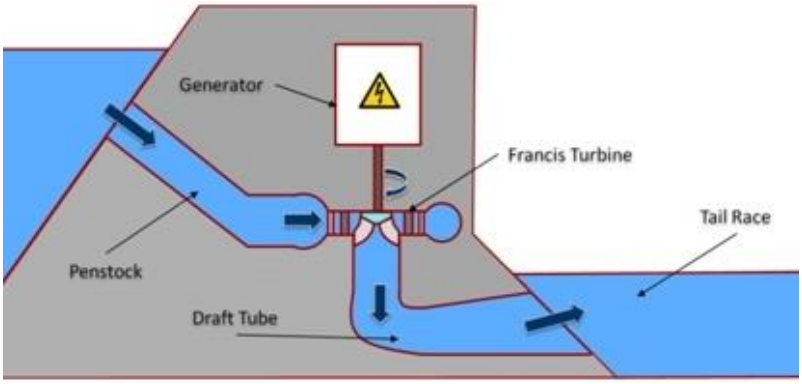


Figure 6. Tailrace and Draft Tube Detail

Draft tubes must be cautiously designed to avoid problems of cavitation in the turbine that would lead to system failure. Cavitation can occur in all type of hydraulic components that are pressurized, however it is a common problem in turbines, so it will be briefly described in this section.

Cavitation is a hydrodynamic effect produced when small vapor cavities, bubbles, are generated inside water or other liquid fluid, due to forces caused by pressure differences, like the ones produced when the fluid passes with a high velocity by a sharp edge. The main cause of cavitation is that at some point of the facility, the fluid reaches the vapor pressure, so air cavities start to form. If these air cavities collide with a surface, they implode causing important corrosive damages, that will lead to an early failure of the prime movers as shown in Figure 7.

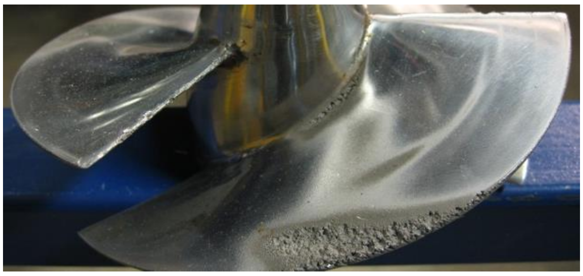


Figure 7. Effects of Cavitation on the Blades of a Turbine

3.1.2.3. Variables of Hydropower Systems

In the case of hydropower systems the variables that are involved in its functioning are both parameters and factors. These are the main factors affecting to the performance and feasibility of a hydropower system, according to the article by M. Majumder [11]:

- Hydraulic Head
- Flow Rate
- Rotational Speed
- Efficiency
- Infrastructure Necessary
- Maintenance
- Cost of the hydropower system
- Lifetime of components

All them are relevant for the project, so they will be described below.

Hydraulic Head

The hydraulic head is a factor which is defined as the measurement of the pressure of a liquid above a vertical datum. Generally, it is measured as the elevation of a liquid surface and it is expressed in length units, such as meters or feet. In the case of the context, head was a parameter, because it was already determined by the conditions of the site. However, for the hydropower system, it is a factor, that can be changed by the use of infrastructure, and for which the prime mover will be selected.

As it was mentioned in Equation 1, head is one of the two parameters that determines the maximum hydropower available in a certain location, so the objective of a hydropower system is to fully exploit the head of a location or even to increase it by means of civil works.

Hydraulic head is commonly used to establish a relationship between the energy of a incompressible fluid and the height of the equivalent static column of that fluid. According to Bernoulli's Principle, the total amount of energy of a certain point in a fluid is the sum of the energies associated with the speed of the fluid, its static pressure and its height with regards to an arbitrary datum, as it can be observed in Equation 2.

$$\frac{V^2\rho}{2} + P + \rho g z = constant$$

Equation 2. Bernoulli's Equation

Bernoulli's Equation expresses the Principle of Bernoulli, being V the speed of the fluid in a determined point, ρ, the density of the fluid, P the static pressure at that point, g the force of gravity and z the height of the fluid in the mentioned point with respect to an arbitrary datum. The sum of the three terms will be constant always when there are no friction losses or work applied or extracted from the fluid.

Thus, total hydraulic head is calculated from four main components according to J. Bear [12]:

- Velocity Head: represents the kinetic energy of a fluid from through a stream. It corresponds to dynamic pressure and to be expressed in length units must be rearranged: $h = \frac{v^2}{2g}$.
- Elevation Head: this term represents the gravitational force acting on a column of fluid due to its weight. It is already expressed in length units, so it is not necessary to rearrange it.
- Pressure Head: it expresses the static pressure of the fluid, the molecular movement of a fluid that applies a force to its container. To express the static pressure in length units it must be rearranged: $h = \frac{P}{\rho g}$.

  Pressure is a crucial parameter not only for the consecution of a proper working head, but for the correct performance of the facilities. In fact, two of the main reasons why hydraulic devices fail are water hammer, a pressure surge caused by the sudden stop of a liquid in motion, and cavitation, that were previously explained, and are caused by a faulty system pressures design.

  According to this, pressure must be strongly taken into account during the design phase, and pressure meters shall be included in the prototype system to have measurements of the pressure of the different points of the system as well as to prevent possible malfunctioning.
- Friction Head: real fluid movement implies energy dissipated by friction, and depending on the type of flow the amount of energy dissipated will be higher or lower. For instance, high speed flows related with turbulent flow dissipate more energy than slow low speed, laminar flows. Friction head can be divided into two main categories, major losses, related with losses per length of pipe, and minor losses, associated with bends and valves. The head losses due to friction in pipes are calculated with the Equation of Darcy-Weisbach, Equation 3, where L, is the length of the pipe, f_D is the friction factor of Darcy, and D, the diameter of the pipe.

$$\frac{\Delta h}{L} = f_D \frac{v^2}{2gD}$$

Equation 3. Equation of Darcy-Weisbach

Flow Rate

The flow rate is a factor that determines the amount of water that passes through the section of a duct or a predefined surface area per unit of time. Flow rate is usually as volume per unit of time, despite in some cases it also can be expressed as the mass that passes through that area per unit of time.

Flow rate is the other crucial parameter to determine the hydropower available in a certain location. As it happened with head, flowrate can be adapted to the needs of the system. For instance, if the flow rate of a stream is too variable, a reservoir can be constructed to store water and make a constant source of it. The only constraint that the flow rate has and head does not, is that the maximum flow rate that a hydropower system can work with, is the flow rate that the stream delivers, which means that unlike head, that could be increased by civil works, flow rate has its maximum determined by the stream.

Flow is a fundamental parameter to take into account because besides it determines the available hydropower, it influences critically the head losses before mentioned. Depending on the flow that will pass through the system, the pipes and equipment should be designed to achieve a proper water speed along the system.

Thus, there are two types of flow that control the behavior of the fluid. They are determined by the number of Reynolds, a dimensionless number used to typify the motion of a fluid, which is defined in Equation 4.

$$Re = \frac{\rho V D}{\mu}$$

Equation 4. Reynolds Number

where ρ is the density of the fluid, V, its velocity, D, the diameter of the pipe and μ, the dynamic viscosity of the fluid. With regards to Reynolds number the flow will be characterized as:

- Laminar: flow will be laminar if the number of Reynolds is under 2100. It is called laminar flow because the fluid behaves as if it was formed by thin layers, with viscosity forces playing the dominant role. Laminar flow is the target for fluid passing through pipes, as it minimizes the head losses.
- Turbulent: flow will be turbulent if the number of Reynolds is over 4000. The controlling forces in this case are inertia forces, the movement of the particles are chaotic which implies important energy losses. Regarding this, turbulent flow is to be avoided in pipes.

Rotational Speed

Rotational speed is the parameter that measures the range of revolutions per minute where the prime movers are able to work. It is a parameter because it is dependent on the flow rate that goes through the prime mover. Thus, a high rotational speed corresponds to a high flow rate, and as flow rate is the factor than can be controlled in the prime mover, rotational speed is a parameter. Despite it could be thought that the higher rotational speed the better for the performance of the machine, it is not necessarily true.

Hydropower prime movers are designed to work within a specific range of speed, so they have an optimal speed range that makes them work at their maximum efficiency level. Thus, working with a higher flow rate will increase the rotational speed, however the output power will not increase proportionally, making the operation less efficient. With regards to this, it is necessary that the flow rate through the prime mover is regulated in order to operate within the range of optimal speed.

Specific Speed is an interesting dimensioned parameter to consider regarding rotational speed, that relates head, flow rate and power generated. Specific speed is particular for each prime mover, and it is usually a parameter provided by manufacturers that refers to the point of maximum efficiency of the machine. Its expression is defined in Equation 5.

$$n_s = \frac{n\sqrt{P}}{H^{5/4}}$$

Equation 5. Specific Speed for Turbines

Where n is the rotational speed expressed in rpm, P, the power in kW and H the water head in meters. Although flow rate does not appear explicitly in the formula of specific speed, rotational speed, n, governs the flow rate that the prime mover works with, and the power that the machine consumes depends directly of the flow rate that it delivers, so it is appears implicitly when considering n, and P.

Observing the specific speed of well-known turbines, Pelton wheels usually have specific speeds around 4, Francis turbines move between 10 and 100 and Kaplan turbines specific speed is above 100. As might be expected, the higher the specific speed of the turbine is, the higher its flow rate will be. Figure 8 shows the relation between the specific speed and the efficiency for the most used turbines.

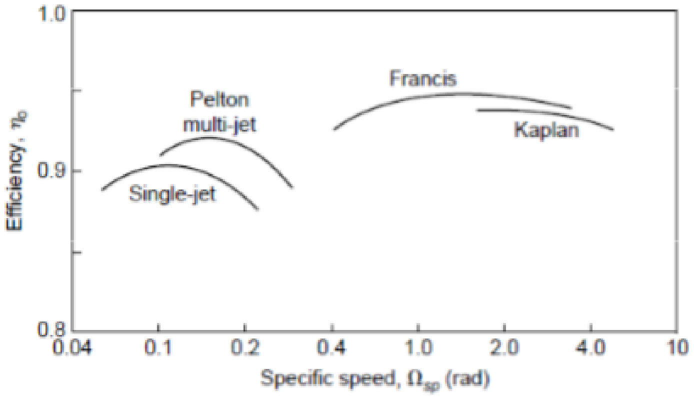


Figure 8. Turbine Chart Efficiency vs Specific Speed

Efficiency

Efficiency is a crucial parameter that relates the hydropower that the turbine extract from the water stream to the power that it generates. This generated power is usually converted into electricity, however, the most interesting cases for this report are the ones where the mechanical power generated is directly used in other devices, such as a pump for irrigation. Efficiency is a parameter because, despite it is not fixed, it is determined by other factors such as head, flow rate and rotational speed.

Efficiency is the ratio between power produced and power used for the intended purpose, and it can move in the range from 0 to 1, meaning 0 that no power is produced and all the hydropower taken is lost, and 1 that the whole hydropower taken from the stream is converted to power, without any losses.

With regards to efficiency, it is important to estimate the percentage of power that is lost regarding at the different components of the turbine. Thus, global efficiency can be divided in three different categories depending on how the power is lost:

- Hydraulic Efficiency: it measures the hydraulic losses, related to friction of the fluid with the different parts of the turbine, that implies a loss of hydraulic head in form of heat.

  Hydraulic losses represent the main source of energy loss in turbines. According to this fact, it is important to make a proper design of the fluid speed along the turbine to minimize them.

- Volumetric Efficiency: it refers to flow leakage. Volumetric losses in reaction turbines can be subdivided into: a) external losses, the ones that involve water escaping by the gap between the casing and the turbine shaft, and b) internal losses, that are caused by part of the pressurized flow not going through the impeller, as it advances to the outlet by interstices.

In the case of waterwheels the volumetric efficiency refers to the percentage of the water flow that has an effective contact with the blades of the waterwheel.

- Mechanic Efficiency: they refer to the power lost by friction of the different parts of the prime mover. Mechanic losses include the power lost due to friction in the impeller and bearings, power lost in transmission and power lost in ancillary elements of the turbine.

There is a wide range of hydropower prime movers regarding at efficiency in operation, some of them reaching up to 96%, as it is the case of Kaplan or Pelton turbines. However, for this project the devices that are considered must work in low head contexts, harvesting kinetic energy, which reduces the range of devices to use. Devices capable to work under these conditions, that are mainly waterwheels and submerged turbines also have a wide range of operation efficiency depending on which device is considered, however they are less efficient than other prime movers, being the maximum efficiency reachable around 80%[13].

Infrastructure Necessary

Infrastructure is a determinant factor to decide in hydropower systems, as it has direct influence on the cost of the project as well as on the input conditions for the system, that may be changed. It depends mostly on the context characteristics and on the head and flowrate aimed by the hydropower system. There are some cases, such as in-stream pico hydropower projects, where the infrastructure cost is not that relevant for the total budget; for instance, Barsha pump requires minimum infrastructure to be installed. However, in most of the hydropower systems, infrastructure costs suppose the major part of the budget. To put another example, aQysta is currently developing a pico hydropower project for irrigation in Híjar, Spain. This project has a hydropower nominal capacity of 2,54 kW, and from the total budget 71% is allocated to infrastructure costs, while the other 29% is allocated to the mechanical elements, being these the prime mover, the transmission and the pump.

Infrastructure costs refer to the construction of the elements necessary for the adaptation of the location where the hydropower system will be installed. Thus, the components of hydropowered systems described in section 3.1.2.2*,* comprise the main elements to consider from the point of view of civil works.

A particular component to analyze is the dam or weir. The majority of the hydropower systems, excluding some cases of the in-stream systems, need an element that regularize the water flow delivered to the system.

For the current project, as it was mentioned before, weirs could be relevant for some locations, while dams are too costly to be in the scope. Despite weirs are considerably less expensive than dams, they still would represent an important cost, however it depends on the dimensions of the weir and the country and location where the weir is constructed., because labor and materials costs may be different.

A good example are the weirs performed in Athi river in Kenia as part of Kinanie Water Weir and Water Storage Project[14], which built two weirs that increased the storage capacity of the river in 120.000 m^3, with an overall cost of 20.266 €. This can give an approach of the costs of a weir regarding the storage capacity increase targeted. However, it is also important to take into account the fact before mentioned that labor and materials costs in Kenia are lower than in

Europe, for instance, so the region where the weir is planned to be built is to be considered in the cost estimation.

Maintenance

Maintenance is an important parameter to guarantee a good performance of the system. If preventive maintenance is not properly carried out, equipment and components will get damaged gradually to failure. Furthermore, maintenance costs usually comprise only between a 3 and 4% of the overall cost of the hydropower project[15]. Thus, to ensure a long lifetime for the facilities is important to carry out a good maintenance, regarding the following aspects:

- Prime movers: this is the critical part of the maintenance. Turbines are the elements that transform the hydropower into mechanic energy. Thus, it is important to execute preventative maintenance to be aware of any malfunctioning. To do so, two main areas of work can be distinguished:
  - Routine Maintenance: depending on the size of the system and the conditions of the context, a determined number of maintenance inspections per year should be arranged, the larger the system, the more inspections. The goal of these inspections is to check that every component of the system is working properly, and take the relevant measures if they are not. The task to be done in these inspections are:
    - Turbine functional checks and inspection
    - Turbine bearing lubrication and inspection
    - Hydraulic system inspection
    - Check all sensors operate correctly
    - Inspection of intake area

  - Non-Routine Maintenance: in case any of the checked element sis worn out, or its lifetime is close to its end it will be necessary to replace it. Thus the main tasks involved in non-routine maintenance are:
    - Bearing replacement
    - Internal (endoscopic) inspections of prime movers
    - Major mechanical repairs and refurbishments
    - Pipeline pigging
    - Pipeline external and internal inspections
    - Flow rate measurements (to verify prime mover performance and consent compliance)
    - Hydraulic accumulator testing and recharging
    - Fish pass / bypass works.
    - Hydro system performance and operational reviews / optimization

    - Environmental permit compliance

- Weir: it is crucial to maintain the weir, because in case of a failure of this element, the volume of water that it stores could flood the adjacent land and cause serious damages. Thus to perform a proper maintenance of the weir it is important to carry out the following tasks [16]:
    - Clean the weir pool upstream, avoiding the settling and accumulation of solids like debris, trees and other sediments that reduce the storage capacity of the weir.
    - Inspections for leakage around the weir structure. In case it is detected, it should be remedied as soon as possible, to avoid bypasses or undercuts that may end by an installation failure.
    - Keep the crest of the weir clean and free of solids and particles that may accumulate and obstruct it. Thus, it is important to check the state of the crest of the weir periodically.

Cost

In every project the overall objective is to achieve the goals established at the same time that project costs are minimized. In the case of this hydropower system the goal is to produce the maximum power at the minimum cost.

Cost is a factor that depends on the magnitude of the project, the technology required and the labor that has to be done, hence, the objective is to minimize it, improving the chance of the project to become profitable. To do so it is important to define the objectives to achieve and make quotation and budget estimations that are the most accurate possible, in order to avoid unexpected cost overrun.

In hydropower projects, the total cost can be divided in different sections with regards to the activities they comprise, and the step of the project they are related to. Thus, these are the main costs of hydropower, according to S. A. Kumar [17]:

- Preinstallation Costs: they account for the greatest expenditure of a hydropower project. They comprise the activities related with location studies, licenses and permits acquisition, and the construction of all the infrastructure necessary for the installation of the system.

  In case the system needs a weir to operate, preinstallation costs would become an important source of the total cost of the project, as it was commented in the previous section *Infrastructure Necessary*.
- Installation Costs: they are related to the cost of the prime mover itself, as well as the adaptation of the prime movers to the hydropower system and the fine-tuning of the elements of the system to start working. While the cost of the prime mover could be assumed to be the major one in this section labor costs are indeed relevant for the estimation, being in some cases even higher than the cost of the prime mover.

Furthermore, before the launch of the hydropower production, facilities should be tested. Furthermore, the monitoring systems should be calibrated and tested too, to conclude everything is prepared for the operation.

Preinstallation and installation costs are the fix costs to invest in a hydropower system, from the time-value of money point of view they should be reduced, to reduce the risk of the project. Actually, hydropower projects are quite risky, as they involve a high initial investment and need an operation time to return this investment.

- Operational Costs: operational costs are related to the costs that the production of hydropower involves. In the case of large hydropower systems, these costs include the technicians that operate the system and supervise that it works properly. In smaller hydropower systems operation costs are lower, for instance, in-stream facilities dedicated to irrigation involve operation costs close to zero.
- Maintenance Costs: these are related to the activities which purpose is to keep the system working efficiently. These activities have been mentioned in the previous section. The costs of maintenance involve labor costs of technicians that perform inspection and change of worn out elements, and the costs of the materials necessary to carry out these maintenance tasks.

Lifetime

Lifetime is the calculated period of time within the system is expected to operate. To be profitable, the value of the system's output should be high enough to outweigh the initial investment of the project during this period. Lifetime depends directly on the cost, so it will be considered a parameter for the study.

According to this, a balance between initial investment and project lifetime should be found to calculate the profitability of the system, taking into account that initial investment can be reduced, however it has a minimum fixed costs to overtake, and lifetime extension usually involves refurbishment and replacement of system components, which would increase the costs.

Lifetime of a mini hydro plant is estimated to be around 50 years without major refurbishment, based on O. Paish article [18]. This means that the initial investment is supposed to be recovered within this period, after it, the system becomes extremely competitive, as the only considered costs are maintenance costs. Thus, lifetime should be tried to be as long as possible, to the point that maintenance costs do not make the system unprofitable.

However lifetime of the system can also be shortened. The reason why the system lifetime could be shortened is the wear and malfunction. If the system is not carefully maintained, not only its efficiency will be reduced, but the elements will probably be seriously damaged over time, which will shorten the operation lifetime of the system noticeably. Thus, maintenance not only ensures an efficient operation of the system within its lifetime, but also it can help to lengthen it.

3.1.3. Subsystem 3: Transmission System

The transmission system is a subsystem which purpose is to transfer the power generated in the shaft of the hydropower prime mover to the pump, taking into consideration that both devices will have different optimal ranges of rotational speed, as it was explained in 3.1. Thus, transmission system will enable both devices to work at their optimal, or close to their optimal rotational speed.

Depending on the speed of the devices, the type of transmission system will be determined. In fact if the decision taken leads to a system where the hydropower prime mover and the pump, both have a similar rotational speed, there would not be need of transmission system. This is the case of both Barsha Pump and HyPump, which design combines a waterwheel with a spiral pump, both joined and rotating at the same rpm.

3.1.3.1. Variables of a Transmission System

In this section the main parameters to consider when assessing the feasibility and suitability of a transmission system will be listed. As the transmission system to be chosen depends on the conditions of the hydropower prime mover and the pump, all the variables of the transmission system are parameters that will motivate the decision of what retransmission to select. The only variable that will be considered as a factor in this section will be the price, that will be considered for the selection of the different alternatives. These variables are the following:

- Speed Ratio
- Torque
- Power
- Efficiency
- Maintenance
- Cost
- Lifetime

In this case, a clear vision about the influential variables for the performance of a transmission system could not be found in academic articles. However, the before mentioned variables have been chosen because they define the performance and the economic behavior of the system.

Speed ratio

The speed ratio is the fundamental parameter of transmission systems, as it determines the suitability of each system for the scenario targeted. Speed ratio is the relation between the rotational speeds of two machines, in this case the hydraulic prime mover and the pump.

Rotational speed, together with torque, are the parameters that determine the power transmitted by a system according to Equation 6.

$$P = M \cdot \omega$$
$$P_{trans} = M_1 \cdot w_1 \cdot \eta = M_2 \cdot w_2$$
$$Speed\ ratio = \frac{w_2}{w_1}$$

Equation 6. Power Transmitted Definition

The transmission can be divided in two main parts: a) the transmitting part, in this case the one that works at the rotational speed determined by the hydropower prime mover, that is characterized with the sub index 1, and b) the receiving part, that in this case would be the one that works with the rotational speed of the pump, characterized with the sub index 2.

The speed ratio is defined by convention as the division of the higher rotational speed by the lower one. In this case, as hydropower prime movers capable to work in low head contexts and to exploit kinetic energy operate at a considerably low rotational speed, the speed ratio will be defined as the pump speed divided by the prime mover speed. Obviously, the higher the speed ratio is the more complex is the system required and the more expensive it will be. Furthermore, not all transmission systems can work with every speed ratio, they have a specific working range of speed ratios.

Torque

Torque is the rotational equivalent of linear force. It refers to the tendency of a force to spin around the axis of an object. A force applied to an object that makes it move at a determined linear speed, generating an amount of power that is defined as the speed times the force. Torque works the same way, though it generates power with regards to the rotational speed of the object that it is applied to.

Likewise rotational speed ratio defines the suitability of different systems to be used as transmission for a particular case, considering the fact that not all types of transmissions can work with a certain speed ratio, torque establish other limitation whether or not to choose a particular transmission, because transmission are designed to work within a certain range of torque. If the actual torque to transmit is out of the range of the chosen system, this will lead to poor efficiency and malfunctioning.

Power

At the end, the purpose of the transmission system is to transfer the power generated by the prime mover to the device where it is going to be used. Rotational speed and torque are the parameters that define the power that each shaft is working with, so they have to be carefully taken into account to achieve the maximum efficiency possible in the transmission. The efficiency of the transmission system implies an amount of the total power that needs to be transferred from the prime mover to the motor is lost.

Efficiency

Efficiency is the key parameter in the transmission method. The fact is that the efficiency of transmission systems is considerably high regarding the efficiency of other mechanic systems, reaching values close to 100% in many cases and with values around 80% in the most unfavorable cases, according to the data gathered of different transmission systems considered working in their optimal range of operation.

Efficiency in the transmission subsystem is such an important parameter because hydropower prime movers that can work in low head contexts have considerable losses in the harvesting of hydropower, being the highest efficiency achieved around 70-80% [13]. Furthermore, the pumps also have certain losses that imply that taking a look at the whole system the chain efficiency will lead to more than 30% loss in available power. To avoid a new decrease in the efficiency of the overall system, the transmission subsystem, should have the minimum losses possible.

In all the considered systems, the efficiency reduces as the speed ratio increases, because the losses due to friction and slippage increment as the speed rises. The losses of power produced in transmission systems are related with friction and slippage between contacting parts. Crucial for maintaining the efficiency as high as possible is to execute proper maintenance tasks, to avoid the wear of elements.

Maintenance

As is the case with hydropower systems, a proper maintenance is crucial to keep the transmission working efficiently. The main tasks to perform in transmission maintenance are slightly different depending on the type of transmission system, however these are the common tasks to perform according to the manufacturer Renold:

- Make regular visual inspections of the transmission system, looking for oil leaks on the input and output shafts, paint discoloration that may be a symptom of overheat.
- It is important to perform a vibration analysis to look for misalignments or friction damages. Vibration analysis includes monitoring the vibrations of gears and internal gears, checking for excessive vibrations that mean impending problems.
- The transmission will probably work in dirty and dusty environments, thus, it will be important to keep it clean to avoid the entrance of contaminants that can wear parts and contribute to overheat.
- Crucial is to follow the manufacturer specifications and lubricate the transmission routinely, making sure that the lubricant used is the proper for the machine.
- Remove cases to check for pitting or worn parts.
- In case the system have breathers check they are clean to avoid their obstruction, that would end in overheat.
- Check backlash and endplay, an increase in backlash would indicate wear to the transmitting components and an increase in endplay would suggest bearing wear, or wear to the housings.
- Check the transmission ratings over its lifetime, because its performance will decrease.

Cost

The costs related with the transmission subsystem are easier to reckon than the ones of the hydropower system. The fact is that a transmission system includes reduced number of identified components to place between the shafts of the prime mover and the pump, and does not involve any construction of items to enhance its operation.

The costs of transmission systems can be divided in two: the cost of the system, and the cost of maintenance. The costs of transmissions are considerably lower than the ones of the hydropower system or the pump. For instance, gearboxes are usually the most expensive type of transmission and their price is around 400 - 1000€ for the scope of the project, depending on its features, based on the information gathered from some manufacturers.

However, as it was before mentioned transmission systems need a high maintenance to keep them working efficiently. Thus, while maintenance costs for hydropower system can vary considerably depending on the magnitude of the system and of the need of a weir, transmission systems maintenance costs are practically constant, varying slightly regarding at the type of system selected.

Summing up, cost of system is lower than the one of hydropower, however, in comparison the maintenance cost is higher for the transmission.

Lifetime

The estimated lifetime for transmission systems ranges from 12.000 to 30.000 hours, being belts the systems with a lower lifetime and gearboxes the ones that last longer [19][20]. This numbers refer to the lifetime of the systems working at their design point, in a controlled environment and with periodic maintenance. Thus, working close to the limits of operation, in harmful conditions and with low maintenance may reduce substantially the lifetime of the transmission system.

3.1.4. Subsystem 4: Pumping System

The pumping system will receive the power generated by the hydropower system and will use it to lift water. The requirement established for the pumping head is that the pump lifts water higher than 40 meters, so water can be directly used for irrigation, or stored in a pond. However, as it was before mentioned in 3.1 the aim of MIT project is to develop a hydropower pumping system being the boundary of the system the pump outlet, so the uses or infrastructure located after it are not within the scope of the project.

Thus, the pumping system will take advantage of part of the flow rate of the stream, that will be lifted, using the power generated by the hydropower prime mover. This way the stream will feed the hydropower pumping system both of water and energy.

3.1.4.1. Components of Pumping Systems

These are the main elements present in pumping systems that will be considered for being included in the project [21]:

- Intake
- Filter
- Pipes
- Pressure Gauges
- Valves
- Pump
- Outlet

Intake

The intake of the pump does not need the extremely sophisticated infrastructure that the hydropower system of the project needs, however it is important to include an intake in the system that permits the water flow to enter in the pump with the appropriate conditions due to speed and pressure. Usually the intake is a pipe submerged in the stream and having valves that regulate the inlet flow, avoiding turbulence that would imply head loss. This is depicted in Figure 9.

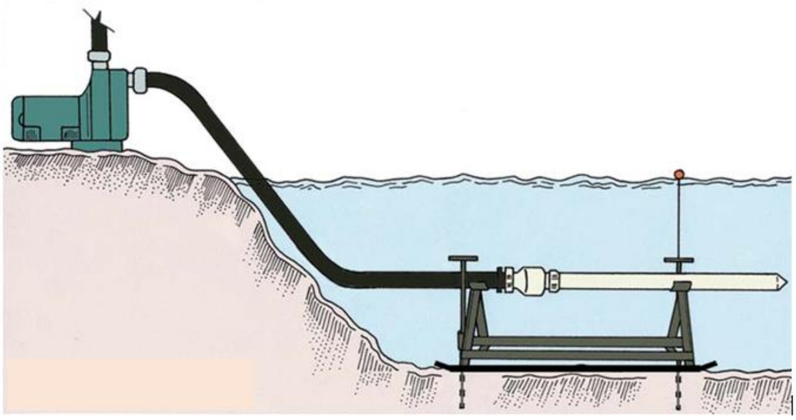


Figure 9. Intake for a Centrifugal Pump by Filter Cradle

Filter

It is necessary to set a filter that impede the entrance of debris and big solids to the pump. In this case as the hydropower system needs also a filter to operate, thus, this filter can be used to filter both the water flow for the hydropower subsystem and the pump.

Furthermore, in case the pump has problems when slurries or floating solids are present in the water flow, it will be necessary to include a source of filter to avoid the major solids to enter in the pump to avoid unnecessary wear.

Based on the article *What types of hydraulic filters are available?* [22] these are the three most suitable types of filters to consider for the intake of a pump: cartridge mesh filters, spin-on filters and bag filters.

- Cartridge Mesh Filters: these are fabric or polymer-based filters designed to remove particulate materials from fluid, that usually flow from the outside of the filter to the inside. They are usually rigid or semi rigid cylinders with the polymer or fabric fixed to the central core. They are disposable and easy to replace.

Figure 10. Hydraulic Cartridge Filter

- Spin-On Filters: they consist of a head mounted in-line with the piping and a cartridge containing a filter element. To prevent leakage, the cartridge seals to the head. These filters are commonly used for hydraulic systems with a low pressure requirements (<35 bar) and are easily replaceable without special tooling.

Figure 11. Spin-On Filters

- Bag Filters: these filters are commonly long cylindrical bags or tubes made of woven or felted fabric filter medium. Fluid passes through the bag and the particles are retained in the bag, that has to be emptied periodically. Bag filters are frequently used in pneumatic systems with air as fluid, however they can also be used for hydraulic systems.

Figure 12. Hydraulic Bag Filters

Pipes

Pipes are necessary for the good performance of the pump, they connect the inlet and the outlet of the pump with the elements where water comes from or where it will be delivered. As it was before commented, intake of the pump is usually a submerged pipe with valves to regulate the flow. The water lifted by the pump will be used for irrigation of land, however the network of pipes for it is not in the scope of the project, as it was stated before.

It is important to design pipes cautiously to avoid turbulence in the network and to minimize the pressure and head loss along the system.

Pressure Gauges

Pressure gauges are elements which purpose is to measure the pressure at a certain point. They can deliver absolute measurements, having the atmosphere pressure as reference, or relative measurements, where the measurement of the pressure of a point is dependent on the pressure of another point of the system, which is actually useful to observe the gradient of pressure between those two points.

Pressure gauges are crucial in pumping systems, especially in the design phase when it is necessary to measure the different variables behavior to ensure the correct functioning of the system. Afterwards, unless the pump generates a high pressure in ducts, it will not be necessary to have a permanent measure of pressure in the system.

However, as it occurred in hydropower prime movers, cavitation is an incipient danger if system is not carefully designed. To avoid this, pressure should be carefully measured and monitored along the system during the design phase to avoid any faulty design that can cause damage in the future.

Valves

Valves are the gates of the system, they are the elements that permit, impede and regulate the water flow in the pump. Valves determine the velocity and pressure in the different point of the system, as well as cut the flow when any maintenance is necessary.

Hydraulic valves can be classified in the following four types, regarding their function [23]:

- Distribution Valves: these valves are in charge of directing the water flow along the system, as well as they can govern the operation of other valves
- Pressure Valves: the function of these valves is to limit pressure in the system. They are also considered as security elements, to prevent any malfunctioning.
- Shut-off Valves: the aim of this type of valves is to impede the flow in one direction, while permitting the circulation in the opposite direction.
- Flow Valves: they are used to limit the speed of the flow that enters in an actuator.

Pump

Pumps are the machines that transfer the mechanic energy they receive to the fluid, giving pressure to it and lifting to a determined height. There are two main categories of pumps, that are the following [24]:

- **Displacement Pumps**: these pumps raise liquids by the reduction and increase of a chamber or cylinder that increase the pressure inside or pushes directly the fluid, moving it to the required height. Basically, when the pump housing increases its volume, a negative pressure is generated that sucks the fluid to it, and when the house reduces its volume, the fluid is pushed to the discharge zone.

  Displacement pumps can be classified according to the mechanism that moves the fluid. The most common methods for displacement pumps are rotary-type which includes internal gear, lobe and vane pumps; reciprocating-type which holds piston, plunger and diaphragm pumps; and linear-type, such as rope or chain pumps.

