The University of Sussex

SCHOOL OF ENGINEERING & INFORMATICS

THE INTERCONNECTEDNESS AND INTERDEPENDENCE BETWEEN POWER AND WATER NETWORKS

Supervisor: Dr Spyros Skarvelis-Kazakos

Candidate Number: 230832

Degree: BEng (with hons) Mechanical Engineering

Word count: 7218

Abstract

This paper discusses interdependent water and power networks and their vulnerability to disturbances. Two models were created using the Simscape toolbox for Simulink, one model being a power distribution system and the other a water distribution system. These models were integrated, and simulations were conducted to analyze the effects of such a disturbance on the power distribution system and the inherent effects on the water distribution system, focusing on two main tests. The first test examined the impact of the time of day on the system's performance during a disturbance, while the second test examined the effect of disturbance duration on system performance. Test 1 showed that disruptions during peak water demand periods (10:00-11:00) result in a much larger decrease in water consumption than those during low-demand periods. Furthermore, Test 2 showed how the duration of a disturbance affects the performance of the system, with longer disruptions leading to more significant decreases in water consumption. Additionally, the simulations showed that backflow, a significant risk for water systems was occurring during the disruptions. Overall, the paper underscores the intricate nature of infrastructure interconnection, as well as the importance of improving resilience in such systems which would lead to a better quality of life for society.

Contents

Chapter 1 – Introduction *1*

1.1 – Background 1

1.2 – Objectives 2

Chapter 2 – Key Concepts and Conducted Research *3*

2.1 – Critical Infrastructure 3

2.2 – Interdependency 3

2.3 – Faults and Failure 4

2.4 – Mitigation 4

2.5 – Resilience 5

2.6 – Historical examples 7

Chapter 3 – Methodology *8*

3.1 – Water Distribution System 8

3.2 – Power Distribution System 11

3.3 – Combined Model 11

3.4 – Conducted simulations 12

Chapter 4 – Results *13*

4.1 – Test 1 Data Presentation and analysis 13

4.2 – Test 2 Data Presentation and Analysis 19

4.3 – Resilience Curves for Both Tests 26

Chapter 5 – Conclusion and Evaluation *28*

5.1 – Conclusion 28

5.2 – Evaluation 28

References *29*

Appendix A ..... *i*

Appendix B ..... *vi*

Turnitin receipt ..... *xxviii*

Statement of Originality

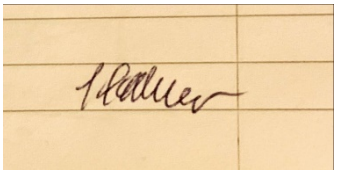
The following parts of this paper are **not** my own work:

- The water pump subsystems used in the water distribution model
- The data for water demand throughout a 24-hour period
- The data for transmission load in the power distribution system
- The specialized power systems to Simscape electrical interface until the generic rotary actuator connected to the ends of the power distribution system

All of the above are mentioned in the paper and the original authors are referenced.

In making this submission I declare that my work contains no examples of misconduct, such as plagiarism, collusion, or fabrication of results. Except for where indicated in the text, all writing, models and figures included in this dissertation are my own original work.

I confirm that I have talked with my project supervisor about whether ethical review will be required, and we have come to the conclusion that it is not necessary.

Signature: 

Chapter 1 – Introduction

1.1 – Background

Water and power networks are essential critical infrastructures which provide vital services to modern society. While these two networks have traditionally been viewed as separate systems, they are in fact highly interconnected and interdependent. The availability of water is crucial for power generation, and power is necessary for the treatment and distribution of water. The interdependence between these two networks, as well as other critical infrastructure has become increasingly complex and intricate as well as more evident in recent years, particularly during natural disasters such as earthquakes which can disrupt both water and power networks simultaneously. This has led to a growing concern that disruptions or failures in one infrastructure could have cascading effects on other interconnected infrastructures, potentially leading to significant societal and economic consequences. As such, it is of the utmost importance to understand not only the risks but also the resilience of these critical infrastructures, as well as to develop strategies to mitigate those risks and enhance the resilience of the infrastructures.

Two approaches are usually used, either independently or in conjunction, in order to face the complex and multi-faceted challenges posed by infrastructure interdependency. The first, and most logical, is is for the design of these key infrastructures to be extremely well-thought out in order to reduce the vulnerability of the systems as much as possible. However, in reality, and for a variety of reasons, is not always feasible: thus the second approach, the use of resilience and mitigation strategies, is brought into play in order to reduce the potential ramifications caused by system interdependencies. Modelling of interconnected systems is therefore extremely important as it allows for simulations of real-life scenarios to be carried out without the societal risks. Understanding of interdependencies and their failures can therefore be improved and applied to actual critical infrastructures. This is the aim of the dissertation: to create a model of a water and power network using Simulink, a MATLAB-based simulation software. More specifically, the physical modelling product Simscape, which includes “Electrical” and “Fluids” toolboxes is used to create the models. A fault is added to the combined version of the models and simulations of an earthquake are produced in order to analyze how the two networks are linked to one another. This enables us to assess risks, as well as resilience and mitigation strategies, which could improve the effectiveness of the two types of networks both on an individual scale and on a connected scale.

1.2 – Objectives

In order to achieve the aim of the project stated in the previous subsection, four objectives were created and split into tasks. These are:

1. Understand and explain how power and water networks are linked
   - **Task 1:** Conduct research and collect information from reliable online sources and material provided by university on power and water networks
   - **Task 2:** Provide important information gathered and introduce concepts used throughout project

2. Creation of integrated model
   - **Task 3:** Create a model of a water network using Simscape Fluids
   - **Task 4:** Create a model of a power network using Simscape Electrical
   - **Task 5:** Combine the two models to get a final model and implement a fault

3. Analysis of the simulation results
   - **Task 6:** Conduct simulation tests
   - **Task 7:** Present data
   - **Task 8:** Analysis of data

4. Evaluation of results
   - **Task 9:** Discussion of conclusions drawn from analysis and comparison of results to case studies
   - **Task 10:** Suggestions for improvements in the model and its limitations

Chapter 2 – Key Concepts and Conducted Research

2.1 – Critical Infrastructure

Critical infrastructure is defined differently across the world depending on the setting and conditions of the region, as both the risks and the impact of a fault on infrastructure vary across countries. That said, there are key similarities between the definitions internationally so it may be generally described as systems or assets which provide vital services to society. The UK's National Protective Security Authority defines critical national infrastructure (CNI) as [1] "Those critical elements of infrastructure (namely assets, facilities, systems, networks or processes and the essential workers that operate and facilitate them), the loss or compromise of which could result in:

a) Major detrimental impact on the availability, integrity or delivery of essential services - including those services whose integrity, if compromised, could result in significant loss of life or casualties - taking into account significant economic or social impacts; and/or

b) Significant impact on national security, national defence, or the functioning of the state"
From the definition, it is clear that investment and proper management of critical infrastructure is of utmost importance to maintain the structure, health, safety and functionality of an economy.

