Washington University in St. Louis
Washington University Open Scholarship

Mechanical Engineering Design Project Class   Mechanical Engineering & Materials Science

Water Reservoir Energy Storage

Kristen Grace

Supapan Thammanok

Leticia Zoratto Lunge

Follow this and additional works at: https://openscholarship.wustl.edu/mems411

This Final Report is brought to you for free and open access by the Mechanical Engineering & Materials Science at Washington University Open Scholarship. It has been accepted for inclusion in Mechanical Engineering Design Project Class by an authorized administrator of Washington University Open Scholarship. For more information, please contact digital@wumail.wustl.edu.

The goal of this project was to create a demonstrative model of a Pumped Hydroelectric Storage System (PHS). A PHS stores energy by draining water from an upper reservoir through a turbine to generate electricity. This water is then pumped from a lower reservoir to the original upper reservoir to restart the system cycle. Using existing PHS applications, a small-scale prototype was built using an aquarium pump and mini turbine, along with PVC and plastic containers. When water is run through the system, a multimeter can be used to show the power output of the system. In addition to functionality, the system was designed to be portable, have low power consumption, and low maintenance for the user.

JME 4110
Mechanical Engineering
Design Project

Water Reservoir Energy Storage

Kristen Grace
Supapan Thammanok
Leticia Zoratto Lunge

Table of Contents

List of Figures

List of Tables

1 Introduction

1.1 Value proposition / project suggestion

The general idea behind this design project is to provide an alternative energy storage solution that allows energy to be created as needed. This type of system is called a Pumped Hydro Storage (PHS) system. The system is made of a lower reservoir, a higher reservoir, and a pipeline. Water from the lower reservoir is pumped up an increasing slope, generating hydroelectric power. At such a time, the water will flow down through a hydroelectric turbine back to the lower reservoir. PHS systems are beneficial because they are a reliable source of emergency power, such as during a power shortage or blackouts.

There are two types of PHS systems. The first is an open-loop system in which one of the reservoirs is a natural water source; contrary, a closed-loop system uses two man-made reservoirs. In both loops, the pump is powered via the electric grid, though there are a wide variety of new power innovations that can be made.

1.2 List of team members

Kristen Grace   Supapan Thammanok   Leticia Zoratto Lunge

2 Background Information Study

2.1 Design Brief

The goal of our project is to design a pumped hydroelectric storage system that can provide energy to the power grid at a time of need. The system will operate using a lower and higher reservoir, the latter of which will be equipped with a level sensor to monitor the water depth in the reservoir; this will be installed to prevent overflow or catastrophic damage as seen in the Taum Sauk dam failure of 2005. The water will flow between the upper and lower reservoirs through a pipe fitted with a pump and a turbine. During times with low energy demand and low net costs, the pump will pull energy from the power supply to move water from the lower reservoir to the higher reservoir. The water will stay in this position until energy needs to be fed back to the power supply. At this time, as commanded by the client, the water will flow through the pipe and turbine down to the lower reservoir. The turbine will generate power as it turns, feeding it out of the system and back into the original power source. Sensors will also be included in the flow pipes to monitor flow rate for safety reasons.

In addition to the features listed above, the PHS systems must be transferable. The functioning prototype must be small and light enough to transport from the site of construction to its testing location/the client's desired location- really, this would be less than 50 lbs and either deconstructable or small enough to be transported in a vehicle/carried by an adult. The pump must also operate at a fixed speed to maintain a consistent and controllable flow rate of water. These features are in place to emphasize the safety and convenience of the design for the client.

2.2 Background summary

A pumped hydrostorage system (PHS) is made of a lower reservoir, a higher reservoir, and a pipeline. Water from the lower reservoir is pumped up an increasing slope, generating hydroelectric power. At such a time, the water will flow down through a hydroelectric turbine back to the lower reservoir. PHS systems are beneficial because they are a reliable source of emergency power, such as during a power shortage or blackouts.

There are two types of PHS systems. The first is an open-loop system in which one of the reservoirs is a natural water source; contrary, a closed-loop system uses two man-made reservoirs. In both loops, the pump is powered via the electric grid, though there are a wide variety of new power innovations that can be made.

3 Concept Design and Specification

3.1 User Needs and Metrics

3.1.1 Record of the user needs interview

Table 1- Recorded Needs

Need number	Need	Importance
1	Should be able to be easily transported.	5
2	Should be at a certain size that would fit inside a shopping cart.	5
3	Preferably 70% efficiency.	3
4	System should be used about one or twice per semester.	4
5	Preferably a quiet system.	3
6	Should be powered through an outlet.	5
7	Should use a switch to turn the system on.	5
8	System should be able to be taken apart.	4
9	Height should vary because of the pressure head.	5
10	System should be compatible to AC power	5
11	System should be open air.	5
12	System should preferably have an emergency shut off.	2
13	System joints should be watertight.	5

3.1.2 List of identified metrics

Table 2- Recorded Metrics

Metric Number	Associated Needs	Metric	Units	Min. value	Max. value
1	3	Efficiency	Percentage	50	80
2	1,2,9	Height	Feet	1	3
3	1,2	Higher pond	Gallon	1	2
4	1,2	Lower pond	Gallon	1	2
5	9	Pipe/hose	Feet	2	4
6	5,6,10,12	System reset	Minute	4	5
7	1,2	Size/volume	Cu. feet	3.5	6.3
8	4,7,11,13	Accessibility	Use/semester	1	2
9	8	Easily put away	Minute	4	8

3.1.3 Table/list of quantified needs equations

Table 3 - Quantified Needs Equations

Water Reservoir		Metric											
		Efficiency	Height	Higher pond	Lower pond	Pipe/ hose	System reset	Size/volume	Accessibility	Easily put away	Need Happiness	Importance Weight (all entries should add up to 1)	otal Happiness Valu
Need#	Need	1	2	3	4	5	6	8	9	10			
1	Should be able to be easily transported.	0	0.2	0.2	0.2	0	0	0.4	0	0		0.125	0
2	Should be at a certain size that would fit inside a shopping cart.	0	0.2	0.1	0.1	0	0	0.6	0	0		0.075	0
3	Preferably 70% efficiency.	1	0	0	0	0	0	0	0	0		0.05	0
4	System should be used about one or twice per semester.	0	0	0	0	0	0	0	1	0		0.1	0
5	Preferably a quiet system	0	0	0	0	0	1	0	0	0		0.025	0
6	Should be powered through an outlet.	0	0	0	0	0	1	0	0	0		0.1	0
7	Should use a switch to turn system on	0	0	0	0	0	0	0	1	0		0.025	0
8	System should be able to be taken apart	0	0	0	0	0	0	0	0	1		0.075	0
9	Height should vary because of the pressure head	0	1	0	0	1	0	0	0	0		0.1	0
10	System should be compatible to AC power	0	0	0	0	0	1	0	0	0		0.1	0
11	System should be open air	0	0	0	0	0	0	0	1	0		0.1	0
12	System should preferably have an emergency shut off	0	0	0	0	0	1	0	0	0		0.025	0
13	System joints should be watertight	0	0	0	0	0	0	0	1	0		0.1	0
Units		Percentage	Feet	Gallon	Gallon	Feet	Minute	Cubic Feet	Uses/semester	Minute	Total Happiness		0
Best Value		80	3	2	2	2	4	3.5	2	4			
Worst Value		50	1	1	1	4	5	6.3	1	8			
Actual Value		50	3	1.5	1.5	3	5	6.125	2	7.5			
Normalized Metric Happiness		0	1	0.5	0.5	0.5	0	0.0625	1	0.125			