  Below there will be listed some of the criteria relevant for the project, that are used to select displacement pumps over velocity pumps [25]:

  - They are commonly preferred in scenarios where high pressure and low flow is required.
  - They provide high efficiency operation, and they have a good performance working at low speed.

- With positive displacement pumps flow varies directly with rotational speed and it is independent of head.

One of the main disadvantages of displacement pumps is that their initial cost is usually higher than for velocity pumps. However when all equipment accessories and controllers are considered, the cost over the life of the pump is comparable if not lower.

- **Velocity Pumps**: velocity or rotodynamic pumps are kinetic machines which moves the fluid by transferring the energy of a rotating impeller to the fluid, contrasting with positive displacement pumps, where fluid is pumped by trapping a fixed volume and forcing it to move to the discharge pipe.

  These pumps are widely used for industrial purposes related with water, as they perform well when handling water-like fluids, the technology is well-known and has been successfully used historically in chemical industry. Furthermore, the main device of this type, the centrifugal pump has an initial cost lower than the one of a displacement pump.

  Rotodynamic pumps also have another important advantage, and this is that they can be set in one or multiple stages, by locating one or more impellers in series. This can be a smart solution to achieve a good performance in high head applications without the need to design a specific pump for that requirements[25].

Outlet

The output of the pumping system is a pressurized waterflow that can be destined to irrigation or to reservoir. In any case the outlet of the pump should be connected to a network of pipes that will deliver water to the required point.

One important goal to achieve in the outlet of the pump is to minimize the head loss due to friction in conduits, to take advantage of the most work of the pump. Head loss cannot be completely eliminated, however, the system will be extremely inefficient if a considerable part of the head generated by the pump is lost in the connecting pipes.

Thus, despite the fact that the network beyond the outlet of the pump, could be not considered as part of the pumping system, it is important to take it into account the portion of head that will not be used for the final objective of the system.

3.1.4.2. Variables of Pumping Systems

The main variables that determine the performance of a pumping system and the assessment of their suitability to operate in a determined scenario to achieve a particular set of goals are listed below. The key performance variables of pumps are the following [26]:

- Pumping Head
- Delivered Flow Rate
- Pressure
- Rotational Speed
- Efficiency

Furthermore, it was considered to include the following variables in the study, in order to take into account the wear of the device and the economic impact of the pumping system:

- Ability to Cope with Solids
- Maintenance
- Cost
- Lifetime

Pumping Head

In this project head is the most important factor of the pump and the one that will determine which kind of pumps are suitable to be chosen. Flow is also important because it defines the amount of fluid that can be delivered to the point where it is needed. However, the purpose of the pump regarding the scope of this project is: a) to transport water from a point to another one that is located at a higher level, and the difference between this two points is the head that the pump should meet, or b) to pressurize water in order to move it a determined distance.

The concept of head was explained in the section of parameters of hydropower systems, and it is the same for pumps. However, there are some differences between the head of a hydropower system and the head of a pump. The total head of a pump is defined by Equation 7.

$$Total\ Head\ of\ a\ Pump = Pump\ Head - Suction\ Head + Friction$$

Equation 7. Total Head of a Pump

Pump head is the maximum head where a pump can raise water, however, pumps have also the ability to suck fluid from a deeper level, which is called suction head. Thus, suction head is defined as the maximum depth from which a pump can raise water, and it is a negative parameter, as the reference point for measuring the depth of suction is the level where the pump is located.

As it happened in hydropower systems friction head is an important component of head for pumps. It is related with velocity of fluid through pipes and the losses that happen in elements such as elbow joints or valves.

The procedure to choose a pump is determine the required head where the fluid should be raised and with this parameter select the pump that meets it and is most suitable due to delivered flow or price.

Delivered Flow Rate

The flow that the pump delivers is the second factor in importance for a pump. Despite the pump used will be selected regarding at the height that can develop, flow rate is important also, because there is no point in selecting a pump that develops a great head if it cannot deliver the flow necessary for the pertinent purpose.

Industrial pumps are clearly differentiating in the two types before mentioned: displacement pumps and velocity pumps. Displacement pumps are focused to industrial processes related with high pressure circuits, and they usually develop an almost constant high head and low flow rate in comparison. These devices are suitable for irrigation because the head they offer is great enough to reach the required level, and despite the flow they deliver is low, it is enough to cover the requirements established in **Error! Reference source not found.**.

On the other hand, velocity pumps characteristics are highly dependent on the rotational velocity of the pump. Thus, higher rotational speed implies high head and flowrate and vice versa. Thus, velocity pumps are suitable for a wider range of scenarios because they can easily adapt to the scenario to meet the requirements of the system, however the are subject to a higher variability in their output which can suppose a drawback in certain contexts.

To conclude, head is the critical parameter when selecting a pump, however flow rate must not be disregarded, because it determines the amount of water that reach the required point under the specified conditions and thus, the use it can be given.

Pressure

In section 3.1.2.3, pressure was defined as one of the components of hydraulic head. In the case of pumps, the relation is still there, however, it should be treated as a different parameter because it has higher relevance than it does for hydropower systems. Thus, it is necessary to define both the head and the pressure to reach by the pump.

The objective of every hydraulic pump is to provide water the enough pressure to overtake a high slope, move it to a determined location, or to move any hydraulic actuator. The purpose of the project, irrigation, does not require a pressure as high as the ones needed in industrial processes, however, pressure is an important parameter to measure during the design phase, as it was mentioned before.

Pressure needed also determines the number of stages that will be necessary to set in the pumping system, meaning by number of stages the number of pumps placed in series to achieve the required pressure, which could be an option to consider.

Rotational Speed

The rotational speed of a pump is an important parameter to consider in this project. Rotational speed is considerably related with the flowrate that goes through the pump, and as flow rate is treated as a factor, rotational speed will be a parameter. Furthermore, in all pumps efficiency is highly related with the rotational speed, having a specific range of optimal operation.

Most pumps operate at rotational speeds between 1000 and 3000 rpm, however there are fast pumps, like centrifugal pumps than can reach the 6000 rpm and slow pumps that can work at 200 rpm [23].

Just like hydropower prime movers, pumps also can be characterized by their specific speed, which constitutes a proper way to decide the most suitable pump design for a given application. However the formula used to calculate the specific speed of a pump is not the same as the one used for determining the specific speed of turbines. Equation 8 displays the formula used to calculate specific speed for pumps.

$$n_s = \frac{n\sqrt{Q}}{H^{3/4}}$$

Equation 8. Specific Speed for Pumps

As it was mentioned before, there are two main type of pumps, displacement pumps and velocity pumps. They differentiate principally in the working principle, however, there is an important difference between them form the point of view of rotational speed.

Displacement pumps lift water to a determined height depending on the input water, being minimally affected by rotational speed, while flow rate delivered is highly dependent on it. Thus, varying the rotational speed of the pump is the way to adjust the water flow that wants to be delivered, obviously the higher the speed the higher the flow.

On the other hand, velocity pumps are designed for a much wider range of head than displacement pumps. The variation of the rotational speed implies that the flow passes through the impeller faster and impeller generates a higher pressure gradient, so it adjusts both the flow and the head.

Thus, depending on the variability of the conditions that will be binding in the application of use, it will be important to choose between displacement, for high variability of flow or rotational speed, or velocity for constant conditions or both reciprocally varying head and flow situations.

It is important to consider that the hydropower prime movers that are suitable for this project operate with a considerable low speed, and in order to make the transmission the less complex and expensive possible, the pump to select should operate at a relatively low speed. This fact gives displacement pumps advantage towards velocity pumps.

Efficiency

Efficiency plays the same role for pumps that for hydropower systems. It is a parameter defined by rotational speed, head and flow rate that determines which proportion of the power that the pump receives is transferred to the fluid. As well as in hydropower prime movers, it depends on hydraulic, volumetric and mechanic losses, that were defined in the section 3.1.2.3.

In order to keep the pump operating with the highest efficiency possible it is important that the pump works near the design point conditions, because limit conditions imply excessive work of some components, overheat and wear. Thus, it is important to carefully chose the pump according to the conditions of the applications, asking the manufacturer for feedback about the suitability of the pump.

Ability to Cope with Solids

In the case of pumps, slurries and floating solids represent an incipient danger to consider when designing the system. While some pump shave no problem working with small solids and slurries in the water flow, other types of pump can suffer considerable wear if they work with solids.

In case the application where the pump will work have tendency to have slurry within the water flow, two options are possible:

- Choosing a pump that works efficiently and without wear with solids. It is possible that the maintenance of the pump is higher than if it worked with a clean waterflow, on the other hand the need of a exhaustive filtering of the waterflow is eliminated.
- Choosing the pump that is more convenient for the application, regardless of the fact that it can or cannot work with solids, and include an intensive filtering phase in the inlet of the pump, that ensure the water flow that enters to the pump to be clean.

Thus, the ability of a pump to work with solids will be considered as a factor to choose, and it will determine the necessity of intensive filtering in the inlet of the pump as well as the maintenance required for the device.

Maintenance

This parameter depends on the duty and the conditions where the pump is working. As it was mentioned before, pumps usually work under conditions of high pressure and this fact implies that the wear they suffer is higher than in the case of hydropower prime movers. According to this, the tasks of maintenance are crucial for keep the pump operating in optimal conditions.

Thus, a regular maintenance should be implemented and followed, including the following tasks, according to manufacturer's guides [27]:

- Determine the maintenance frequency, consulting the manufacturer and scheduling periodic maintenance for the moments that the pumps are not operating.
- Observe the pump while it is working, looking for leaks, unusual sounds and strange vibrations, that are a sign of malfunction.
- Pumps may work in dusty environments where dirt accumulates, so it is important to isolate properly the pumps in order to avoid them to get dirty and overheat.
- Mechanical inspections, checking the case, seals, bearings and inspecting the pump flanges for leaks. If the pump has its own filters, it will also be important to check and clean them.
- Lubrication tasks should be performed according to the manufacturer guidelines, with periodic changes of oil, as well as visual inspections of its level and its state, looking for strange bodies and dirt.
- Replace damaged parts, if during an inspection any component is seen to be damaged it will be necessary to replace it and prevent a possible failure.

Cost

As it happened with hydropower systems, costs associated to pumping systems will be divided in the same four main sections: preinstallation costs, installation costs, operation costs and maintenance costs.

- Preinstallation costs: unlike hydropower systems, pumping systems do not usually require a high infrastructure to work and thus, preinstallation costs are considerably lower than in hydropower systems. However, it is necessary to consider the costs associated to the setting up of the pertinent pipes, filters and valves, as well as the preparation of the inlet and outlet conduits.
- Installation Costs: installation costs are referred to the investment the pump requires, and the expenses necessary to install it in the system and for it to be ready to start working.

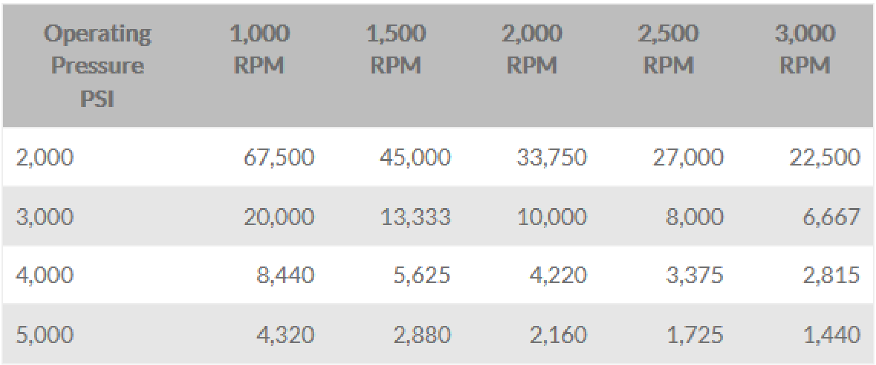
  Some concepts have been developed to minimize the cost of installation of pumps. These include maximizing the extent of manufacturing and installation in shop environment, simplifying the transportation, providing modularized components that are easy to change, and encouraging unmanned operation.

  Installation costs should include labor costs that are the hours that a worker has to spend mounting the system. Usually labor costs are underestimated, and they actually have much larger cost overruns compared to other cost components.

- Operational Costs: they involve all the costs related with the functioning of the pump, thus, if it is driven by diesel or electricity, the cost of fuel or electricity will be included, as well as the labor cost if a worker has to run it. In the case of this project, operational costs would be close to zero, as the pumps does not require fuel or electricity to operate, and it is supposed to work unmanned.
- Maintenance Costs: maintenance and repairs costs are important for pumps that work with untreated water. As it was commented before, pumps are exposed to high wearing conditions and a careful maintenance should be executed on them.

Lifetime

The estimated lifetime for pumping systems is parameter that depends on the type of system that is chosen. Thus, a centrifugal pump should last at least 15 years if it is working near to its design point, while for displacement pumps, the lifetime depends on the rotational speed and pressure of work, that can vary. As it is shown in Figure 13, lifetime reduces when the rotational speed and the pressure increases.



Operating Pressure PSI	1,000 RPM	1,500 RPM	2,000 RPM	2,500 RPM	3,000 RPM
2,000	67,500	45,000	33,750	27,000	22,500
3,000	20,000	13,333	10,000	8,000	6,667
4,000	8,440	5,625	4,220	3,375	2,815
5,000	4,320	2,880	2,160	1,725	1,440

Figure 13. Expected Lifetime of a Piston Pump in Hours

According to this, it is important to consider the conditions of work of the pump at the time of estimating the lifetime of a pump, as well as execute a proper maintenance, to avoid shortening the effective lifetime of the device.

3.2. Selection of the Components and Variables to Consider in the Analysis

Once the context and all the subsystems involved in the performance of the hydropowered pumping system have been described and their variables have been identified, the next step is to decide which of these variables are more relevant and find relations between them that allow to reach a better understanding of the system in order to later set the objectives and goals that the system to design should fill. Table 3 displays the resulting components and variables that will be considered in this phase.

Subsystems	Components	Variables	
		Factors	Parameters
Context	-	-	Head Flow Rate Environmental Sensitivities Slurries and Solids Weather Conditions Terrain
Hydropower System	Weir Flow Control System Solids Rejection System Prime Mover	Hydraulic Head Flow Rate Infrastructure Necessary Cost	Rotational Speed Efficiency Maintenance Lifetime
Transmission System	Transmission	Cost	Speed Ratio Torque Power Efficiency Maintenance Lifetime
Pumping System	Intake Filter Pipes Pressure Gauges Valves Pump Outlet	Pumping Head Delivered Flow Rate Ability to Cope with Solids Cost	Pressure Rotational Speed Efficiency Maintenance Lifetime

Table 3. Relevant Components and Variables to Consider

To start the selection process the approach will be changed, because the objectives in this step of the research are difficult to determine in terms of each subsystem, so it is preferable to define them regarding at the fields that in this early stage of the project can be easily approached. Thus the hydropowered pumping system will be considered from two different perspectives: energy and cost.

Energy

In the section of energy a scheme will be generated that shows the process that follows hydropower since it enters the system until, how it is transformed in the different devices and the output that the system generates. Variables will be included to relate the changes that power experiments with the different components of the system. Figure 14 depicts the energy diagram.

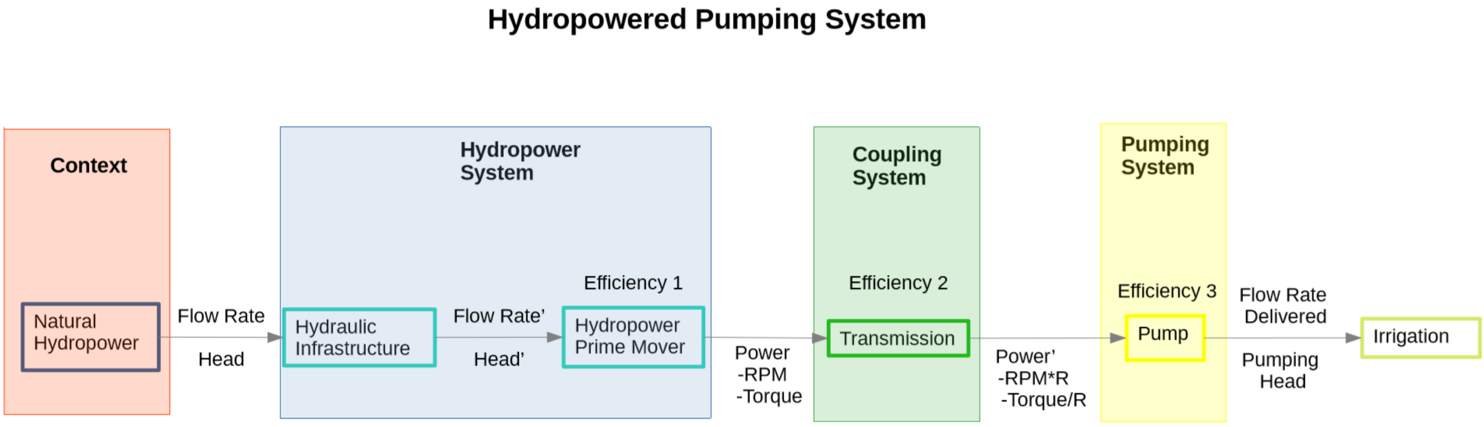


Figure 14. Hydropower Pumping System Energy Diagram

In this diagram hydropower is initially available in the stream by the combination of a natural head and the flow of water that the stream delivers. These two parameters can be modified and boosted with the construction of a proper hydraulic infrastructure, such as a weir to provide a higher head and a constant flow rate avoiding variability of the stream. In any case even it is minimum, infrastructure is necessary to install the hydropowered pumping system in the riverbanks.

In terms of the modified head and flow rate, available hydropower is used by the hydropower prime mover to produce mechanical power with a determined efficiency that defines the losses in this process. The power generated in the hydropower prime mover must be then transmitted to the pump to use it.

To do this, unless both devices work at the same rotational speed, which is not the common case, it is necessary a coupling method which efficiency will transmit the power regarding the torque and the rotational speed of both devices. Thus, the prime mover will input power in the transmission system, with low rotational speed and high torque. The transmission will increase the rotational speed with a ratio “R”, that is the same with which torque will be reduced. This is what ideally would happen, but in fact transmission have an efficiency, so the output power will be a bit lower than the input.

Finally, mechanical power will be transmitted to the pump, with the rotational speed and torque that the pump needs to operate. The pump works with a determined efficiency, and will transform the mechanical power received back into hydropower, in terms of the pumping head and delivered flow rate that will cover the needs of the crops to be irrigated.

Costs

The second section will be related to the overall costs of the system, considering all the costs from the previous chapter. Thus, it will list all the elements to consider in the different subsystems: the infrastructure that is necessary for the system to operate and the devices that integrate the system. These elements will determine the initial investment of the system, furthermore, it is necessary to take into account maintenance costs that in principle constitute the only variable costs of the hydropower pumping system, as it does not have operational cost. Figure 15 depicts the costs to consider for the initial investment of the system.

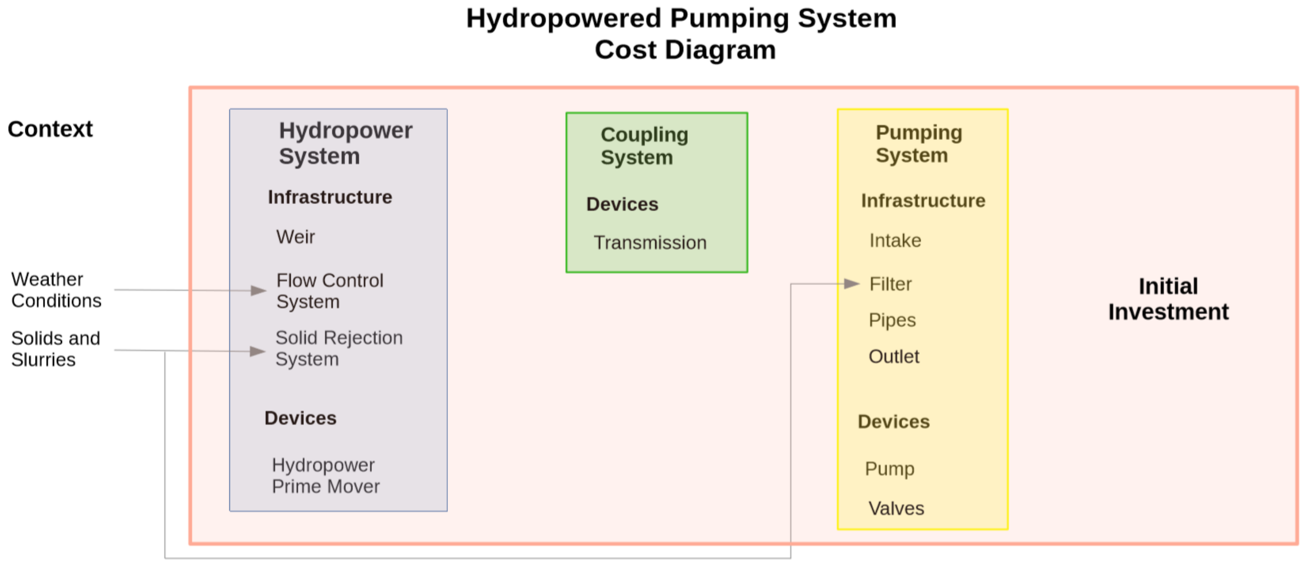


Figure 15. Hydropowered Pumping System Cost Diagram

The initial investment includes the costs of the machines (hydropower prime mover, transmission and pump) and the costs related to the infrastructure. These last depend highly on the conditions of the context where the system will be installed. For instance, if weather conditions in the contexts are highly variable, the flow rate can be affected and have considerable variations, thus, a flow control system will be necessary. Furthermore, the presence of solids and slurries affects both the hydropower system and the pumping system infrastructure. In a context with frequent presence of debris and logs a solid rejection system is necessary for avoiding them to damage the system, whether if the pump is not prescribed to work with solids and slurries, a filter should be placed in the intake of the pump.

The costs of the machines depend on the type of device that is selected, for instance waterwheels are considerably cheaper than turbines, as well as gearboxes are more expensive than belts or chains. Initial investment should be as low as possible taking into account that some potential customers cannot allow a great expenditure, even if the variable costs are minimum.

Variable costs only involve maintenance costs. The main advantage of hydropowered pumping systems with regards to other pumping systems is that the operation costs associated with it are considerable almost null, as it does not need any fuel or electricity, only involving the launch of the system . On the other hand, maintenance costs can be slightly higher than for other pumping systems, however if maintenance is done properly, these costs will not suppose any economic disadvantage and the overall variable costs will be still much lower than the ones related to other pumping systems.

The final objective of the system is to be profitable for the customer. To achieve this, it is necessary to define what is the product lifetime necessary for pay back the initial investment and variable costs, and try to lengthen it as possible to keep generating profit without any related costs.

3.2.1. Components Selected

Regarding the components listed in Table 3, all them were found relevant to be included in the system. However, two of them could be discarded because they enter in conflict with some of the requirements settled for the system, or they are not necessary to be included permanently in the system.

The first is the case of the pipes. Pipes are components that ensure a good conduction of water through the system, however the target system has the requirement of being portable by two people, so it must be short, and as light as possible. Hence, the piping network should be minimized to a pipe that joins the pump intake with the pump inlet, and in case it was necessary, a pipe located in the outlet of the pump. Thus, pipes will not be considered as a component from now on.

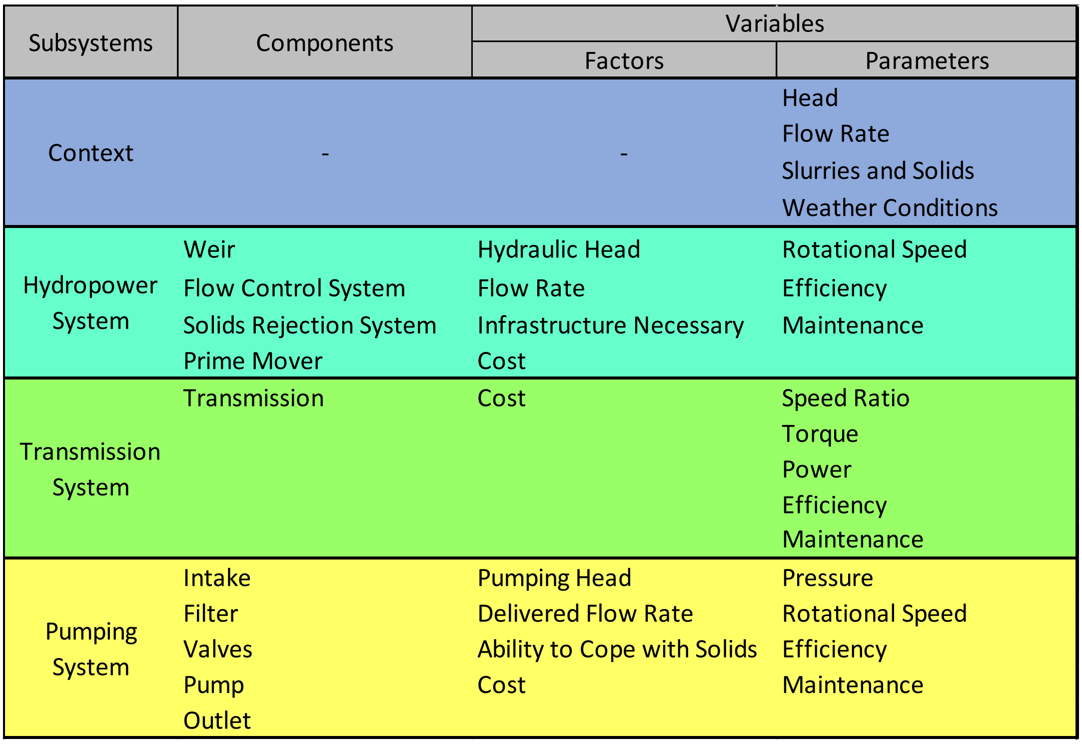
The second case is the case of pressure gauges. Pressure gauges are a crucial component during the design and testing phase, in order to ensure that there are no sudden pressure changes that can damage the system, and that phenomena such as cavitation or water hammer are avoided. However, pressure gauges will not be included in the system as a permanent component, so they will not be considered as a component in the future analysis.

3.2.2. Variables Selected

In the case of variables, some of the ones mentioned in Table 3 are not considered relevant enough to take them into account in the further analysis of the performance of the system. This is the case of:

- Environmental Sensitivities: it is an important parameter to consider in large scale fixed systems. However, the target system will not be large and it will be portable, so the environmental impact it may cause in the context where it is installed should be minimum and not generate any legal issues.
- Terrain: as the system will not be fixed to the ground the terrain characteristics play a minor role regarding the conditions of the context, so it will not be considered as a relevant parameter further on.
- Lifetime: it is an important parameter to consider in order to calculate the profitability of the system and the point in time when the initial investment is paid back and the system generates profit without any related costs further than maintenance. However, its relevance for the study of the performance of the system is low compared to other variables, and thus, it will not be considered as a relevant parameter.

Table 4 displays the final list of components and variables that will be considered in the later phases of this thesis.



Subsystems	Components	Variables	
		Factors	Parameters
Context	-	-	Head Flow Rate Slurries and Solids Weather Conditions
Hydropower System	Weir Flow Control System Solids Rejection System Prime Mover	Hydraulic Head Flow Rate Infrastructure Necessary Cost	Rotational Speed Efficiency Maintenance
Transmission System	Transmission	Cost	Speed Ratio Torque Power Efficiency Maintenance
Pumping System	Intake Filter Valves Pump Outlet	Pumping Head Delivered Flow Rate Ability to Cope with Solids Cost	Pressure Rotational Speed Efficiency Maintenance

Table 4. Final List of Components and Variables to be Considered

It is important to mention that within the variables, factors have a higher importance than parameters, because the value of factors can be easily modified and by changing it, the value of parameters can be also varied. However, some of the parameters have considerable importance in the performance of the system.

Rotational speed for instance is considerably important in order to determine both the efficiency and the suitability of the transmission system selected. Furthermore, efficiency is highly important because it determines the amount of usable power. Hence, factors values must be cautiously defined taking into account the relation with parameters values. In all the three subsystems efficiency will be tried to keep as high as possible, and maintenance cost will be tried to be kept low.

4. Ideation

The goal of this chapter will be to find or generate ideas and concepts to be used for the hydropowered pumping system that will be developed. The steps of this phase will the following:

- A research about the state of the art of hydropowered pumping systems. It will focus on finding a) systems that are currently being used, analyzing why are they successful, as well as b) possible devices to combine and constitute a hydropowered pumping system.
- A research about techniques for inventive problem resolution in order to, based on the solutions found in the state of the art research, develop improvements for their performance in case it was necessary, and modifications for these systems in order to adapt them to the scope of the project. The main techniques that will be studied in this research will be TRIZ methodology and morphological chart.
- With the information acquired in the researches about the state of the art and about techniques for inventive problem resolution, the last step will be to generate innovative ideas or modifications for hydropowered pumping systems, that will be proposed to be the system to develop by MIT WWPCP project. These will be the result of the ideation process.

4.1. State of the Art

The research about the state of the art for hydropowered pumping systems will have the purpose to find relevant devices, principles and solutions that can be considered to be applied in MIT WWPCP project. Thus this research will be based on four different topics.

The first topic will be hydropower prime movers. The requirements defined in 2.3.1.1 and 2.3.1.2 were highly insightful to filter the available hydropower prime movers. The most suitable devices regarding these requirements are waterwheels and underwater turbines, according to available data on this topic [28].

The second topic of the research will be pumps. For this project, all the pumps that meet the requirements about head and flowrate will be considered, paying special attention to the ones that have a low rotational speed, because this feature will simplify the transmission of the system.

The third topic to study in this research will be the suitable transmission systems, where the hydropower prime movers and pumps previously chosen will play a determinant role at the time of selecting the types of transmissions to be considered.

The last topic to study will be the hydropowered pumping systems that are currently being used, to observe which is their working principle, their target and why are they successful, in order to get ideas that could be used to develop the system.

4.1.1. Hydropower Prime Movers

One of the most remarkable outputs from the interviews that were performed in section 2.1 was the clear focus of the team of aQysta on waterwheels to be the motor of the hydropowered pumping system. This was motivated because of the ability of waterwheels to take advantage of the kinetic energy of water, their scalability and the experience that aQysta has in the design of these devices. However, underwater turbines can also give a good performance in the defined contexts, keeping in mind the fact that the river stream or canal should be deep enough for the installation of these devices.

4.1.1.1. Waterwheels

Waterwheels are machines that transform the energy of a water stream or waterfall into mechanic energy. Traditional waterwheels consist of a wheel that has several blades or buckets in its periphery, which convert the kinetic energy of the flow of water that contacts them into mechanic work. The fact is that when water is reflected in the blades, it generates turbulence, that results in a high energy loss, and that means a low efficiency.

Waterwheels were frequently used until XX century to mill flour, make paper or to hammer iron. Nowadays they are in disuse, as the efficiencies and ranges of power where they work are much lower than the ones offered by other turbines. However, they are an interesting option to consider for a hydropowered pumping system used for irrigation, because of their capability to use kinetic energy from water streams to produce power, and the simplicity for being scalable.

Depending on the way that the water makes contact with the wheel in the inlet and configuration of the blades, the following types of waterwheels can be distinguished:

- Free-stream Undershot Wheel
- Poncelet Wheel
- Zuppinger Wheel
- Sagebien Wheel
- Breastshot Wheel
- Overshot Wheel
- Pitchback Wheel
- Backshot Wheel

From the mentioned wheels, Undershot, Poncelet, Zuppinger, Breastshot and Sagebien do not require or require a minimum infrastructure to operate, while Overshot, Pitchback and Backshot need of a considerably more costly infrastructure to work. According to this, the first ones are more suitable regarding a cost minimization, despite the last ones have a greater power capacity and operation efficiency.

Thus, Overshot, Pitchback and Backshot waterwheels are not relevant because they can only work with considerable head falls, so they will not be further taken into account. The remaining devices will be briefly described, depicted below and their performance values will be shown in a table based on the articles by M. Denny [29], Z. Jones[30], and specially on the information retrieved form the work of Dr. G. Muller and E. Quaranta, which are renowned experts on waterwheels[13][31][32] [33][34].

Free-stream Undershoot Wheel

Undershot waterwheel main characteristic is that the flow of water that they use to generate mechanic energy is running in the bottom quarter, so only the blades that are located in the lower part are moved by the stream.

This waterwheels are commonly used when there is no natural slope and the water is not very fast. It requires a considerable volume of water to move it and is the less efficient type of waterwheels, because only the 25% of the waterwheel is working in every moment, and that is why Undershot waterwheels are currently in disuse. Figure 16 depicts an Undershot common wheel.