2.2 – Interdependency

Lewis and Petit [2] describe interdependency between critical infrastructure as "a bidirectional relationship between two assets". As stated by Rinaldi [3] there are four different types of interdependencies between critical infrastructure, namely physical, cyber, geographical, and logical.

Physical interdependencies

A physical interdependency describes the relationship between two infrastructure systems which are physically linked, and their inputs and outputs directly affect each other. An example of a physical interdependency would be water and power supply as water supply infrastructure depends on electricity for its pumps to operate, while power supply infrastructure requires water for multiple reasons such as cooling and generating steam to operate turbines.

Cyber interdependencies

Cyber interdependencies are apparent when an infrastructure's state depends on transmission of information from communication infrastructure. It is the most modern type of interdependency, a result of computerization and automation. An example of a cyber interdependency would be power supply depending on the information provided about consumer consumption of electricity.

Geographical interdependencies

Geographical interdependencies are formed between infrastructures wherein the occurrence of an environmental event results in changes of state of all infrastructures. For example, if elements of a power distribution system and water supply system are in close proximity, both networks are susceptible to correlated damage and failures in cases of flooding/earthquakes/fires etc.

Logical interdependencies

Logical interdependencies describe the relationship of infrastructures which are not directly connected, i.e., there are no physical, geographic, or cyber connection.

2.3 – Faults and Failure

Infrastructure failure is described by Schultz et. al [4] as when the capacity of a structure to provide a designated level of service is exceeded. The formation of interdependencies results in higher risk of failures occurring [5], and these failures can be categorized as cascading, escalating, or common cause [3].

Cascading failures

A cascading failure is when failure in one system leads to a disruption in a component of a different system, resulting in a failure of the second system. An example of a cascading failure would be if a power distribution system underwent a disruption, pumps in a water distribution system would also be disturbed as electricity demands would not be met, in turn causing a failure in the entire water distribution system.

Escalating failure

Escalating failure is defined as an already existing disruption in one infrastructure resulting in an increase in severity of an independent disruption in another infrastructure. For example, if there was a failure in a power infrastructure which required maintenance or repair, and meanwhile there was a disruption in road transportation, this could result in an increase in repair time for the power infrastructure, as response time would be increased due to traffic, thus escalating the severity.

Common cause failure

Common cause failures are when failures in two or more infrastructures occur due to the same reason, at the same time. An example of this would be an earthquake causing damage to a power, water, and gas systems.

The listed types of failure may occur due to different types of events. Kazakos et al. [6] explain how for interdependent networks, cascading failures are most often the failure mode seen, usually caused by high impact low-frequency events. They also state how different natural disasters result in different consequences both geographically and in terms of damage done, with earthquakes for example causing damage to underground system over a large general area whereas tornadoes cause damage over a narrow, overground trajectory.

2.4 – Mitigation

In the context of interdependent infrastructure, mitigation can be defined as the reduction of infrastructure vulnerability and the risks faced using risk management and mitigation strategies. Though it might not be possible to completely prevent a failure from occurring the aim is to minimize the ramifications, allow for swifter recovery and potentially extend the provision of critical services for as long as possible after the occurrence of a disruption. The mitigation strategies enforced may include physical changes or aim to improve modelling of the networks, for example installing backup generators or redundant water supplies in preparation for any disasters. Such strategies also include policy changes to improve coordination and communication between infrastructure operators thereby reducing extrinsic uncertainties mentioned by Roe et al. [7].

For interconnected water and power systems Xiang He [8] includes only post disaster mitigation strategies as most of the disturbances caused in such networks are extremely unpredictable. The strategies he lists that are relevant specifically to interdependent water and power systems include:

- "Two component importance measures based on an interdependent networks resilience optimization model are proposed to prioritize the restoration process of the disrupted components in each infrastructure network such that the resilience of the interdependent infrastructure networks is maximized" – Post disaster
- "A best-case decentralized model is proposed to allow controllers to develop a full recovery plan to minimize recovery cost." – Post disaster
- "A Markov decision process-based optimization approach is proposed which incorporates different sources of uncertainties to compute the restoration policies." – Post disaster
- "An optimization model for determining an optimal joint restoration strategy at infrastructure component level by minimizing the economic loss from the infrastructure failures is proposed" – Post disaster
- "A resilience-driven multi-objective restoration model is developed using mixed-integer programming that aims to maximize the resilience of the system of interdependent infrastructure networks while minimizing the total cost associated with the restoration process. The restoration model considers the availability of limited time and resources and provides a prioritized list of components, nodes or links, to be restored along with assigning and scheduling them to the available work crews" – Post disaster

2.5 – Resilience

Resilience is a term which has meaning in a variety of different studies, though for interdependent infrastructure OFWAT [9] defines resilience as "the ability to cope with and recover from disruption and anticipate trends and variability in order to maintain services for people and protect the natural environment now and in the future." OFWAT also states that resilience can be categorized into three different types: operational, financial, and corporate. Ciapessoni et al. [10] claim that – for power infrastructure at least – it is not such a one-dimensional concept, stating that it more than "the ability to bounce back", but also something which requires an organization seeking it to have "focus on aspects related to the potential for multiple failures at all levels of the organization". Furthermore, it is also necessary to aim for improvement in emergency preparedness as well as operational protocol before, during and after major disruptions and service interruptions. Finally, Ciapessoni et al. state the importance of learning from prior events and implementing those lessons to improve. Even though this definition was created in a power system analysis, it can be translated to water systems too, which is also evident from [11] claiming that other than the ability to bounce back from a disruption, resilience also entails a system's adaptation to deal with future disruptions.

Resilience assessment

According to Vugrin et al. [12], resilience is the system's ability to efficiently reduce the magnitude and duration of a disruption, thus resilience assessment can be seen as an analysis of how to reduce the duration and magnitude of a disruption. There are numerous methods of resilience assessment, but the 4R by Tierney and Bruneau [13] model explains the fundamental factors to be considered when improving resilience. The first R is Resistance, and as the name suggests indicates a system's ability to resist or endure a failure. Past events and assumptions are used in defining a particular system's resistance and allow for improvements to be made by increasing the ability of a system to function in a broader range of conditions, also known as reliability. Next, Redundancy refers to the insurance that a system has spare capacity in the event of a disruption. To improve resilience in terms of system redundancy, it would be ideal to isolate components of a system in order to ensure that failure of one component does not lead to a cascading chain of failures. Finally, Response and Recovery are often combined and relate to a system's ability to react to a disruption efficiently and effectively in order to localize the disruption and lead to faster repair times.