3.2 CONCEPT DRAWINGS

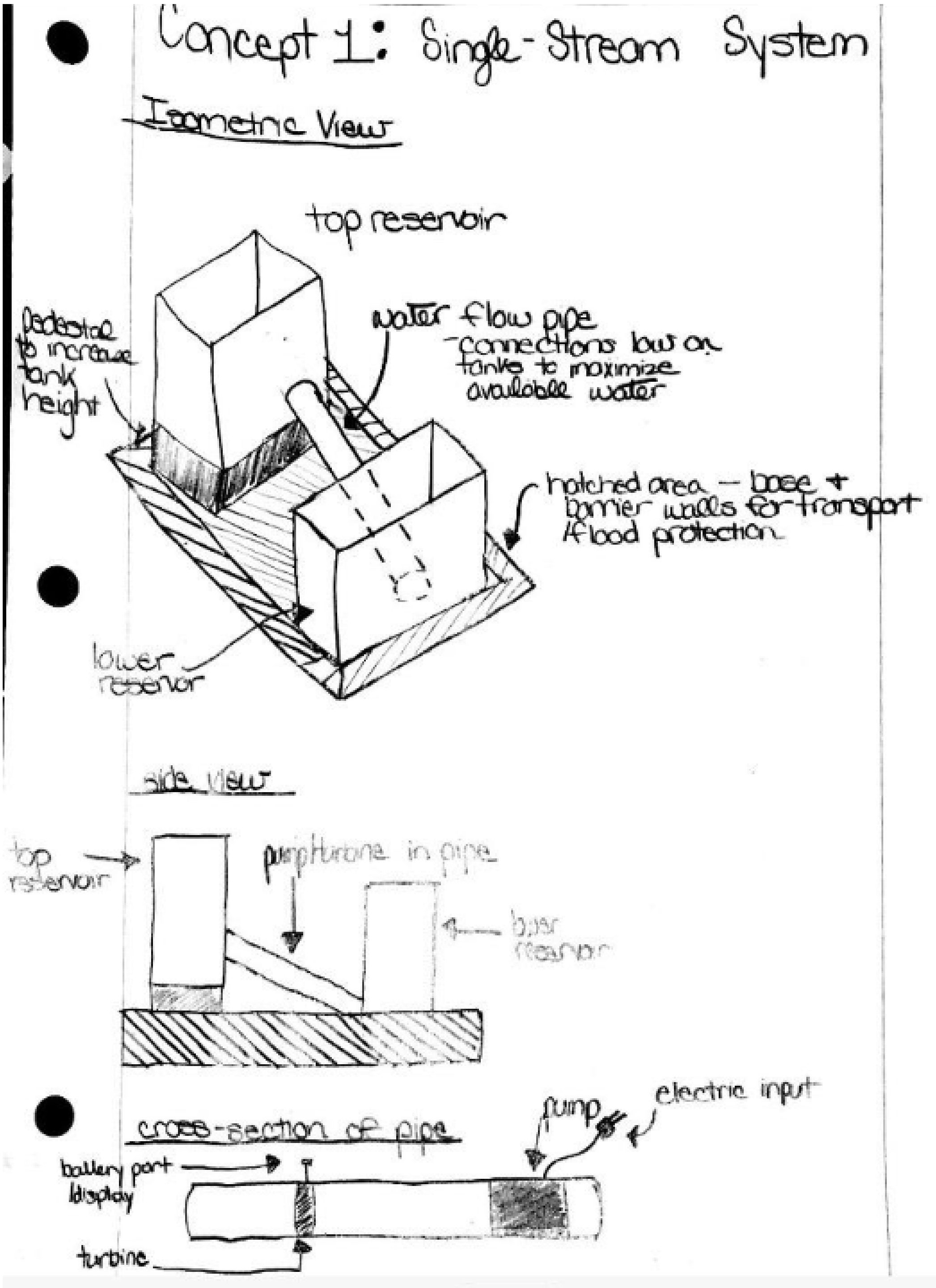

Figure 1- Concept Drawing 1

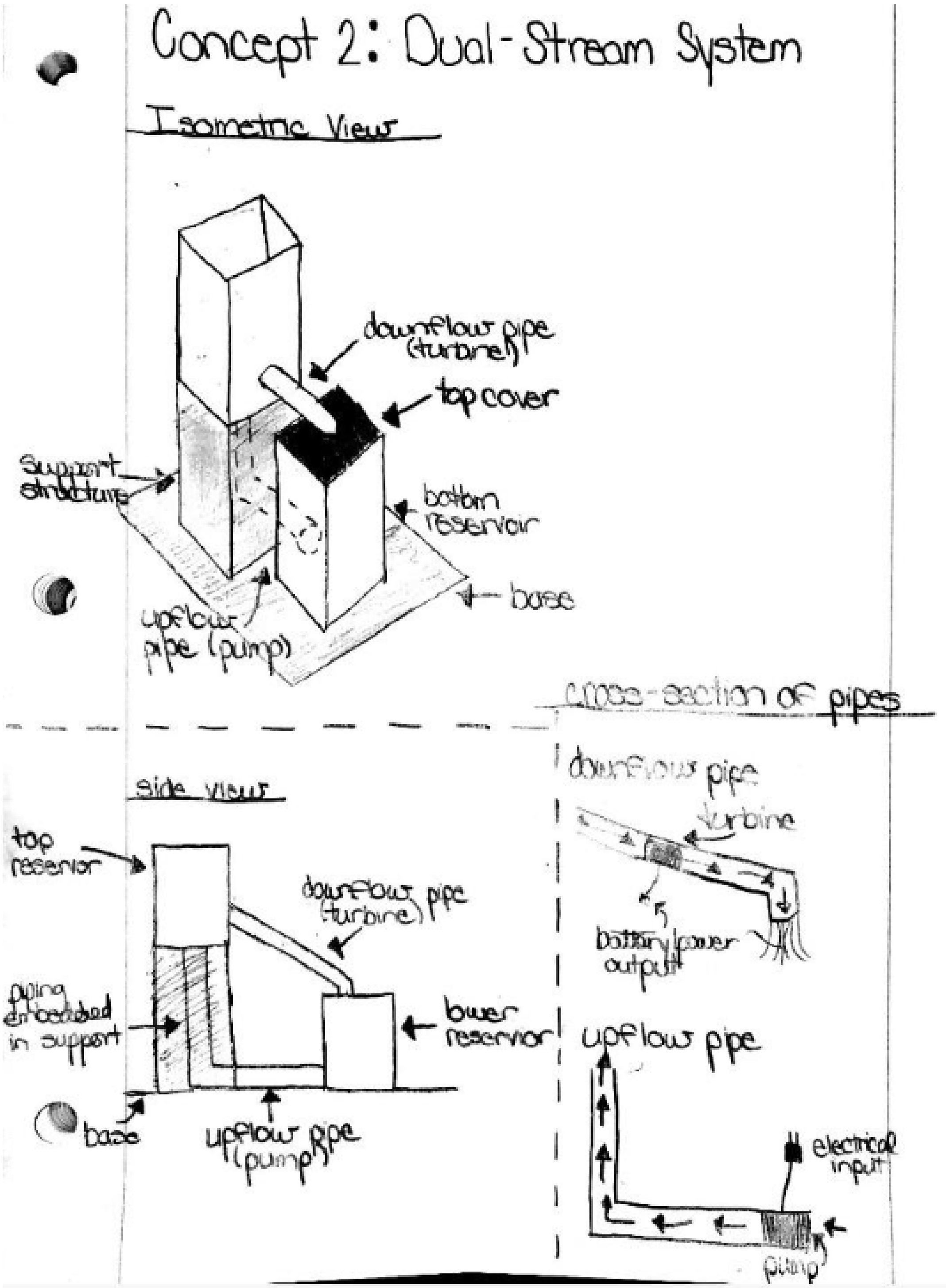

Figure 2- Concept Drawing 2

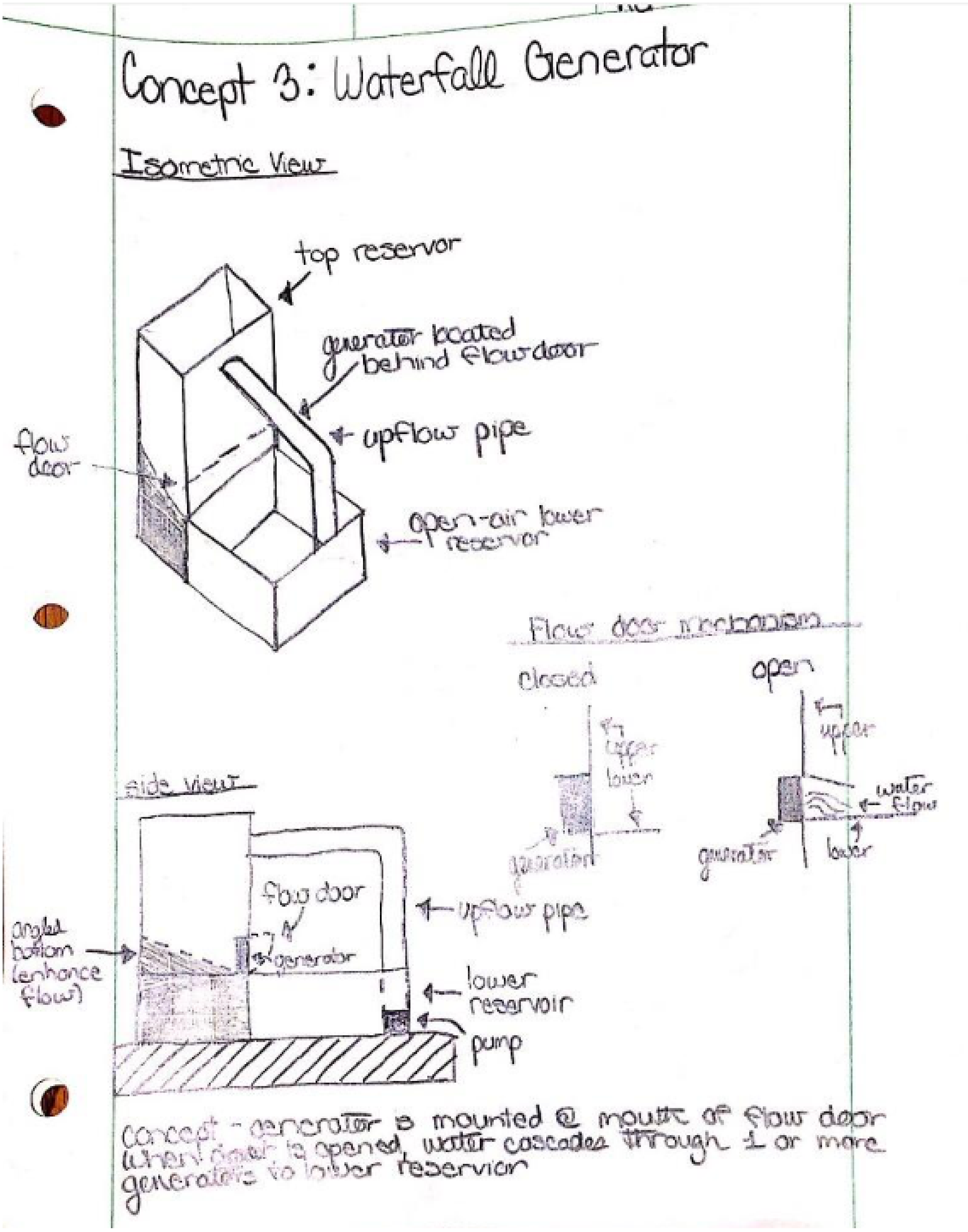

Figure 3- Concept Drawing 3

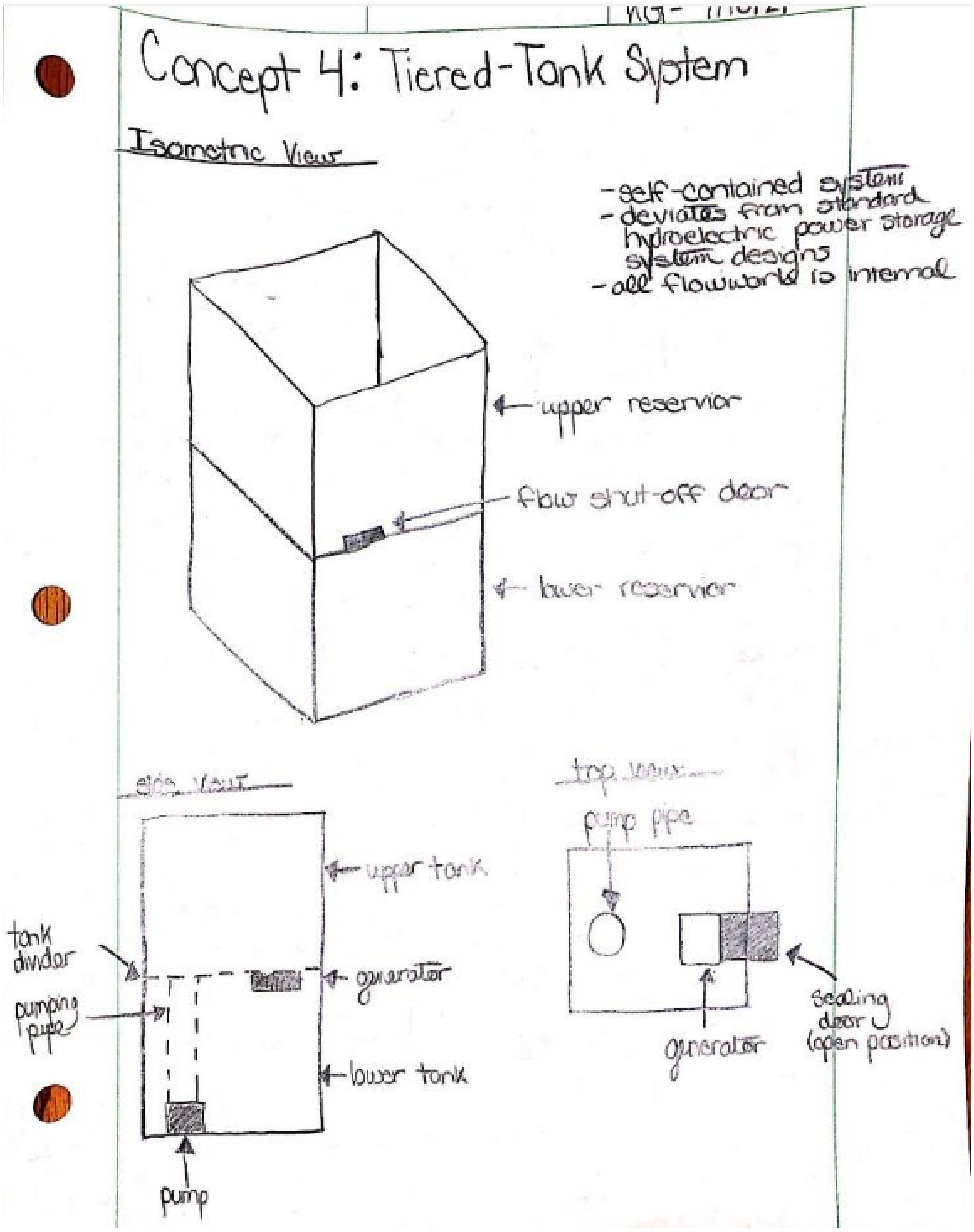

Figure 4- Concept Drawing 4

3.3 A CONCEPT SELECTION PROCESS

3.3.1 Concept scoring

Each concept was scored using the Quantified Needs Equation sheet shown in Table 3.