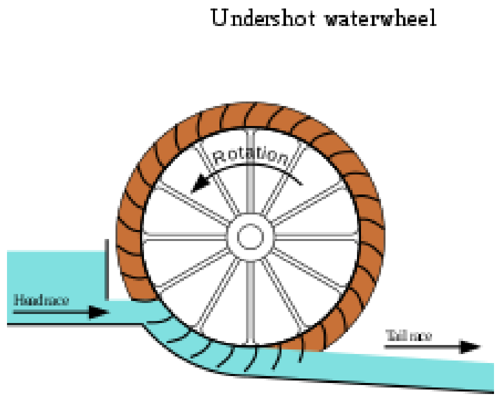


Figure 16. Undershot Common Wheel

Poncelet Wheel

This is a particular type of undershot waterwheel invented by Jean-Victor Poncelet that doubles the efficiency of ordinary undershot wheels due to an specific configuration of the blades and the modification of the inlet adding a specific curve geometry and an entry angle of 60º, that permits to reduce the turbulence losses. Figure 17 shows Poncelet wheel.

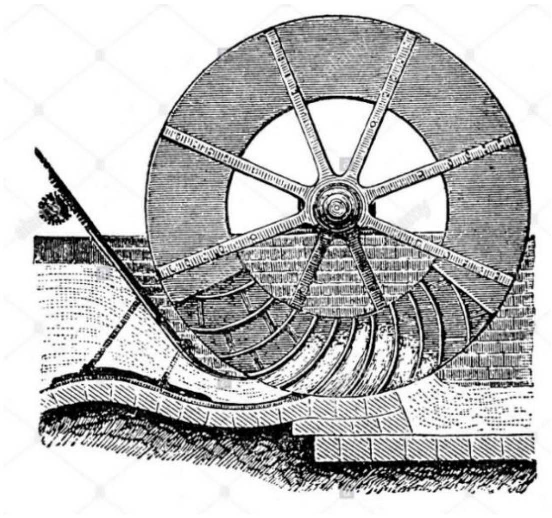


Figure 17.Poncelet Wheel

Poncelet waterwheels were very popular in the 19th century, at that time numerous advances and research was done on them. However, scarce information was found about the performance values of Poncelet wheels, none about how is the behavior of efficiency towards other variables. This, together with the fact that Poncelet wheel is currently in disuse, led to the decision of not considering Poncelet wheels for further steps.

Sagebien Wheel

This is other specific type of Breastshot wheel which instead of buckets or flat blades uses angled blades and differentiates from ordinary Breastshot wheels in the water entry, while in Breastshot water falls from the edge of a canal, in Sagebien it enters in contact with the blades horizontally, and the wheel is opened in the interior, so water can flow up to the channel. Sagebien wheels are highly efficient, being able to reach up to 84% of efficiency. Figure 18 depicts a Sagebien wheel.

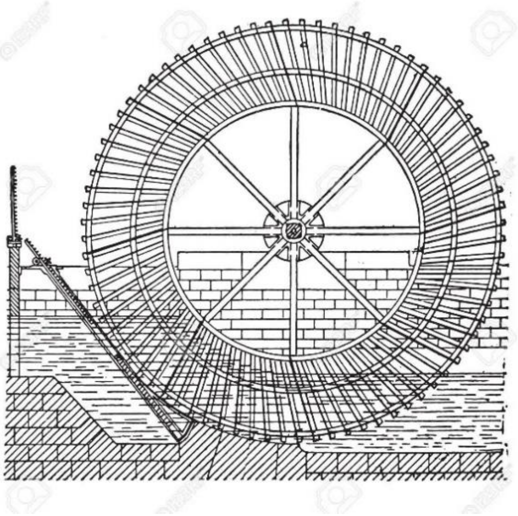


Figure 18. Sagebien Wheel

Zuppinger Wheel

Invented by the swiss hydraulic engineer Walter Zuppinger in 1853, Zuppinger wheels are thought to operate in locations with very low head differences. This wheel is similar to Sagebien, with the main difference that its blades are curved back in the end, which improves the contact of the fluid with them.

There are two main types of Zuppinger wheels regarding the inflow configurations, depending on the head available. One of them is a Breastshot wheel for heads from 1,2 to 2,5 meters with an inflow weir to control the upstream water level. The other one is a low head wheel for heads from 0,3 to 1,5 meters, without inflow weir. Recent tests show that Zuppinger wheels can reach a maximum efficiency of 85%.Figure 19 depicts a Zuppinger wheel.

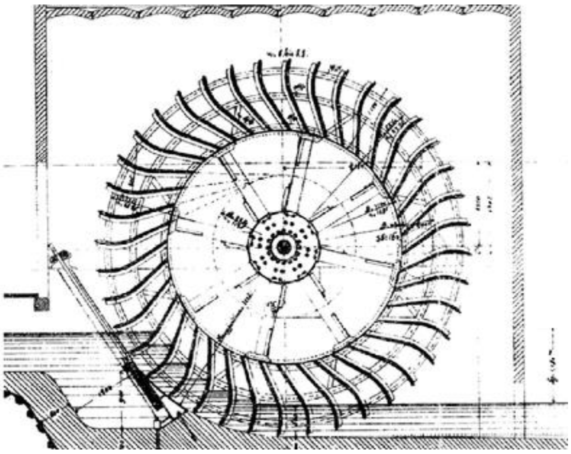


Figure 19. Zuppinger Wheel

Breastshot Wheel

This is a vertically mounted waterwheel which design implies the water hitting the blades or entering to the buckets at half of the height of the wheel. This configuration is used in scenarios where there is a considerable slope of water, not being high enough to place an overshot wheel.

Breastshot wheels take advantage of the weight of water besides its velocity, so they are more efficient than undershot wheels, and their main disadvantage is that the weight of water can be only used in one quarter of the rotation, and not in a half as it happens in overshot wheels, so it is less efficient. Figure 20 depicts a Breastshot wheel.

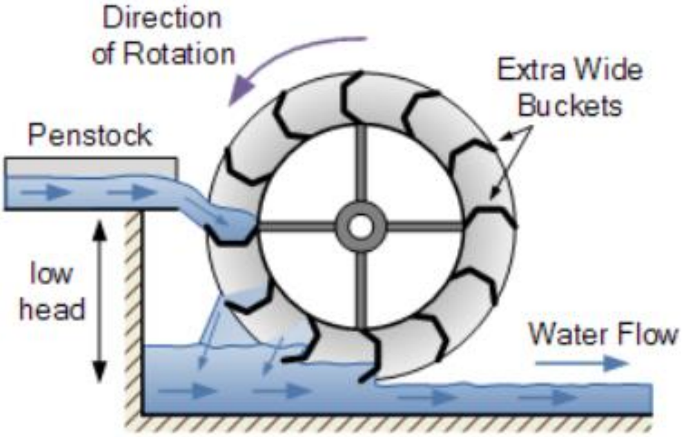


Figure 20. Breastshot Wheel

Table 5 shows the operation values of the waterwheels. With these values and the characteristics of the context where the system will operate, the next step is to estimate the costs related to the infrastructure necessary for each of the waterwheels to determine which of them is preferable, assessing the output versus the costs.

Name	Type	Head (m)		Flow (l/s)		Efficiency		Speed (rpm)	
		Min	Max	Min	Max	Min	Max	Min	Max
Free-stream undershoot wheel	Impulse	0	0,5	500*	950*	45	77	5	20
Poncelet Wheel		0,5	2,5	-	1000*	70	80	5	20
Zuppinger Wheel		0,3	2,5	-	1200	75	85	5	20
Sagebien Wheel		0,3	1,5	-	1200	60	84	5	20
Breastshot Wheel		1,5	4	500*	750*	80	85	5	20
*(flow per meter width)									

Table 5. Performance Values of Waterwheels

4.1.1.2. Underwater Turbines

Apart from water wheels there are two other devices that are interesting to be considered because of their suitability to low head contexts and high applicability. These are Tyson turbine, Gorlov helical turbine, Screw turbine and Savonius turbine, that will be described below.

Tyson turbine

It is a hydraulic turbine that can be directly introduced in the water stream without need of casement. It consists of an impeller similar to the ones used for Kaplan turbines with a slightly higher number of large blades that are fixed to the axis. Its main use is to recover energy from water streams.

Its advantages are that it can be easily transported or relocated if necessary, it does not need civil work engineering, and the maintenance required is minimum. Its main drawback is the low efficiency it displays, being the maximum that the turbine reaches in optimal conditions 32% [35].

Figure 21 depicts the Tyson turbine.

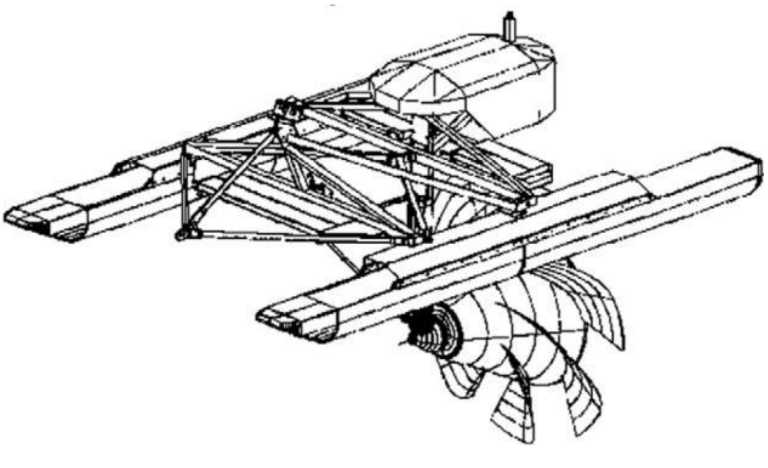


Figure 21. Tyson Turbine

Gorlov helical turbine

This turbine is a variation of the Darrieus turbine modifying it with helical blades. One important characteristic of Gorlov helical turbine is that it can be positioned in two different ways regarding the water flow, with its axis in a vertical or an horizontal position, as it is depicted in Figure 22. Gorlov helical turbine. It is used in low head micro hydro installations, without need of a dam or weir, which reduces drastically the civil works costs and the environmental impact. The main drawback of Gorlov helical turbines is their low efficiency, that is reported to be up to 35% [36] [37].

Figure 22. Gorlov helical turbine

Screw turbine

this water turbine is based on the Archimedean screw and uses its working principle to transform the potential energy of a stream of water into mechanic work. It is basically an Archimedean screw rotating in a semicircular tube by the action of water, with a gearbox connected to the upper part that connects it to the generator.

It is mainly used in low head and medium flowrate applications, and it is actually considerably efficient, moving in a range from 70 to 86% [38]. Figure 23 depicts the operation of a screw turbine.

Figure 23. Screw Turbine

Savonius turbine

Savonius turbines are a particular type of turbines which are based in the Savonius rotor, a type of wind turbine consisting of two hollow semi cylinders that join in one of their directrices making the shape of an ‘s’.

Savonius turbines are partially submerged in streams, so the two cylinder blades are pushed consecutively by the water flow. Savonius turbines have a poor efficiency, being the maximum achievable 35% [39] [40].

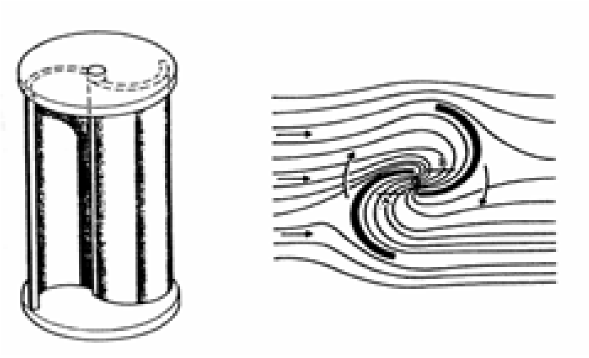


Figure 24. Savonius turbine

Table 6 displays the performance values of the before mentioned devices.

Name	Type	Head (m)		Flow (l/s)		Efficiency		Speed (rpm)	
		Min	Max	Min	Max	Min	Max	Min	Max
Tyson turbine	Reaction	-	10	-	1000	16	32	15	120
Gorlov helical turbine		-	10	-	-	35	35	30	300
Screw turbine	Impulse	1	10	10	14500	70	86	20	40
Savonius		-	30	-	-	-	45	10	70

Table 6. Performance Values of Underwater turbines

4.1.2. Pumps

This section will include information about the pumps that can be suitable for being used in this project considering the requirements due to pumping head (40-70 m), flowrate delivered (1-2 l/s), cost and an actually considerably determinant parameter, that is the rotational speed. It is such a determinant parameter because the hydropowered prime movers considered work at low ranges of rotational speed, while pumps usually work at minimum rotational speeds of 300 rpm, being the common rotational speed around 1000 rpm.

This is actually an important restriction to consider, because the transmission system will depend on it. A transmission system with a gearing ratio higher than 50 would increase the costs of the hydropowered pumping system significantly, so the pump to be selected must consider carefully this limitation.

The pumps considered for this study are the following:

- Piston pumps
- Plunger pumps
- Diaphragm pumps
- Vane pumps
- Progressive cavity pumps
- Centrifugal pumps

Piston, plunger, diaphragm, vane and progressive cavity pumps are positive displacement pumps while centrifugal pump is a velocity pump. The fact that most of the considered pumps are of the type positive displacement is because they can operate at relatively low rotational speed, which is a crucial limitation for the pump to choose.

Furthermore, the head achieved by these devices is not dependent on its rotational speed, which is important too, given the possibility that the flow in the context is variable. Thus, listed are the positive displacement pumps that met the requirements of minimum head and flow rate.

However, centrifugal pumps have also been included in this study. This is because the high applicability these pumps have, its good performance values and the reduced cost it involves. The main drawbacks of these pumps are the high rotational speed they need to operate, which would involve an expensive special transmission system to enable the operation, and the fact that centrifugal pumps head depend highly on the rotational speed.

This implies that if the speed of the waterwheel reduces because of the variability of the flow, the speed of the pump will reduce too, and the head will be affected by this, which could lead to not achieving the necessary head for irrigation. This issue must be cautiously considered at the time of studying the feasibility of centrifugal pumps.

General information of these devices was retrieved from the book Pump Characteristics and Applications [25], while more specific information of each of them was found in other sources that will be mentioned later on.

Piston Pumps

Piston pumps are reciprocating positive displacement pumps that take advantage of a piston to move fluid through a cylindrical chamber. These pumps have cavities that contract and expand in a reciprocating to generate the aimed pressure. They usually operate with a rotational mechanism to create a reciprocating motion along an axis, which originate the pressure for moving the fluid in a cylinder.

The working principle is based on lowering the pressure inside the cylinder when the piston removes from the it, so the fluid goes into the cylinder, and when the piston gets inside the cylinder the pressure increases pushing the fluid to the discharge zone. Piston pumps are highly efficient [41][42].

Plunger Pumps

The functioning of this devices is very similar to the piston pumps, however instead of a piston pushing the fluid, in this case the high-pressure seal is stationary and a cylindrical plunger slides through the seal. This methods permits to reach higher pressure than the piston pumps, whereas they are less efficient that piston pumps [42]. Piston and plunger pumps are depicted in Figure 25.

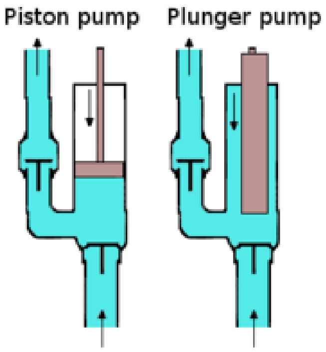


Figure 25. Piston and Plunger pumps

Diaphragm Pumps

Diaphragm pumps also called membrane pumps base their working principle in the reciprocating action of a rubber or thermoplastic diaphragm combined with valves placed in both sides of the diaphragm to pump a fluid. The diaphragm can have several configurations depending on the pumping means:

- Diaphragm is sealed with one side in the pumped fluid and with the other side in hydraulic fluid or air. The hydraulic fluid makes the diaphragm flex by pressing it and this provokes an increase or reduction in the pumping chamber.

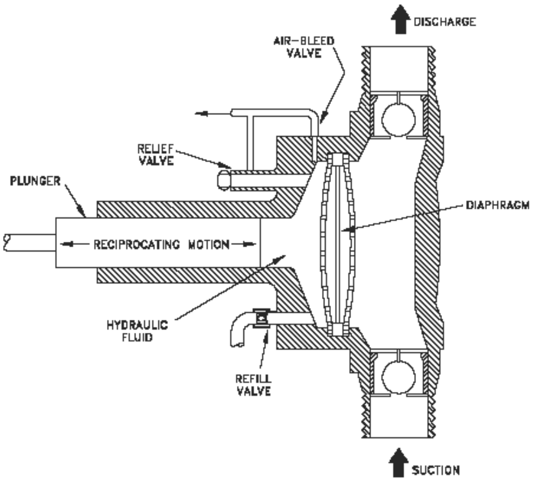


Figure 26. Hydraulic Diaphragm Pump

- Diaphragm is pushed by volumetric positive displacement with a lever a piston or a crank, provoking the change of volume in the pumping chamber.

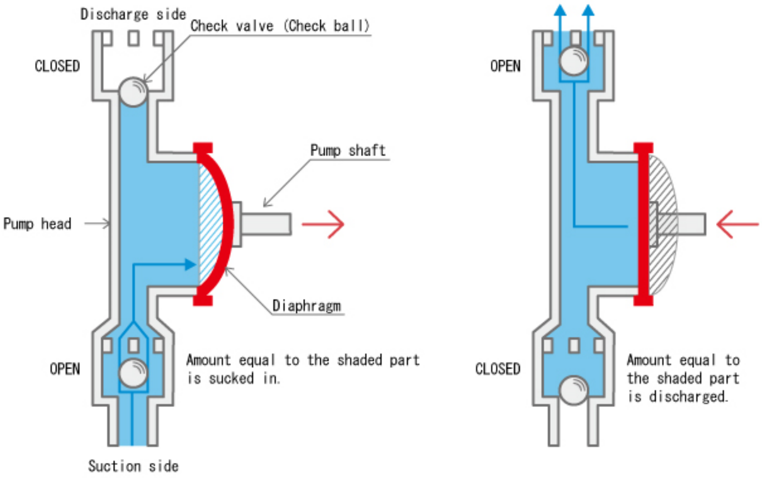


Figure 27. Diaphragm Pump Using a Piston

- One or more unsealed diaphragms are used to pump the same fluid on both sides, alternatively, by the action of valves that let or imped the fluid to get in each side pumping chamber.

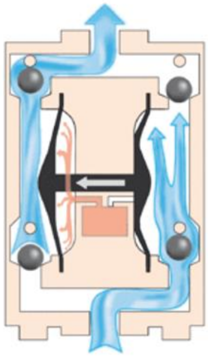


Figure 28. Double Action Diaphragm Pump

Diaphragm pumps have to alternative states, when the pump chamber is not pressed by the diaphragm the pumped fluid introduces in it, and then the diaphragm starts to push the fluid and forces it out to the discharge pipe. When this state is completed, the cycle starts again.

Diaphragm pumps can reach high pressures and efficiencies and as the diaphragm is sealed, they can cope with solids successfully [43].

Vane Pumps

Rotary vane pumps are a type of positive displacement pumps, which main characteristic is having vanes mounted to a rotor which spins in a hollow cylinder. The mentioned vanes either have a variable length or are tensioned to maintain the contact with the walls of the hollow cylinder.

The most common type of vane pump consists of a circular rotor inside a circular cavity. The peculiarity of its configuration is that, unlike other rotating pumps, the centers of the rotor and the cavity are not the same, provoking an eccentricity in the spin. Thus, vanes slide in and out of the rotor to achieve the sealing of the chambers generated by them. The pump is configured in such a way that in the intake the chambers are increasing their volume, and they are filled with fluid sucked by the inlet pressure, while in the outlet the volume of the chambers decreases displacing the fluid to the outlet.

There is other important type of vane pumps that is flexible impeller pumps. Flexible impellers main characteristic is that their impeller is made of rubber materials which are flexible and can be bent, generating vacuum that push the fluid from the inlet to the discharge zone. Unfortunately, flexible vane pumps do not meet the requirement of achieving a head higher than 40 meters, so they will not be considered [44] [45]. Figure 29 shows he operation of a vane pump.

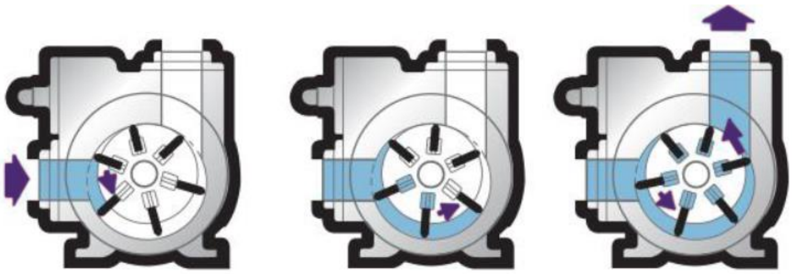


Figure 29. Vane pump operating

Progressive Cavity

These devices are usually conformed by an helical rotor with a twin helix, which is twice the wavelength of the helical hole in the stator. The rotation generates a sort of fixed-size cavities between rotor and stator, which are tightly sealed. This sealed cavities move along the axis of the rotor while they do not change their volume, and they carry the fluid from the inlet to the discharge pipe.

The progressive cavity pumps flows rates are proportional to the rotation speed despite that the flow rates they reach are actually not as high as other pumps. On the other hand they can work with high pressures, taking into account that the higher the pressure, the more cavities necessary, in order to avoid the leak of fluid by the sliding cavities, by reducing the pressure difference each cavity should cope with.

These devices have also the advantage of producing low levels of shearing and can work either with viscous and non-viscous fluids[46]. Figure 30 depicts a progressive cavity pump.

Figure 30. Progressive Cavity Pump

Centrifugal Pumps

There are several types of centrifugal pumps such as the volute pumps, turbine pumps and regenerative pumps. This study will focus on volute pumps because it is the most common type, the one which offers a wider range of operation values and the less costly one.

Volute casing pump is the most common type of centrifugal pump. A volute is a curved funnel located around the impeller, that increases its area as it is closer to the discharge pipe.

The main characteristic of the volute that makes it so important, is that it is designed to maintain the fluid velocity through the diffuser. The flow of fluid existing in the volute increases as it travels through it, however the cross section of the volute increases in such way that if it is working close to the nominal values the velocity is maintained constant.

It is important to distinguish between the volute and the diffuser. The volute does not convert kinetic energy into pressure , just maintain fluids velocity. The diffuser is and additional part that only some pumps have. It is located between the impeller and the volute, and its function is to reduce the velocity of the fluid while increasing the pressure. The fluid conditions at the outlet of the diffuser will be maintained in the volute until the discharge pipe[47] [48]. Figure 31 shows the difference between centrifugal volute pumps with and without diffuser.

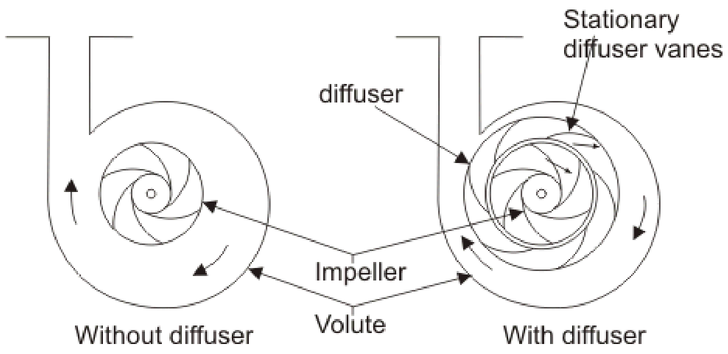


Figure 31. Volute Pump with and without Diffuser

Table 7 shows the range of values for the main performance characteristics of the before described pumps. These values are illustrative, and they have been retrieved both from the articles before mentioned and from some manufacturers websites.

Category	Name	Type	Head (m)		Output Flow (l/s)		Efficiency (%)		Speed (rpm)		Solid Handling *
			Min	Max	Min	Max	Min	Max	Min	Max	
Displacement Pump	Piston/bucket pumps	Cyclic	10	3518	1,39	44,17	50	90	100	5000	3
	Plunger pumps		40	70354	0,56	75,70	60	85	100	1500	3
	Diaphragm pumps		1	12312	0,56	113,56	78	86	50	1500	2
	Vane Pumps	Rotary	5	140,7	0,3	157,7	78	85	600	1800	3
	Progressive cavity		10	1407	0,56	151,40	30	70	150	1800	1
Velocity Pumps	Centrifugal (volute) pumps		4	60	0,28	1000,00	60	90	500	2000	1

* Rating for 1 is best, 3 is medium, 5 is worst

Table 7. Performance Values of Pumps

4.1.3. Transmission Systems

As the hydropower prime movers that are suitable for the project are slow, the pumps were filtered to reduce the transmission ratio of the system, because the higher the transmission ratio is, the more expensive and complex will be the transmission system.

Thus, transmission systems considered for this research need to have a gearing ratio higher than 10, because if not, hydropower prime mover and pump would not spin under optimal conditions. Looking at the common gearing ratios of the different devices, these are the transmission systems that will be taken into account for the research:

- Belts
- Chains

- Gears
- Archimedes drive
- Shiftless transmission

There are some other transmission systems that could have been considered, however they have finally not, because of unsuitable operating values. These are the cases of torque converter or drive shaft, that do not meet the requirement of a gearing ratio higher than 10 [49] [50], or hydrostatic transmissions, that could meet the requirements, however they involve a considerable number of components as well as a system of control, which would increase costs and complexity, so they were finally discarded [51]. Electric transmission were also initially considered for the study, however they also involve an important number of variables given the fact that mechanical power must be transformed to electricity and vice versa. This increases complexity of the system, and the more variables included in the system the more expenditure and maintenance will be necessary, so electric transmissions were finally not considered.

Belts

Belts are a type of mechanical transmission based on the transference of the rotational move of one or more pulleys by means of a continuous tape or belt, that is moved by forces of friction, transmitting the rotation from the driving wheel to the other ones. They are commonly used for low torque and high speed applications.

There is also a variation of belts, more similar to chains that are toothed belts. This variation, more efficient than the common one, have a different working principle, as they transmit the rotation by means of interference with the pulleys using its teeth.

In the old times, belts were made of leather, despite the mechanical properties of this material due to friction and fatigue are not the best. Because of this, nowadays belts are manufactured with several layers of cotton or nylon, with reinforcement strands and coated with rubber or other synthetic materials to increase the friction forces between the belt and the wheels, reducing the slippage [19] [52].

Figure 32. Common and Toothed Belts

Chains

Transmission chains are an improved version of toothed belts. They transmit the force drag movement between toothed wheels called sprockets, by means of the interference between the teeth of the wheels and the links of the chain.

They are used in situations where is required to transmit a high torque with a medium or low speed, and they need to be cautiously maintained by lubrication with oil.

Chains can be made from several materials, the most of them metals, being the most common ones the nickel and zinc alloys for humid and highly corrosive atmospheres, stainless steel for chains in contact with water, and when the use of lubricants is not necessary or avoided, they are made out of polymers [52].

Figure 33. Common Transmission Chain

Gears

Gears are power transmitting mechanisms formed by two toothed wheels, being the winder, or driving wheel, the biggest one, and the pinion the smallest one. If the system is formed with more than two wheels it is called gear train. Gears transfer the torque and the rotatory movement by the contact of the winder with the rest of the wheels, and their main advantage regarding belts is that they prevent slippage, so the transmission ratio calculations are more accurate. The disadvantage of gears is that they need to be cautiously maintained by oiling.

The most common type of gears is spur gears, however there are other types such as helical, that reduces the noise made by gears, bevels, that allow to transmit torque between perpendicular axis, or worms that achieve a high torque ratio, with the disadvantage of reducing the efficiency.

Figure 34. Types of Gears, from left to right: Spur Gear, Bevel and Worm Gear

Gears are manufactured with a wide range of materials. One is steel subjected to a treatment of temple and cementation in order to increase the surface hardness. This material is commonly used when the strain to transmit is high, if not other materials such as aluminum alloys or smelting are suitable [52].

Archimedes Drive

This is a new innovative system developed by IM Systems, a startup in Yes!Delft, that allows to transmit torque with extremely high ratios. It is based on the planetary transmission, using friction of metal tubes instead of teeth interference to transmit the movement. Thus the central driving tube, or *sun*, transmit the rotation to the surrounding tubes, or *planets*, and these transmit it finally to the grounded output annulus.

As it is a project still in development, some materials are being tested to analyze their behavior. Some of them are steel and aluminum alloys strengthened to bear the huge strain the components are subjected to [53].

Figure 35. Archimedes Drive

Shiftless Transmission

The continuously variable transmission, best known as shiftless transmission, is a type of mechanical transmission that can vary the speed ratio within its limits regarding at the needs of the system.

It was developed in 1958 by Huub van Doorne, and it is named as continuously variable because the relation of speeds is not determined by just to gears, but by two rollers joined by a chain that transmits power.

Thus, a hydraulic circuit is in charge of changing the width of the pulleys, and the transmission of the force to the motor machine is done by a conventional clutch or a torque converter. The main drawback of this system is the torque that it is capable to transmit, being suitable for applications where low torque transmission is required [54].

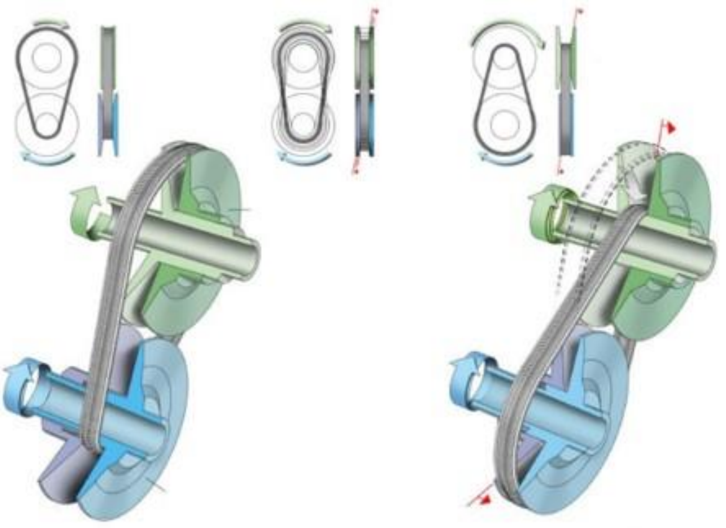


Figure 36. Scheme of Functioning of Shiftless Transmission

Table 8 displays the range of the main performance values of the transmission systems considered, that were retrieved from different manufacturers websites and articles.

Coupling Methods								
Methods	Reducing Ratio		Power Transmission (kW)		Torque Transmission (kNm)		Efficiency (%)	
	Min	Max	Min	Max	Min	Max	Min	Max
Belts	1	10	-	400	-	150	92	98
Chains	1	20	-	610	-	250	93	98,5
Gears	4	115	-	4825	-	400	94	96
Archimedes Drive	50	10000	-	800	-	70	80	90
Shiftless Transmission	1	130	-	3000	-	500	88	92

Table 8. Performance values of the considered Transmission Systems

4.1.4. Current Hydropowered Pumping Systems

Nowadays there is a sort of ready solutions that use hydropower to run pumps. All these solutions are used to provide water for irrigation, or to lift water to a pool to later give it several uses. The most relevant and successful system will be listed below:

- Hydraulic Ram
- Chinese Water Turbine-Pump
- Multipropeller turbine + displacement pumps
- Garman turbine
- Tyson turbine
- Waterwheel driven pumps

Hydraulic Ram Pump

It was first recorded to be used in 1796. It is a cyclic type of pump that uses the kinetic energy of a water hammer to make the upper part of that fluid raise to a higher level.

A water hammer is an effect provoked by the sudden closure of a valve that impedes the fluid flow through a pipe, generating an overpressure that in common installations is one of the reasons of failure. However, the hydraulic ram gets advantage of the water hammer to pump water without further damage to the installation.

Thus, the hydraulic ram operates by conducting water from one level to lower one. This water increases its velocity as it gets down in the pipe, and then the valve in the lower level outlet closes, provoking a water hammer that makes the water take a secondary way, which is actually the real outlet, to a level is located over the other two. The pressure generated by the water hammer is enough to push all the water flow to this mentioned outlet. The efficiency achieved by the hydraulic ram is near to 70% [55].

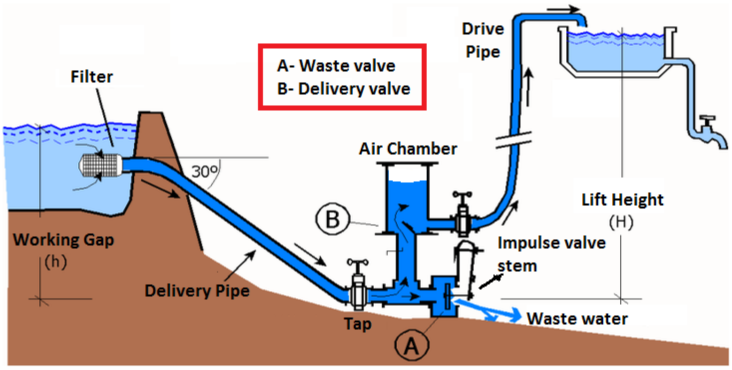


Figure 37. Hydraulic Ram Pump Scheme

Chinese Water Turbine-Pump

These devices were invented in 1954 and their use was extended in the decade of 1960. It is formed by a small Kaplan turbine combined with a centrifugal pump by a coaxial shaft coupling. It was used for low head applications, being highly successful because of the good performance it provided, reaching a lifted amount of water of 15 m^3/s with a head ratio from 4:1 to 6:1, meaning by this that if the ratio is 4:1, per 1 meter of head for the Kaplan turbine the pump lifts water 4 meters.