Stress tests

Stress testing is described by the NIC [14] as "testing a representation or simulation of a system to reveal its performance under certain conditions or to reveal the conditions that could lead to failure." The NIC also shows stress testing as the main method of resilience measurement for water and energy infrastructure in [15].

Graphical representation of resilience metrics

Panteli et al. [16] and Meng et al. [17] show methods of measuring resilience of power and water systems respectively through graphing resilience metrics and analyzing the graph shape. Such metrics accounted for include but are not exclusive to: failure duration, time to failure, severity, and recovery rates.

Furthermore, Poulin et al. [18] suggest that to represent resilience, three performance measures (i.e. the horizontal axis of the graph) can be defined as availability, productivity and quality. Then, these criteria can be plotted together for open ended interpretation by stakeholders. Finally, the measures are normalized in order to allow for comparisons of different situations and systems. The figure below is an example of what a resilience curve looks like.

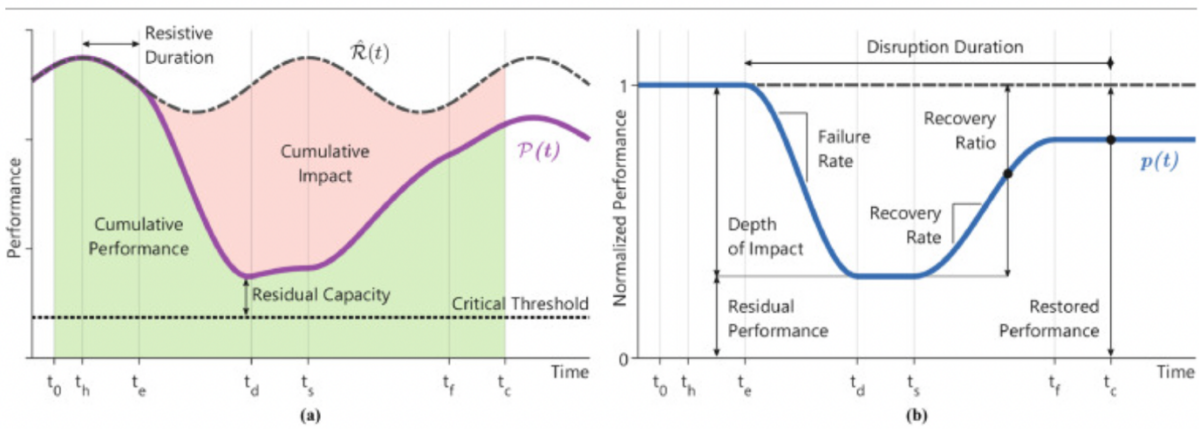


Figure 2.1: Resilience curves of actual and normalized performance (Source: [14])

Poulin also explains that the rate metrics "quantify how a systems performance changes over time" and that the failure rate is "associated with resistance and adaptive capability" whereas the restoration rate is the ability for the system's performance to be restored. The duration metrics are those which "quantify the time between milestones" such as disruption duration, recovery time etc. Magnitude metrics quantify the performance of the system at different points in time. These are seen in figure 2.1 as residual performance, cumulative performance and impact, etc. The threshold-based metrics are associated with "non-linear transitions in quantitative interpretation". The two types of threshold-based metrics include time-dependent metrics which are associated with the rate metrics explained above, as well as performance based which include the critical threshold, the minimum level of performance which is acceptable for system operation. Finally, the recovery ratio is the ratio between the minimum performance of the system and the performance at any time during the recovery phase of the system. Because it can be defined at any point during the recovery time it can be used to show the improving resilience over time.

2.6 – Historical examples

Brazil and Paraguay 2009

On November 10th 2009, Brazil and Paraguay experienced a large-scale blackout after enduring heavy rainfall and winds which caused a transmission failure in the Itaipu dam, one of the largest hydroelectric plants in the world. 18 states were affected and one third of Brazil's population was without power for approximately 5 hours [19].

Haiti 2010

On January 12th 2010, an 7.0 magnitude earthquake hit Haiti and caused massive damage to the cheap and poor quality water infrastructure. Half a million people were either killed or injured, almost 10% of the population was left homeless and even more without access clean water [20].

Tohoku 2011

The 2011 Tohoku earthquake, with a magnitude of 9.0, was the largest ever recorded in Japan and one of the most destructive. Following the earthquake, a tsunami occurred devastating the northeastern coast of Japan [21]. The impact of the disaster was further amplified by a chain reaction of events that resulted in a nuclear powerplant meltdown, causing radioactive contamination in the region. The two disasters in succession of one another had a cascading effect on the critical infrastructure of the region. As a result of the two events, the transmission lines and power stations had been destroyed which caused a widespread power outage. In turn, the water pumps in the water distribution system were unable to function, leaving the community and local infrastructure, more specifically the nuclear plant without access to water. Nuclear power plants require water for cooling the reactor cores, however water was not available as the combination of the natural disasters – the earthquake and tsunami that followed – destroyed the redundancy power generators and water supplies, resulting in a nuclear meltdown. After further inspection it was found that the failure of the power plant was due not only to the intrinsic factors - the earthquake and the tsunami - but also human factors, as maintenance of the plant had been sub-par and safety checks had not been conducted for many years [21] as no-one believed that a disaster of this proportion would occur. The cascading failures that occurred during the Tohoku earthquake highlight the importance of understanding the interdependency of critical infrastructures and developing resilience strategies that take these interdependencies into account. The disaster underscores the need for redundancy and backup systems, as well as improved infrastructure operation coordination and modelling. By analyzing the interdependence of water and power networks and developing mitigation and resilience strategies, future disasters can be better prepared for and their impact on society may be minimized.