Need#	Need	Efficiency	Height	Higher pond	Lower pond	Pipe/ hose	System reset	Size/volume	Accessibility	Easily put away	Need Happiness	Importance Weight (all entries should add up to 1)	Total Happiness Value
	Water Reservoir	1	2	3	4	5	6	8	9	10			
1	Should be able to be easily transported.	0	0.2	0.2	0.2	0	0	0.4	0	0	0.484	0.125	0.0605
2	Should be at a certain size that would fit inside a shopping cart.	0	0.2	0.1	0.1	0	0	0.6	0	0	0.476	0.075	0.0357
3	Preferably 70% efficiency.	1	0	0	0	0	0	0	0	0	0.67	0.05	0.0335
4	System should be used about one or twice per semester.	0	0	0	0	0	0	0	1	0	1	0.1	0.1
5	Preferably a quiet system	0	0	0	0	0	1	0	0	0	0.5	0.025	0.0125
6	Should be powered through an outlet.	0	0	0	0	0	1	0	0	0	0.5	0.1	0.05
7	Should use a switch to turn system on	0	0	0	0	0	0	0	1	0	1	0.025	0.025
8	System should be able to be taken apart	0	0	0	0	0	0	0	0	1	0.5	0.075	0.0375
9	Height should vary because of the pressure head	0	1	0	0	1	0	0	0	0	1.25	0.1	0.125
10	System should be compatible to AC power	0	0	0	0	0	1	0	0	0	0.5	0.1	0.05
11	System should be open air	0	0	0	0	0	0	0	1	0	1	0.1	0.1
12	System should preferably have an emergency shut off	0	0	0	0	0	1	0	0	0	0.5	0.025	0.0125
13	System joints should be watertight	0	0	0	0	0	0	0	1	0	1	0.1	0.1
	Units	Percentage	Feet	Gallon	Gallon	Feet	Minute	Cubic Feet	Uses per semester	Minute	Total Happiness		0.6422
	Best Value	80	3	2	2	2	4	3.5	2	4			
	Worst Value	50	1	1	1	4	5	6.3	1	8			
	Actual Value	70	2	1.5	1.5	2.5	4.5	5	2	6			
	Normalized Metric Happiness	0.67	0.5	0.5	0.5	0.75	0.5	0.46	1	0.5			

Figure 5- Concept 1 Scoring

Need#	Need	Efficiency	Height	Higher pond	Lower pond	Pipe/ hose	System reset	Size/volume	Accessibility	Easily put away	Need Happiness	Importance Weight (all entries should add up to 1)	Total Happiness Value
	Water Reservoir	1	2	3	4	5	6	8	9	10			
1	Should be able to be easily transported.	0	0.2	0.2	0.2	0	0	0.4	0	0	0.606	0.125	0.07575
2	Should be at a certain size that would fit inside a shopping cart.	0	0.2	0.1	0.1	0	0	0.6	0	0	0.634	0.075	0.04755
3	Preferably 70% efficiency.	1	0	0	0	0	0	0	0	0	0.67	0.05	0.0335
4	System should be used about one or twice per semester.	0	0	0	0	0	0	0	1	0	1	0.1	0.1
5	Preferably a quiet system	0	0	0	0	0	1	0	0	0	0.5	0.025	0.0125
6	Should be powered through an outlet.	0	0	0	0	0	1	0	0	0	0.5	0.1	0.05
7	Should use a switch to turn system on	0	0	0	0	0	0	0	1	0	1	0.025	0.025
8	System should be able to be taken apart	0	0	0	0	0	0	0	0	1	0.375	0.075	0.028125
9	Height should vary because of the pressure head	0	1	0	0	1	0	0	0	0	1.625	0.1	0.1625
10	System should be compatible to AC power	0	0	0	0	0	1	0	0	0	0.5	0.1	0.05
11	System should be open air	0	0	0	0	0	0	0	1	0	1	0.1	0.1
12	System should preferably have an emergency shut off	0	0	0	0	0	1	0	0	0	0.5	0.025	0.0125
13	System joints should be watertight	0	0	0	0	0	0	0	1	0	1	0.1	0.1
	Units	Percentage	Feet	Gallon	Gallon	Feet	Minute	Cubic Feet	Uses/semester	Minute	Total Happiness		0.697425
	Best Value	80	3	2	2	2	4	3.5	2	4			
	Worst Value	50	1	1	1	4	5	6.3	1	8			
	Actual Value	70	2.5	1.5	1.5	2.25	4.5	4.5	2	6.5			
	Normalized Metric Happiness	0.67	0.75	0.5	0.5	0.875	0.5	0.64	1	0.375			

Figure 6- Concept 2 Scoring

Water Reservoir		Metric											
		Efficiency	Height	Higher pond	Lower pond	Pipe/ hose	System reset	Size/volume	Accessibility	Easily put away	Need Happiness	Importance Weight (all entries should add up to 1)	Total Happiness Value
Need#	Need	1	2	3	4	5	6	8	9	10			
1	Should be able to be easily transported.	0	0.2	0.2	0.2	0	0	0.4	0	0	0.1678	0.125	0.020975
2	Should be at a certain size that would fit inside a shopping cart.	0	0.2	0.1	0.1	0	0	0.6	0	0	0.1392	0.075	0.01044
3	Preferably 70% efficiency.	1	0	0	0	0	0	0	0	0	0.167	0.05	0.00835
4	System should be used about one or twice per semester.	0	0	0	0	0	0	0	1	0	1	0.1	0.1
5	Preferably a quiet system	0	0	0	0	0	1	0	0	0	0.7	0.025	0.0175
6	Should be powered through an outlet.	0	0	0	0	0	1	0	0	0	0.7	0.1	0.07
7	Should use a switch to turn system on	0	0	0	0	0	0	0	1	0	1	0.025	0.025
8	System should be able to be taken apart	0	0	0	0	0	0	0	0	1	0.25	0.075	0.01875
9	Height should vary because of the pressure head	0	1	0	0	1	0	0	0	0	1	0.1	0.1
10	System should be compatible to AC power	0	0	0	0	0	1	0	0	0	0.7	0.1	0.07
11	System should be open air	0	0	0	0	0	0	0	1	0	1	0.1	0.1
12	System should preferably have an emergency shut off	0	0	0	0	0	1	0	0	0	0.7	0.025	0.0175
13	System joints should be watertight	0	0	0	0	0	0	0	1	0	1	0.1	0.1
Units		Percentage	Feet	Gallon	Gallon	Feet	Minute	Cubic Feet	Uses per semester	Minute	Total Happiness		0.558515
Best Value		80	3	2	2	2	4	3.5	2	4			
Worst Value		50	1	1	1	4	5	6.3	1	8			
Actual Value		55	1.25	1.25	1.25	2.25	4.3	6	2	7			

Figure 7- Concept 3 Scoring

Water Reservoir													
		Efficiency	Height	Higher pond	Lower pond	Pipe/ hose	System reset	Size/volume	Accessibility	Easily put away	Need Happiness	Importance Weight (all entries should add up to 1)	Total Happiness Value
Need#	Need	1	2	3	4	5	6	8	9	10			
1	Should be able to be easily transported.	0	0.2	0.2	0.2	0	0	0.4	0	0	0.425	0.125	0.053125
2	Should be at a certain size that would fit inside a shopping cart.	0	0.2	0.1	0.1	0	0	0.6	0	0	0.3375	0.075	0.025312
3	Preferably 70% efficiency.	1	0	0	0	0	0	0	0	0	0	0.05	0
4	System should be used about one or twice per semester.	0	0	0	0	0	0	0	1	0	1	0.1	0.1
5	Preferably a quiet system	0	0	0	0	0	1	0	0	0	0	0.025	0
6	Should be powered through an outlet.	0	0	0	0	0	1	0	0	0	0	0.1	0
7	Should use a switch to turn system on	0	0	0	0	0	0	0	1	0	1	0.025	0.025
8	System should be able to be taken apart	0	0	0	0	0	0	0	0	1	0.125	0.075	0.009375
9	Height should vary because of the pressure head	0	1	0	0	1	0	0	0	0	1.5	0.1	0.15
10	System should be compatible to AC power	0	0	0	0	0	1	0	0	0	0	0.1	0
11	System should be open air	0	0	0	0	0	0	0	1	0	1	0.1	0.1
12	System should preferably have an emergency shut off	0	0	0	0	0	1	0	0	0	0	0.025	0
13	System joints should be watertight	0	0	0	0	0	0	0	1	0	1	0.1	0.1
Units		Percentage	Feet	Gallon	Gallon	Feet	Minute	Cubic Feet	Uses per semester	Minute	Total Happiness		0.4628125
Best Value		80	3	2	2	2	4	3.5	2	4			
Worst Value		50	1	1	1	4	5	6.3	1	8			
Actual Value		50	3	1.5	1.5	3	5	6.125	2	7.5			
Normalized Metric Happiness		0	1	0.5	0.5	0.5	0	0.0625	1	0.125			

Figure 8- Concept 4 Scoring

3.3.2 Preliminary analysis of each concept's physical feasibility

Preliminary Physical Analysis

Design 1: Single-Stream System

This design is based on existing Pumped Hydroelectric Storage systems. This design is one of the most feasible out of the four drawn above- it shouldn't require special construction or materials, and has been shown to work on a full-size scale. The main hurdle for this design would be finding an appropriate flow rate that will satisfy both the pump and the generator as they both sit in the same pipe. That being said, the mechanisms are simple and the construction and operation seem similar.

Design 2: Dual-Stream System

This design is also inspired by existing PHS systems. Opposed to design 1, the dual-stream system uses a closed-loop with the generator and pump each having a dedicated pipeline. One special consideration for this design is finding a pump with adequate head as the distance between the lower reservoir and the higher reservoir is greater. However, standard materials such as PVC, EVA foam, plastic tanks, and silicone sealant can still be used in this design. While construction is slightly more complex than design 1, the isolated mechanisms make for simpler calculations regarding fluid mechanics and power.

Design 3: Waterfall Generator

Design 3 uses a similar concept to the previous designs with the major difference being in the generator set-up. Rather than flowing through a pipe to the generator, the water cascades through a flap or door in the wall of the upper reservoir, similar to how locks and dams are set up. In this situation, the generator is mounted inside the tank against the door so that the water will also flow through it. Special consideration for this design would be how to install and best utilize the generators. We would need to use a waterproof generator (opposed to a pipe-based one) that can be safely submerged in the water. In addition, since the flow area is wider, the generator would either need to be the width of the reservoir or there would need to be multiple generators in order to capture the flow of all the water. Overall, this design is feasible, but is complex for the task at hand, especially when compared to designs 1 and 2.

Design 4: Tiered-Tank System

Design 4 is the most out-of-the-box design we produced. The stacked tanks require both the pump and generator to be fully submerged in water; this brings up issues with safe electrical powering and general construction. In addition, should anything need to be serviced or modified, the entire system would need to be dismantled rather than just one part. Hypothetically, this design could work. That being said, given the timeline and goal of this project (to prove PHS systems work), the tiered tank systems are bulky, complex, and have too many variables compared to the other three to be considered a reasonable contender. While it is technically feasible, it isn't functionally feasible for the sake of the project.

3.3.3 Final summary statement

The design we chose to proceed with is Design 2- the Dual Stream System. This design is based on current HPS systems, which adds a degree of confidence to it. The separate generator and pump flow pipes allow for flexibility in flow rates for each mechanism and for easy maintenance/assembly/transport. In addition, the dual-stream meets the requirements set by our User Needs Interview for easy transportation for a classroom setting.

There were multiple reasons the other designs were not chosen, some of which were stated above. For Design 4, there were concerns regarding the feasibility of the design in terms of it being reasonable compared to the first three designs. If we were opting to completely redesign current PHS systems, this may have ranked higher, but ultimately wasn't practical for this project.

Design 1 was perfectly feasible and similar to our chosen design. The main deciding factor was the singular flow rate and the happiness equation. The single-pipe design simply didn't perform as high as Design 2, but it was a close contender. In addition, Design 1 was slightly more complex in the fluid dynamics as opposed to being able to have two different flow rates for Design 2.

Design 3 fell between Designs 1 and 4. It was more feasible than design 4, but much more impractical than designs 1 and 2. Ultimately the cascading system proved to be unnecessarily complex when it came to finding an adequate generator system that could balance efficiency with the price-conscious tech available to us. It could definitely be done but isn't the most reasonable design in terms of transportation, construction, or storage.

Based on our primary user need of easy transportation/assembly in a classroom, Design 2 is the ideal design for our project.

3.4 Proposed performance measures for the design

For this design, we chose efficiency and size to be the main performance measures. The goal is to have an efficiency of 70%, and for the PHS system to be no bigger than 3.5 cubic feet. These values were reached using feedback from the user needs interview, and by focusing on these measures, we believe the design will best fit what the customer is looking for.