This solution is also very convenient because it does not need any transmission method, it Is directly coupled, taking advantage of the fact that the centrifugal pump and the small Kaplan turbine can spin at the same speed, despite the fact that this makes the system less efficient [56].

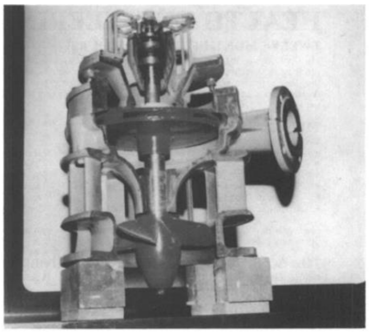


Figure 38. Chinese water turbine pump

Multipropeller turbine + displacement pumps

Devices like Hydrobine by EB engineering or Turbo water pump by Ndume are solutions that combine Multipropeller turbines with a positive displacement pump are an innovative way of hydropowered pumping system that targets ultra-low head scenarios making possible efficient water pumping without the necessity to have a considerable head conditions.

Figure 39. Hydrobine by EB Engineering; Ndume Turbo water pump

Waterwheel driven pumps

Several solutions are being currently used that harvest water power with waterwheels. Apart from Barsha pump and HyPump, that combine a waterwheel with spiral pumps. ZM Bombas in Brazil, is currently using diaphragm pumps in combination with overshot waterwheels, offering a broad portfolio with scaled devices that can be used to pump medium or low flow rates to a wide range of heights.

Furthermore, Mangal turbine is an Indian device formed by a centrifugal pump and an undershot waterwheel, that only requires low heads up to one meter to deliver water for the irrigation of 10 hectares. It is actually applied in rural areas and its use is being extended all over India.

Figure 40. ZM 51 pump by ZM Bombas; Mangal Turbine

4.2. Research for Innovative Problem Solving Techniques

This section will include descriptions and insights from two main methodologies of solving problems: TRIZ and morphological chart.

In all industries it is frequent to find conventional problems, for which a conventional solution has been developed, so they are not challenging to solve. However, it is also common that new problems emerge, that cannot be solved by the ordinary conventional solutions. In this case it is necessary to develop new solutions by combining, changing and improving the available knowledge and techniques.

TRIZ and morphological chart are techniques frequently used to find solutions to these new problems that emerge. Both techniques will be considered to generate new ideas from current technology, combine devices in an innovative way or modify ready solutions to provide an improved hydropowered pump.

4.2.1. TRIZ

TRIZ is a Russian methodology that literally means "theory of the resolution of invention-related tasks". It is a problem solving technique developed by the inventor and science fiction writer Genrich Altshuller in 1946.

This theory was developed regarding the patterns in the invention process observed in multiple patents of different scientific fields, and one of its important focus is to achieve an algorithmic approach for the invention of new technic systems and the perfection of the existing ones. It involves a practical methodology, tools and knowledge and technology both based in abstract models to generate new ideas and solutions.

The three main insights of this theory are the following:

- Problems and solutions are repeated in all sciences and industries.
- Technological evolution patterns are also repeated in all sciences and industries.

- Innovations are based on the use of these insight to create and improve products services and systems.

Thus TRIZ theory defines five different levels of inventive:

- **Level 1:** it involves routine problems solved by well-known methods, where no invention was necessary. This level includes approximately the 32% of problem solutions.
- **Level 2:** it involves minor improvements to an existing system by methods known in the industry. This level includes 45% of problem solutions.
- **Level 3:** fundamental improvements to an existing system, by methods external to the industry. 18% of problem solution are included in this level.
- **Level 4:** a new generation of solutions that uses a different principle to perform the functions of the system. These solutions are more related to science than to technology. Only 4% of the solutions are included in this level.
- **Level 5:** a scientific discovery or the invention of a new system are essentially included in this level. Only 1% of problem solutions are included in this level.

Basically TRIZ methodology is a way of systematic thinking, were specific problems must be transformed into generic problems to then find a generic solution that will be converted to a specific solution.

Thus, it is important to model the problem as a system, where there is a contradiction between the different parameters included in it. This contradiction emerges when the improvement of one parameter causes the worsening of other one. The goal of TRIZ theory is to eliminate the contradictions.

To do this, the matrix of contradictions is used. This matrix is defined by 39 different parameters that are listed below:

1. Weight of moving object
2. Weight of stationary object
3. Length of moving object
4. Length of stationary object
5. Area of moving object
6. Area of stationary object
7. Volume of moving object
8. Volume of stationary object
9. Speed
10. Force (intensity)
11. Stress or pressure
12. Shape
13. Stability of object's composition
14. Strength
15. Duration of action of moving object
16. Durability of action of stationary object
17. Temperature
18. Illumination intensity Brightness
19. Use of energy by moving object
20. Use of energy by stationary object
21. Power
22. Loss of energy
23. Loss of substance
24. Loss of information
25. Loss of time
26. Quantity of substance
27. Reliability
28. Measurement accuracy
29. Manufacturing precision
30. Object-affected harmful factors
31. Object-generated harmful factors

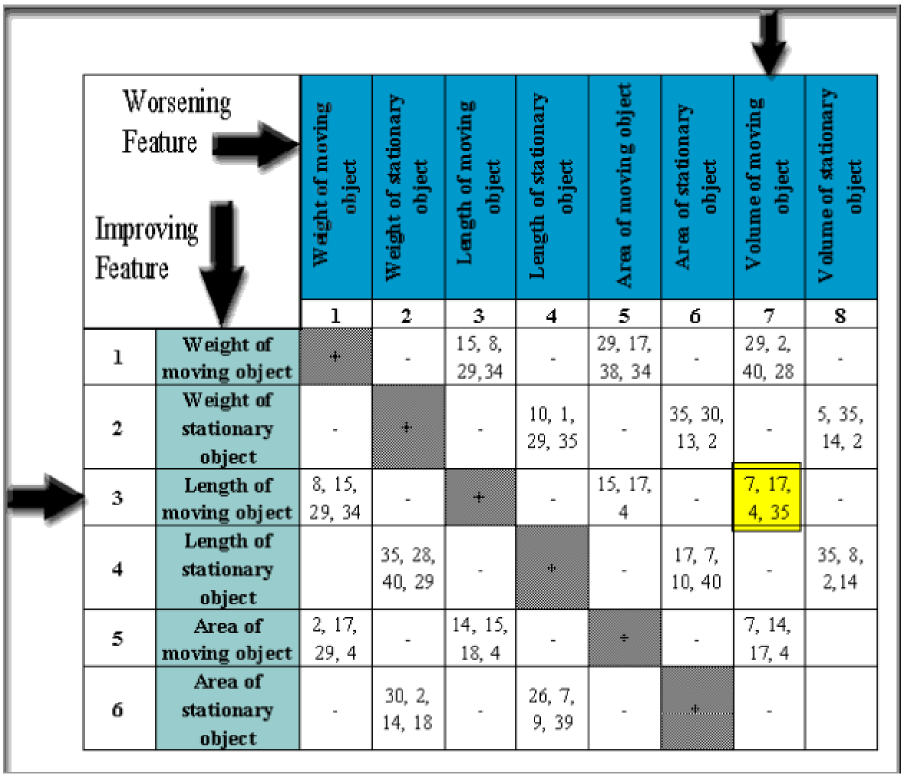
32. Ease of manufacture
33. Ease of operation
34. Ease of repair
35. Adaptability or versatility
36. Device complexity
37. Difficulty of detecting and measuring
38. Extent of automation
39. Productivity

Obviously, not all the parameters are relevant for the current research, in fact, the major part of them is not, so in the case that TRIZ is used for generating innovative ideas in this research, instead of using these 39 parameters proposed by TRIZ, the ones that will be used are the parameters defined as relevant in the previous section.

The parameters are then related with synergies, where the improvement of a parameter also improves other additional parameters, contradictions that were before explained, or have no relation with other parameters. The objective of TRIZ is to eliminate contradictions between parameters by using the following 40 principles:

1. Segmentation
2. Taking Away
3. Local Quality
4. Asymmetry
5. Combining
6. Universality
7. Nested Doll
8. Anti-weight
9. Prior counteraction
10. Prior action
11. Beforehand cushioning
12. Equipotentiality
13.Other way round
14. Spheroidality
15. Dynamicity
16. Partial or excessive action
17. Another dimension
18. Mechanical Vibration
19. Periodic Action
20. Useful Action Continuity
21. Skip
22. Turn the harm to good
23. Feedback
24. Intermediary
25. Self-service
26. Use of Copies
27. Cheap short-life
28. Mechanical Principle Replacement
29. Pneumatic and Hydraulic structures
30. Flexible shells and thin films
31. Le materiau poreux
32. Changing color
33. Homogeneity
34. Rejecting and regeneration of parts
35. Change of physical and chemical parameters
36. Phase transitions
37. Thermal expansions
38. Strong Oxiders
39. Inert Atmosphere
40. Composites

Thus, an example of a contradiction matrix is depicted in Table 9. There, the requirements for the product (a car) are to be long but small, so when the parameter *length of moving object* is improved *the volume of moving object* worsens. Then there are 4 principles that can be applied to solve the contradiction: 4. Asymmetry, 7. Nested Doll, 17. Another Dimension, 35. Change of Physical or Chemical Parameters [57] [58].



Worsening Feature Improving Feature		Weight of moving object	Weight of stationary object	Length of moving object	Length of stationary object	Area of moving object	Area of stationary object	Volume of moving object	Volume of stationary object
		1	2	3	4	5	6	7	8
1	Weight of moving object	+	-	15, 8, 29,34	-	29, 17, 38, 34	-	29, 2, 40, 28	-
2	Weight of stationary object	-	+	-	10, 1, 29, 35	-	35, 30, 13, 2	-	5, 35, 14, 2
3	Length of moving object	8, 15, 29, 34	-	+	-	15, 17, 4	-	7, 17, 4, 35	-
4	Length of stationary object		35, 28, 40, 29	-	+	-	17, 7, 10, 40	-	35, 8, 2,14
5	Area of moving object	2, 17, 29, 4	-	14, 15, 18, 4	-	+	-	7, 14, 17, 4	
6	Area of stationary object	-	30, 2, 14, 18	-	26, 7, 9, 39	-	+	-	

Table 9. Generic TRIZ Contradiction Matrix

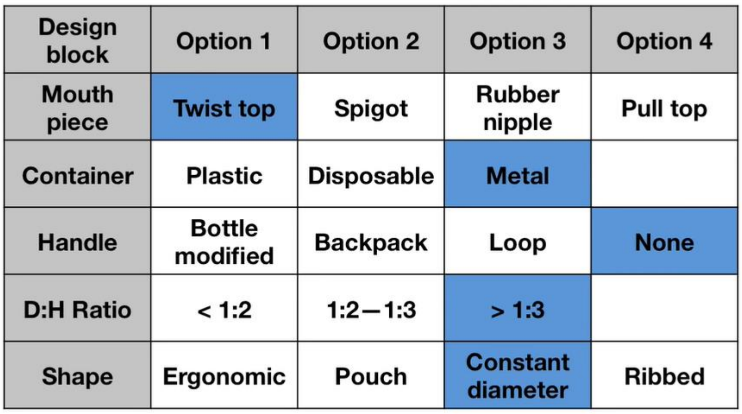
4.2.2. Morphological Chart

The morphological chart is a methodology frequently used in design engineering, which purpose is to generate concepts and ideas in an analytical and systematic way. In the left part of the chart there is a list of the problems or subproblems that want to be solved, and each row includes the different solutions that each function/problem can have. The solutions included in the morphological chart are concrete and specific, and they are known from existing solutions.

Thus, for using the morphological chart it is necessary to split the product in a set of functions and subfunctions. For each of them different solutions are proposed, and later a substantiated selection and combination of solutions for the subproblems is done, to create the overall idea that meets all the requirements.

New solutions are found by transforming the abstract parameters into concrete ones by the establishment of technical principles. Thus, the morphological chart is an evolutionary methodology: functions and solutions evolve in parallel until the final morphological chart is made.

Table 10 displays an example of morphological chart applied to the design engineering of a liquid recipient. There, the different sub solutions for each of the functions are shown in the rows, and a particular sub solutions is chosen for each function, being the overall solution for the design a metal bottle with no handle, twist top and a constant diameter.



Design block	Option 1	Option 2	Option 3	Option 4
Mouth piece	Twist top	Spigot	Rubber nipple	Pull top
Container	Plastic	Disposable	Metal	
Handle	Bottle modified	Backpack	Loop	None
D:H Ratio	< 1:2	1:2—1:3	> 1:3	
Shape	Ergonomic	Pouch	Constant diameter	Ribbed

Table 10. Morphological Chart for a Water Recipient

For each problem a sort of different solutions are proposed, which means that an important number of combinations is possible, so it is important to choose wisely the solution for each problem in order to reach the optimal overall solution. Also, in order to limit the number of options, there are two evaluation strategies that are possible:

- Analysis of the rows: this strategy consists in ordering the different sub solutions for each function in a first and second preference, regarding the behavior of the sub solutions towards the requirements imposed. By using this strategy the number of possible solutions are reduced.
- Grouping the functions: the functions that are considered in the chart are grouped depending on their importance, so in a first round of evaluation only the most important group of functions is considered. Afterwards, when some combinations have been discarded the rest of the functions are considered in the assessment.

Thus, a general procedure to follow when using morphological chart in design engineering is the following one:

1. The problem to be solved must be properly formulated.
2. Identify all the functions and subfunctions which might occur in the solution.
3. Construct a morphological chart (a matrix).
4. Fill the rows with the sub solutions that belong to each particular function.
5. Use the evaluation strategies (analysis of rows and grouping of functions) to limit the number of overall solutions.
6. Create overall solutions by the combination at least one sub solution from each function.
7. Analyze the solutions regarding the design requirements, and choose a limited number of overall solutions.

Furthermore, some concerns that should be mentioned to use morphological chart properly are to draw the sub solutions instead of describing them with words, and to challenge the selection of sub solution combinations by making counter-intuitive combinations in order not to reach the conventional safe overall solutions[59][60].

4.3. Study of Innovative Solutions

Once the two methodologies of solution development have been described, it is the moment to choose which one to use, to generate sub solutions to the different problems that emerge in the design of the hydropowered pumping system, to the combine them and obtain overall solutions to evaluate in the final step of the thesis.

Regarding TRIZ methodology, it supposes a proper manner to generate solutions that optimize the different parameters minimizing the drawbacks that that optimization implies sometimes. Despite TRIZ have been successfully used to improve and invent products, services and systems several times, there are numerous interdependencies between the variables of the hydropowered pumping system that would be necessary to resolve.

For each contradiction found it would be necessary to observe which of the 40 general principles to apply, and then find a specific solution for that principle to solve the contradiction. Furthermore, when all the contradictions are solved with different principles, it is still necessary to select and evaluate the different options and combine them to obtain overall solutions.

This process can be considerably abstract and time-consuming, and regarding the lack of time for develop these innovative solutions, TRIZ methodology will be discarded to be used. On the other hand, morphological chart represents a more visual tool, oriented to present in a matrix the different alternatives for the design of the product, being a proper methodology to develop solutions for the different problems or functions that the hydropowered pumping system has, in an easy and low time-consuming manner. Thus, morphological chart will be the chosen tool to generate the innovative ideas for the hydropowered pumping system that will be developed.

Thus, the process that will be followed to generate these innovative ideas will be the following:

- Identify the functions that the system must have regarding the requirements defined in 2.3.1.2.
- Group problems/functions to reduce the complexity of the matrix and order them to determine the importance of each one.
- Think about concrete solutions for each of the functions.
- Combine them to generate innovative overall solutions

Despite the fact that in the concerns of use of morphological chart it is advised that to draw the different sub solutions is a recommended practice, in this case the sub solutions will be described by writing them, because in some cases drawings are not explanatory as well as there could not be a big visual difference between some sub solutions.

4.3.1. Problems Identification

The first step in the morphological chart methodology will be to identify the problems and functions that the hydropowered pumping systems may have. As recommended, problems have been grouped in several categories to reduce the complexity for the assessment of solutions.

Furthermore, problems can be classified into first and second order. First order problems are those related with the selection of general components. Thus, the selection of the prime mover or the debris protection system would be first order problems. Second order problems are referred to the particular issues derived from the selection of specific components. For instance, the inclusion of a weir because a particular prime mover needs a higher head would be a second order problem.

On the other hand, the categories that have been chosen to group the problems/functions found were the following:

- Infrastructure
- Hydropower Prime Mover
- Pump
- Transmission System
- Portability

The first order problems that were considered to be included in the morphological chart matrix are the following, once they have been grouped by categories:

Infrastructure

The infrastructure considered for this system basically consists of: a) a flow controlling system to regulate the flow rate that enters in the hydropower prime mover, and b) a solids rejection system to avoid the entrance of debris, logs and other solids to the system, that can provoke damages in it. Thus, the problems regarding infrastructure will be:

- What are the possibilities for controlling water flow through the hydropower prime mover?
- What are the possibilities for avoiding the entrance of solids into the systems?

Hydropower Prime Mover

In the case of the hydropower prime mover the only problem that will be considered is which of the devices that meet the requirements before established is more suitable due to performance and cost:

- Which are the possible HPPM to use that:
  - Can work with low stream heads (<0,5 m)
  - Can exploit kinetic energy

Pump

As well as it happened with the hydropower prime mover, the main problem for the pump is which of the selected devices to choose regarding the performance and the price. Furthermore, pumps are more sensitive to solids, so it is important to define the possibilities for the intake of the pump.

- Which devices can be used to pump water with these characteristics:
  - Head= 40-70 m

- Flow = 1-2 l/s
- Rotational Speed < 1000 rpm

- Which are the possibilities for the pump intake?

Transmission

Depending on the hydropower prime mover and the pump chosen for the system, the gearing ratio for transmitting the power will be higher or lower. The main problem for the transmission system is which of the proposed systems is more suitable for the given ratio looking at efficiency and cost. Besides this, transmission systems have to be properly protected against dirt, because they wear easily due to dirt, however this problem is dependent on the selection of the transmission, so it is a second order problem. Thus the main problem will be which transmission to use:

- Which devices can be used to transmit power with the given ratio?

Portability

For the portability it is important to consider the weight of the whole and the techniques to make the transportation easier. However, weight depends on the devices chosen to operate the system, so the only problems that can will be included in this section is the design of the system regarding the detachability and the transportation techniques

- How can the system be transported by two people?

4.3.2. Solutions Suggestion

In this section, different sub solutions will be proposed for each of the problem stated. These sub solutions will be later on combined to generate overall solutions for the design of the hydropowered pumping system.

The hydropower prime movers, pumps and transmission systems that were considered in this morphological chart have been explained before in section 4.1, so they will not be commented now.

How to control water flow through the hydropower prime mover?

In wild environments like streams, rivers and even canals water variability might become a problem, as a low flow will translate in insufficient power to drive the system, and a high flow rate can decrease its efficiency and even provoke damages to some components. In this sense the possibilities considered are:

- A bypass
- Control gates
- An intake funnel
- Not to include a flow control system

The bypass is a system that deviates the overflow to let the proper volume of water into the system. The gates just open and close regulating the flow that enters in the system. Both of the system solve the situation of having overflow in the system, however, it is important to keep the cost of the system in mind, in order not to increase it too much. Figure 41 shows a hydraulic project where both a bypass canal and hydraulic gates are used.

Figure 41. Hydraulic project with a bypass and hydraulic gates

One other easier solution is to build a funnel or conduit in the intake of the prime mover, in order to determine the flow rate that goes through it and mitigate the variability of the river flow. A funnel does not necessarily imply a great expenditure, and it is highly compatible with including a debris protection system in its intake.

How to avoid the entrance of solids into the system?

The solid rejection system is essential for the good performance and protection of the system, the possibilities considered for it are the following:

- A trash rack
- A screen filter
- Set a grill in the intake
- A deflector

The trash rack is the most coarse solution, although it is also the very economic. It consist of a set of vertical bars and sometimes horizontal too, in the shape of a grill. This component avoids the entrance of big and medium solids, however the small ones can get into the system. Screens filters are constructed with small wires which are woven together to create a cloth, that can be plastic or metallic which retain smaller solids, cleaning water. Figure 42 displays a trash rack and a hydraulic self-cleaning screen used for crossflow turbines.

Figure 42. Left: Trash Rack, Right: Hydraulic Screen

Other option considering the case that there is an intake for the system, is to set a grill there. A grill is a set of bars or filaments placed perpendicularly in the shape of a net. Thus, grills suitable for this purpose can be found easily, for instance, plastic or metal fences usually have a convenient shape, so it would only involve acquiring a grill and attaching it to the intake of the prime mover.

It is important to take into account that this systems accumulate solids in the intake of the hydropowered pumping system, and if they are not periodically cleaned these solids may obstruct the intake, reducing the flow through the system.

The last option considered could solve the problem of removing debris periodically. This solution is to include a deflector in the system. The idea is to put a component in front of the system that deviates debris and lets the water into the system. It may look similar to a trash rack, however, there is a big difference between them. While in a trash rack solids are retained and stay there until they are removed, the deflector deviates solids so they continue the path of the river.

Which are the possibilities for the pump intake?

The pump intake is important to guarantee that water enters the pump with the proper conditions. Some pumps are sensitive to suspended solids and particles, so in case that one of these pumps is chosen, water should be properly filtered to avoid wear and excessive maintenance.

The possible solutions considered are:

- A submerged pipe
- A filter
- A combination of both
- A direct intake to the pump
- Use the intake of the hydropower prime mover for the pump

The submerged, previously depicted in Figure 9 would be the component that ensures that the pressure in the inlet of the pump is proper, avoiding undesirable phenomena like cavitation. On the other hand, the filter will avoid the entrance of solids to the pump. The filters considered for the pump inlet are the ones mentioned in section 3.1.4.1.: cartridge mesh, spin-on and bag filters. The figures depicting the submerged pipe and the mentioned filters where posted before in the report, so they will not be included again in this section.

If designed properly, it could be possible to use the intake of the prime mover for delivering water both for prime mover and the pump. However, this solution might not be suitable if the pump is sensitive to solids and slurries, because no filter would be included in it.

How can the system be transported by two people?

The solutions proposed for designing the systems regarding detachability are the following:

- One set with handles
- One set with wheels to push it rolling
- Make it a detachable system

The first option is to design the system as one system with handles so two people can carry it comfortably. This option needs that the system weight is not high, in order to be carriable by two people without over effort. Also if the system weight is higher there is the possibility of designing it as a portable set, and involve more people to transport it. This option is the most suitable regarding complexity.

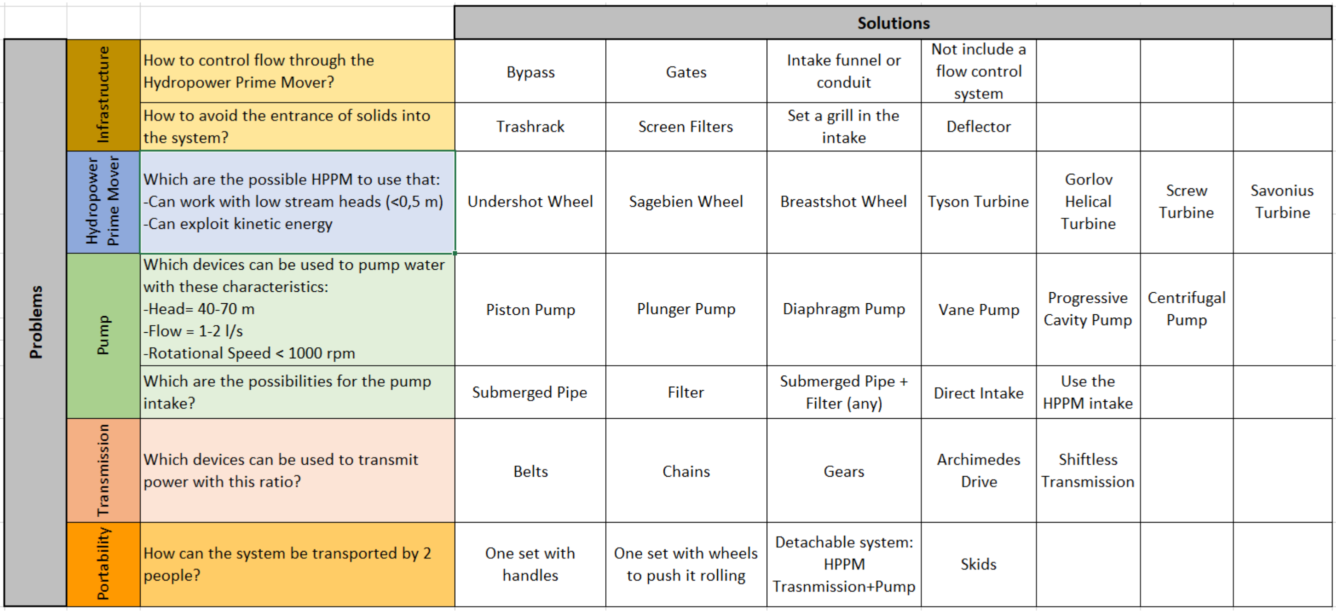
The other option is to include wheels in the system in order to facilitate the transportation of the system. By including wheels the system could be carried by pushing it. The problem that the inclusion of wheels could involve, apart from a slight increase of cost, is that wheels can get stuck in the transportation, or if they are fixed, dirt can accumulate in them and provoke a malfunctioning that hinders the transportation.

Figure 43 shows on the left an example of handles used for transporting Barsha Pump; on the right there is a firefighting pump in a wheeled structure, that could be replicated in a higher size for the hydropowered pumping system of MIT project.

Figure 43. On the left, hydropowered pumping system with handles; on the right, a pump in a wheeled structure

On the other hand, it exist the possibility of designing it as a detachable system. For instance, the system could be separated into waterwheel and pump + transmission, which could decrease the difficulty to transport it, as it would turn into two lighter and smaller sets. This option however involves an important problem, which is the fact that the system must be dismantled and mounted back each time it is transported. The shaft of the prime mover will be disconnected and connected from the transmission, which could lead to a mispositioning of the shaft and a malfunctioning of the system for some transmissions and system designs, if the system is not properly mounted back.

Table 11 displays the morphological chart with the problems before explained and the sub solutions that have been considered for each of them.



			Solutions						
Problems	Infrastructure	How to control flow through the Hydropower Prime Mover?	Bypass	Gates	Intake funnel or conduit	Not include a flow control system			
		How to avoid the entrance of solids into the system?	Trashrack	Screen Filters	Set a grill in the intake	Deflector			
	Hydropower Prime Mover	Which are the possible HPPM to use that: -Can work with low stream heads (<0,5 m) -Can exploit kinetic energy	Undershot Wheel	Sagebien Wheel	Breastshot Wheel	Tyson Turbine	Gorlov Helical Turbine	Screw Turbine	Savonius Turbine
	Pump	Which devices can be used to pump water with these characteristics: -Head= 40-70 m -Flow = 1-2 l/s -Rotational Speed < 1000 rpm	Piston Pump	Plunger Pump	Diaphragm Pump	Vane Pump	Progressive Cavity Pump	Centrifugal Pump	
		Which are the possibilities for the pump intake?	Submerged Pipe	Filter	Submerged Pipe + Filter (any)	Direct Intake	Use the HPPM intake		
	Transmission	Which devices can be used to transmit power with this ratio?	Belts	Chains	Gears	Archimedes Drive	Shiftless Transmission		
	Portability	How can the system be transported by 2 people?	One set with handles	One set with wheels to push it rolling	Detachable system: HPPM Trasnmission+Pump	Skids			

Table 11. Morphological Chart for the Hydropowered Pumping System

All these ideas will be considered to be combined and become the resulting hydropowered pumping system of MIT project. Thus, their combination needs to be assessed in terms of performance and cost regarding the requirements and expectations before explained.

5. Development of a Hydropowered Pumping System

To analyze the suitability of the previous solutions, an assessment model have been developed, that will evaluate the different combinations regarding different objectives that will be commented in the following section. After the assessment is done the best performing solutions will be the ones recommended to be developed by aQysta in the future.

5.1. Development of a Model to Assess Solutions

The model that have been used for evaluating the suitability of the different combinations was developed in Excel. In the beginning, both Excel and Matlab were considered as possible applications to develop the model. Despite Matlab provides a higher mathematical and computational capacity, and the tool Simulink is considerably visual for the representation of models, the final decision was to use Excel.

Excel is a visual tool that allows an easy management of data, and a high mathematical capacity was not necessary for the model. Furthermore, to develop a complete an accurate model in Simulink requires considerable time and Matlab command, and regarding the time available for the development of the model, it would not have been feasible to do it in Simulink.

The Excel sheet is divided in five different tabs, that are the following:

- A scenario tab: this is the principal tab, where all the relevant data and the analysis of the different solutions is carried out.
- Prime movers data tab: this tab gathers all the information about the selected prime movers performance, cost and weight.
- Pumps data: this tab includes relevant information about the selected pumps performance, cost and weight.
- Transmissions data: this tab contains data about the performance, cost and weight of the transmission systems considered.
- Infrastructure data: where information about the infrastructure from different projects that aQysta have carried out is included in order to estimate the cost of the possible infrastructure components to include in the system.

The mentioned tabs are depicted and explained in more detail in Annex II.

5.2. Assessment of the Solutions Suggested

The objective of this section is to discuss the advantages, disadvantages, special characteristics additional problems and synergies of the sub solutions proposed in the previous section.

To do so, it is necessary to analyze suitability of combining the components included in the Assessment Model, taking into account any possible restriction that may impede some of them to operate together or hinder the overall performance of the system. Then, the output values of the system studied must be compared with the requirements established in section 2.3.1.2, to evaluate the extent in which those requirements are accomplished by the system.

5.2.1. Devices Discarded

Firstly, the components that were considered in the state of the art which were discarded afterwards will be enumerated, and the reasons why they were discarded will be briefly explained.

- In the case of prime movers, none of them were discarded. Despite the suitability of some of them was significantly higher than for others, all them could work under the given conditions with a reasonably good performance.
- Regarding pumps, only two devices passed the analysis successfully: AR 245 BP diaphragm pump and WIndTrans Zelda Pump vane pump. The rest of the pump were discarded because they could not operate under the specified conditions.

  In the case of plunger and piston pumps, they both presented the same drawbacks, they are designed for high pressures and low flow rates, usually over 500 mca and under 5 liters per second. Thus, it is difficult to find devices that can operate under the needed conditions, and those which can would provide a low efficiency that is not acceptable regarding the high cost of these pumps. Because of this, piston and plunger pumps will not be used for MIT project.

  Progressive cavity pumps were discarded mainly because they cannot self-prime, which is an important characteristic for this project, and they cannot run dry, and the variability of the river or stream leads to the fact that at some point the pump may run dry. Due to this, the progressive cavity pump would worn out prematurely.

  In the case of centrifugal pump, it was discarded because variability in the head reached by the pump is not desirable, it is a fast device that would involve an expensive transmission, and the cavitation problems can make it wear out prematurely.

  Finally, the flexible impeller pump suggested by the expert of Verder, Verder Jabsco, was not included within the final selection mainly because it was only able to reach 45 meters, and the target of the project is that the pump can provide water fro a range of head between 40 and 80 meters.
- In the case of transmission systems, only belt drives and gearboxes were finally included in the selection.

  Chain drives offered a similar performance that belt drives, with the drawbacks of sudden failure in case of overload or sudden change of speed, perfect alignment of shafts necessary for efficient operation, need of constant lubrication and a higher cost, being the only advantages slightly higher efficiency in operation. Thus, it was decided to cover the range of short gearing ratio with belt drives and not to consider chain drives.

  On the other hand Archimedes Drive was not suitable because the maximum torque it could work with is 150 Nm and the fact that it is still under development. In the prime mover side torque is over 500 Nm, so this system could not handle it.

  Finally, shiftless transmission was discarded for being used in this project because up to now its design is focus on the automotive industry, operating with power ranges around 100 kW, much higher than the scope of MIT project. Thus, shiftless transmission would have a remarkably poor performance having few advantages with regards to its still high cost.

- Infrastructure elements were all considered as suitable in principle, despite later on it will be commented which ones are not recommended to be used with some other components, as well as the ones that create synergy with some components.

5.2.2. Analysis of Considered Devices

This analysis will determine the best performing devices of each category as well as the synergies between them. The analysis of the performance in the Assessment Model was done assuming the following context conditions:

Context Natural Conditions		
Head	Static Head (m)	0,3
	Water Speed (m/s)	1
	Velocity Head (m)	0,051
	Total Head (m)	0,351
Flow	Nominal Flow Rate (l/s)	800
	Variability (%)	50
	Max Flow Rate (l/s)	1200
	Min Flow Rate (l/s)	400
Hydropower Available	Nominal (kW)	2,75
	Maximum (kW)	4,13
	Minimum (kW)	1,38

Table 12. Conditions Assumed for the Design Context of MIT project

These conditions have been established considering the decisions taken in section 2.3.1.1, choosing medium values within the ranges in order to be conservative. This values can be augmented or reduced, taking into account that it will affect the hydropower available to harvest, and the design of the system could change too in order to operate optimally.