Chapter 3 – Methodology

3.1 – Water Distribution System

The water distribution system seen in figure 3.1 was modelled using the Simscape Hydraulics toolbox and based off a 15-node water distribution test system as shown in figure 3.2 by Dr. Masood Parvania [22]. It is composed of a water reservoir which is connected to a pump station that feeds water from the reservoir through a system of hydraulic pipes. Within the system are two more pumping stations to keep the water flowing through to the two storage tanks, as well as to the three subsystems which are composed of a flow control valve and a signal representing the valves' opening (water demand) at different times of day. Lastly, there are output tanks connected to the valve subsystems which are used to measure the consumption of water by connecting their volume outputs to a "scope" block. The composition of the pump stations and subsystems can be seen in figures 3.3 and 3.4 respectively. The only part of the model which is not my own work are the pump stations, which were taken from the "Water Supply System" on the official MathWorks website [23]. A small alteration was made changing the two "constant" blocks to "From" blocks representing angular speed produced by motors connected to the power system which is explained in the next subsection.

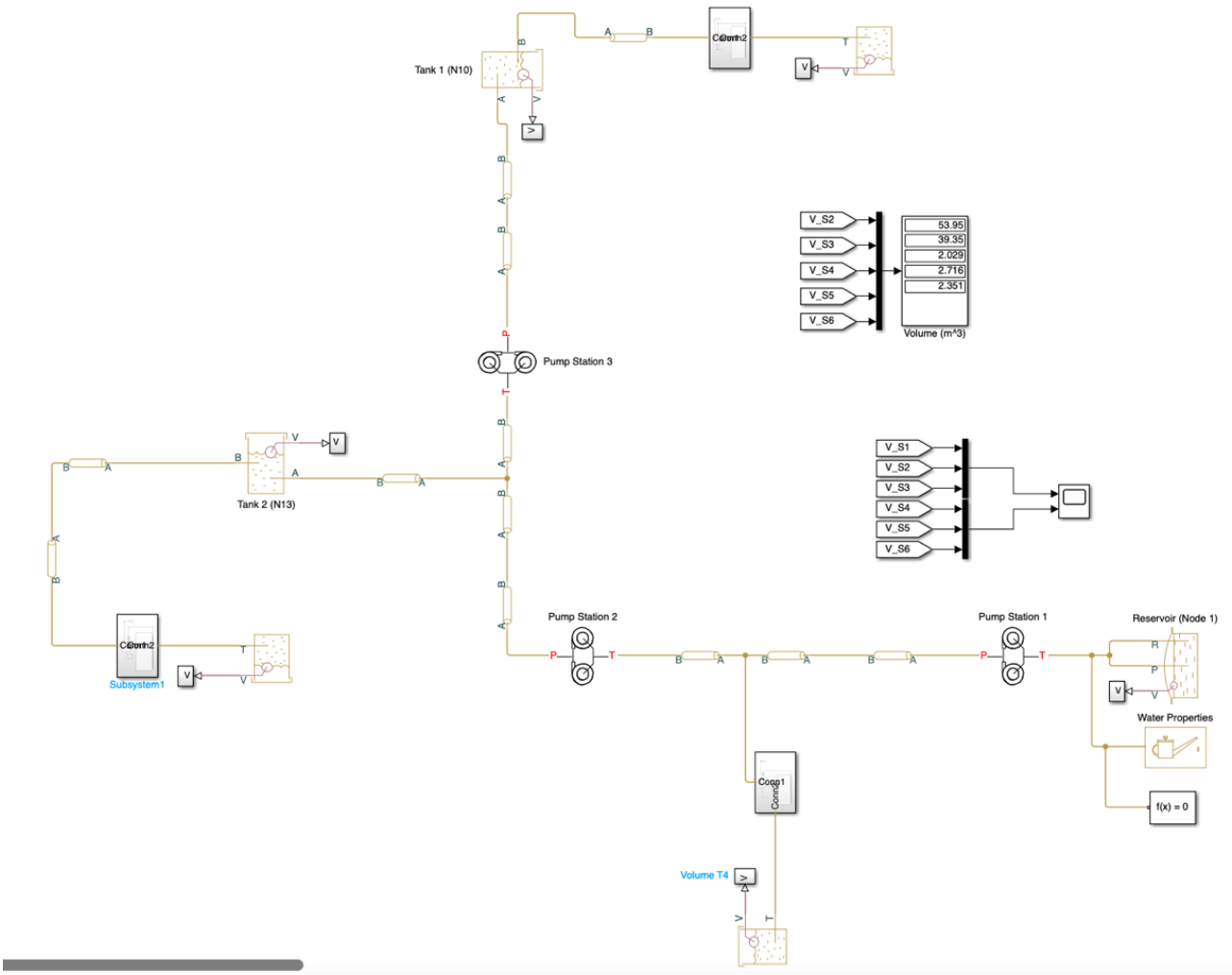


Figure 3.1: Water distribution system Simulink model

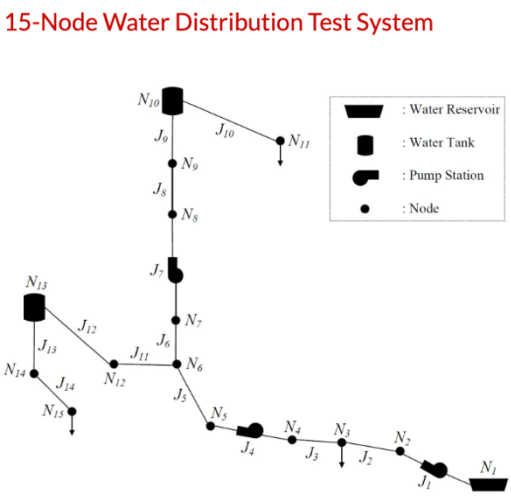


Figure 3.2: 15-Node test water distribution system used to create Simulink model [22]

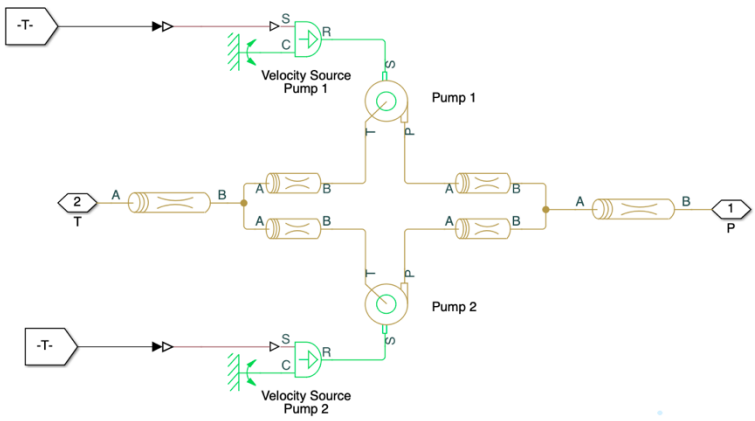


Figure 3.3: Composition of "Pump Station" block [23]