3.5 Revision of specifications after concept selection

After selecting concept 2, we made one change of adding shut-off valves to the design. This change was guided by the user needs specifications, specifically the preference of an emergency shut-off mechanism. Two PVC ball valves were added into the piping before the turbine and after the pump. These changes can be seen below in the Initial Embodiment Sketch (Figure 10).

4 Embodiment and fabrication plan

4.1 Embodiment/Assembly drawing

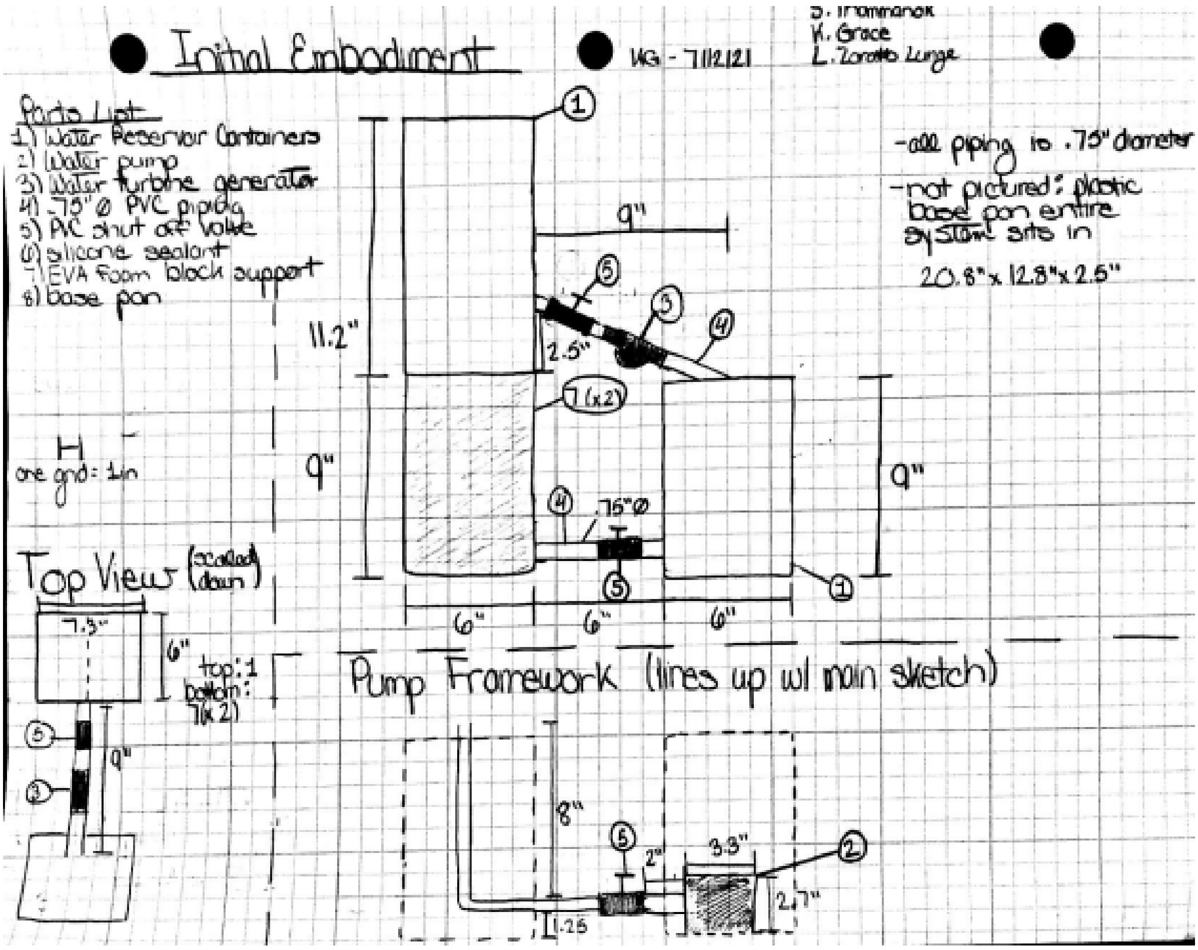

Figure 9- Initial Embodiment Sketch

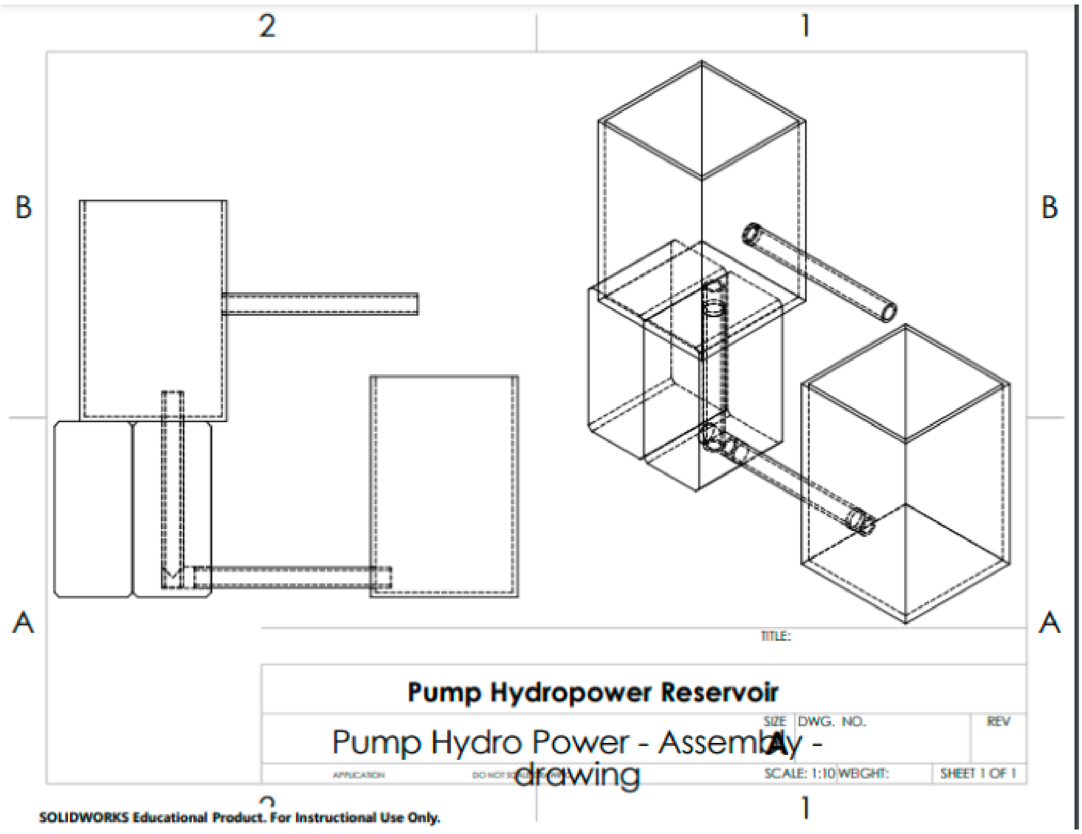

Figure 10- Overall Assembly

4.2 Parts List

Table 4- Initial Parts List

No.	Item Description	Source	Unit Cost	Qty.	Total
1	PVC Midline Shut-Off Valve	Amazon	$9.49	2	$18.98
2	550 GPH Pond Water Pump	Amazon	$19.86	1	$19.86
3	12 V Water Turbine Generator	Amazon	$9.90	1	$9.90
4	.75" PVC Piping	Amazon	$7.95	1	$7.95
5	Silicone Plumbing Sealant	Amazon	$7.84	1	$7.84
6	Plastic Food Storage Containers	Amazon	$30.99	1	$30.99
7	EVA Foam Block	Amazon	$11.99	2	$23.98
8	.75" PVC Elbow	Lowes	$0.73	1	$0.73
9	Cold Food Insert Pan	Amazon	$12.99	1	$12.99

The total cost for obtaining all the parts listed above would be $133.22.