5.2.2.1. Hydropower Prime Movers

First topic to discuss will be the performance of the hydropower prime movers for these conditions, as well as the infrastructure they would need to operate. Table 13 shows the performance values of prime movers for the conditions before stated.

Name	Type	Head (m)		Flow (l/s)		Efficiency			Speed (rpm)		Cost (€)	Weight (kg)
		Min	Max	Min	Max	Actual	Min	Max	Min	Max		
Tyson turbine	Reaction	-	10	-	1000	**28,24**	16	32	15	120	**TO DETERMINE**	**TO DETERMINE**
Gorlov helical turbine		-	10	-	-	**30,94**	22	35	30	300	**4433**	**50**
Free-stream undershoot wheel	Impulse	0	0,5	500*	950*	**71,513**	45	77	5	20	**3360**	**112**
Zuppinger Wheel		0,3	2,5	-	1200	**78,70**	75	85	5	20	**3360**	**112**
Sagebien Wheel		0,3	1,5	-	1200	**83,08**	60	84	5	20	**3360**	**112**
Breastshot Wheel		1,5	4	500*	750*	**79,25**	80	85	5	20	**3360**	**112**
Screw turbine		1	10	10	14500	**84,38**	70	86	20	40	**1960**	**168**
Savonius Turbine		-	30	-	-	**38,0**	-	45	10	70	**1960**	**560**

Table 13. Performance Data of Considered Hydropower Prime Movers

The first thing that should be noticed is that the efficiency of some of the devices is remarkably low. This is the case of underwater turbines, which by the way were already reported to have a lower performance than other possible prime movers. The fact why these turbines were considered is because despite their efficiency they could be less costly than other options, achieving a higher cost effectiveness.

- Tyson turbine presents an efficiency of 28,24%, and regarding the lack of information about its design, its cost and weight are to be determined. Having the lowest efficiency of the list as well as uncertainty about the cost makes Tyson turbine an unlikely candidate to be chosen for the project.
- Gorlov Helical turbine presents a slightly higher efficiency, 30,94%, still low compared to the rest of devices. The main drawback of this device is its price, which according to the information retrieved from *Small-scale Water Current Turbines for River Applications* scales to 4433 € for the range of power required. This makes it the most expensive device of the list, and regarding its efficiency, it is not competitive for being selected.
- Savonius turbine presents the highest efficiency of underwater turbines, 35,3%. Furthermore, its cost is the lowest of the list together with the screw turbine, which makes it an attractive option. However, it has a substantial drawback, and it is its weight, 560 kg, that makes it completely unsuitable for being transported. This turbine works submerged in the stream so high load machinery would be necessary to place it and remove it, which is not the objective of the project. Thus, Savonius turbine is not suitable for the objective of the project.

Underwater turbines are still young technologies that have not been developed to the point of competing in cost and efficiency with other possibilities. However, taking into account the boom of renewable energy of last decade, this technology may be developed to be competing, improving the values gathered in this thesis.

Hence, the remaining devices would be all the waterwheels considered and the screw turbine. All them are designed for a specific flow rate, and depending on this, the costs weight and efficiency vary. In order to keep a common criteria for all of them the design flow was set in the value of nominal flow rate of the context.

This is an advisable decision because looking at the efficiency curves of these prime movers, all them reach their highest value for Q/Qdesign=1. However, it also have drawbacks to take into consideration. The value Qdesign has direct influence in the power capacity of the device, and for all these prime movers cost is measured as €/kW, thus, the higher power capacity, the higher the cost of the device will be. Furthermore, weight has been also assumed to scale with the power capacity. For these reasons it may be fair to choose a Qdesign lower than 1 in order to reduce the overall cost of the system as well as the weight to enhance the transportability, despite prime mover efficiency can decrease a few.

However, the assessment of these prime movers will be done for Q/Qdesign. If in a future the system needs to be scaled down in power capacity in order to meet cost or weight requirements, it is only necessary to change the value of *Design Flow* in the tab *Scenario*, and reevaluate which system configuration is more convenient.

Once this have been clarified, next step is to study the performance of the prime movers and determine which one is more convenient.

- Screw turbine provides three important advantages as well as two considerable drawbacks. Its main advantages are:
  - + The efficiency it displays, 84,38%, which is the highest among the prime movers.
  - + Its cost, 700 €/kW, which is the lowest, being considerably lower than the cost of waterwheels.
  - + Its rotational speed, ranging from 20 to 40 rpm, which imply a lower gearing ratio than for waterwheels, that spin from 5 to 20 rpm.

  However, it also have important drawbacks:
  - Its weight is estimated to be 60 kg/kW, which is 50% higher than the one of a waterwheel. This reduces highly the possibilities for transporting the system, because a system with a weight higher than 200 kg, is hardly carriable even with the transporting techniques suggested.
  - The other drawback is that this turbine need a minimum hydraulic head of 1 meter to operate. Thus, in the considered scenario a weir would be necessary to achieve this head, and it would imply an additional cost of 1050 € which would reduce the advantage of the cost of screw turbine with regards waterwheels. However, screw turbine does not need specific flow control system, despite it would enhance its operation.
- Regarding waterwheels, all them were assumed to have the same values of cost and weight per kilowatt, 1200 €/kW and 40 kg/kW, respectively. Furthermore, they all are rated to operate between 5 and 20 rpm, which as commented before, makes them less suitable to be chosen than screw turbine, for instance. Hence, the characteristics that should be studied are the efficiency they display and the need of infrastructure of each device. From the point of view of infrastructure, the best performing devices raking would be:
  1. Sagebien Wheel: 83,08%
  2. Breastshot Wheel: 79,25%
  3. Zuppinger Wheel: 78,70%
  4. Free-stream Undershot Wheel: 71,513%

  Apart from free-stream undershot wheel, that have an efficiency a bit lower than the rest, the other waterwheels present a good performance due to efficiency with values around 80%.

  From the point of view of infrastructure needed, the three components before commented should be considered:

  - ▪ Weir: free-stream undershot do not need weir, because it is designed to operate for the desired range of hydraulic head (0-0,5 meters). Zuppinger and Sagebien wheels would need a weir to reach the minimum 0,3 meters of head if they were not available, however in this case they would be perfectly suitable without weir. Finally, Breastshot wheel can only operate in contexts with a minimum head of 1,5 meters, needing thus a weir that increases the head of the considered context 1,2 meters, which would involve an additional cost of 1800 €, that suppose an important drawback of this waterwheel.
  - ▪ Flow Control System: the flow control system is not strictly necessary for any of these waterwheels, they can all operate without it. However, in order to guarantee the design flow and limit its variability, this component is important. Nevertheless, it does not affect to the decision of the prime mover.

- Debris Protection: this is a compulsory element to include with independence of the waterwheels selected, so it neither makes any difference to their selection.

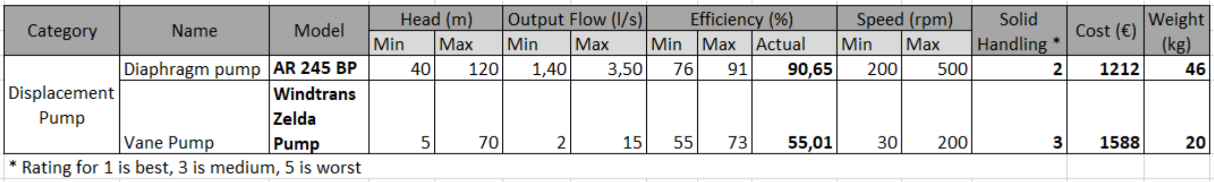
Once all the characteristics of prime movers have been discussed it is the moment of discussing which one is the most suitable for this scenario.

Sagebien wheel is the prime mover with the best overall performance. It is the waterwheel with highest efficiency and it does not require any specific infrastructure to operate in this context, and its weight despite a bit high is much lower than screw turbine, which improves the options for transportability. Once this is stated, there are two important comments to make:

1. Screw turbine is also a high performance prime mover, which displays lower cost and higher rotational speed and efficiency, which are very important advantages. Thus, in case that the scenario considered changes and the system does not need to be transported, or the distance to transport it is short, screw turbine would be the best performing prime mover, and the option to recommended.
2. If the scenario considered changes and the available natural head is null or lower than 0,3 meters, Free-stream undershot wheel would become the best performing prime mover, because despite having an efficiency almost 12% lower than Sagebien, it does not need any head to operate so its cost would be lower. In this case a study of preferences cost vs efficiency should be performed in order to determine which one, Sagebien wheel or Free-stream undershot wheel is preferred.

5.2.2.2. Pumps

In the section of pumps there are only two possibilities remaining: AR 245 BP diaphragm pump, and WIndTrans Zelda Pump vane pump. The rest of possibilities were discarded. Table 14 shows the performance values and characteristics of these pumps. It can be observed that all them have advantages and drawbacks, that will be commented below.



Category	Name	Model	Head (m)		Output Flow (l/s)		Efficiency (%)			Speed (rpm)		Solid Handling *	Cost (€)	Weight (kg)
			Min	Max	Min	Max	Min	Max	Actual	Min	Max			
Displacement Pump	Diaphragm pump	**AR 245 BP**	40	120	1,40	3,50	76	91	**90,65**	200	500	2	**1212**	**46**
	Vane Pump	**Windtrans Zelda Pump**	5	70	2	15	55	73	**55,01**	30	200	3	**1588**	**20**

* Rating for 1 is best, 3 is medium, 5 is worst

Table 14. Performance Values of Considered Pumps

- The diaphragm pump AR245 BP can operate with a considerably high efficiency for the requirements established: its flow rate delivered ranges from 1,4 to 3,5 l/s, and it can pump water up to 120 mca. Furthermore, according to Annovi Reverberi, this device can operate from 200 to 500 rpm, which is an acceptable range for achieving an adequate gearing ratio. Its main advantages are:
  - + Its high efficiency, ranging from 76 to 91% for the given conditions.
  - + Its cost, 1212 € that is the second lowest of the list, and makes it an attractive option from the point of view of cost effectiveness.
  - + Its ability to handle solids, which makes it suitable to operate in context with solids without risk of premature worn out.

  On the other hand, its drawbacks are:

  - Its weight, 46 kg which is high for a pump and would lead to a heavier system to transport.
  - The fact that the minimum speed that is operates is 200 rpm. This leads to a minimum gearing ratio of 10 for waterwheels, in the case they operate at 20 rpm, which imply that the only transmission possible is a gearbox, that is more expensive and heavier than a belt drive.
  - Despite the flowrate delivered by this pump is perfect for the requirements established, in case the customer would like to have a higher flow rate, this pump would not be suitable to provide it.

- The vane pump WindTrans Zelda Pump is an interesting option that has an important clarification to make. The pump operation has only been tested for pressures under 30 mca. Thus, all performance data has been registered for pressures under 30 mca. However, the manufacturer ensures that the machine can work for higher pressures, up to 70 mca. Trusting the word of the manufacturer to reach the required pressure, its main advantages are:
  + Its low rotational speed range of operation, 30 to 200 rpm. This positive displacement pump delivers flow rate depending on the rpm that it operates, and it delivers 2 l/s at 30 rpm and 14,2 l/s at 190 rpm. Thus the range of speed where the pump would work is between 30 and 60 rpm. This implies a reduced gearing ratio (1,5-6 depending on the speed selected for both pump and prime mover) that would be highly suitable for the use of a belt drive, which is less costly and lighter than a gearbox.
  + As mentioned in the previous point it is able to deliver up to 14,2 l/s, a flow rate considerably higher than the rest of the pumps. Furthermore, it delivers this flow rate at 200 rpm, which is close to the minimum rotational speed of the other devices. Thus, for 100 rpm, a speed that is still suitable for the use of a belt drive as transmission, it would deliver 7,57 l/s. This characteristic makes the pump suitable for scenarios with a higher flow rate requirements.
  + Its weight, 20 kg makes it suitable to be carried by one person. Thus, including this pump in the system will enhance its transportation due to a decrease in the overall weight.

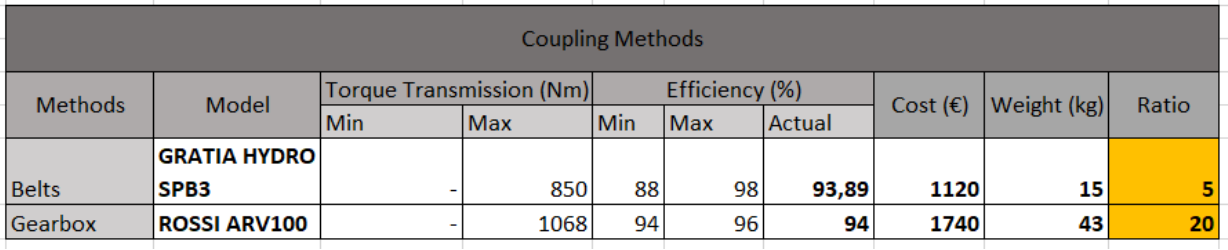
  Its principal drawbacks are the following:

  - Its efficiency is remarkably low, achieving values between 55 and 62% for the given conditions. This is an important disadvantage because almost the half of the power that the pump receives is lost, however, this values of efficiency are registered for pressures under 10 mca, and displacement pumps achieve higher efficiencies as the pressure rises. Thus, it is sensible to think that if the pump can finally operate at higher pressures, as the manufacturer claimed, the efficiency will rise.
  - Its cost, 1588 €, while acceptable is higher than the ones of diaphragm pump and centrifugal pump, which makes it less attractive from the economic point of view.
  - It handles solids and slurries mediocrely, which means that in scenarios with high presence of suspended solids and slurries the pump will worn out prematurely.
  - Despite the manufacturer ensures that the pump can work for pressures up to 70 mca, there is no empiric certainty about this, because the pump is still under

testing process to study its operation at high pressures. There is a possibility that the tests with higher pressures are not successful and the pump cannot provide the required hydraulic head.

5.2.2.3. Transmission Systems

The transmission systems that were finally considered were belt drives and gearboxes. Table 15 displays the performance and characteristics of these two systems.



Coupling Methods									
Methods	Model	Torque Transmission (Nm)		Efficiency (%)			Cost (€)	Weight (kg)	Ratio
		Min	Max	Min	Max	Actual			
Belts	**GRATIA HYDRO SPB3**	-	850	88	98	**93,89**	**1120**	**15**	**5**
Gearbox	**ROSSI ARV100**	-	1068	94	96	**94**	**1740**	**43**	**20**

Table 15. Performance Values of Considered Transmission Systems

In this table the belt drive considered had a gearing ratio of 5:1, the one with the information provided by Gratia Hydro experts. However, if the ratio is different, the cost of the belt drive would vary, as well as its weight. For instance, if the gearing ratio of the belt drive is 3:1, the its cost would be 820 € and its weight would be 11 kg. Thus, just by changing the value of the ratio in the orange cell corresponding to belts, the values of cost and weight will update.

The same happens with the gearbox selected. In this case Rossi ARV100 has been chosen, to see the difference in performance with belt drives. However, there is a list of possible gearboxes with different ratios and different values for cost and weight, the ones shown in Table 23, that can be chosen. To do so, there is a drop down list in the orange cell corresponding to gearbox, where the gearing ratio is chosen, and the information about the corresponding model updates.

Once this has been clarified, the advantages and drawbacks of both methods will be analyzed:

- Belt drive SPB3 proposed by Gratia Hydro would work with efficiency values between 91 and 95,6% for the range of operation conditions considered. Thus, the main advantages of this belt drive are the following:
    - \+ It has good efficiency values above 90%, and its efficiency scales with the power input. Thus, this system would be suitable for scenarios where the power to transmit is higher, always the torque limit is not reached.
    - \+ It is considerably less costly than gearboxes. The mechanism of a belt drive is simpler than the one of a gearbox, and thus the cost of manufacturing is lower. The price of the belt drives ranges from 600 to 1420 € for gearing ratios from 1,5:1 to 7:1.
    - \+ It is considerably light. A belt drive would add an additional weight between 9 and 19 kg for the range of gearing ratios before specified. Thus, this transmission enhances the transportability of the whole system.

  On the other hand its main drawbacks are the following:

    - \- It can only operate with gearing ratios up to 7 in one step. As mentioned before, gearing ratios higher than 7 in one step would imply slipping of the belt and would reduce remarkably the efficiency of the transmission. Furthermore, to install a belt drive with more than one step would highly increase the cost the volume and the weight of the transmission, so it would not be cost effective. Thus, this is the principal drawback of belt drives, which will only be suitable to be used in scenarios with gearing ratios lower than 7.

  - Despite it can transmit high loads, the maximum torque it allows is estimated to be 800 Nm, which is lower than the one allowed by gearboxes. If this limit is reached, the belt will start slipping which implies extra wear and decrease in the efficiency. Thus, its suitability for this aspect must be carefully studied in the hydropower prime mover side, which presents low speed and high torque values.
  - Belts get worn out in a considerable shorter time than gearboxes. While the expected lifetime of a gearbox is 25000 hours, the one of a classic V belt is estimated to be around 5000 hours in the best case [61]. However, this lifetime applies only to the belt not to the pulleys, thus, every 5000 hours only belt should be changed, which cost is estimated in 180 €.
    Hence, despite the initial cost of the belt drive is lower than the initial cost of the gearbox, when taking into account the change of belt cost over 25000 hours they are noticeably similar.

- Gearboxes suggested by Rossi are the a considerably reliable option to choose, in fact they have already been selected to be the transmission system operating in the case of Híjar. The main advantages of these gearboxes are the following:
  - + There is a wide range of models available for different gearing ratios. Despite the ones considered cover the range between 10:1 and 35:1, there are gearboxes both for lower and higher ratios, so they basically have no problem regarding gearing ratio, unlike belt drives.
  - + For the range of power that the gearbox will transmit, Rossi experts ensured that their devices will operate with an efficiency of 94%. This is value is satisfactory, and the fact that it does not vary within the considered range of load makes it a reliable transmission in terms of efficiency.
  - + It has a higher limit of maximum torque to transmit than belt drives, which could be determinant if the torque in the hydropower prime mover side is high to use a belt drive.
  - + Another positive point about gearboxes is that, unless malfunction they only need periodic oil change and their lifetime is estimated to be 25000 hours. Therefore, maintenance cost associated to gearboxes are considerably lower than the ones for a belt drive.

Finally, the drawbacks of using a gearbox are the following:

  - Their main drawback is that they are costlier than belt drives. The price of these devices ranges from 1480 to 2000 €, depending on the gearing ratio selected, while belt drives cost up to 1400 €.
  - The other drawback that gearboxes have is that they are heavy. Its weight vary from 25,2 kg for low power input and gearing ratio devices to 96 to the ones with higher values. This makes them hinder the transportability of the system.

5.2.2.4. Ancillary Components

In this section, the suitability of the different components regarding infrastructure, filters and the transporting methods.

With regards to the hydraulic infrastructure necessary, it was already commented in section 5.2.2.1 the scenarios where a weir could be necessary, so weir will not be treated in this section. Thus, the elements that will be analyzed will be the flow control system and the solid rejection components.

As said before, a flow control system is not strictly necessary, however it would reduce variability of the flow improving the performance of the system. These are the advantages and disadvantages of the options considered:

- Upstream gate: it is the methodology that best regulates the flow rate as it can be manually regulated to let the necessary flow in for each situation. However, it is also the most expensive, with a cost around 1000 €. Furthermore, it requires a canalization to be settled, a gate in the middle of a wild stream or river would be pointless.
  Thus, from the point of view of control this would be the best option, however it is not a cost effective solution, and it requires minimum existing infrastructure.
- Bypass: the bypass considered is a do-it-yourself solution that can help to deviate the overflow from the system, however it is not able to regulate with precision the flow rate that enters in the system. Its cost is estimated in 380 €, considering sand bags as main conforming element, however it may increase depending the dimensions and materials used.
  It is a cost effective solutions, still from the control point of view is not the most accurate.
- Intake conduit or funnel: this solutions that involves a conduit to control the water that passes through the system has an estimated cost around 300 €. It is useful for avoiding overflow, however, as it happened with the bypass, it cannot control precisely the flow rate that goes through the system, so it is cost effective, however not very accurate in flow control.

Unlike flow control system, debris protection elements are essential in order to avoid that floating objects damage the system. These are the advantages and disadvantages of the debris protection elements considered:

- Trash Rack: this element is commonly used in hydropower projects and its reliability is beyond doubt. The trash rack necessary for this project is estimated to cost around 300 €, which is a positive aspect. However, it should be fixed in front of the system to operate, and to do so it is necessary to include some ground infrastructure, or to fix it to the intake of the system, increasing its weight and hindering its transportability. To do so, it is necessary that the hydropower system has some elements in the intake where the trash rack can be attached, such as the ones of Barsha pump shown in Figure 44.

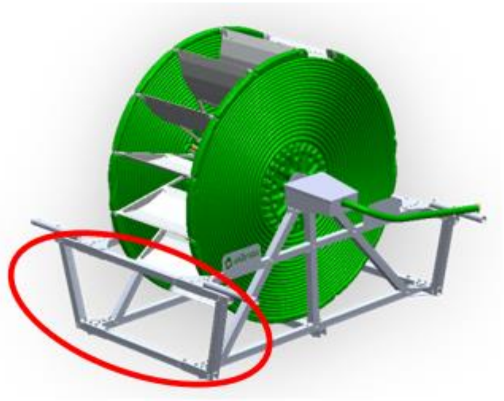


Figure 44. Possible fixing point for the trash rack/screen/grill

Furthermore, depending on the distance between bars, some rocks or minor floating objects can get into the system and damage it. The last disadvantage it has is that debris accumulate in it so it should be periodically cleaned.

- Screen Filter: this is an improved version of trash rack, with regards to solids retention, as it includes a net of bars or filaments. Accordingly it is more expensive than a trash rack, being its estimated cost around 500 €. Furthermore, it also needs to be periodically cleaned, and to be fixed to the ground or attached in front of the system.
- Grill in the Intake: this is another do-it-yourself solution, based on a grill placed in the intake of the system. Thus, the first drawback it has is that it needs an intake for being positioned, for instance a conduit or a structure similar to the one depicted in Figure 44. Secondly, grills are not though to work as a solid retainer partially or totally submerged in water, thus, its reliability is lower than the one of the other options. As well as the two previous options it should be periodically cleaned. However, this is the most economic option with an estimated cost around 45 € and also the most simple, which are important advantages to consider.
- Deflector: this solution that is currently being developed by aQysta could be suitable for future projects. Its price is estimated to be around 500 € when the production process is mature, which is higher in comparison with other possibilities. Nevertheless, its advantages are that it does not need to be cleaned because it just push debris aside front the hydropower pumping system, and it does not need to be attached to the system, as it floats, so it would not increase the weight of the system.

Regarding the filters considered for the inlet of the pump, they can only be analyzed in terms of cost and time to change. Thus, the spin-on filter would be the most expensive with an estimated cost around 28 €, however it is the one that can operate longer time, from 3 to 5 years, depending on the application. Cartridge filters, by the way need to be changed each one or two years at maximum and its cost is around 16 €, being the intermediate type of filter. Finally, bag filters are the less costly, with a cost around 6 €. However they last considerably less than the rest, because they basically accumulate dirt in the bag, gradually obstructing the inlet of the pump. Thus, its time to be changed is estimated around six months.

Finally, the last components to be analyzed are the ones related with the transportation of the system. The selection of these components is based on the total weight of the system with regards to being transported by two people.

According to international standards, the maximum weight a person can lift for work is 25 kg, and in special cases, if the lift of the weight is sporadic and under safe conditions, 40 kg [62]. This, leads to a maximum weight of the system of 80 kg if it wants to be manually lifted by two people. Once this has been clarified, these are the advantages and disadvantages of the different transporting methods:

- Handles: this method involve designing the system as a set, and locating handles in it in order to transport it manually by two persons. This method is advantageous because of its simplicity, and does not require additional components, however it has an important limitation, it is only feasible if the weight of the system is close to 80 kg.
- Wheels to push it rolling: this method would include wheels under the system for push it rolling it. The option of setting them fixed is not very reliable, because it would imply that wheels are submerged and they can get stuck because of dirt and rusty in the worst case.

  One more interesting option is to locate mechanisms for mounting and dismantling the wheels, so when the system is operating in the river they have are dismantled, and when it is necessary to remove the system from the river the wheels are mounted and it is pushed rolling.

  Thus, this solution is more complex than handles, because it implies adding mechanisms and wheels to the system and, unlike handles, that can get stuck because of dirt, overload or time. However, they have important advantages: the ease to drive the system is high, regarding the turn that wheels enable, and especially, that weight is not limited to 80 kg, because pushed rolling the equivalent weight of the system is reduced according to the following expression [63]:

$$Equivalent\ weight\ (kg) = \frac{Total\ weight\ of\ the\ system\ (kg)}{20} + 6{,}5$$

  This expression was developed for objects of 160, 200, 300, 350 and 400 kg pushed rolling over a four wheel cart in a concrete flat ground, so it is important to clarify that in an irregular step ground the weight will not be reduced that much.

- ❖ Skids: this is a solution similar to the wheels with other different advantages and disadvantages. The main advantages of skids are that they are less likely to get worn out as they do not involve rolling mechanisms, and they are more simple than wheels, without need of being dismantled during system operation.

  However, they reduce the weight to push considerably less than wheels, and the ease to drive the system is lower than with wheels because skids do not turn.
- ❖ Detachable system: the last option for transporting the system in case the weight is too large for handling it at once is to make the system detachable. The advantage of this solution is that it does not require any additional component, just a design that enhances the detachability.

  The main disadvantage is that components may be damaged during the process of mounting and dismantling of the system, and if the process of mounting is not properly done, it may lead to malfunction because of misalignment of components.

  However, some configurations, for instance a system with belt drive transmission could be highly synergistic with the detachability of the system. The dismantling of the system would only imply removing the belt drive from the pulleys and separating the pump from the prime mover. Furthermore, as belt drives do not require perfect alignment to operate efficiently, the process of mounting it back would not need to be so precise.

Once all the different components and solutions have been analyzed, the final step would be to decide which are the most suitable combination of devices, based on this previous analysis, and provide solutions to the additional problems that these combination may involve.

5.3. Decision Making and Results

Before starting with the decision making it is important to clarify that the suitability of the combinations will be assessed based on the context conditions and the requirements for the system stated in sections 2.3.1.1 and 2.3.1.2.

5.3.1. Recommended configuration number 1

As it was claimed in previous section Sagebien Wheel is the best performing devices, all considered. It provided the highest efficiency among the waterwheels, and it does not need additional infrastructure to operate. With regards to the cost and weight, they have been estimated to be the same for all waterwheels, while screw turbine, that is the other main candidate, is less costly but heavier. Thus, the first combination will involve a Sagebien wheel.

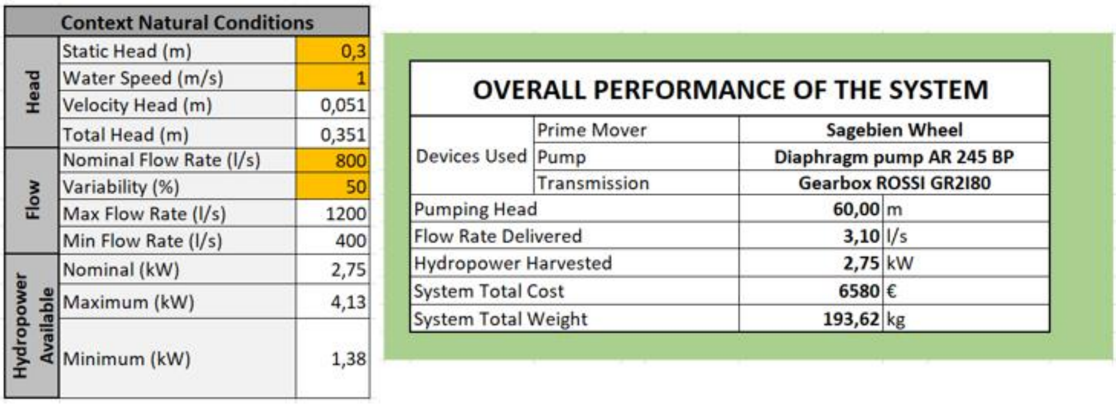
These wheels can operate with rotational speeds between 5 and 20 rpm, so in order to be conservative the design rotational speed will be assumed to be 15 rpm.

With regards to the hydraulic infrastructure, the weir is not necessary. In principle none of the flow control systems will be chosen to be included, because it they are not strictly necessary. However, if further business cases are carried out and the context conditions imply the need of one flow control system, an analysis of flow control versus cost can be carried out to determine which option is the most suitable. Finally, a trash rack will be chosen to protect the system against debris. Making a cost-reliability analysis it is the best performing option, because screens are more costlier, grills are less reliable and the deflector proposed by aQysta is still under development.

In the case of pumps, AR 245 BP diaphragm pump is the best option, regarding the maturity of the technology, the good performance due to head, flow rate and efficiency and the lower cost. The main drawback of this pump is that it operates faster than the vane pump, however, the manufacturer ensured that this pump could operate at a minimum speed of 200 rpm. Thus, the design speed will be decided regarding the flow targeted, trying to avoid values close to 200 rpm in order not to force the pump, for instance 250 rpm. In the intake of the pump a spin on filter will be placed, because it the long term it is the most economic option, and the difference of cost between it and the cartridge filter is not significant regarding the total cost of the system.

Finally, in order to couple the wheel and the pump only gearboxes are suitable, so the model Rossi GR2I80, that has a gearing ratio of 15,7 is the most suitable option, achieving a speed in the pump of 236 rpm.

With these components and for the conditions specified in Table 12 the performance values and characteristics of the system are the following:



Context Natural Conditions		
Head	Static Head (m)	0,3
	Water Speed (m/s)	1
	Velocity Head (m)	0,051
	Total Head (m)	0,351
Flow	Nominal Flow Rate (l/s)	800
	Variability (%)	50
	Max Flow Rate (l/s)	1200
	Min Flow Rate (l/s)	400
Hydropower Available	Nominal (kW)	2,75
	Maximum (kW)	4,13
	Minimum (kW)	1,38

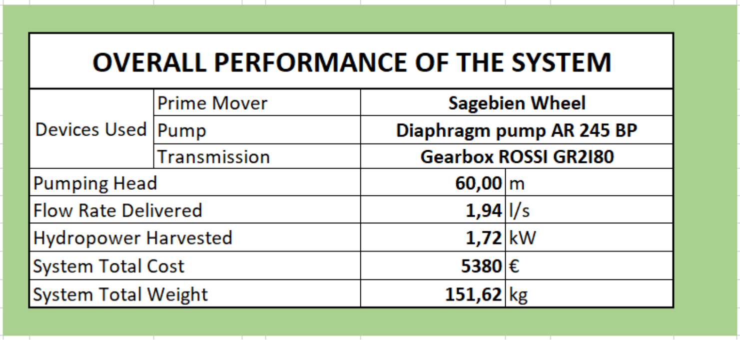
OVERALL PERFORMANCE OF THE SYSTEM			
Devices Used	Prime Mover	**Sagebien Wheel**	
	Pump	**Diaphragm pump AR 245 BP**	
	Transmission	**Gearbox ROSSI GR2I80**	
Pumping Head		**60,00**	m
Flow Rate Delivered		**3,10**	l/s
Hydropower Harvested		**2,75**	kW
System Total Cost		**6580**	€
System Total Weight		**193,62**	kg

Table 16. Input and output values of the Configuration number 1

The objective pumping head was set to 60 meters, and with the given conditions, the flow rate delivered is 3,1 liters per second, which is more than enough regarding the 1-2 liters per second targeted.

The cost of the system is 6580 € which is noticeably higher than the 2500 € targeted. The main source of cost is the wheel, which estimated cost for a 2,8 kW design is 3360 €. This makes the system more expensive than expected. However, the system is highly versatile and can operate for higher pumping heads with lower flow rates and vice versa. For instance, if the pumping head is set to 130 meters, the flow rate delivered would be 1,57 liters per second, and for a head of 40 meters the flow rate delivered would be 4,52 liters per second.

It is also important to consider that in case the system is too costly, the power designed can be lowered, for instance, if the system is, with the same natural conditions, designed for a nominal flow rate of 500 liters per second, and subsequently a nominal power of 1,72 kW, the table of the overall performance of the system would be the following:



OVERALL PERFORMANCE OF THE SYSTEM			
Devices Used	Prime Mover	**Sagebien Wheel**	
	Pump	**Diaphragm pump AR 245 BP**	
	Transmission	**Gearbox ROSSI GR2I80**	
Pumping Head		**60,00**	m
Flow Rate Delivered		**1,94**	l/s
Hydropower Harvested		**1,72**	kW
System Total Cost		**5380**	€
System Total Weight		**151,62**	kg

Table 17. Output values of Configuration number 1 designed for 1,72 kW

As it can be observed, for the same pumping head, the flow rate delivered have been reduced, as well as the system total cost and its weight. Thus, for all the combinations, the output values will be displayed are the ones related with the conditions shown in Table 12 and Table 16. However, it must be taken into account that if the cost or weight of the system are too high, or simply such high head and flow rate are not necessary, the system can be scaled down by setting a lower design flow.