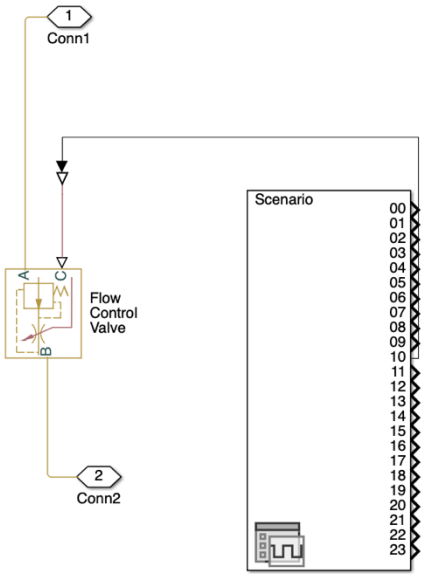


Figure 3.4: Control valve subsystem

The signals created to control the valve opening in the subsystem presented in figure 3.4 were made using the following data:

Water Demand Data

Hour	Node N3 (m^3/sec)	Node N11 (m^3/sec)	Node N15 (m^3/sec)
1	0.03996	0.03996	0.03996
2	0.02569	0.02569	0.02569
3	0.022833	0.022833	0.022833
4	0.02569	0.02569	0.02569
5	0.031397	0.031397	0.031397
6	0.071357	0.071357	0.071357
7	0.148423	0.148423	0.148423
8	0.191237	0.191237	0.191237
9	0.1998	0.1998	0.1998
10	0.19409	0.19409	0.19409
11	0.17982	0.17982	0.17982
12	0.15984	0.15984	0.15984
13	0.13986	0.13986	0.13986
14	0.128443	0.128443	0.128443
15	0.117027	0.117027	0.117027
16	0.11988	0.11988	0.11988
17	0.128443	0.128443	0.128443
18	0.14557	0.14557	0.14557
19	0.156987	0.156987	0.156987
20	0.156987	0.156987	0.156987
21	0.14557	0.14557	0.14557
22	0.13415	0.13415	0.13415
23	0.111317	0.111317	0.111317
24	0.077067	0.077067	0.077067

Figure 3.5: Water demand data [22]

The signal editor feature was used to generate the signals as follows: The water demand shown above is divided by 10 as the Simulink model is made as a smaller scale water distribution system. For each hour of the day, the water demand of the previous hour was used as the starting point. The final point takes the value of the water demand for the specific hour, i.e., for 10-11AM the starting point is 0.01998 and the end point is 0.019409 as shown in the figure below. Even though the data in figure 3.5 is for demand in m^3/s and the signal provided by the signal generator is the valve opening in m, the water demand through the hour is still accurately represented, as is the percent change of demand between hours.

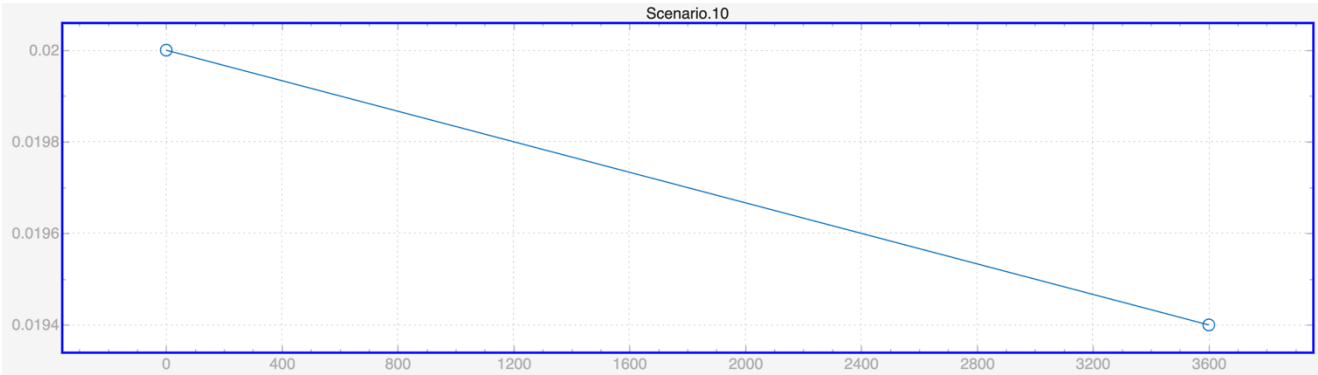


Figure 3.6: Signal generated for valve opening for 10:00-11:00

3.2 – Power Distribution System

Figure 3.7 below shows an IEEE 33 bus power distribution system Simulink model created with the Simscape Specialised Power Systems and Electrical toolboxes. It is composed of a three-phase voltage source of 12660 and 50Hz frequency, 33 buses - as the name suggests - which are connected to 32 lines represented by the three-phase RLC branches, and a load which is transferred through each of these buses. The data used for the line loads as well as the resistances and inductances in the RL branches was that of Baran and Wu (1989) IEEE 33 Bus System [24].

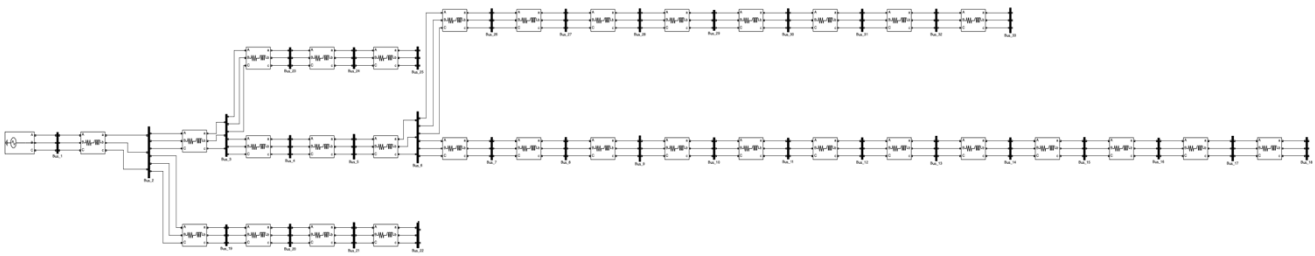


Figure 3.7: IEEE 33 Bus Power System Simulink model

3.3 – Combined Model

In addition to modelling the IEEE 33 bus power system, in order to integrate the two models, it was also necessary to also connect three motors to the power system which as mentioned in subsection 3.1, produce an angular speed for the pump stations to function. These motors were placed at the ends of buses 18, 22 and 33, which are the rightmost buses of the longest series of buses in figure 3.7. The addition of the motors required a parallel resistance to be connected past the buses mentioned as well as the implementation of an interface to allow for blocks from the Specialised Power Systems toolbox to be connected to blocks from the Electrical toolbox. Next a voltage sensor is to convert measured voltage into a physical signal to be inputted to a rotary actuator which acts as a motor.