4.3 Draft detail drawings for each manufactured part

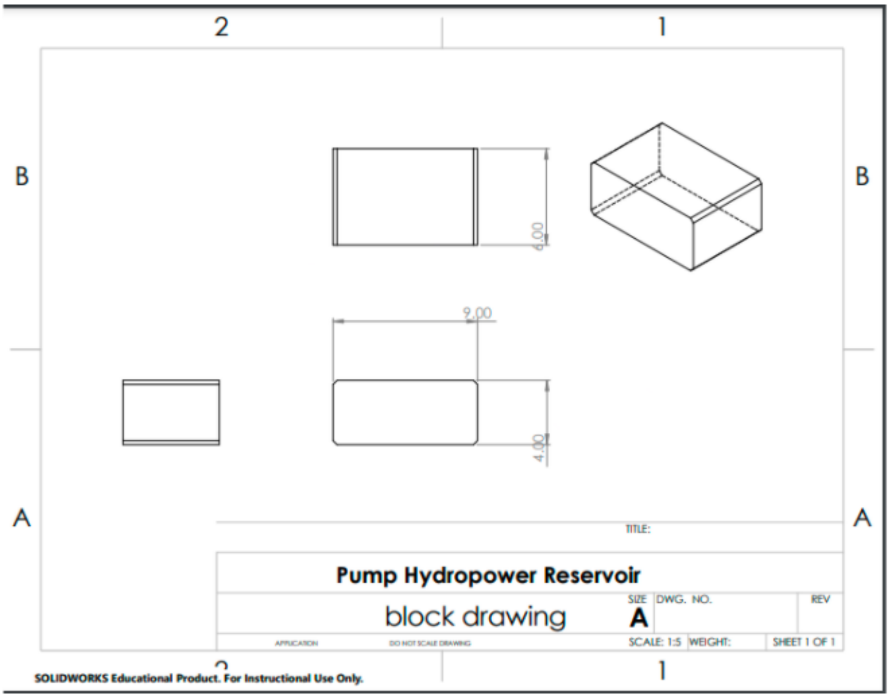

Figure 11- Support Blocks

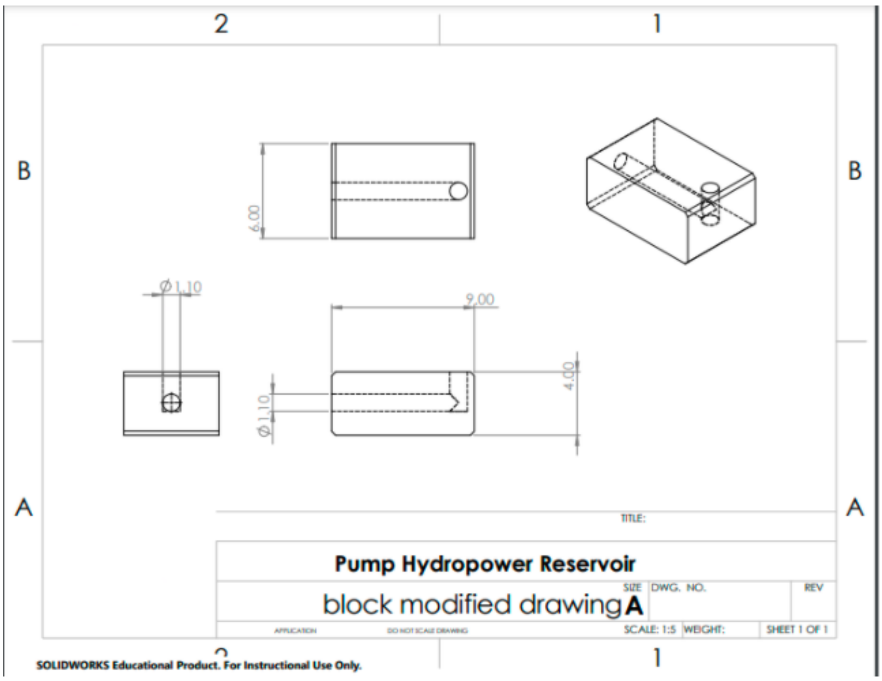

Figure 12-Modified Bottom Support Block

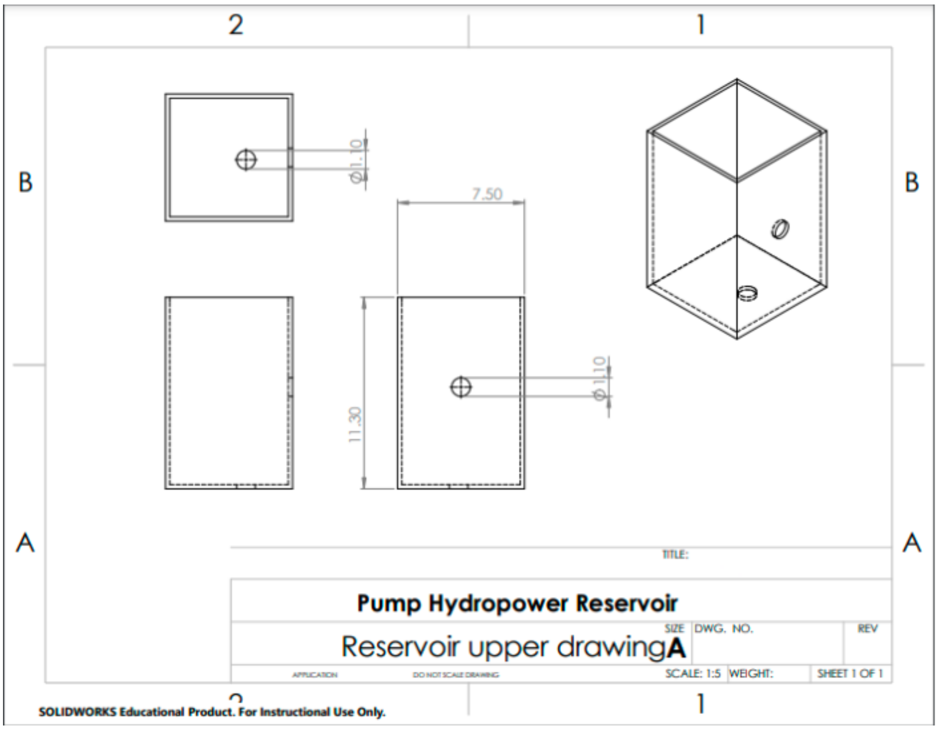

Figure 13-Upper Container Modifications

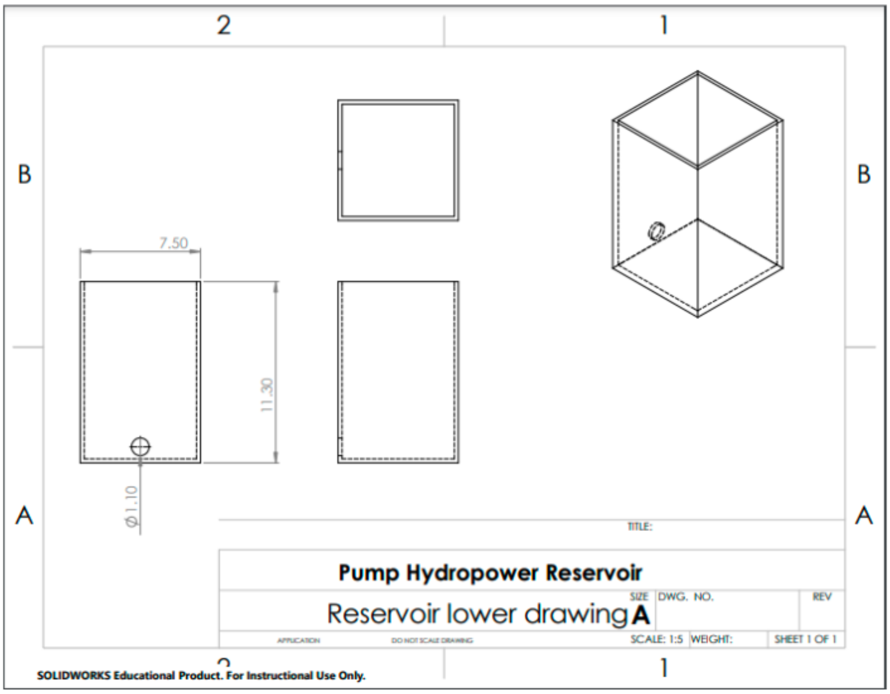

Figure 14- Lower Container Modifications

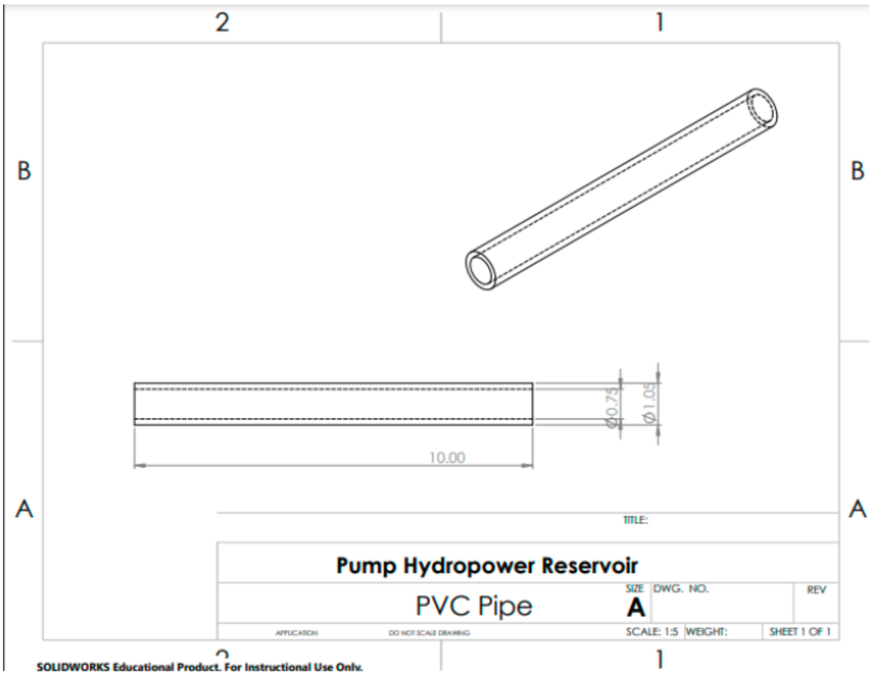

Figure 15- PVC Pipe Modified

4.4 Description of the design rationale

Overall, our general approach to our design was to initially select parts and dimensions based on rationale, then make adjustments based on how our calculations came out. Luckily, the reservoir sizes and pipe diameter worked out as selected. As previously mentioned, the main issue we came across was in our efficiency with our original pump and turbine. Online, there is a much wider variety of pumps available than there are turbines. We knew we wanted a pump with a variable flow rate we can adjust and a power output ranging between 10W and 15W. Based on the products available, we settled on the 15W pump that will be used in the fabrication. The only other small adjustment was a PVC adapter- this will connect the pump outflow to the PVC pipe. Our PVC piping system is .75" inner diameter, while the pump output nozzle is .5". The adapter will allow us to keep our .75" piping that worked in our calculations without a significant overhaul.

5 Engineering analysis

5.1 Engineering analysis proposal

5.1.1 Signed engineering analysis contract

MEMS 411 / JME 4110
MECHANICAL ENGINEERING DESIGN PROJECT

ASSIGNMENT 5: Engineering analysis task agreement (2%)

ANALYSIS TASKS AGREEMENT

PROJECT: Water Reservoir Energy Storage INSTRUCTOR: Mark Jakiela
NAMES: **Kristen Grace**
Supapan Thammanok
Leticia Zoratto Lunge

The following engineering analysis tasks will be performed:

Pre-Fabrication
1) Trigonometric analysis to determine the ideal height of the sloped downflow pipe
2) Efficiency calculations to determine ideal pump power using known turbine power
3) Calculation of the flow rate using fluid mechanics and ideal values for effective head and efficiency
4) Calculate volumetric flow rate related to pipe diameter

Post-Fabrication
5) Measure time for the system to reset from a fully-drained water position
6) Efficiency calculations comparing theoretical efficiency vs actual power levels
7) Adjust and finetune flow rate from pump based upon above calculations

The work will be divided among the group members in the following way:
Supapan Thammanok: 2,3 (ST)
Kristen Grace: 5,6,7 (KG)
Leticia Zoratto-Lunge: 1, 4 (LZ)

Instructor signature: Craig J. Geismann Print instructor name: Craig J. Geismann
Instructor signature: Mark Jakiela Print instructor name: Mark Jakiela

(Group members should initial near their name above.)

Figure 16- Signed Engineering Analysis Contract

5.2 Engineering analysis results

5.2.1 Motivation

Regarding our pre-fabrication analysis, we wanted to include efficiency and flow rate calculations in order to choose what materials to use in our prototype, as well as the measurements of the system, such as pipe diameter, and ideal pump power. In addition, before starting building our prototype, we did a trigonometry analysis of the system, so we could determine the height of the sloped downflow pipe, as well as determining the angle that the pipe would form with the container wall.

In the post-fabrication analysis, we plan on measuring how long it will take for the system to reset since we want it to take no longer than five minutes. We will also measure the efficiency of the system when it is fully built, and compare it to our theoretical efficiency value.

Analyzing these topics will help us get a better understanding of what we need to do in order to improve our prototype, and what needs to be perfected within the system.

5.2.2 Summary statement of analysis done

The relevant calculations done for this project are shown below.

Lower reservoir	volume	Filled water			% of transferred water	Headloss due to turbulance and drag 75 - 95%							
0.00803853612	m^3	6 liters	0.006	m^3	0.75	0.0045	m^3	4.5	liter	0.1635	m		
Upper reservoir	volume				0.8	0.0048	m^3	4.8	liter	0.1672	m		
0.00803853612	m^3				0.85	0.0051	m^3	5.1	liter	0.1724	m	4 liter =	0.1587 meter
					0.9	0.0054	m^3	5.4	liter	0.1739	m	5 liter =	0.171 meter
					0.95	0.0057	m^3	5.7	liter	0.1768	m	6 liter =	0.1817 meter

Find appropiate flow rate					
Efficiency(%)	0.6666666667				
Water density	1000				
gravity	9.81				
Headloss (m)	E, energy in Joule	1 min = 60 sec	Watt = J/s	kW	Estimated Flow rate
0.1635	8.5955	60	0.1433	0.000143	0.13146789
0.1672	8.7900	60	0.1465	0.000146	0.131272401
0.1724	9.0634	60	0.1511	0.000151	0.131467517
0.1739	9.1423	60	0.1524	0.000152	0.131454859
0.1768	9.2947	60	0.1549	0.000154	0.131419683
Efficiency(%)	0.8333333333				
Headloss (m)		1 min = 60 sec	Watt = J/s	kW	
0.1635	10.7444	60	0.1791	0.000179	0.1314300656
0.1672	10.9876	60	0.1831	0.000183	0.1314300656
0.1724	11.3293	60	0.1888	0.000188	0.1314300656
0.1739	11.4278	60	0.1905	0.000190	0.1314300656
0.1768	11.6184	60	0.1936	0.000193	0.1314300656

$$P\ (kW) = 10 \times \eta \times Q \times H_{effective}$$

Figure 13 Simplified equation for hydro power in kW, expressed in terms of generator efficiency, water flow rate and effective head

$$E\,[J] = 9.81 \rho_{water} V_{res} h_{head} \eta$$

Where:
E is the energy stored in joules. Divide by 3.6 x 106 to convert to kWh.
ρ_{water} is the density of water, usually about 1000 kg/m^3.
V_{res} is the volume of the reservoir in cubic meters.
h_{head} is the head height in meters.
η is the efficiency of the energy conversion, and must consider losses like turbine efficiency, generator efficiency, and hydrodynamic losses.