Finally, with regards to the weight of the system, it is estimated to be 193,62 kg for this configuration. It means that handles are not a feasible method for transporting it. As it uses a gearbox as transmission element, detachability would be complex, so the most suitable methods would be wheels or skids. In this case wheels are chosen, because of the higher degree of handling they provide.

To sum up, the components included in this first configuration are the following:

- Trash rack
- Sagebien Wheel
- AR 245 BP diaphragm pump
- Gearbox Rossi GR2I80
- Spin-on filter
- Wheels to transport the system

5.3.2. Recommended Configuration number 2

In this configuration, the hydropower prime mover that will be used is the screw turbine, due to its numerous advantages: high efficiency, higher operation speed and lower cost than waterwheels. This is an important advantage in order to achieve a cost effective system, because while waterwheels cost is estimated to be around 1200€/kW, screw turbine would cost around 700€/kW, which is considerably lower. Screw turbines can operate within 20 to 40 rpm, which also provides an important advantage regarding the reduction of the gearing ratio. Thus, the screw turbine can be designed for operating at a nominal speed around35 rpm, in order not to operate it at the limit of 40 rpm. However for this configuration a weir would be necessary, in order to reach the meter of head required for the use of the screw turbine. Furthermore, the weight of the system will increase, so transportability will be slightly hindered.

Thus, the hydraulic infrastructure used will be the following: a weir of 0,7 meters in order to reach the meter of head. The cost of this weir is estimated to be around 1050€, however, there are several possibilities with regards to its inclusion in the project:

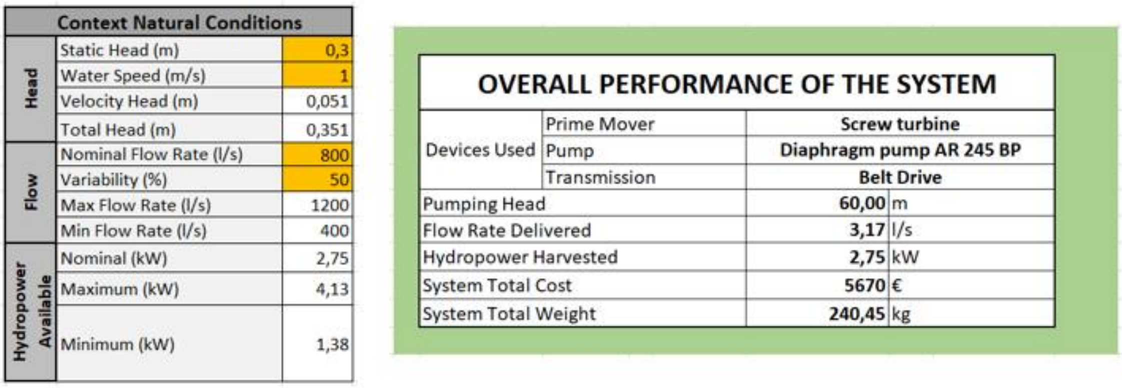
- To include it within the scope of the project
- To guide customers to build it themselves

If the cost of the system is too high to be assumed by customers, aQysta can provide guidance to them about how to build a weir themselves, with cheap materials, such as sand bags, which are easily manageable. By contrast, if project budget allows it, the weir can be included within the scope of the project. In this case the cost will be included within the project.

Like Configuration number1, Configuration number2 will not include any flow control system, because it is not necessary for its performance. Finally, the debris protection system chosen will be a trash rack, for the same reasons that were explained for Configuration number1.

In this configuration, the pump selected will also be AR 245 BP pump because it is more mature and reliable than Zelda Pump, which performance at high pressure still has not been verified. In this case it would be interesting to try to operate the pump at lower speed than in Configuration number1, 220 rpm for instance, because with this configuration it would be possible to use a belt drive to transmit power, which would reduce the cost of transmission. Thus, the transmission proposed for this configuration is a belt drive with a gearing ratio of 6:1. In this configuration the spin on filter will be also selected to be placed in the intake of the pump, for the same reasons as in Configuration number 1.

The performance values and characteristics of Configuration number 2 would be the following:



	Context Natural Conditions	
Head	Static Head (m)	0,3
	Water Speed (m/s)	1
	Velocity Head (m)	0,051
	Total Head (m)	0,351
Flow	Nominal Flow Rate (l/s)	800
	Variability (%)	50
	Max Flow Rate (l/s)	1200
	Min Flow Rate (l/s)	400
Hydropower Available	Nominal (kW)	2,75
	Maximum (kW)	4,13
	Minimum (kW)	1,38

OVERALL PERFORMANCE OF THE SYSTEM			
Devices Used	Prime Mover	**Screw turbine**	
	Pump	**Diaphragm pump AR 245 BP**	
	Transmission	**Belt Drive**	
Pumping Head		**60,00**	m
Flow Rate Delivered		**3,17**	l/s
Hydropower Harvested		**2,75**	kW
System Total Cost		**5670**	€
System Total Weight		**240,45**	kg

Table 18. Input and output values of the Configuration number 2

As it can be observed, it provides a slightly higher flow rate than Configuration number 1, and the cost of the system is 5670 €, 910 € lower than the one of Configuration number 1, even with the weir included in the scope of the system. The main lack of this configuration is the weight, that is 50 kg higher than for Configuration number 1. However, this overweight can be effectively handled with the wheels system to push the system rolling at the time of transporting it. In this case detachability could have been a solution, but the screw turbine itself has a weight of 168 kg, which is not suitable to be carried, even by two people.

As commented for Configuration number 1, this system can be scaled in power in order to achieve other performance values and other costs and weight related. To conclude, these are the components included in Configuration number 2:

- Weir
- Trash rack
- Screw turbine
- AR 245 BP diaphragm pump
- Belt drive SPB3 6:1
- Spin-on filter
- Wheels to transport the system

5.3.3. Recommended Configuration number 3

As it was mentioned before, currently the Zelda Pump has only been verified for low pressures close to 30 mca, which is not suitable for this project. However, WindTrans experts are working to reinforce the vanes in order to achieve pressures higher than 50 mca, which is the target of this project. For Configuration number3, the assumption that these tests about WindTrans Zelda Pump working efficiently within the range of pressures required have been successfully passed will be taken.

In this case the prime mover selected will be Sagebien wheel, designed for 2,75 kW and to operate nominally at 15 rpm. It does not need any infrastructure but the trash rack to protect it from debris.

Obviously, for this scenario the Zelda Pump vane pump will be the one chosen, and to achieve the correct equilibrium between head and flow rate it should operate at 29 rpm. It is important to observe that in the model, the efficiency of the pump for this operational speed would be 50,73%, which is remarkably low. This would be one of the values that the assumption before explained would change. One of the characteristics of displacement pumps is that their efficiency scales with pressure, thus, if in the future the pump is able to reach higher pressures it is sensible to think that the efficiency will increase too. However, it must be noticed that the range of rpm where the pump would operate in this project due to the requirements is the begin of the efficiency curve estimated, shown in Figure 45.

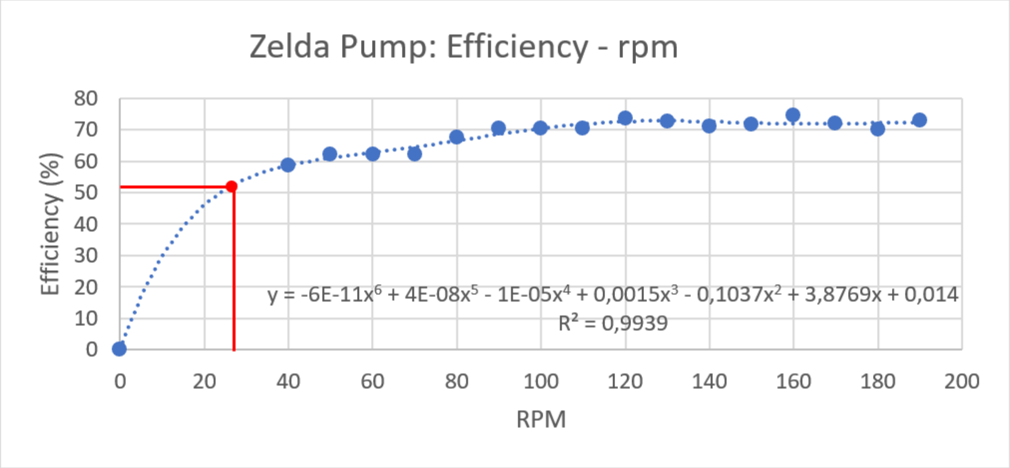


Figure 45. Efficiency curve of Zelda Pump

This means that despite the maximum efficiency achievable increases, the efficiency of the pump for these operation points would not increase with the same rate. For instance, Figure 46 shows the estimated curve for this conditions, and in that case the efficiency Zelda Pump would display for 29 rpm would be around 63%, which is still low.

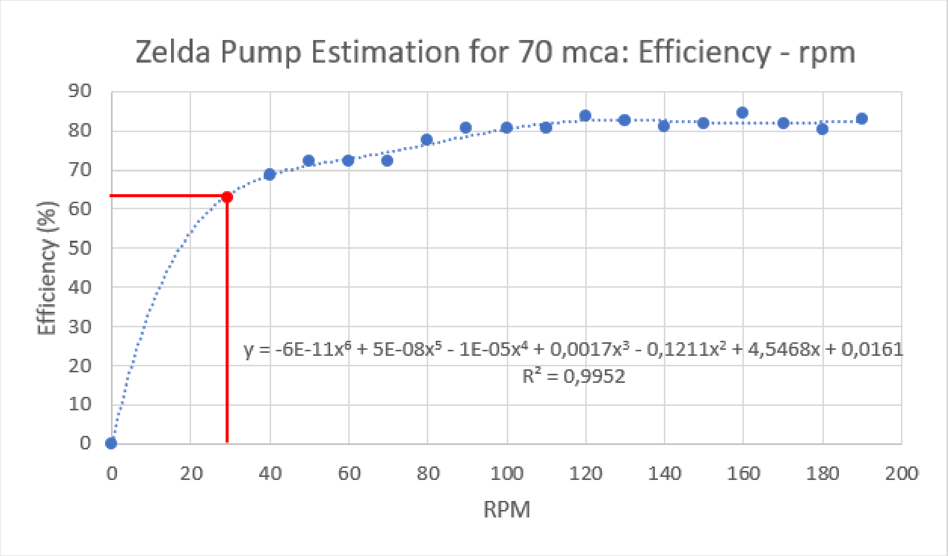
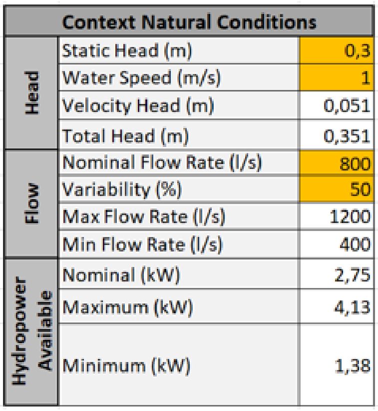


Figure 46. Estimation of efficiency of Zelda Pump for higher pressure

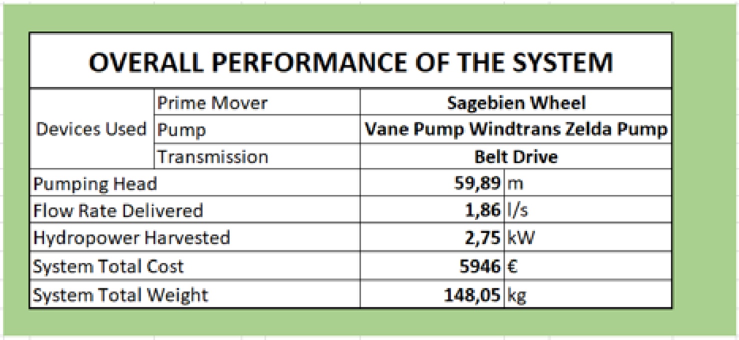
However, all this is based on the estimation of the curve for higher pressures, that not necessarily will be like that, thus the efficiency that will be currently assumed will be 50,73%, that is the one provided by WindTrans technical sheets.

The spin on filter will be also the filter placed in the intake of the pump.

Regarding the transmission system, the gearing ratio resulting of these two devices would be 1,93:1, which is absolutely suitable for a belt drive. Furthermore, as the gearing ratio is considerably low, the cost of the belt drive to install will be low too, being estimated around 670 €. Table 19 provides the performance values and characteristics of Configuration number3:



Context Natural Conditions		
Head	Static Head (m)	0,3
	Water Speed (m/s)	1
	Velocity Head (m)	0,051
	Total Head (m)	0,351
Flow	Nominal Flow Rate (l/s)	800
	Variability (%)	50
	Max Flow Rate (l/s)	1200
	Min Flow Rate (l/s)	400
Hydropower Available	Nominal (kW)	2,75
	Maximum (kW)	4,13
	Minimum (kW)	1,38



OVERALL PERFORMANCE OF THE SYSTEM			
Devices Used	Prime Mover	**Sagebien Wheel**	
	Pump	**Vane Pump Windtrans Zelda Pump**	
	Transmission	**Belt Drive**	
Pumping Head		**59,89**	m
Flow Rate Delivered		**1,86**	l/s
Hydropower Harvested		**2,75**	kW
System Total Cost		**5946**	€
System Total Weight		**148,05**	kg

Table 19. Input and output values of the Configuration number 3

It can be observed that for the same power input that the other configurations had , the flow rate delivered at 60 meters is noticeably lower, 1,86 liters per second, due to the low efficiency of the vane pump. However this configuration is in the midpoint between configurations number 1 and number 2 regarding cost. It is less costly than Configuration number 1, however more than Configuration number 2, and it is the lightest configuration with a total weight of the system of 148,05 kg.

This fact, together with the use of a belt drive as transmission system makes it suitable to be designed as a detachable system regarding transportation. Nonetheless, the system would be detached into a pump, which weight would be 25 kg, including the pulley of its side, and the wheel, which weight would be 125 kg, also with its pulley included. Perhaps 125 kg is too heavy to be carried by two people, so in case it is found unfeasible, wheels can always be added to the system in order to push it rolling.

The resume of the components involved in Configuration number 3 would be the following:

- Trash rack
- Sagebien wheel
- Zelda Pump vane pump
- Belt drive SPB3 2:1
- Spin-on filter
- Detachable (if feasible)/Wheels to transport the system

5.3.1. Recommended Configuration number 4

Finally, configuration number 4 will be the last system proposed and it relies on the closeness between the rotational speeds of screw turbine and Zelda Pump vane pump. Screw turbine operates from 20 to 40 rpm and Zelda Pump, for the required output values would operate between 25 and 48 rpm. This leads to the possibility of operating them without any transmission system involved, just a flexible coupling between both devices, reducing the cost, the weight and the complexity of the system.

Thus Configuration number 4 would have a screw turbine designed for 2,75 kW and to operate at a nominal speed of 32 rpm, with the weir of 0,7 meters before commented and the trash rack to protect the system against debris.

The pump chosen for this configuration will be the Zelda Pump and it will be operating at a nominal speed of 32 rpm. Thus it will be possible set the same rotational speed for both devices, so they can be directly coupled by a flexible coupling. As it happened in all the other configurations, spin on filter is the filter chosen for the pump.

The flexible coupling was not included within the transmission methods considered in section 4.1.3, because the possibility of achieving a system where both prime mover and pump rotate at the same speed was not considered, given the low range of speed that prime movers operated with, and the higher range of speed that pumps displayed. Only after observing the performance values of Zelda Pump, and that it can operate at low rpm, the idea of a direct coupling emerged. This happened at the final step of the thesis, so it would take a lot of effort and time to include the flexible coupling in the previous steps. Thus, it will be briefly explained below, and included in the Assessment Model.

Flexible couplings are a type of transmission system which transmits torque from one shaft to another. They are frequently used when the two shafts are slightly misaligned, because they can cope with this misalignment, either it is an angle misalignment or a parallel misalignment. However, for the system resulting of MIT this is not the main advantage of flexible couplings, but the fact that they transmit power with a ratio 1:1, so they can be used in this particular configuration. There are several types of flexible couplings: jaw, gear, grid, fluid and torsional. For this application the ones selected will be jaw type, because they are the most simple and economic.

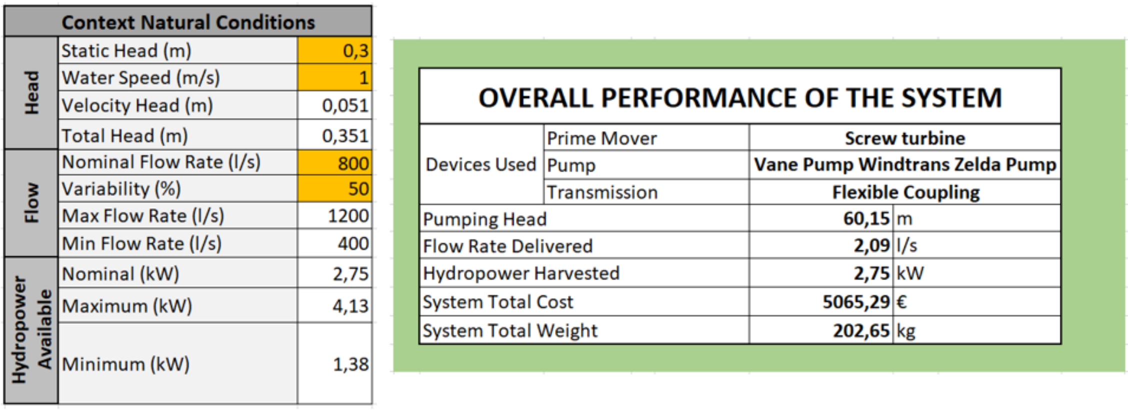
Jaw couplings are formed by three elements: two metallic hubs (the metallic parts of Figure 47) and an elastomer insert commonly referred as a spider(the red part of Figure 47). The three parts press fit together with a jaw from each hub fitted alternately with the lobes of the spider. Jaw coupling torque is transmitted through the elastomer lobes in compression.

Figure 47. Jaw Flexible Coupling

Looking at the websites of different manufacturers such as The Rowland Company [64] and KTR [65] technical information about these couplings was found out. There are jaw couplings of different sizes design to operate with different torque specifications. In the catalogue of The Rowland Company the model Sure-Flex 12" was studied, and its performance is suitable for the project. It can operate with a maximum of 813 Nm and 8,5 kW at 100 rpm, which is more than enough in order to cover the 2,3 kW at 32 rpm that need to be transmitted. Its weight would be around 5 kg.

Furthermore, in a quotation of KTR elements two different jaw couplings were quoted: one for a maximum torque of 310 Nm with a price of 89,12 € and other for 3600 Nm with a price of 385,8 €. None of them is suitable for this project, the first because the maximum torque is too low and the second one because it would be overdesigned. However an estimation of the cost of the proper jaw coupling can be done with this quotation. The result of this estimation is that a jaw coupling for 813 Nm would cost around 132,59 €.

Thus, the performance values and main characteristics of Configuration number 4 would be the following:



Context Natural Conditions		
Head	Static Head (m)	0,3
	Water Speed (m/s)	1
	Velocity Head (m)	0,051
	Total Head (m)	0,351
Flow	Nominal Flow Rate (l/s)	800
	Variability (%)	50
	Max Flow Rate (l/s)	1200
	Min Flow Rate (l/s)	400
Hydropower Available	Nominal (kW)	2,75
	Maximum (kW)	4,13
	Minimum (kW)	1,38

OVERALL PERFORMANCE OF THE SYSTEM			
Devices Used	Prime Mover	**Screw turbine**	
	Pump	**Vane Pump Windtrans Zelda Pump**	
	Transmission	**Flexible Coupling**	
Pumping Head		**60,15**	m
Flow Rate Delivered		**2,09**	l/s
Hydropower Harvested		**2,75**	kW
System Total Cost		**5065,29**	€
System Total Weight		**202,65**	kg

Figure 48. Input and output values of the Configuration number4

With regards to the performance values at the speed of 32 rpm it reaches 60,15 meters and delivers 2,09 liters per second. Furthermore the limits of operation would be 1,15 liters per second delivered at a height of 85 meters for 20 rpm and 2,71 liters per second delivered at a height of 50,4 meters for a speed of 40 rpm. Despite the efficiency of Zelda Pump is low, these are good performance values which can cover the range required.

Furthermore, this is the less costly configuration, even with the weir included within the scope of the project. The total estimated cost is 5058,59 €. This makes it an attractive option from the cost effectiveness point of view. Besides this, its weight is estimated to be 202,65 kg which is not a poor value regarding transportability. The wheels are the component that fits best with this configuration, because the weight is too high to carry it and wheels provide a higher ease for handling it than skids.

To sum up these are the components included in the Configuration number 4:

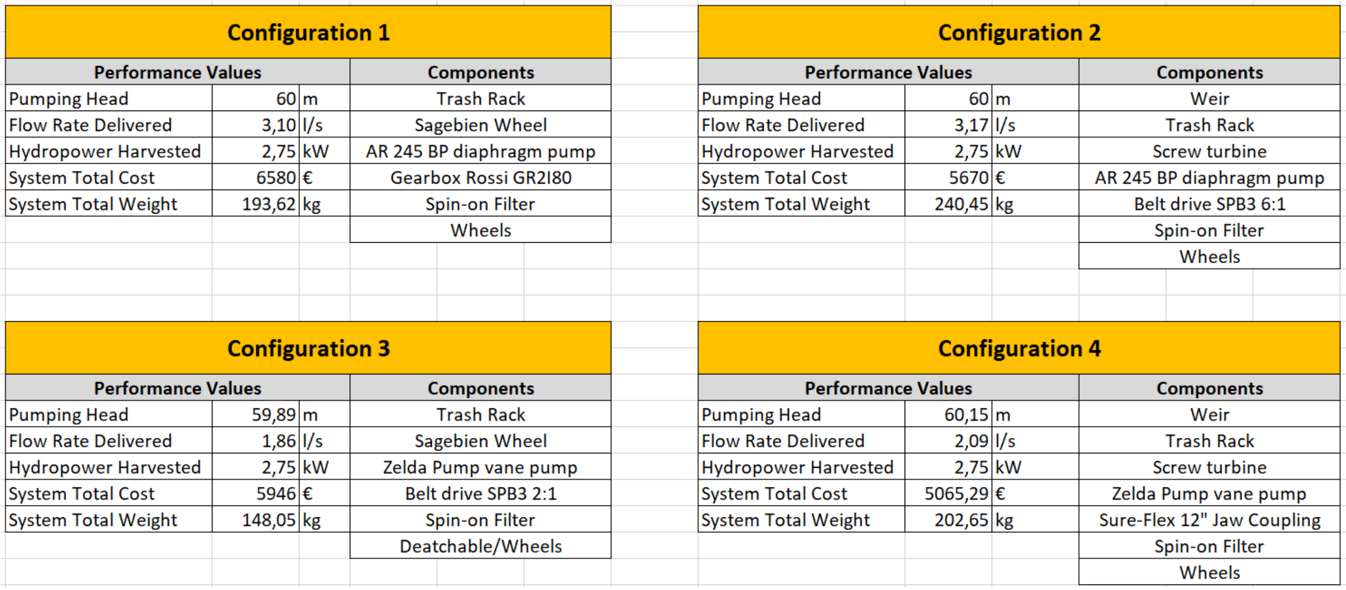
- Weir
- Trash rack
- Screw turbine
- Zelda Pump vane pump
- Sure-Flex 12” Jaw Coupling
- Spin-on filter
- Wheels to transport the system

These are the four configurations proposed for the system to be developed in the future by aQysta as result of MIT project. Each of them have different characteristics regrading performance, cost, reliability or maturity of the technology used, however, there is no one configuration that outstands in all these features. Thus, in order to decide which of the configurations is more convenient for aQysta, preferences should be made about which of these features are more important.

6. Conclusions and Recommendations

6.1. Conclusions

The result of this thesis are the four configurations recommended in section 5.3, which overall performance is resumed in Table 20. In order to reach the performance values that are displayed in this table many data was retrieved from scientific articles and manufacturers brochures as well as many assumptions have been taken in order to estimate unavailable data that was necessary and to simplify the model and the calculations.



Configuration 1

Performance Values			Components
Pumping Head	60	m	Trash Rack
Flow Rate Delivered	3,10	l/s	Sagebien Wheel
Hydropower Harvested	2,75	kW	AR 245 BP diaphragm pump
System Total Cost	6580	€	Gearbox Rossi GR2I80
System Total Weight	193,62	kg	Spin-on Filter
			Wheels

Configuration 2

Performance Values			Components
Pumping Head	60	m	Weir
Flow Rate Delivered	3,17	l/s	Trash Rack
Hydropower Harvested	2,75	kW	Screw turbine
System Total Cost	5670	€	AR 245 BP diaphragm pump
System Total Weight	240,45	kg	Belt drive SPB3 6:1
			Spin-on Filter
			Wheels

Configuration 3

Performance Values			Components
Pumping Head	59,89	m	Trash Rack
Flow Rate Delivered	1,86	l/s	Sagebien Wheel
Hydropower Harvested	2,75	kW	Zelda Pump vane pump
System Total Cost	5946	€	Belt drive SPB3 2:1
System Total Weight	148,05	kg	Spin-on Filter
			Deatchable/Wheels

Configuration 4

Performance Values			Components
Pumping Head	60,15	m	Weir
Flow Rate Delivered	2,09	l/s	Trash Rack
Hydropower Harvested	2,75	kW	Screw turbine
System Total Cost	5065,29	€	Zelda Pump vane pump
System Total Weight	202,65	kg	Sure-Flex 12" Jaw Coupling
			Spin-on Filter
			Wheels

Table 20. Resume of the Configurations Proposed

Thus, next step is that aQysta team studies the benefits and disadvantages of each configuration and decides which one is the most suitable due to the requirements and expectations of the potential customers. Once a configuration is chosen to be develop the phase of design and prototyping would begin.

In this design phase the data available in this thesis should be properly verified, because some of the assumptions and estimation can lead to inaccurate data, and further contacts with manufacturers and experts should be carried out in order to expand the information about devices as well as getting advices of the best practices with them.

Furthermore, it is important to clarify that all these configurations are just suggestions for the design of the hydropowered pumping system. Thus, one interesting advantage is the flexibility available for the design: if one particular character or component of a configuration is not desired or other one is found that could provide a better performance, there is a possibility of changing them.

Also system can be designed for other different conditions regarding the hydropower available in the context if necessary as well as it can be designed for other specific nominal values of power and rotational speed if they generate a more suitable system.

6.2. Recommendations for Future Research

Finally, some advices and recommendations will be given in order to improve the Assessment Model and use it to generate a high performance hydropower pumping system, and to learn from the mistakes that were made to not repeat them.

- As it was commented before, several assumptions have been made during this thesis in order to simplify or to estimate unavailable data. Generally these estimations were not just assuming random values but elaborating formulas to estimate with the available data and choose values for the unavailable based on other similar cases found.

  However, these estimations may not be as precise as desired and could lead to mistaken information, thus, it would be recommendable to revise them, verify data and estimate again the values that are not fair enough.

- In this thesis the infrastructure was assumed to be included within the scope of the system. Thus, in principle aQysta would provide both the system and the infrastructure necessary for it to operate in each context. It is important that this is reconsidered and clearly defined, because it makes a big difference both regarding cost and complexity of the project to just provide the hydropower pumping system or provide the infrastructure too.

- Despite in this thesis the requirements of the system and the conditions of the context were defined, they were defined as intervals instead of concrete values. It could be advantageous to shorten these intervals or to set concrete values, in order to determine the suitability of different devices. For instance, one flexible impeller pump suggested by the expert of Verder could reach the 45 meters, so it could not cover the whole interval of head, 40-80 meters, however it could have been considered if the pumping head is set to 40 meters.

- With regards to the previous point, there was not a clear definition of who are the potential customers of the system resulting of MT project. This is important because it could change the definition of requirements and the budget of the system. For instance, if the target customer is a farmer with small land, the budget will be low and the requirements too. On the other hand, if target customers are big farmers or cooperatives, the requirements will be higher as well as the cost of the system.

- The conditions assumed for the context where the hydropowered pumping system will operate are defined by ranges of values. For instance, head is between 0 and 0,5 meters and natural flow rate between 200 and 2000 liters per second. Thus, systems that do not meet these conditions would not be in principle suitable for the installation of the hydropower pumping system.

  However, it could be advisable to consider a design of the system that enhances scalability in order to operate in other conditions. Hence, the system is designed for the given conditions, however if it is observed that there is a group of contexts with different conditions that could be interesting for the installation of the system, the system could be scaled in order to operate efficiently in this other group of system with different characteristics.

- In the Assessment Model one approach was made in order to simplify the coupling of prime mover and pump. This approach is based on the assumption that the rotational speed of both devices can be selected, so for instance the waterwheel is set to operate at 16 rpm and for convenience of gearing ratio the pump operates at 250 rpm.

  This is actually not possible, when two of these devices are coupled both of them have a curve of power versus speed. In order to couple them effectively it is necessary that they both operate in the point of intersection of their curves, or point of equilibrium. Thus, this point is the one that fixes the rotational speed of both devices, they could not be defined arbitrarily.

  Furthermore, each hydraulic system has a particular curve head versus flow rate that has to be matched with the pump curve as shown in Figure 49. The equilibrium pump determines the pressure that the pump needs to provide to lift water to the specific point and the flow rate delivered.

  It is important to clarify that each pump has different head versus flow rate curves depending on the speed that it operates. Thus, in order to define the rotational speed of both prime mover and pump it is necessary to determine first which is the rotational speed of the pump that provides the required conditions due to head and flow rate, and then design the hydropower prime mover so the curves power versus speed of both devices can match in the necessary point.

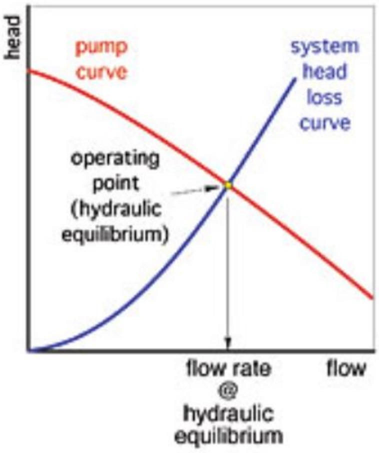


Figure 49. Equilibrium point of a hydraulic system

- Related with the first point, the estimations made for determining the costs of the infrastructure elements included in the project were rough. In some cases they were based on information that aQysta had of past projects while in others it was just calculated by assuming materials and labor costs. These estimations may not be accurate, so if the infrastructure is decided to be included within the scope of the project, it would be highly recommendable to make a more accurate estimations for the costs of those elements.

- In this thesis a wide range of devices techniques and technologies for hydropower harvesting, pumping and power transmission have been considered. However, it is possible that some punctual devices or techniques have been discarded or not considered even when they could have performed well. Thus, it could be advantageous to observe the devices and techniques that have been considered, and try to find other ones that could be suitable too in order to included them in further studies.

- In relation with the previous point, some young technologies have been considered during this thesis, and some of them, as the Zelda Pump was recommended to be used. However, in the case of this young technologies it is crucial to follow closely their development in order to be aware of any news. Some technologies may be found not suitable for this purpose during testing phase, will the suitability of others may increase.
- Finally, a highly remarkable comment to include is the fact that from the recommended configurations the less costly is estimated to cost around 5065 € which is more than twice the price that was proposed by aQysta board and stakeholders, that was between 1500 and 2500 €.

  The fact is that to design a hydropowered pumping system that meets the performance requirements for such a low price is almost unconceivable. The aggregate cost of all the components involved make the cost increase, surpassing the price proposed. It is possible to scale the system in power and reduce slightly the cost, however, the cost of some components is fixed, so the price proposed is not reachable.

  Nevertheless, if the price willing to pay increases up to 4000 – 5000 €, all the combinations proposed are suitable, and the performance ranges they offer are wide, from the minimum requirements imposed to higher values. Thus, these configuration correspond to higher cost - higher performance hydropowered pumping systems, as it was explained in section 2.3.1.2.

  In order to find out suitability of this type of system within the market, a market research should be done to know if this kind of systems are seen positively by potential customers, or oppositely they are not willing to pay more than the price proposed in the surveys.