The angular velocity is then measured using an ideal rotational motion sensor and converted from rad/s to RPM. The output is fed into a "Goto" block which returns the angular speed to the pump stations using the previously mentioned "From" block. Finally, a three-phase fault was added to the system in parallel before the Power Systems to Electrical conversion. This block implements a short-circuit in the phases of the system which can be triggered temporally and have a certain duration until normal conditions are restored. Figure 3.8 shows the series of blocks added to the ends of buses 18, 22 and 33. Once the extension to the power system was made, the two models were integrated producing the final combined model. The faults implemented to the power system would in turn affect the consumption of water, allowing for interdependence analysis. My supervisor Dr Skarvelis-Kazakos provided invaluable help with the implementation of the conversion interface and motor. The final model can be seen below in figure 3.8 (the model is very large thus not very clear due to zooming out, larger scales of figures 3.7 and 3.8 can be found in Appendix A)

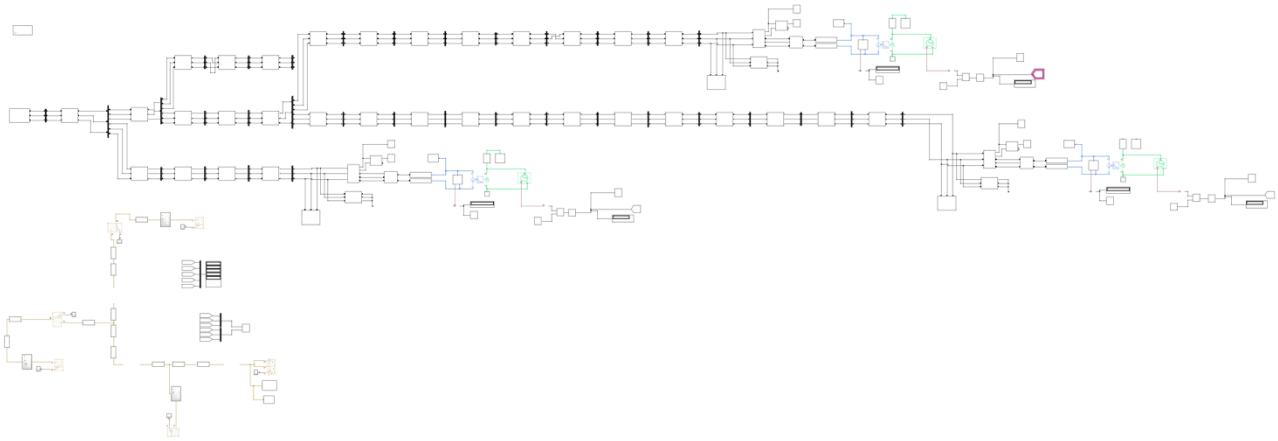


Figure 3.8: Combined water and power distribution system models

3.4 – Conducted simulations

The simulations were conducted with the aim of identifying important aspects with regard to the resilience of interdependent systems. Two different tests were run to achieve this. The first test involved simulating a disruption lasting 10 minutes in each hour of the day to determine at which time of day a disruption would have the biggest disturbance and what time is the least damaging for an earthquake to occur. The hypothesis for Test 1 is that at the time of day where demand is highest, the disturbance would also have the biggest effect on consumption and alternatively, the time of day with the least demand would be the best time of day for a disruption to occur. On the basis of that logic, a disruption at 03:00 would be the best-case scenario and a disruption at 09:00 would be the worst. The model was run normally for 900 seconds (15 minutes) before the fault block flipped the switch for the circuit-break which lasted until 1500 seconds (25 minutes).

Test 2 entailed understanding how fault duration affects the water system's output. The obvious answer is that a longer disturbance would result in less consumption, but the test aimed to find out the degree to which time affects output. For Test 2, the simulation process remained the same as Test 1, other than the fault being set to switch off at 2100 seconds (35 minutes) instead of 1500 seconds for the first set of data of Test 2 and 2700 seconds (45 minutes) for the second. This setup allowed for a comparison of a 10, 20 and 30 minute disturbance and allowed for the implications of restoration speed to be analysed.

Chapter 4 – Results

4.1 – Test 1 Data Presentation and analysis

For Test 1, a total of 72 figures were created, each consisting of two graphs showing the volumes of the reservoir and storage tanks in one of the graphs, and the volumes of the output tanks in the second. For the data presentation section, only the graphs for the time of day with the highest and lowest consumption of water will be presented as these will be the times figures analyzed - the rest of the graphs can be found at the end of the document in Appendix B.