You can convert from flow rate in meters cubed per second to power in kW using the following equation:

$$P\,[kW] = 9.81\, \rho_{water} h_{head}\, \eta\, F / 1000$$

Where:
F is the flow rate in meters cubed per second.

Figure 17- Head and Efficiency Calculations

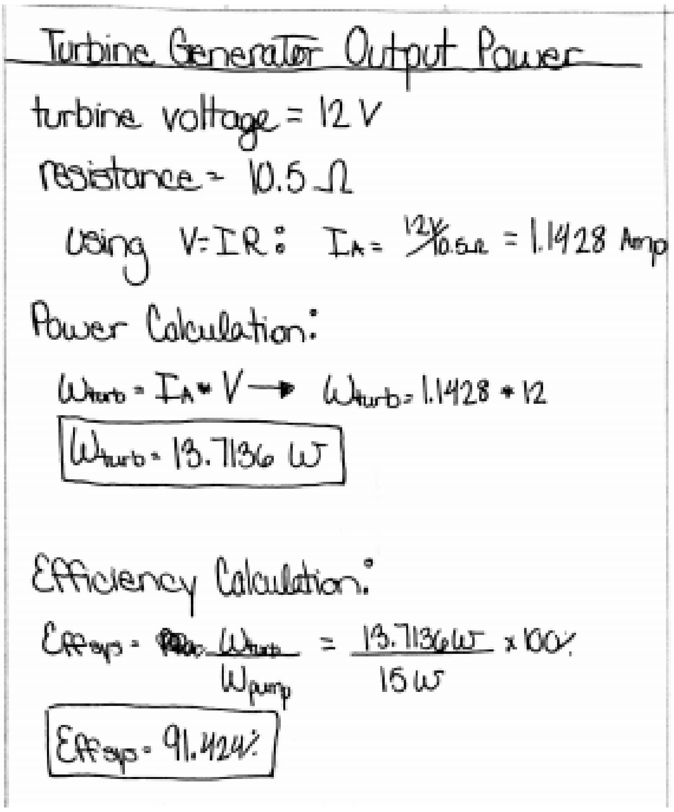

Figure 18- Theoretical Power and Efficiency

5.2.3 Methodology

The analysis for the pre-fabrication was done by using equations, and formulas to obtain the desired values. For the trigonometric analysis for the angle of the outflow pipe, we opted to decide during construction by physically holding the PVC pipe to the reservoirs as they were assembled. Different lengths were tested. This provided an adequate result, so we did not opt for further calculations.

After testing and running the system, we recorded the time it took to reset, which was a total of 4 minutes, taking 18 seconds to fill the top reservoir and the remaining 3 minutes and 42 seconds to drain to the lower reservoir. The reset time for the system met the requirement from our user needs.

The flow rate was measured at 3.5L over roughly 222 sec, resulting in an average flow rate of 0.016L/sec, or 16mL/sec. This was computed by measuring the water placed into the system, subtracting the amounts of water left in each reservoir, and dividing the water amount by the downflow time.

5.2.4 Results

From our analysis results, we were able to determine the angle of the pipe from the upper container to the lower container would be 60 degrees. And we realized we would have to make the upper container higher in order to bring more water back to the lower container within the five-minute reset time the users wanted, therefore we added another foam block to support the upper container. Once we get our system ready to run, we will be able to test the reset time and compare the experimental and theoretical efficiency values. From our pre-fabrication analysis, we determined which pump would be the best fit for the system, and what the flow rate of water would be while the transfer from the lower reservoir to the upper one would be.

For our efficiency analysis, our calculations showed a power output from the turbine of 13.7136 W. This was higher than the power listed for the turbine (10W). This increases our efficiency from 66.6% to 91.424%.

5.2.5 Significance

After we consulted with the professors, we had one major update to our prototype. Initially, we were going to use two dense foam blocks to support the reservoir, but after our analysis, we must add on another block for support, so we can get a high enough water head level we need to get the desired efficiency. This will add an additional 6" of height and allow us to place the outlet piping lower in the reservoir, increasing the total volume of water flowing through the system and the head, as mentioned above. It was suggested to change the turbine out for one with better power, however, upon looking online, it was difficult to find an adequate turbine that met our power needs. We instead chose to use a pump with a lower power intake that was still able to produce enough head in the system. This change, combined with the theoretical power calculation for the pump above, leaves us confident in the system and efficiency analysis.

6 Risk Assessment

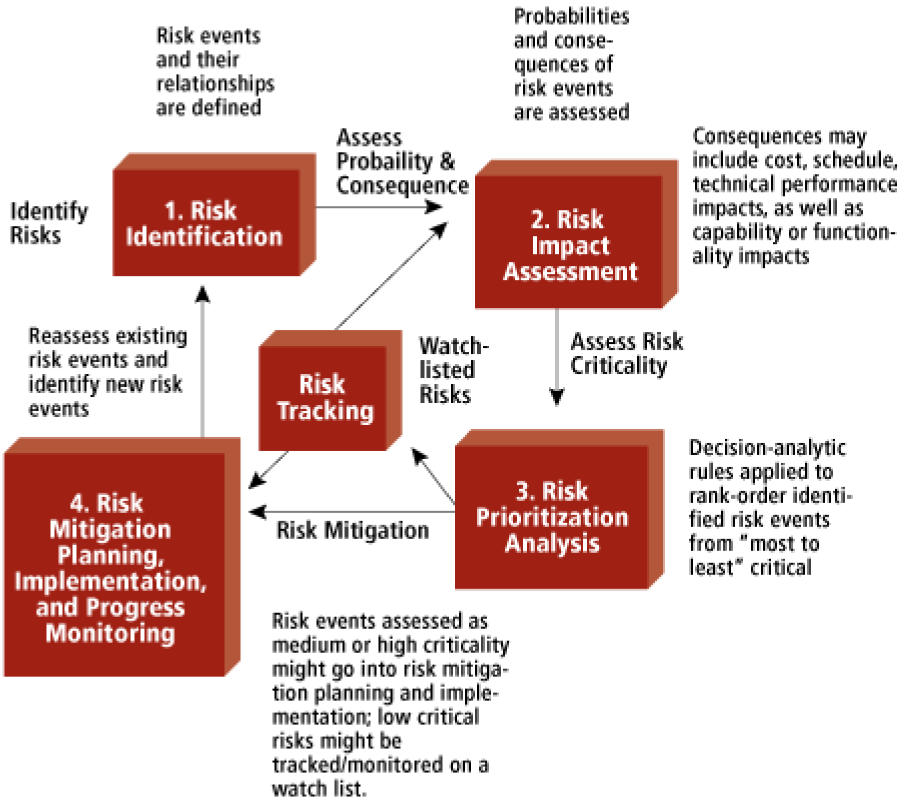

Figure 19- Risk Assessment Flow Chart

6.1 Risk Identification

- Performance Risks
  - The turbine fails to generate power.
  - Power efficiency is under 70%.
- Scheduling Risks
  - Materials are not ordered in time/delivery is delayed.
  - Scheduling conflicts arise between group members.
- Materials Risks
  - Piping connections to reservoirs/turbine/pump/etc aren't compatible.
  - Silicone sealant fails to seal connections.
- Safety Risks
  - Water leaks onto open electrical components.
  - Sharp edges on the cut components of the design.

6.2 Risk Analysis

- Performance Risks
  - Turbine fails to generate power
    - The project would be functionally useless.
  - Power efficiency is under 70%.
    - Failure to meet user specifications.
- Scheduling Risks
  - Materials are not ordered in time/delivery is delayed.
    - Construction would be delayed and rushed.
  - Scheduling conflicts arise between group members.
    - Not all members can be present for construction/construction is delayed.
- Materials Risks
  - Piping connections to components aren't compatible.
    - Project will not be able to be assembled.
  - Silicone sealant fails to seal connections.
    - Water would leak from the project.
- Safety Risks
  - Water leaks onto open electrical components.
    - Electrocution/shock hazard for the user.
  - Sharp edges on the cut components of the design.
    - Laceration/sprinter risk for the user.

6.3 Risk Prioritization

Frequency of Scenario	Severity of Consequences		
	Low Severity	Medium Severity	High Severity
High Frequency	Medium	High	High
Medium Frequency	Low	Medium	High
Low Frequency	Low	Low	Medium

Figure 20- Sample Risk Assessment Matrix

As shown in Figure 20 above, the risk level was determined using the likelihood of the risk occurring and the severity of the consequences. The higher the likelihood or severity, the higher the risk factor. Red risks receive the highest priority and strongest mitigation strategies; green risks are left to be addressed if they occur or are risks we can easily eliminate in the construction process; yellow risks have a basic contingency plan but are not the main focus. A full ranking of our risks can be found below in Table 4.

Table 5- Risk Assessment Matrix for PHS Design

RISK	LIKELIHOOD	SEVERITY	RISK FACTOR
Turbine failure	Low	High	Medium
Efficiency < 70%	Medium	Medium	Medium
Late materials	Low	Medium	Low
Schedule conflict	Medium	Low	Low
Bad connections	Low	Low	Low
Unsealed connections	Medium	High	High
Water leaks	Medium	High	High
Sharp edges	Medium	Low	Low

7 Codes and Standards

7.1 Identification

1. International Plumbing Code 605.3- Water Service Pipe: Water service pipe or tubing...shall have a working pressure rating of not less than 160 psi (1100 kPA) at 73.4 degrees F
2. International Plumbing Code 304.4- Openings for Pipes: In or on structures where openings have been made in walls, floors, or ceilings for the passage of pipes, the annular space between the pipe and sides of the opening shall be sealed with caulking materials or closed with gasketing systems compatible with piping materials and locations.

3. IEC 60335-2-51- Particular Requirements for Stationary Circular Pumps for Heating and Service Water: Pumps only affixed to a pipe should be placed against a wall of the corner and pump away from the corner.
4. ISO 10591- Sealant should retain cohesion properties after being submerged in water

7.2 Justification

1. The structure is built primarily out of PVC piping. As a primary component, it needs to be able to be used safely and without the concern of bursting.
2. For our project, there are multiple joints and openings in the reservoir; for example, the top reservoir has two openings to fit the piping, and there are four joints leading down to the lower reservoir between the piping, shut-off valve and turbine. In addition, the piping is fed through foam support blocks which also have air pockets around the piping and elbow joint. If left as-is, our project would leak all over the place and wouldn't work.
3. Our pump is placed in the lower reservoir of the project and is not affixed to a wall; it has suction cups but the only permanent connection is to the outflow pipe.
4. The sealant we use on our project will be inside the container so the water pressure will help seal up the gaps. As we move the project, the sealant will likely experience forces (even with the project glued together) and the sealant needs to be able to maintain its structural integrity.

7.3 Design Constraints

1. The PVC we choose to work with has to be able to withstand at least 160 psi, even if we don't anticipate reaching that pressure.
2. All gaps, voids, and loose joints in our piping and support system need to be sealed up to prevent leaking.
3. The pump must be placed between the wall of the reservoir and the piping to allow the compression to hold it in place.
4. We need to use a waterproof silicone sealant.

7.3.1 Functional

The pump needs to provide at least 18" of head to move the water to the upper reservoir.

7.3.2 Safety

The design needs a container or bin to catch any potential water spills.

7.3.3 Quality

The design materials should be able to withstand transportation and multiple demonstrations.

7.3.4 Manufacturing

A waterproof sealant needs to be used at all joints and connections.

7.3.5 Timing

The system should take no more than five minutes to reset.

7.3.6 Economic

The total material cost should not exceed $120.

7.3.7 Ergonomic

The design needs to be easy to turn on/off via either an accessible plugin or switch.

7.3.8 Ecological

The system should use as little power to operate as possible.

7.3.9 Aesthetic

The design construction should be clean and classroom-presentable.

7.3.10 Life cycle

The design should be sturdy enough to use twice a semester and not need to be maintained.

7.3.11 Legal

Per the International Plumbing Code, all PVC piping needs to be rated for at least 160 psi.