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ANNEXES

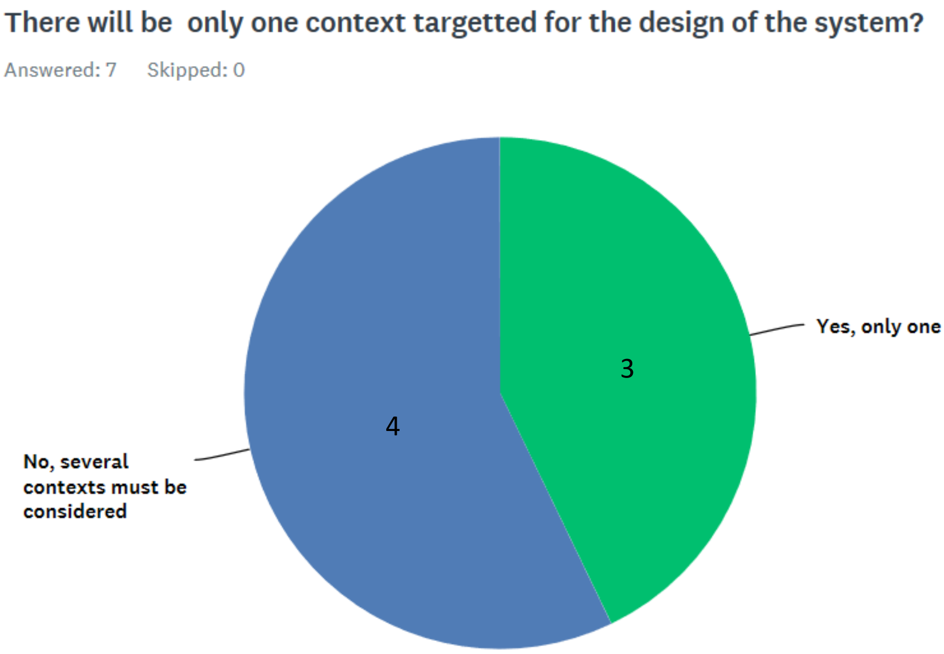
Annex I: Survey

This Annex includes all the information about the questions and answers that were formulated in the survey to define the requirements of the hydropowered pumping system and the context conditions.

Context Definition

- There will be only one context targeted for the design of the system?

Yes, only one	No, several contexts must be considered



In the first question the survey respondents did not reach a common response, 3 of them answering that the system should focus on one context for its design, and 4 that it should consider more than one context in its design, so the system should be applicable to several contexts.

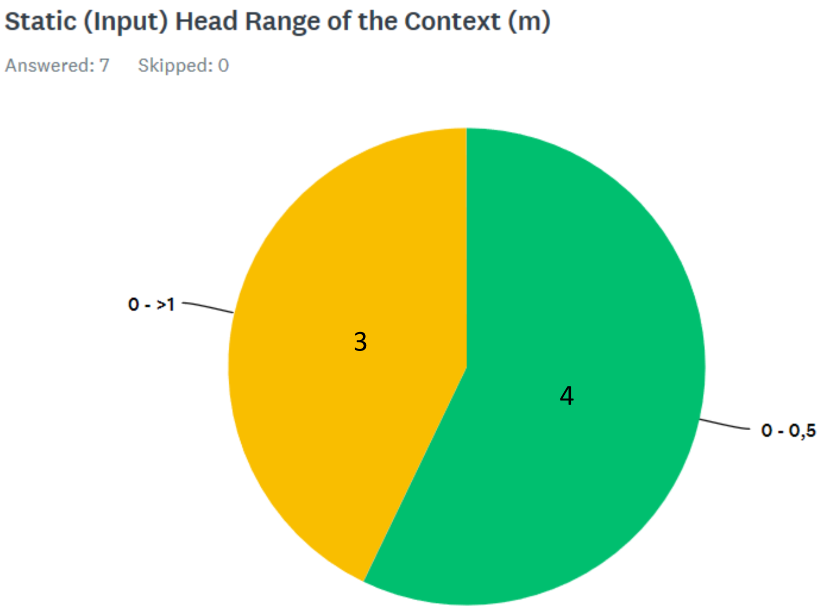
Despite there is a light majority of the respondents that chose several context to be considered, one of the main complaint of Barsha pump was the poor performance it provides in some contexts. This is because Barsha pump was designed to fit a great number of contexts, not having a good performance and achieving a low efficiency in most of them, what is commonly called "one size fits all".

In order not to repeat past mistakes a different decision will be made. The design of the system will be focus on one context, that will be the one that is most available, the one that is defined in the later questions of the surveys. Furthermore, just in case there are some other different contexts where the hydropowered pumping system could operate, it is important to consider making the system scalable, so that by changing the scale of some components it can have a good performance for the conditions of these other contexts.

With this approach, the objective is to develop a system with a good performance in the specific context targeted, with the possibility of scaling it in order to achieve a good efficiency in scenarios with different conditions.

- Static input head range of the context (m)

0 – 0,5	0 - 1	0 - >1	Other (specify)

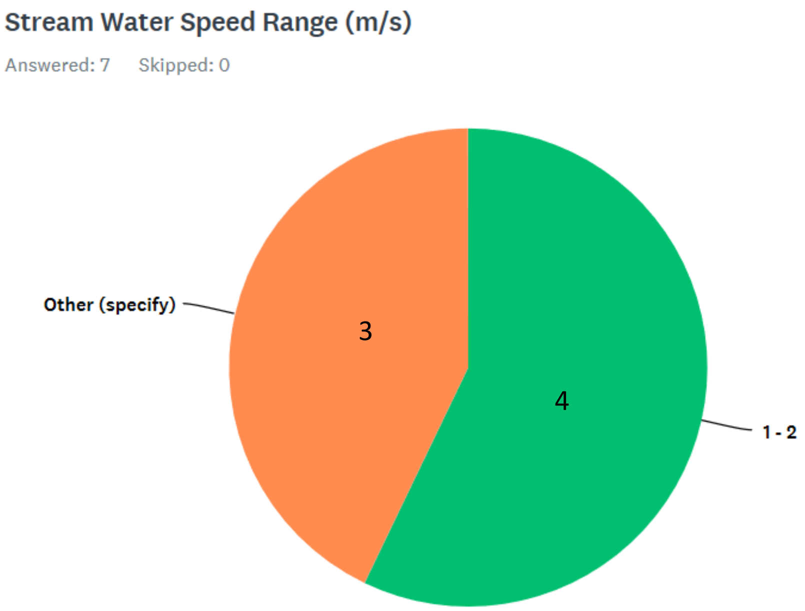


In the second question two different responses were chosen: a context that considers a static input head up to 0,5 meters and other where the static input head can reach values higher than 1 meter.

The fact is that considering contexts with a static input head higher than 1 meter would be to include contexts with considerable different conditions under the same category. Thus, a device that operates efficiently in a context with 0,3 meters of input static head cannot be guaranteed to operate with the same efficiency in a 2 meters context. Thus, to avoid the previous mentioned concept of one size fits all, the targeted contexts will be the ones with a static input head up to 0,5 meters. If at some point there is an aim to operate in higher head contexts it will be necessary to scale the system.

- Stream water speed range (m/s)

1 - 2	2 - 5	5 – 8	> 8	Other (specify)



Other Responses:

- 0,5 – 1 m/s
- 0 – 2 m/s
- 0,4 – 1,5 m/s

In this third question, there was a quorum between the respondents, being the most chosen answer a water speed of 1 – 2 m/s. However, some people thought that it is advisable to consider lower water speed. The fact is that water speeds around 0,5 m/s are not source of energy:

$$Velocity\ head = \frac{v^2}{2 \cdot g} = \frac{(0{,}5\ m/s)^2}{2 \cdot 9{,}81\ m/s^2} = 0{,}012\ m$$

As the upper equation shows, the velocity head corresponding to a stream with a water speed of 0,5 m/s is insufficient for the purpose of the system, and to prove it a simple estimation will be done. Let us assume an scenario where the required pumping head and flow rate are 50 meters and 1 liter/second respectively, according to the answers provided by stakeholders in the previous section. The context is having no static head, and a water speed of 0,5 m/s, and the efficiency of the overall system is 50% to be conservative. The required stream flow rate for the system to operate would be:

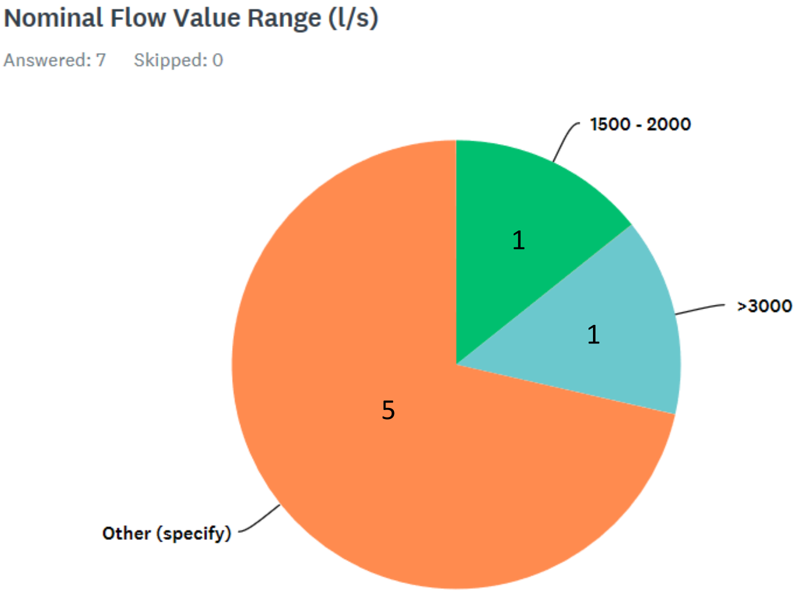
$$P_{need} = \frac{h_{pump} \cdot Q_{pump} \cdot g}{\eta_{system}} = h_{context} \cdot Q_{context} \cdot g$$

$$Q_{context} = \frac{h_{pump} \cdot Q_{pump}}{\eta_{system} \cdot h_{context}} = \frac{50\ m \cdot 1\ l/s}{0{,}5 \cdot 0{,}012\ m} = 8.333\ l/s$$

The calculated flow rate is noticeably high and it could restrict considerably the number of contexts where the system will work. Thus, making the same calculations for a water speed of 1 m/s, the required flow rate is 2.000 l/s, which is still high, however the number of scenarios that can provide it will be much higher than the ones which can provide 8.333 l/s. Thus, the targeted context will be assumed to have a water speed of 1 – 2 m/s.

- Nominal flow value range (l/s)

1500 - 2000	2000 - 2500	2500 – 3000	> 3000	Other (specify)



Other Responses:

- 100 - > 3000 l/s
- 100 - > 1000 l/s
- < 2000 l/s
- 500 – 1500 l/s
- < 1500 l/s

In this question many different answers were given, however some common features can be observed. Five of the seven answers implied a minimum for the nominal flow rate of 500 l/s, and 4 of them even considering 100 l/s as the minimum. However, a nominal flow rate of 100 l/s would need a head higher than the defined to provide the power needed by the pump. Assuming a flow rate of 100 l/s an input head of 0,5 meters and the output values of 40 meters and 1 liter/second, with a system overall efficiency of 50% to be conservative:

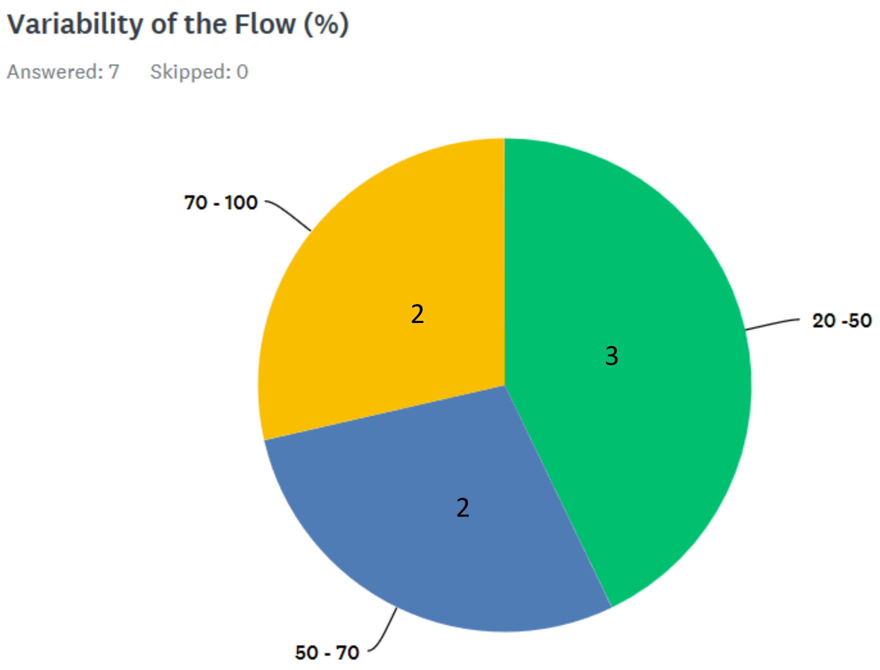
$$P_{available} = 0{,}5 * 100 * 9{,}81 = 490{,}5\ W$$

$$P_{necessary} = \frac{50 * 1 * 9{,}81}{0{,}5} = 981\ W$$

The hydropower available would be the half of the hydropower necessary to meet the requirements established. Thus, it is appropriate to set the minimum nominal flow rate targeted in 200 l/s, which under those conditions would achieve the goal. The maximum nominal flow rate is less important to be defined for the context, because if the stream, canal or river has a higher flow rate, it is possible to limit the flow that goes through the system. Thus, the upper limit will define the flow rate that goes through the system, and it will be 2000 l/s, that is the average of the upper limits provided by respondents.

- Variability of the flow (%)

20 - 50	50 - 70	70 - 100	Other (specify)

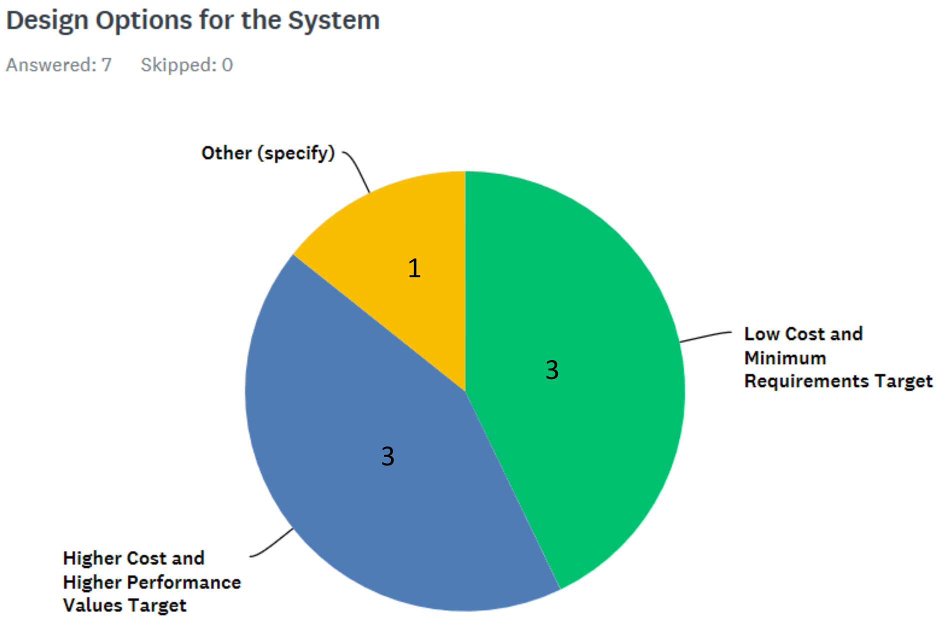


The variability of the flow rate is a topic where the respondents did not agree. Actually, the three answer proposed got 2, 2 and 3 respondents respectively. A variability of 20 – 50% was the most chosen option, however, to consider the answers provided by the other people the final range of variability will be chosen to be 40 -60%.

<u>Performance Values of the System</u>

- Design options for the system

Low cost and minimum requirements target	Higher cost and higher performance values target	Other (specify)



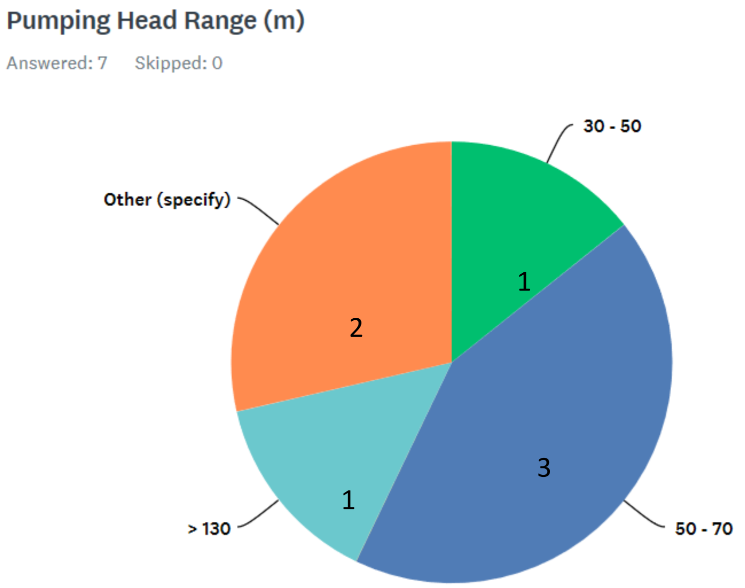
Other Responses:

- Low cost and higher performance values

The two design options suggested for the system were a higher cost-higher performance system, or a low cost-minimum requirement satisfying system. The two options were equally voted with 3 votes each. The fact is that Barsha pump is a low cost and minimum requirements satisfying device, and as in this project the aim is to innovate with a new device, it is reasonable to develop a system that outperforms Barsha pump, that is more costly, thus, a higher cost-higher performance system. However, the target price of the device will be determined in the last question of the survey.

- Pumping head range (m)

30 - 50	50 - 70	70 – 130	> 130	Other (specify)



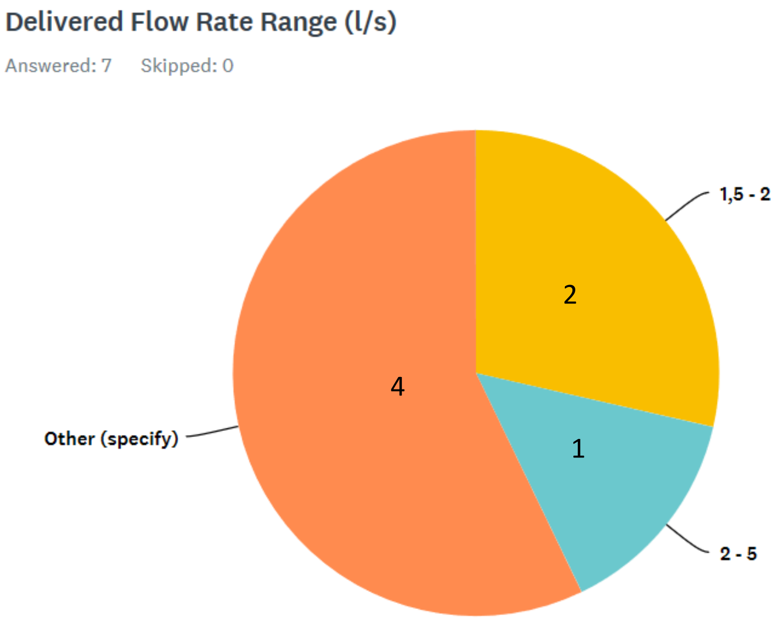
Other Responses:

- 40 – 60 m
- 40 – 62,6 m

Despite one respondent thought that the proper pumping head to target was at least 130 meters, in general there was quorum. 3 people voted for a pumping head range between 50 and 70 meters, other two for a range between 40 and 60 and one person between 30 and 50. To take into consideration their responses, the system pumping head targeted will be fixed to the range 40-70 meters.

- Delivered flow rate range (l/s)

0,5 - 1	1 – 1,5	1,5 - 2	2 - 5	Other (specify)



Other Responses:

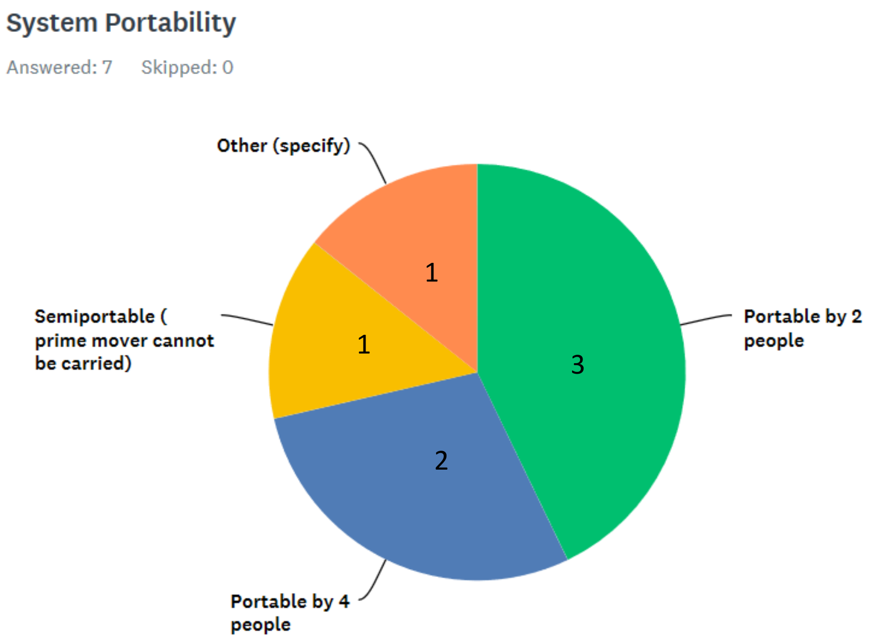
- 1 – 2 l/s
- > 5 l/s
- 0,5 – 1,75 l/s
- 1 – 2 l/s

Although at first sight it might seem that respondents did not agree about the delivered flow rate to target this is not true. Two responses recommended to target a delivered flow rate between 1 – 2 l/s, other two between 1,5 and 2 and other one between 0,5 and 1,75 l/s. Then one respondent voted for a flow rate range between 2 – 5 l/s and the last one required a flow rate higher than 5 l/s.

As the most common response involved having a maximum flow rate of 2 l/s, it will be the upper limit for the requirement of the device. The lower limit will be fixed to 1 l/s that is an intermediate value between 0,5 and 1,5 and it was also proposed in two answers.

- System portability

Portable by 2 people	Portable by 4 people	Semiportable (prime mover cannot be carried)	Non portable	Other (specify)



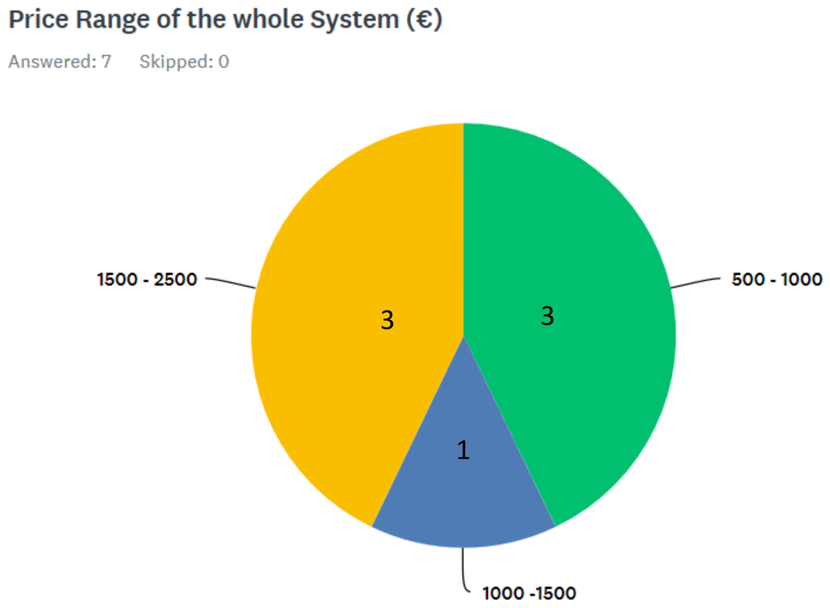
Other Responses:

- Portable by 1 – 2 people

As the most repeated answer was that the system should be portable by 2 people, including the answer that includes 1 - 2 persons to carry it, the objective for the system in terms of portability is that it must be able to be carried by 2 people.

- Price range of the whole system

500 - 1000	1000 - 1500	1500 – 2500	> 2500	Other (specify)



Price Range of the whole System (€)

Answered: 7 Skipped: 0

Regarding the price of the system, as it was commented in the question about the design options for the system, the target will be a higher cost higher performance system. Thus, despite both 500 – 1000€ and 1500 – 2500€ had 3 votes each, the price of the system will be targeted at 1500 – 2500 €.

This does not mean that if the system is finally developed and commercialized its price will be between 1500 and 2500 €, because in the design process some components may increase the cost of the overall system and thus the selling price will be higher.

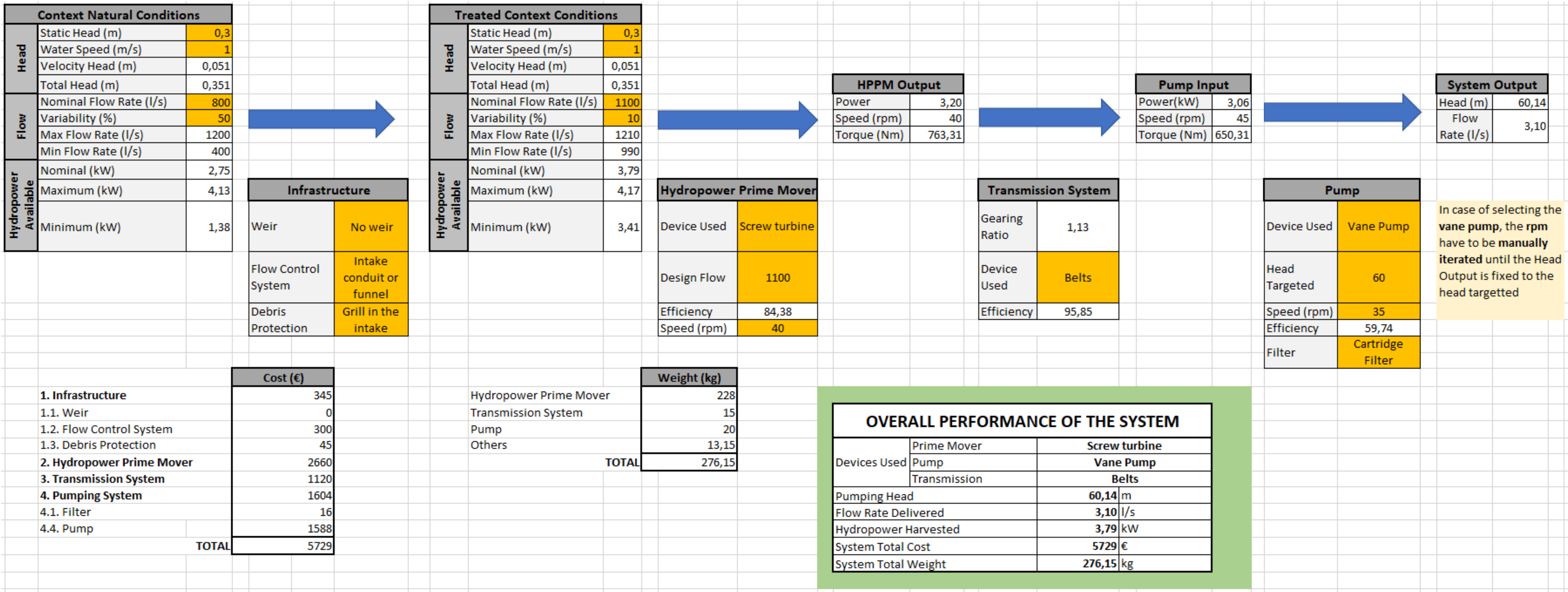
Annex II: Assessment Model

Annex II explains in detail the structure of the Assessment Model, how it works as well as the sources where the information available has been taken and the assumptions made in order to make the calculations and simplifications of the model.

Scenario

This tab is where the model is basically displayed. It is shaped as a diagram where power advances and changes between the different steps of the system. Figure 50 shows the appearance of the model in the scenario tab. This model is interactive, because user should decide the values of some variables and choose between the options that are proposed. Orange mark the cells where user must assign a value to the given variable or choose between the different option that are given.

Thus, the model starts with the definition of the parameters that determine the hydraulic behavior of the context naturally. Here , regarding static and velocity head, and flow rate and its variability, the hydropower available in that context is defined in terms of nominal maximum and minimum values.



	Context Natural Conditions	
Head	Static Head (m)	0,3
	Water Speed (m/s)	1
	Velocity Head (m)	0,051
	Total Head (m)	0,351
Flow	Nominal Flow Rate (l/s)	800
	Variability (%)	50
	Max Flow Rate (l/s)	1200
	Min Flow Rate (l/s)	400
Hydropower Available	Nominal (kW)	2,75
	Maximum (kW)	4,13
	Minimum (kW)	1,38

Infrastructure	
Weir	No weir
Flow Control System	Intake conduit or funnel
Debris Protection	Grill in the intake

	Treated Context Conditions	
Head	Static Head (m)	0,3
	Water Speed (m/s)	1
	Velocity Head (m)	0,051
	Total Head (m)	0,351
Flow	Nominal Flow Rate (l/s)	1100
	Variability (%)	10
	Max Flow Rate (l/s)	1210
	Min Flow Rate (l/s)	990
Hydropower Available	Nominal (kW)	3,79
	Maximum (kW)	4,17
	Minimum (kW)	3,41

Hydropower Prime Mover	
Device Used	Screw turbine
Design Flow	1100
Efficiency	84,38
Speed (rpm)	40

HPPM Output	
Power	3,20
Speed (rpm)	40
Torque (Nm)	763,31

Transmission System	
Gearing Ratio	1,13
Device Used	Belts
Efficiency	95,85

Pump Input	
Power(kW)	3,06
Speed (rpm)	45
Torque (Nm)	650,31

Pump	
Device Used	Vane Pump
Head Targeted	60
Speed (rpm)	35
Efficiency	59,74
Filter	Cartridge Filter

System Output	
Head (m)	60,14
Flow Rate (l/s)	3,10

In case of selecting the **vane pump**, the **rpm** have to be **manually iterated** until the Head Output is fixed to the head targetted

	Cost (€)
1. Infrastructure	345
1.1. Weir	0
1.2. Flow Control System	300
1.3. Debris Protection	45
2. Hydropower Prime Mover	2660
3. Transmission System	1120
4. Pumping System	1604
4.1. Filter	16
4.4. Pump	1588
TOTAL	5729

	Weight (kg)
Hydropower Prime Mover	228
Transmission System	15
Pump	20
Others	13,15
TOTAL	276,15

OVERALL PERFORMANCE OF THE SYSTEM			
Devices Used	Prime Mover	**Screw turbine**	
	Pump	**Vane Pump**	
	Transmission	**Belts**	
Pumping Head		**60,14**	m
Flow Rate Delivered		**3,10**	l/s
Hydropower Harvested		**3,79**	kW
System Total Cost		**5729**	€
System Total Weight		**276,15**	kg

Figure 50. Scenario tab from the Assessment Model

Afterwards, user should choose the infrastructure that should be included in the system. For doing it, three different drop down list are presented, regarding the possibilities for the weir, the flow control system and the solid rejection system.

The decisions taken about the infrastructure included in the system affect the hydraulic conditions of the context, thus next section gathers the values of the different variables once the infrastructure is installed, and the natural hydropower available for being harvested.

Then, next step is to choose which is the hydropower prime mover of the system. In this part users must select a prime mover form the drop down as well as the value of the design flow and the design rotational speed. Depending on the selections the prime mover will have a determined efficiency.

The output of the hydropower prime mover is displayed in the next set of cells, giving values of speed, torque and power that needs to be transmitted to the pump. Before selecting the transmission system, it is necessary to choose the pump, in order to know which will be the gearing ratio that the transmission system will need to work with.

Thus, user must select a pump between the possibilities, setting the pumping head and the rotational speed of the device. Based on these, the efficiency of the pump chosen will be estimated, and the gearing ratio between hydropower prime mover and pump will be determined. Furthermore, user should choose the type of filter for the intake of the pump.

The last step will be to choose a transmission system suitable for the gearing ratio and maximum torque defined. When it has been done, the efficiency of the transmission is defined and the input power for the pump is known, so regarding the performance of the pump the output values of pumping head and flow rate delivered are finally determined.

It is also important to comment that in this tab, underneath the power diagram of the model, there are some cells that track the changes in total cost and total weight of the system. Thus, every time a component is added the cost and weight will vary their value with regards to the cost and weight which that component involves. Finally, there is an output board that condense all the performance values of the system.

Prime Movers Data

The prime mover data tab includes relevant information about the prime movers that were selected in previous steps. Basically, it includes the ranges of operation for the different devices, as well as the specific efficiency cost and weight of the device regarding the conditions and requirements of the system.

For submerged turbines, such as Tyson Turbine, Gorlov Helical Turbine and Savonius Turbine there was not much information because currently their production is quite reduced, however articles before referenced in 4.1.1 and the article *Small-scale Water Current Turbines for River Applications* [66] provided some information about their performance and manufacturers webpages. Thus, in most cases data about efficiency, cost and weight could be estimated, however, Tyson Turbine costs were not registered so they should be determined depending on the design.

In the case of the waterwheels, information of the efficiency curves was retrieved from articles of G. Muller and E. Quaranta before mentioned, as well as an article of J. Hameed [67]. Figure 1Figure 51 depicts the efficiency curves and equations for the different prime movers chosen.