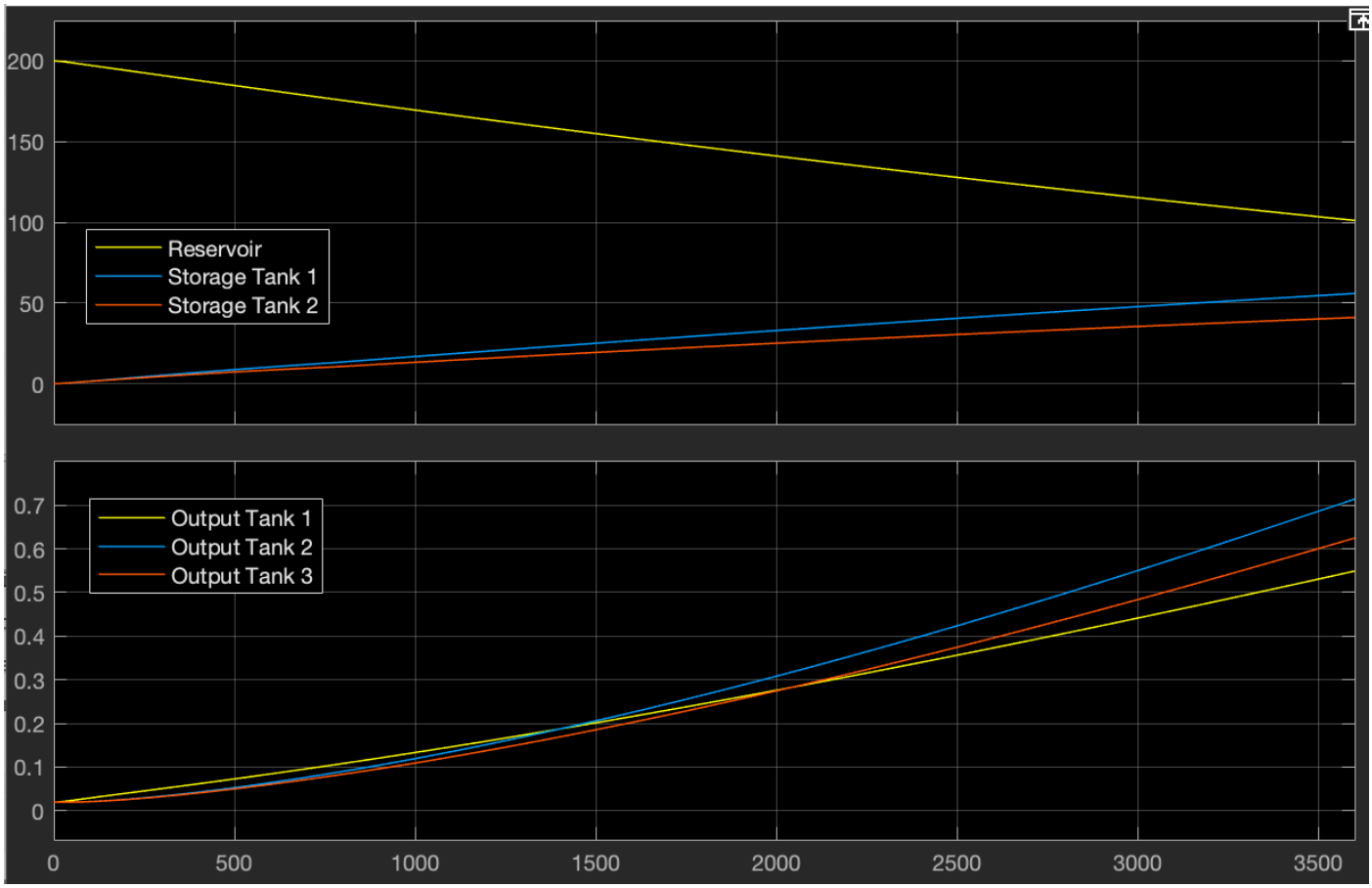


Figure 4.1: Hour 03 without fault

Backflow

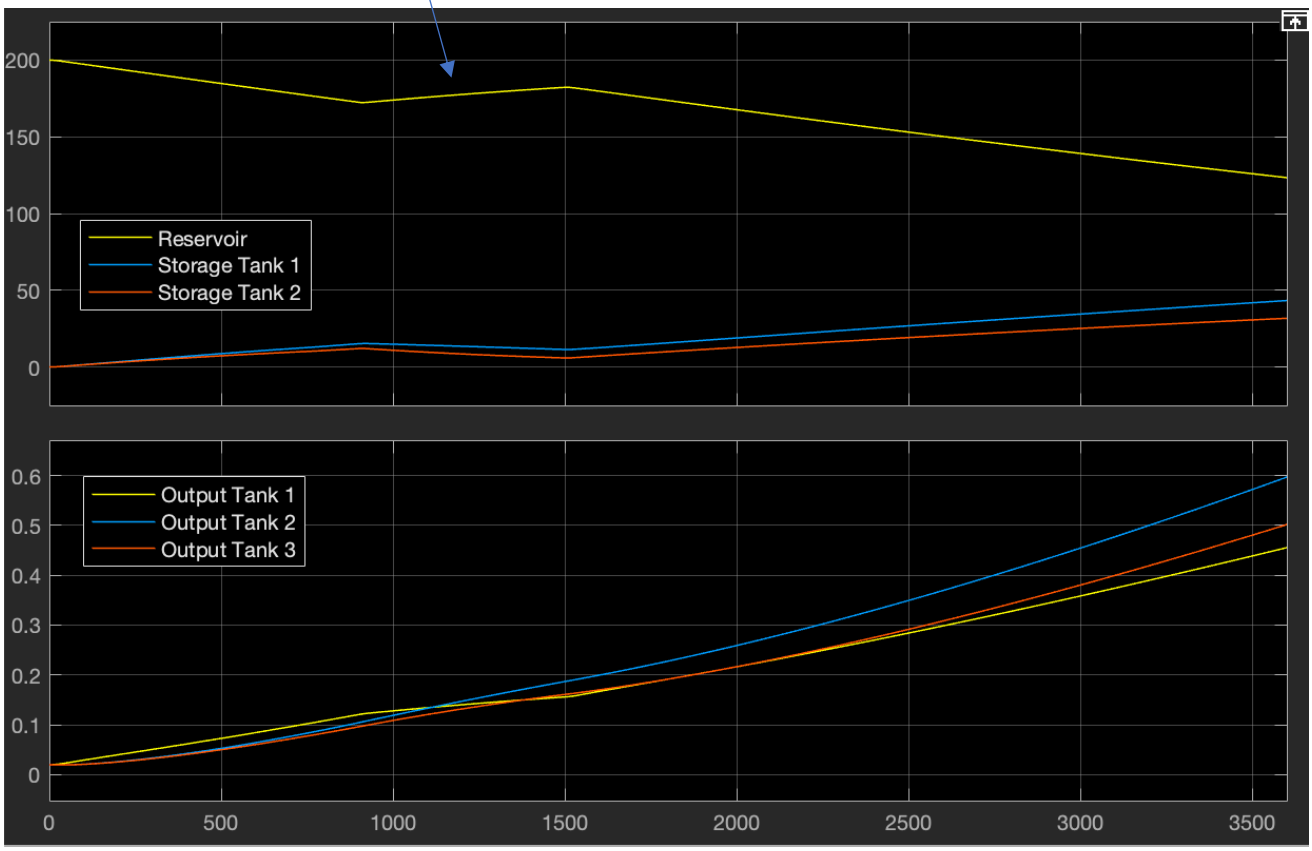


Figure 4.2: Hour 03 with fault

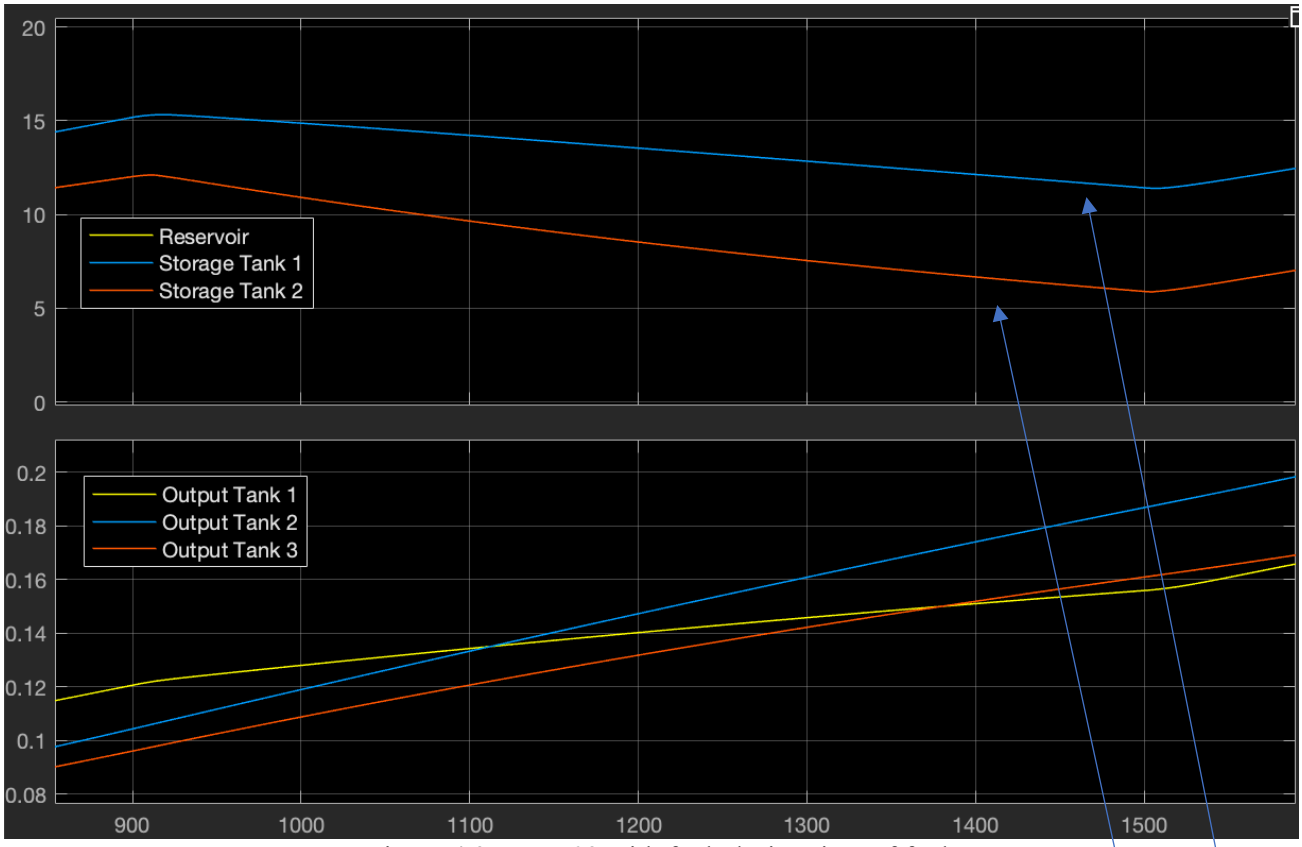