7.4 Significance

1. While the sizing of the PVC piping didn't change, we did need to be conscious of the material grade when selecting our piping. Below we have included a screenshot of the receipt showing the PVC we are using is rated for up to 480 psi.

3/4-in x 10-ft 480-PSI Schedule 40 White PVC Pipe	QTY
Item #: 23971 | Model #: PVC 04007 0600	1
Unit Price $3.83 | Subtotal $3.83	

Figure 21: PVC Pipe Grade

2. Rather than just using plumber's tape, we chose to purchase a silicone caulk specifically used in plumbing applications. Shown below are product specifications that meet the guidelines listed above (note- image cropped for space-saving).

Figure 22: Silicone Sealant Specifications

3. Originally, our pump was placed in the center of the lower reservoir, as we figured this would allow for the best location to pull water from. By now moving it back against the reservoir wall, our design has changed to extend the piping an extra 1.5". Below are the initial vs final embodiment drawings showing the updated pump location.

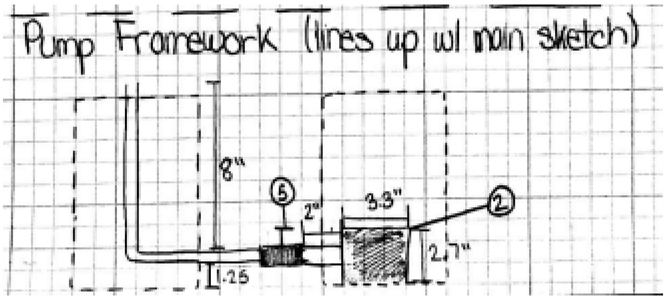

Figure 23- Initial Pump Framework

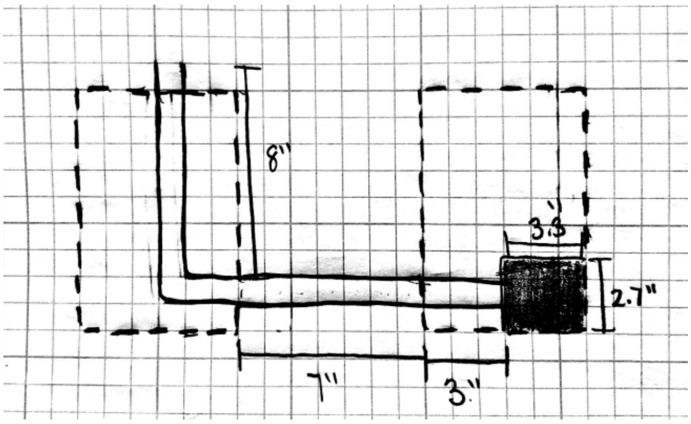

Figure 24- Final Pump Framework

4. As previously mentioned, we chose to use a silicone sealant rated for plumbing applications. While not perfect or as strong as glue, the silicone is waterproof and will not fall apart when submerged in the reservoirs. In addition, once fully assembled, the entire design will be glued down to minimize joint movement, assisting the sealant in maintaining its integrity. Specifications for this sealant can be found in Fig. 23.

8 Working prototype

8.1 prototype Photos

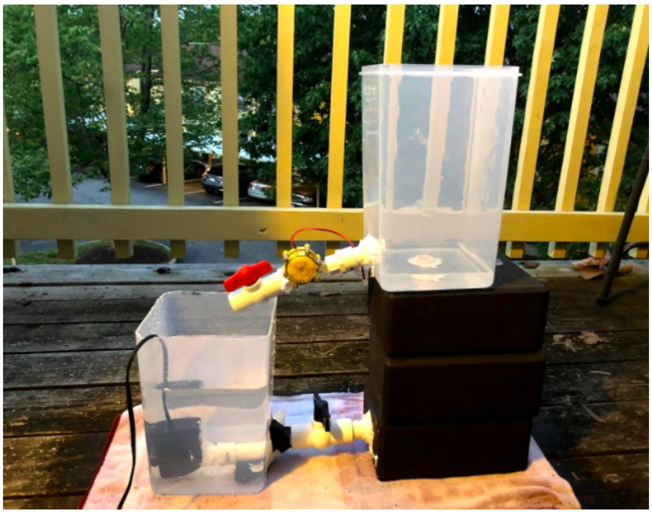

Figure 25- Image of entire pump hydropower storage prototype

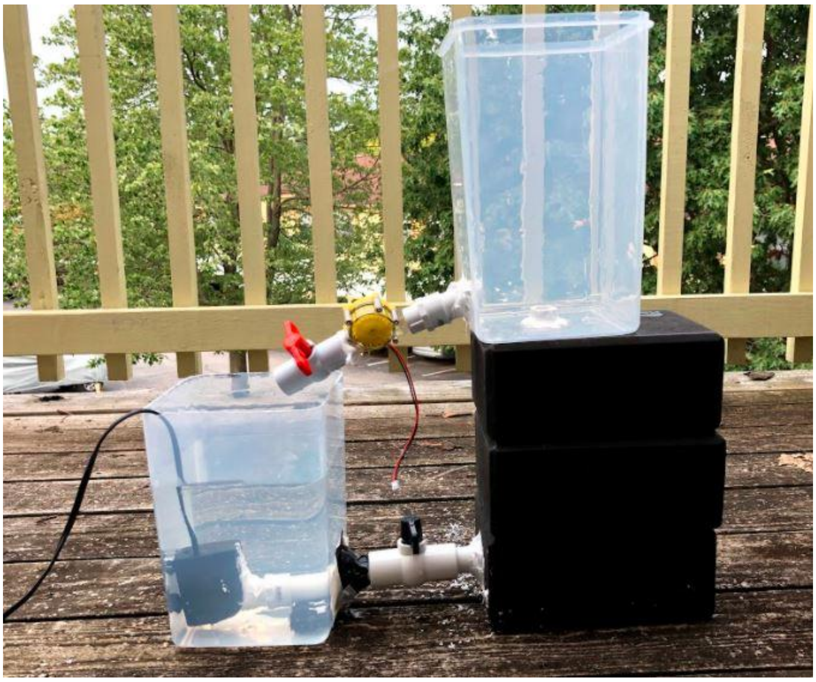

Figure 26- Close Up of Prototype

8.2 Working Prototype Video

Working Prototype Demo: https://www.youtube.com/watch?v=UxZqmIVo8_E

8.3 Prototype components

Figure 27- Turbine Generator and Valve

Figure 28- Submerged Pump in Lower Reservoir

Figure 29- Bottom Valve

Figure 30- Power (V) generated from the turbine

9 Design documentation

9.1 Final Drawings and Documentation

9.1.1 Engineering Drawings

See Appendix C for the individual CAD models.

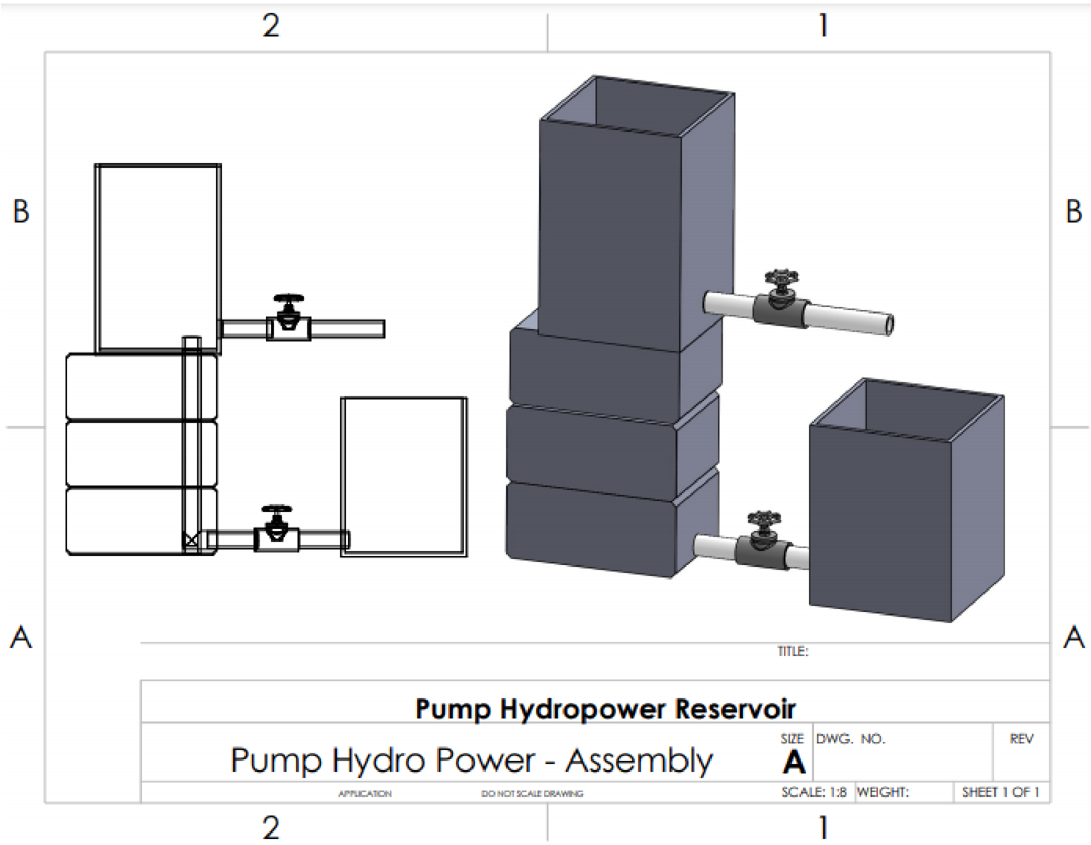

Figure 31- CAD Drawing of Full Assembly

9.2 Final Presentation

Link to final presentation: https://www.youtube.com/watch?v=Kscpg621BsM

10 Teardown

No teardown was necessary as the team opted to keep the project.

11 Appendix A - Parts List

Table A1- Parts List

No.	Item Description	Source
1	PVC Midline Shut-Off Valve	Lowes
2	15W Pond Water Pump	Amazon
3	12 V Water Turbine Generator	Amazon
4	.75" PVC Piping	Lowes
5	Silicone Plumbing Sealant	Amazon
6	Plastic Food Storage Containers	Amazon
7	EVA Foam Blocks	Amazon
8	.75" PVC Elbow	Lowes
9	.75" to .5" PVC adapter	Lowes
10	Mini Multimeter	Lowes

12 Appendix B - Bill of Materials

Table B1- Bill of Materials

No.	Item Description	Source	Unit Cost	Qty.	Total
1	PVC Midline Shut-Off Valve	Lowes	$4.98	2	$9.96
2	15W Pond Water Pump	Amazon	$14.99	1	$14.99
3	12 V Water Turbine Generator	Amazon	$10.90	1	$10.90
4	.75" PVC Piping	Lowes	$3.83	1	$3.83
5	Silicone Plumbing Sealant	Amazon	$7.84	1	$7.84
6	Plastic Food Storage Containers	Amazon	$30.99	1	$30.99
7	EVA Foam Blocks	Amazon	$11.99	2	$23.98
8	.75" PVC Elbow	Lowes	$0.73	1	$0.73
9	.75" to .5" PVC adapter	Lowes	$0.82	1	$0.82
10	Mini Multimeter	Lowes	$19.98	1	$19.98
				TOTAL	**$124.02**