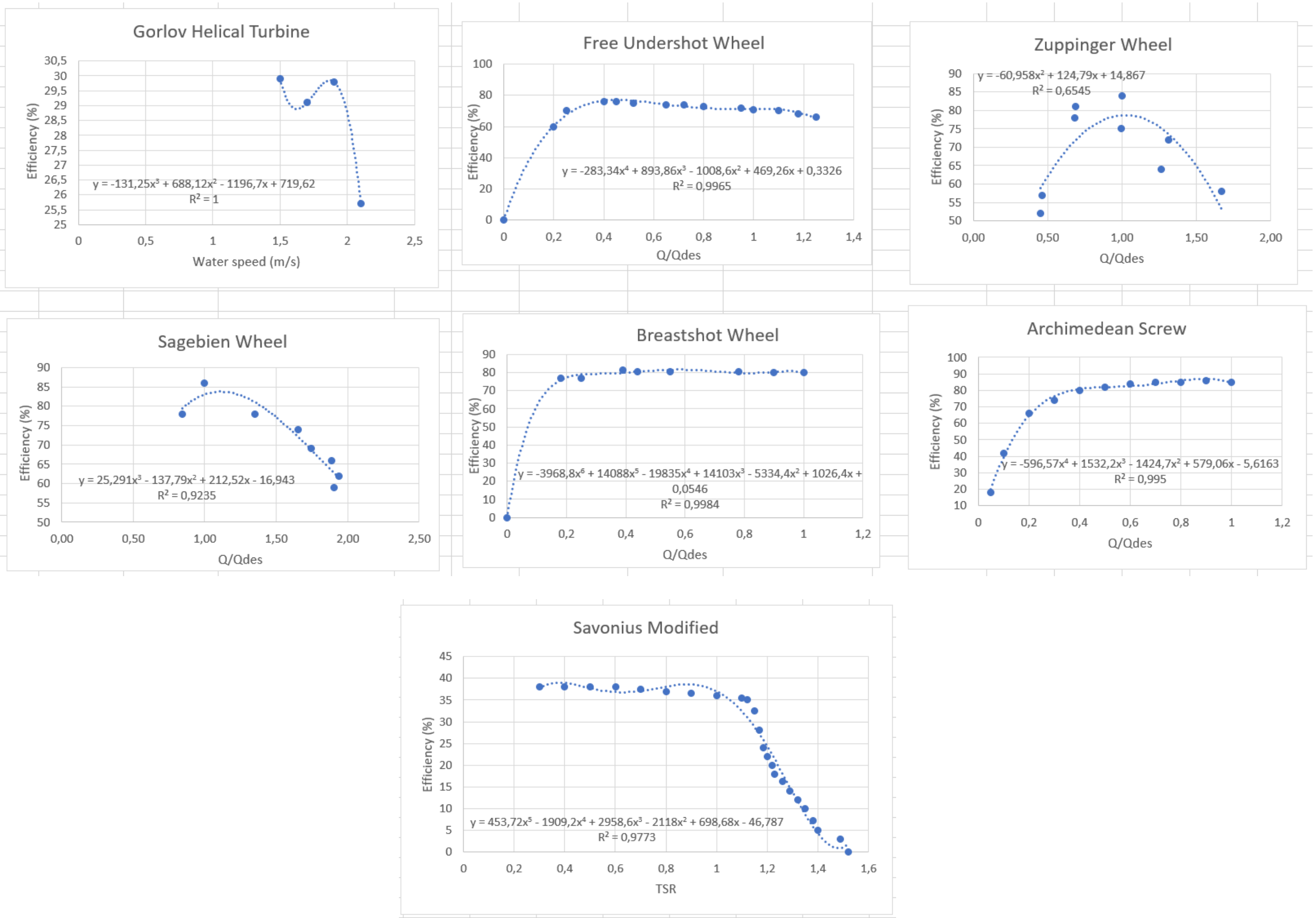


Figure 51. Efficiency Curves and Equations of the selected Hydropowered Prime Movers

Despite there are differences in the number of blades, its position or shape, the production process of these waterwheels is assumed to be similar because they all but the Breastshot wheel are undershot wheels, which design is supposed to be similar. Thus, it was assumed that all them had the same cost and weight per kilowatt. Due to lack of specific information of cost and weight of a Breastshot wheel and with the aim of simplify, the Breastshot wheel cost and weight was also estimated to be equal to the others.

Furthermore, aQysta has experience developing waterwheels, thus, data from a project developed in Híjar was used to estimate the information about cost and weight of waterwheels. Hence, the cost of the waterwheel installed in Híjar has been estimated to be around 4000 € for a Sagebien wheel with capacity of 4kW. This translates in a rate of 1000€/kW for a waterwheel.

It will be assumed that this rate can decrease when producing a large number of waterwheels, when the producing process is more or less standardized. Thus, the cost will be set in 700 €/kW, for all the waterwheels, since the production is almost equal for all of them.

Furthermore it is necessary to consider the costs of the axle and the bearings within the hydropower prime mover section. The axle will be also scaled due to power, because the price of an axle depends on its size and the operations that is necessary to do to it to achieve the required shape. A lower power capacity of the waterwheel implies lower loads and a smaller size. Furthermore, it will be assumed that its cost can be reduced with standardization.

Bearings will be supposed to scale with power too, because the lower the power, the lower the load bearing must cope with. However they will not be full scaled to power, assuming that they have a fixed cost to consider.

Taking all these facts into account, the final price for all the waterwheels will be 1200 €/kW. Besides, the weight of the waterwheel will be also assumed to be dependent on the power capacity, and it will be fixed at 40 kg/kW.

Finally, information about the efficiency, cost and weight of screw turbines was retrieved both from *Renewables First* [68], and the report of the project *A Feasibility Study Into The Use Of An Archemedian Screw Turbine For Hydroeletric Generation At Teddington Weir, London* [69]. In the last one a lot of detailed information about a hydropower project that involved a screw turbine was provided. According to it, the cost of the turbine is 800 €/kW, that will be assumed to be slightly lower, 700 €/kW, taking into account that standardization in production process minimize costs.

Pumps Data

This tab is similar to the one related to the information of hydropower prime movers. In this case, the information about each different pump has been retrieved from brochures of pump manufacturers.

However, in some cases the research showed that the pumps selected were not suitable for the purpose of the system. For instance, piston and plunger pumps are not designed for working with low pressure ranges. They usually work over 50 bar (≈500 mca) with a considerably high efficiency, around 90%. Despite they can operate at low pressures like the ones targeted for MIT project, the efficiency they present for those pressure is low compared to their design point efficiency, as it can be seen in Figure 52.

Furthermore, piston and plunger pumps are designed for high head and low flow delivered scenarios, and in most cases the maximum flow rate they deliver is not enough to meet the requirements before established. There are big piston pumps that can operate with a higher flow rate that meets the requirements, however they are designed for even high pressure ranges, which increases considerably the cost as well as it implies a lower efficiency for the operation point aimed. There are also some cases of mini piston pumps that work efficiently in the range of pressures required for the project, however, they deliver a really low flow rate so they cannot be used for this purpose.

Thus piston and plunger pumps will be discarded to be used in the project.

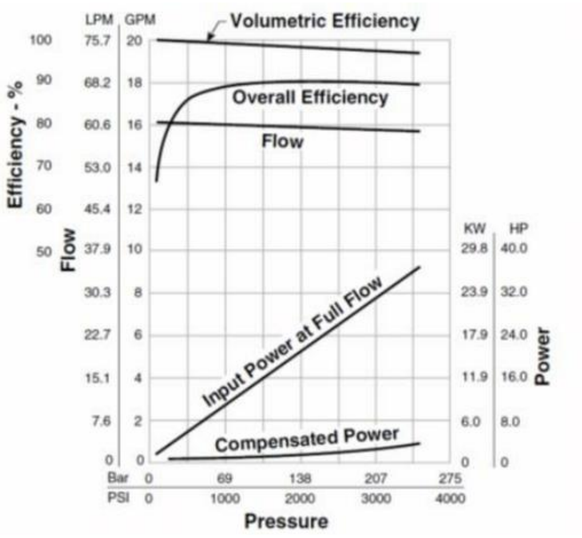
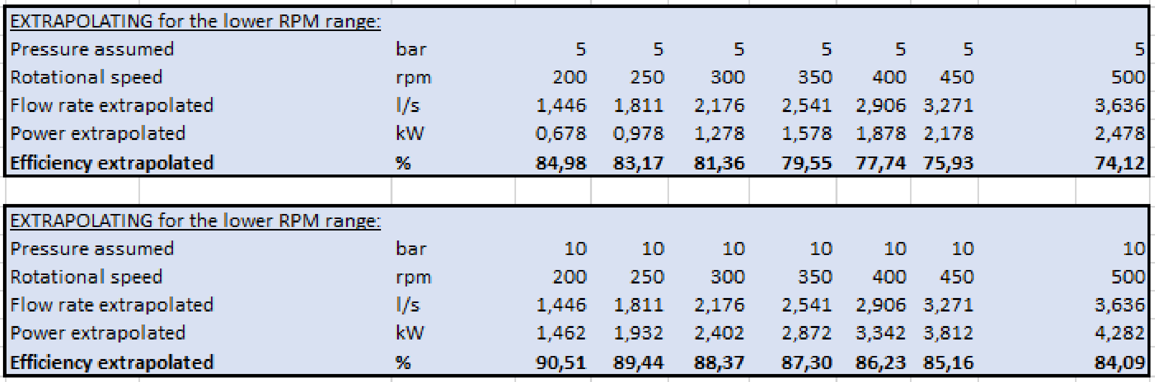


Figure 52. Performance curves of a Piston Pump

For the other options of pumps selected, relevant information was found about their performance, cost and weight. It is important to clarify that the information found is related to specific models of each of the pumps. The models taken into account are the following:

- **Annovi Reverberi 245BP** for the diaphragm pump. aQysta interested in this Italian manufacturer in order to use their diaphragm pumps for the case of Híjar at the beginning of the course. Since this moment frequent contacts and information exchange was carried out between both.

  Thus, Annovi Reverberi [70] provided information about the performance from 400 rpm forward, and they informed that these pumps could work at lower rpm so values for lower rpm were extrapolated with the information available. Table 21 shows the performance values of the pump for the desired range, and Equation 9 displays the equation for the efficiency calculated by interpolation.



EXTRAPOLATING for the lower RPM range:								
Pressure assumed	bar	5	5	5	5	5	5	5
Rotational speed	rpm	200	250	300	350	400	450	500
Flow rate extrapolated	l/s	1,446	1,811	2,176	2,541	2,906	3,271	3,636
Power extrapolated	kW	0,678	0,978	1,278	1,578	1,878	2,178	2,478
Efficiency extrapolated	**%**	**84,98**	**83,17**	**81,36**	**79,55**	**77,74**	**75,93**	**74,12**

EXTRAPOLATING for the lower RPM range:								
Pressure assumed	bar	10	10	10	10	10	10	10
Rotational speed	rpm	200	250	300	350	400	450	500
Flow rate extrapolated	l/s	1,446	1,811	2,176	2,541	2,906	3,271	3,636
Power extrapolated	kW	1,462	1,932	2,402	2,872	3,342	3,812	4,282
Efficiency extrapolated	**%**	**90,51**	**89,44**	**88,37**	**87,30**	**86,23**	**85,16**	**84,09**

Table 21. Performance Data of AR 245BP

$$\eta = (2{,}96 \cdot 10^{-4} \cdot H - 0{,}051) \cdot n + 0{,}05134 \cdot H + 89{,}656$$

Equation 9. Efficiency of AR245BP

Despite this pump delivers a higher flowrate than necessary it was chosen instead of 180 BP, because this second model, given the requirements for the pump, would operate close to its limits, which would wear more rapidly its components and shorten its lifetime.

- **Windtrans Zelda Pump** for the vane pump. This American manufacturer was chosen due to the innovativeness of the Zelda Pump as well as the low price of the device. Despite the technology is still in development for pressures higher than 30 mca, this option could be an interesting choice in the future, regarding the possibility of operating at low rpm, which would make the transmission easier and less costly.

  Very complete information was found in their webpage about the performance of the pump for a determined operation point. For this operation point the pressure provided by the pump was around 30 mca, however, the manufacturer said that this pump could reach the pressure required for MIT project. Figure 53 displays the performance graphs elaborated with the information provided by WindTrans [71].

  It is important to mention that positive displacement pumps increase their efficiency with higher pressures, so Zelda Pump will probably present an higher overall efficiency for the targeted range of pressure. However, in order to be conservative, the efficiency registered in this Excel model was the one provided in the webpage for 30 mca.

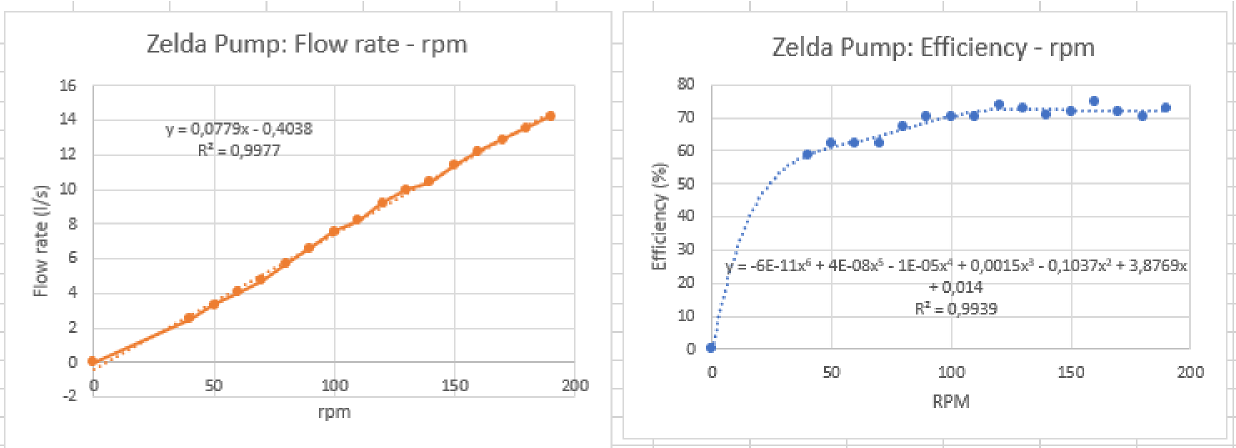


Figure 53. Performance Graphs of Zelda Pump

- **VERDERPRO VPS 52** was the model chosen for progressive cavity pumps. Verder [72] is a Dutch manufacturer with more than 90 years of experience in pumps. Thus, VPS 52 was chosen regarding its performance values. It can provide up to 120 mca of pressure and a maximum of 5 liters/second, which are perfectly suitable values.

  A meeting with an expert salesman of Verder was carried out to have further information about the performance and characteristics of this progressive cavity pump, as well as for centrifugal pumps.

  In relation with the VPS 52 he provided the following information:

    - The range of efficiency for this pump goes from 30 to 67%, scaling with the rpm. These efficiencies are not high, however, the pump could meet the imposed requirement with the power input of the waterwheel.

    - The range of operation rotational speed for this pump goes from 150 to 600 rpm, which makes it a fast device within the list of pumps considered. Thus, it only could be coupled with the prime mover by a gearbox.

    - Its cost would be around 1900 €, which is higher than other pumps considered, but still feasible to take it into consideration as a possibility. Furthermore, its weight is around 80 kg, which makes it a bit to heavy and would hinder the transportation of the system.

    - The maintenance of this type of pump, specially the change of rotor and sealing requires high knowledge of the field. Thus, this tasks cannot be done by customers, as in other types of pumps, a skilled technician is necessary to carry it out.

    - The pump cannot run dry. This means that if the pump is operating and it does not receive water to pump, it will wear out. This situation may happen in moments were the stream flow rate is lower due to the variability of the conditions, so inability to run dry is a totally undesirable characteristic.

    - This pump has not self-priming. This is a crucial aspect that makes the pump totally unsuitable for the purpose. The fact is that it will be located at a certain height from water, because it will be coupled to the axle of the prime mover by a gearbox.

      A pump without self-priming located at a higher point from water level cannot suck water at the start up, so it would run dry and wear out, as explained before. To avoid this, an electronic valve control should control the flow and prime the pump when necessary, however this would increase the cost and complexity of the system considerably.

  All these reasons, specially the inability to run dry and the lack of self-priming make the progressive cavity pump unsuitable for the purpose followed in the project, so they will be discarded from the list of possibilities.

- **Ebara 3LM 32-200/5,5** had been the model of centrifugal pump chosen due to its suitable performance, with pumping heads from 50 to 70 mca, delivering flow rates up to 5 liters per second. Looking at the technical sheets of the pump it was observed that the efficiency of this pump was low, having a maximum of 57,6% for 50 meters of head and 5 liters per second delivered. This efficiency is considerably low, however centrifugal pumps are the cheapest pumps of the market, in equality of conditions, so they could still be considered. However in the meeting with the expert of Verder, the following information was provided about centrifugal pumps:

    - Centrifugal pumps are extremely sensitive to cavitation. Thus, the pressure in the inlet must be well designed and constant in order to avoid reaching the steam pressure. In a highly variable context such as a river, with flow rate fluctuations would provoke variations in the inlet pressure and this leads to cavitation, which fastens the worn out of the pump.

- Centrifugal pumps usually operate at a minimum of 1500 rpm, with variations up to 50 rpm. This makes them extra fast devices within the list of pumps considered, and to couple them to the prime mover a gearing ratio around 100 would be necessary, which would imply a rise in the cost of the transmission.
- They vary both the flow rate and the pumping head with the rpm, unlike displacement pumps that only vary the flow rate. This is an important drawback, because the objective of the hydropowered pumping system is to pump water to a determined height, being the flow rate a secondary objective. Thus, if the centrifugal pump rotates slow and the head decreases too much the pump could not fulfill the head requirement and the system would be useless.

Despite centrifugal pump are widely used because of reliability and cost effectiveness, they are not suitable for this specific project because of their sensitiveness to cavitation and their operation regarding to speed, that variates both head and flow and it is considerably high. Thus, centrifugal pumps will be also discarded from the list of possible pumps to use in MIT project.

- In section 4.1.2, rotary vane pumps were divided into vane pumps and flexible impeller pumps. However, only rotary vane pumps (WindTrans Zelda Pump) had been considered for this final step. In the meeting with the expert of Verder, he advised that a flexible impeller pump could be a suitable solution for the project.

  Thus, he recommended pumps from **VERDER Jabsco** series, which can run dry and have self-priming. Furthermore, they are considerably compact, with a weight around 60 kg and with a cost around 1470 €. They can perfectly handle solids and slurries and their maintenance is straight forward and can be done by users with the proper guide.

  With regards to the performance values of this pump, the flow they are able to deliver, 8,3 liters per second, is more than enough for the purpose of this project, and it is able to reach up to 70% of efficiency in operation. This value is not as high as desired, however, is acceptable.

  The main important drawback of this pump is the maximum head it is able to pump, 45 mca, which is close to the lower specification of MIT project. Thus, the pump will be further considered, however it must be clarified that it cannot cover the whole range of head targeted, 40 to 80 mca.

  Hence, VERDER Jabsco will not be considered as a possibility for this project, because despite of its cost competitiveness and good performance due to operating under the context conditions, it can only provide a maximum of 45 meters, and the target is to develop a system that can pump water to a range of 40-80 meters.

Transmission Data

For the transmission system 5 different methods were considered: belts, chains, gears, Archimedes drive and shiftless transmission. The fact is that some of them turned out to not be suitable for the requirements.

Belt Drives

Belt drives are very suitable for applications were the gearing ratio is not too high (<7:1). The ideal scenario for a belt drive is an application with a gearing ratio from 1:1 to 3:1. In this range the efficiency of the belt is considerably high, usually over 95% depending on the nominal torque. For higher ratios slippage begins to provoke major power losses reducing considerably the efficiency of the transmission.

One solution for using belts in situations where the gearing ratio is higher than 6 is to use a two-step belt transmission. To do so the following elements would be necessary:

- 4 pulleys
- 2 SPB V-belts
- 4 taper locks
- 1 auxiliary axle with a construction to support it
- 2 bearings

An ancillary axle is necessary, which rotates at an intermediate speed and is the element in between the two steps. This axle must be mounted on a construction specifically designed for this purpose. This option is not recommendable, as it involves two belt drives for the transmission, which:

- Will increase the overall cost of the transmission, stopping to be competitive with regards to other options.
- The installation will be more difficult as it requires a specific construction to be designed for this purpose.
- It will require double maintenance, furthermore, SPB V-belts require regular adjustment and replacement.
- The efficiency will decrease, taking into account that two steps of transmission are required.

Thus, belts will be only a choice to consider if the gearing ratio is equal or under 7:1.

Belt drives efficiency depends on the power input as it can be observed in Figure 54. In this project input power will range from 1,5 to 4 kW, which means that the efficiency that the belt drive will provide will be between 90 and 95%.

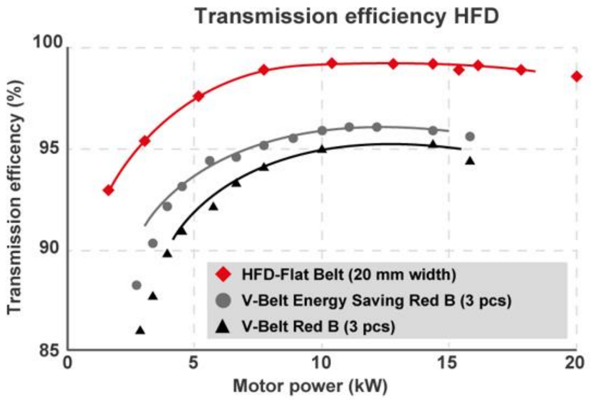
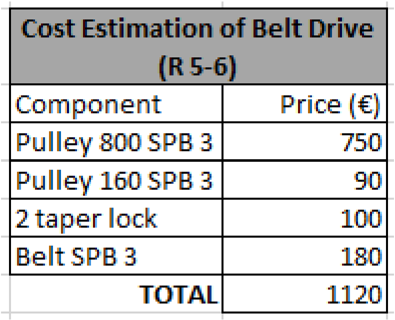


Figure 54. Belt Drive Efficiency

According to the transmission systems manufacturer Gratia Hydro, a belt drive transmission for a ratio around 5:1-6:1 could be designed in one single step with a total cost around 1120 €, regarding Table 22. In case that the gearing ratio is changed, the cost varies because the diameter of the pulleys also changes to achieve this new ratios, however the belt cost does not change.



Cost Estimation of Belt Drive (R 5-6)	
Component	Price (€)
Pulley 800 SPB 3	750
Pulley 160 SPB 3	90
2 taper lock	100
Belt SPB 3	180
TOTAL	1120

Table 22. Belt Drive Cost Estimation

Summing up, in the case that the gearing ratio is lower than 6:1, belts are economical, efficient and despite they require maintenance in variable conditions operation such as the ones of MIT project, its maintenance is considerably cheaper than other options, so they would probably be the preferred option. Information about belt drives was retrieved from the website *The Industrial Wiki* [73] and from the manufacturer *Gratia Hydro* [74].

Chain Drives

A similar problem happens with chains. Chain drives are suitable for applications with a gearing ratio up to 8:1: this ratio can be easily altered by changing the diameter of the sprockets while maintaining the distance between shafts. Unlike belt drives, chains do not slip and they provide a higher efficiency, up to 98%, transmitting more power than belts.

However, chains have several important disadvantages to consider for this project:

- As it happened with belt drives more than one step would be necessary for ratios higher than 8:1, with all the implications before commented about cost, efficiency and maintenance.
- Installation and production costs are higher than for belts, for the same features.
- They need to be lubricated constantly.

- The shafts of the driver and the driven must be perfectly parallel and aligned. If not, malfunctioning will occur, reducing considerably the efficiency in the transmission and in the worst case ending in failure.

Furthermore, chain drives are a considerable rigid transmission system, considerably sensitive to overload and jerks, which failure is sudden and total. Thus, any brusque variation in the rotational speed, will damage the chain, reducing drastically its life expectancy.

MIT project application involves a considerable variability in the conditions of the river, which translate in variability in the input power and speed for the chain drive. Under this conditions chain will suffer significant wear and frequent maintenance will be necessary, and unlike belt drives, chain drives maintenance is substantially expensive.

Thus, regarding the fact that chain drives do not add any value towards the use of belts, they are more expensive and more maintenance demanding, which is also more expensive than for belts, chain drives will not be considered form now on. Information for taking this decision was retrieved from the advice of the expert in transmission of aQysta, and data from *Power Transmission Engineering* [75] and *Gratia Hydro* [74].

Gearbox

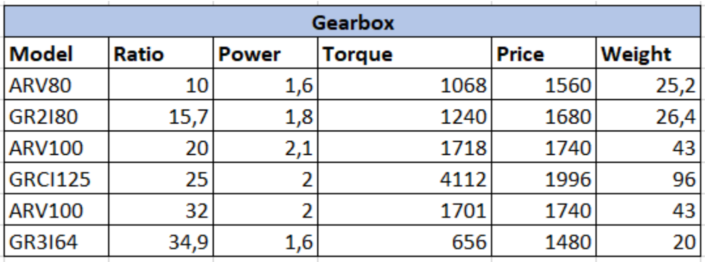
Despite gearboxes are, in principle, the most expensive transmission system of the ones considered, they are also the most suitable regarding the range of gearing ratios that we have, that for almost all cases is higher than 10. I say in principle, because belt and chain drives are less costly for gearing ratios up to 8, however, if the ratio is higher several steps are needed and the total cost of the transmission overtakes the cost of a gearbox.

Gearboxes are also suitable because they have a longer service life compared to belt ad chain drives, they are considerably polyvalent, operating both with high torques and gearing ratios, regarding the conditions of MIT project. Furthermore, they provide a high efficiency for different power scales and they are compact, which is important regarding the transportability of the system [75].

Thus, to get information about the performance and characteristics of gearboxes, the Italian manufacturer Rossi was selected, because aQysta already had some contacts with it for other projects, and also they has a very intuitive and useful tool in their website that allows customer to see which gearboxes are suitable for the specifications of the application where it will be used.

Looking at the different combinations between prime movers and pumps, the range of possible gearing ratios goes from 10 to 35 approximately, taking into account that if the ratio is lower than 10 belt drives will be used, due to their simplicity and cheapness.

Hence, Table 23 shows the information about different models of gearboxes retrieved from the interactive tool in Rossi's website [76].



Gearbox					
Model	**Ratio**	**Power**	**Torque**	**Price**	**Weight**
ARV80	10	1,6	1068	1560	25,2
GR2I80	15,7	1,8	1240	1680	26,4
ARV100	20	2,1	1718	1740	43
GRCI125	25	2	4112	1996	96
ARV100	32	2	1701	1740	43
GR3I64	34,9	1,6	656	1480	20

Table 23. Data about Rossi's gearboxes models

Rossi’s interactive tool provides information about operation values such as gearing ratio, speeds of the devices connected, power or torque, however it does not provide information about the efficiency of the transmission. To get this information, direct contact was made with Rossi experts, and they claimed that for the desired operation conditions the efficiency of suitable gearboxes is estimated in 94%.

Archimedes Drive

Archimedes Drive is a technology currently in development by IM Systems. As explained in section 4.1.3, it is based in planetary transmission, and it allows gearing ratios between 50 and 10.000. Despite gearing ratios higher than 50 are a bit unlikely in this project, Archimedes Drive could be considered for the cases that have these ratios.

The fact that makes the Archimedes Drive currently not suitable for MIT project is the maximum torque that it is able to transmit, which, according to the technical specifications provided by IM Systems in their brochure, is only 150 Nm. This is an important problem, regarding that in the hydropower prime mover side, the slow side of the transmission, torque reaches high values, above 500 Nm in all the cases.

Furthermore, as the Archimedes Drive is a young technology that is still in development, it is difficult to estimate its cost and actual performance values. The problem of torque makes Archimedes Drive currently unfeasible for the project, however, it would be advisable to follow its development because in case it improve its feature values, it could be an alternative to consider for future projects by aQysta.

Shiftless Transmission

Although the efficiency of this transmission is considerably high, reaching a maximum of 95,5%, most of the devices are designed for short gearing ratios, and thought to be used in the automotive industry. Furthermore, shiftless transmissions are designed specifically each context conditions, which makes them an expensive choice. However, it is actually not much more costly than the next most expensive transmission, gearboxes.

Besides this, shiftless transmission is recommended to be used in applications where the power to transmit is higher than 100 kW, which is not the current case, where the power to transmit will be ranged from 1,5 to 4 kW.

On the other hand, shiftless transmission is also a young technology that automakers are developing to improve its performance and this could widen its application fields. Furthermore, shiftless transmissions are estimated to last more than five years, and they provide a good operation regarding torque and speed.

Thus, shiftless transmission would currently have a low performance under the given conditions so it will not be considered in further steps for this thesis. However, as it is being developed and it is a promising ground-breaking transmission, it would be advisable to follow its development for considering it in the future.

Infrastructure Data

The infrastructure data tab is the last tab of the *Assessment Model* sheet. In this tab there is information about the components of the infrastructure used in the before mentioned project of Híjar.

The scale of the project carried out in Híjar is larger than the scenarios targeted for MIT project, with 20 hectares of land irrigated and an average flowrate in the canal “Acequia de Gaén” of 2226 liters/second. Water will be lifted to be storage in a pond to later be used for irrigation.

Thus, the waterwheels used will be a Sagebien wheel of 4kW of capacity, and a considerably costly infrastructure will be required. Many of the components used in Híjar project will not be necessary to be included in MIT system, and the ones that are considered to be included in the system can be scaled down regarding the decrease of power capacity of the system and the standardization of the process.

The weir that may be built in this project will be smaller than the one in Híjar, so the cost will assumed to be proportional to the height of the weir. Furthermore, the conduit or funnel, from the constructive point of view is similar to a weir, a structure that diverts water into a particular direction, so could be treated as a small weir for estimating its cost.

This does not happens with the upstream gate, where the main parameter that makes the cost scale is the width of the gate. Thus, despite the flow targeted for MIT project is lower than the one in Híjar, the width of the gate would not decrease considerably. With regards to this, the cost of a control gate can be assumed to be lower, but not significantly.

This section also contains components that were not included in the project of Híjar. For instance, the bypass system was estimated regarding Figure 41. There, a cost effective bypass was built by the accumulation of sand bags. This idea is suitable to generate a bypass without increasing too much the cost of the project. Thus the cost of this bypass was estimated by considering the cost and number of sand bags necessary, as well as the labor cost that would be necessary to achieve it.

Finally, the rest of the components, that are all related with the rejection of solids and debris, were quoted regarding the price settled by manufacturers and distributors:

- Trash rack: the cost of the trash rack depends on the size material and site of manufacturing of the device.

  Thus, according to a cost estimation for a pond by the United States Department of Agriculture, the price of a trash rack is around 570 €. It is necessary to clarify that this trash rack dimensions are 50x50 cm and it would operate completely submerged, hence, it is made of stainless steel to avoid rust.

  However, looking at the quotation of RK Trading Company, an Indian manufacturer, the price for a carbon or stainless steel trash rack 1 meter height and up to 4 meters width would be around 200 €.

As the price of this component is highly dependent on the manufacturer and geographical zone, it will be assumed to be 300 € per trash rack, in order to be conservative just in case the low cost manufacturers are not selected to provide it.

- Screen filter: because screen filters are a more complex version of trash racks, due to the higher number of bars or filaments that they have, they are more expensive that trash racks. The estimated cost for them is around 500 € for the dimensions needed.
- Grill in the intake: this is the most affordable solution because it only involves a metallic fence that should be positioned in the intake of the system. However it is also the less reliable, because fence are not designed for this purpose.

  According to the prices of Leroy Merlin, a Spanish company expert in do-it-yourself products a metallic fence on 0,8x2,5 meters would cos around 25 €, and to this the cost of fixing it to the system intake should be added. Thus, the estimated price for this solution is 45 €.
- Deflector: this option has already been studied by the team of aQysta, that has already developed and tested a prototype. The idea consisted in a floating deflector, which had a number of long metal pipes underneath to deflect big objects. Thus, it is able to move surface and subsurface debris away from the inlet of the system.

  This first prototype that was developed had a cost around 1000 €, however, according to the opinion of the developer, its cost could be remarkably reduced, due to wise selection of materials and standardization of the production process. Thus, its cost will be estimated to be around 500 €.
- Cartridge filter: WindTrans, the company that was contacted before for getting technical information and a quotation for the vane pump, provides also, among other components cartridge filters suitable for pumps. Thus, the cost of these components would be between 15 and 20 €.
- Spin-on filter: the information about spin-on filters was retrieved from EATON website. The cost of the suitable filter for this system would be 28 €. Furthermore, one of their main benefits, regarding cartridge filters, is that they need to be replace in a longer time than the others.
- Bag filters: these filters are the simplest ones. Thus, according to the website of Pentair, a company that was considered for acquiring diaphragm pumps in other projects, the cost of a bag filter would be around 6 €. However, these filters have a considerably shorter lifetime than cartridge or spin-on, so they should be frequently replaced.