13 Appendix C – Complete List of Engineering Drawings

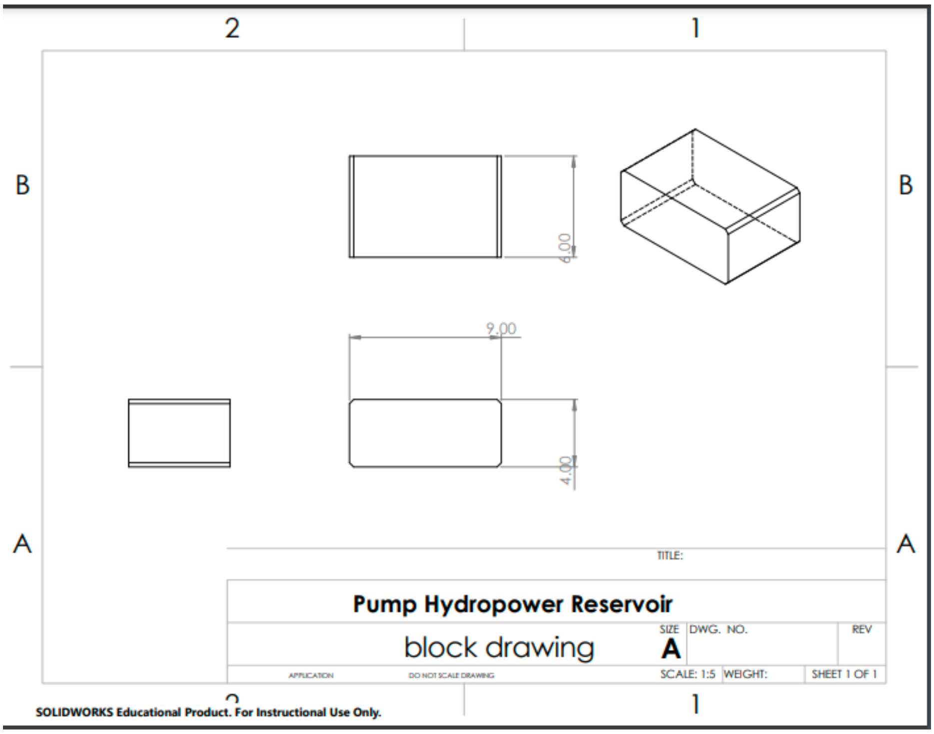

Figure C1-Block Drawing

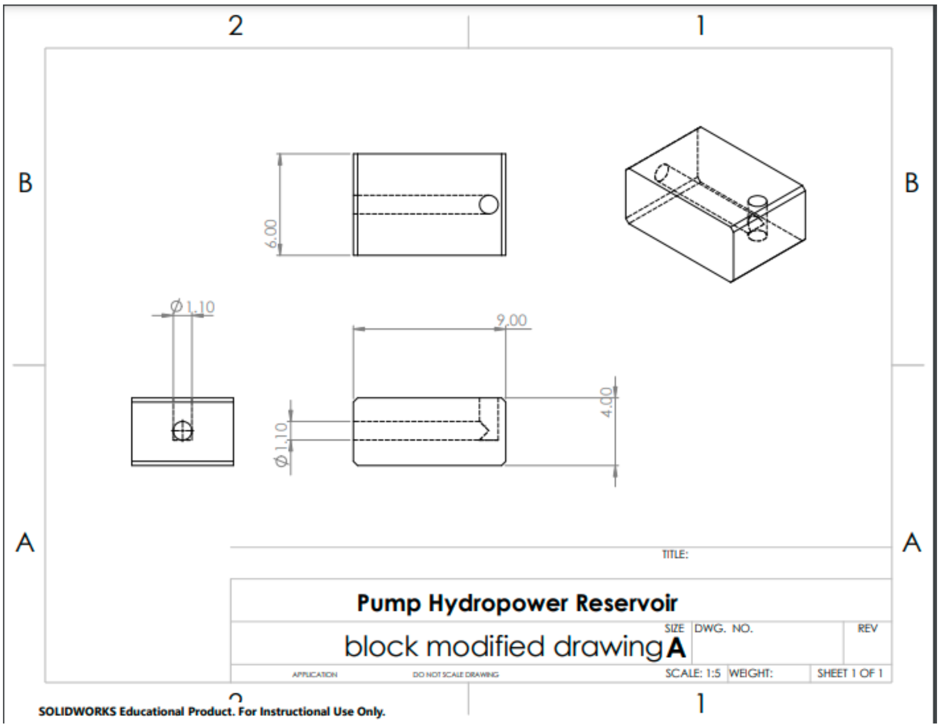

Figure C2-Modified Block Drawing

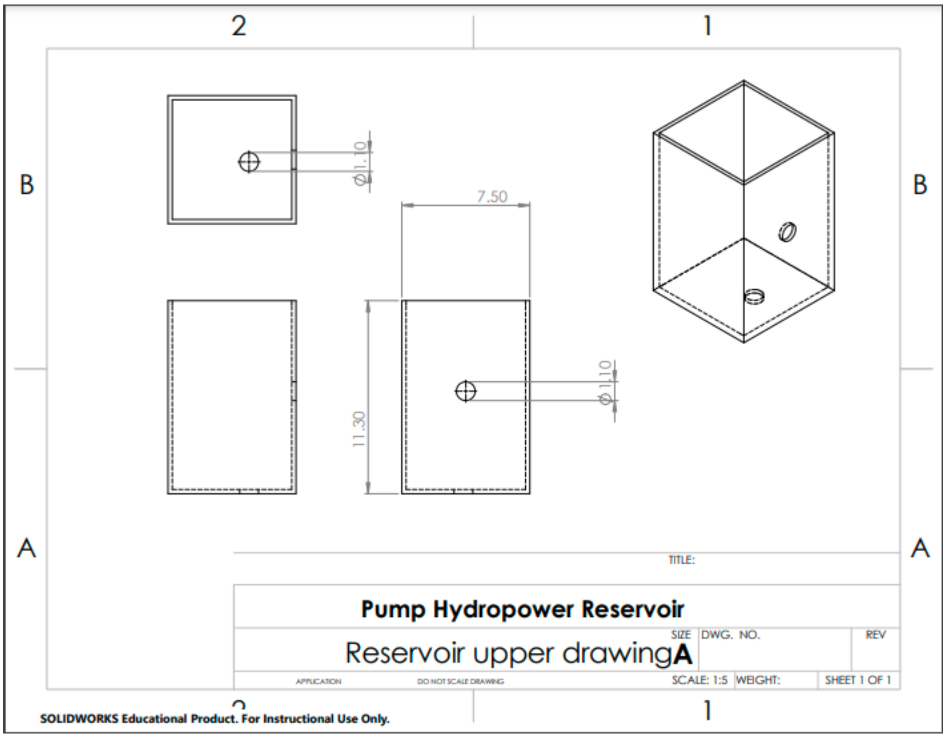

Figure C3- Upper Reservoir Drawing

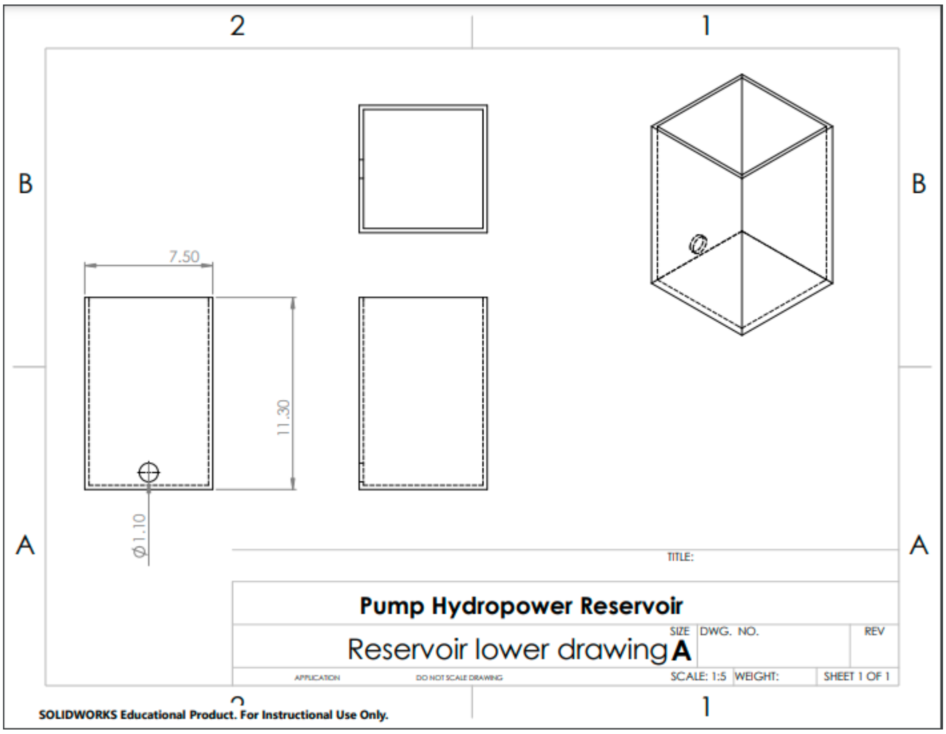

Figure C4- Lower Reservoir Drawing

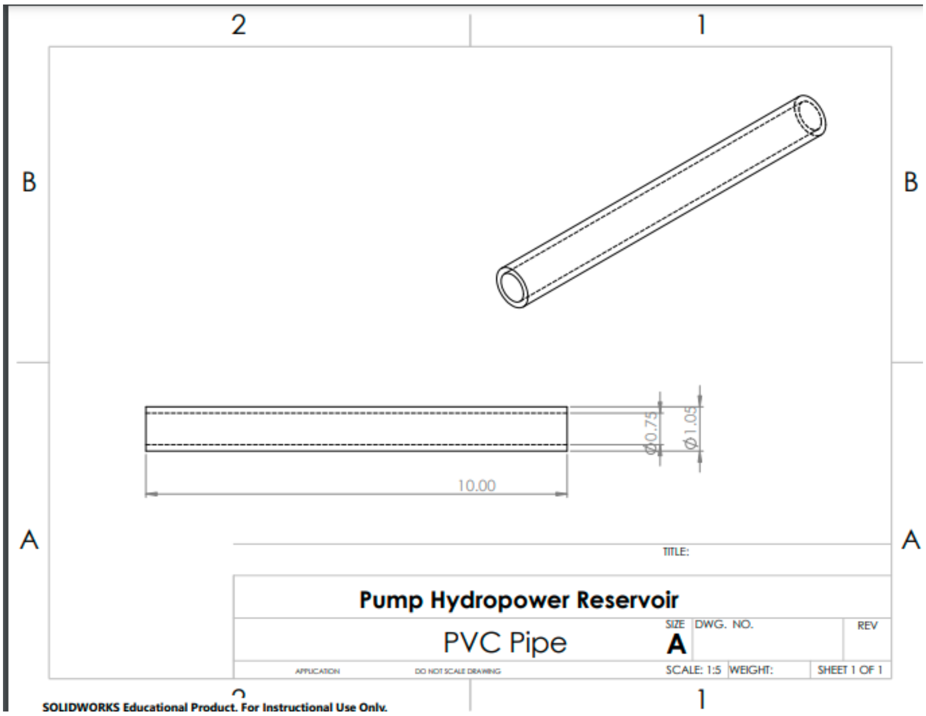

Figure C5- PVC Pipe

14 Annotated Bibliography

[1] (ICC), I. C. C. (2017, August). *2018 international plumbing CODE (ipc): Icc digital codes*. 2018 INTERNATIONAL PLUMBING CODE (IPC) . https://codes.iccsafe.org/content/IPC2018.

-Used to source PVC standards for the project

[2] International Electrotechnical Commission. (n.d.). *IEC 60335-2-51:2019*. ITeh Standards Store. standards.iteh.ai/catalog/standards/iec/bdf90caf-42c4-4165-a668-cddae8d8c1e3/iec-60335-2-51-2019.

-Used to source electrical safety standards for the project

[3] International Standards Organization. (2020, November 2). *ISO 10591:2005*. ISO. https://www.iso.org/standard/35011.html.

-Used to source silicone sealant standards for the project

[4] *Pumped Hydropower*. Energy Storage Association. (2021, April 7). https://energystorage.org/why-energy-storage/technologies/pumped-hydropower/.

-Used to source background information on PHS systems and how they work

[5] Vatanpour, S., Hrudey, S., & Dinu, I. (2015). Can public health risk assessment using risk matrices be misleading? *International Journal of Environmental Research and Public Health*, *12*(8), 9575–9588. https://doi.org/10.3390/ijerph120809575

-Source for sample risk matrix image