Figure 4.3: Hour 03 with fault during time of fault

Water flow continuing to output tanks

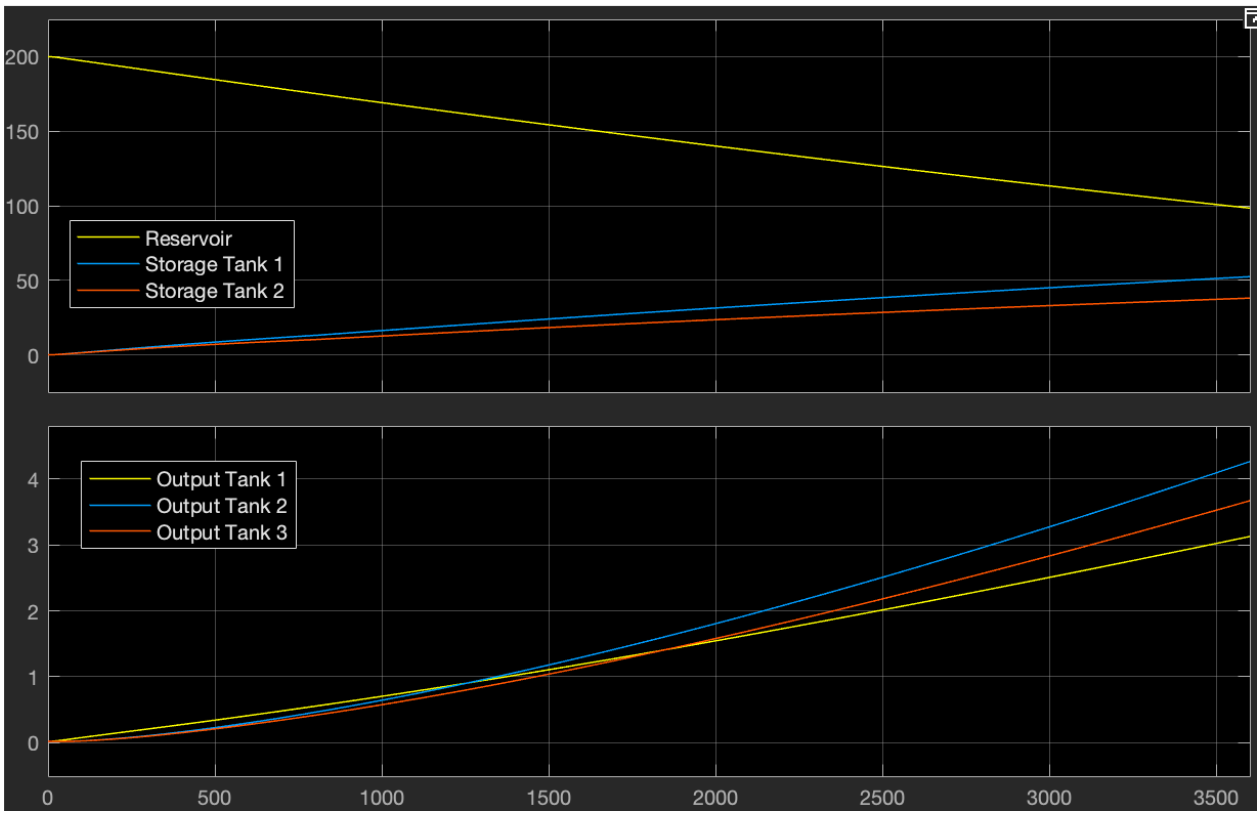


Figure 4.4: Hour 10 without fault

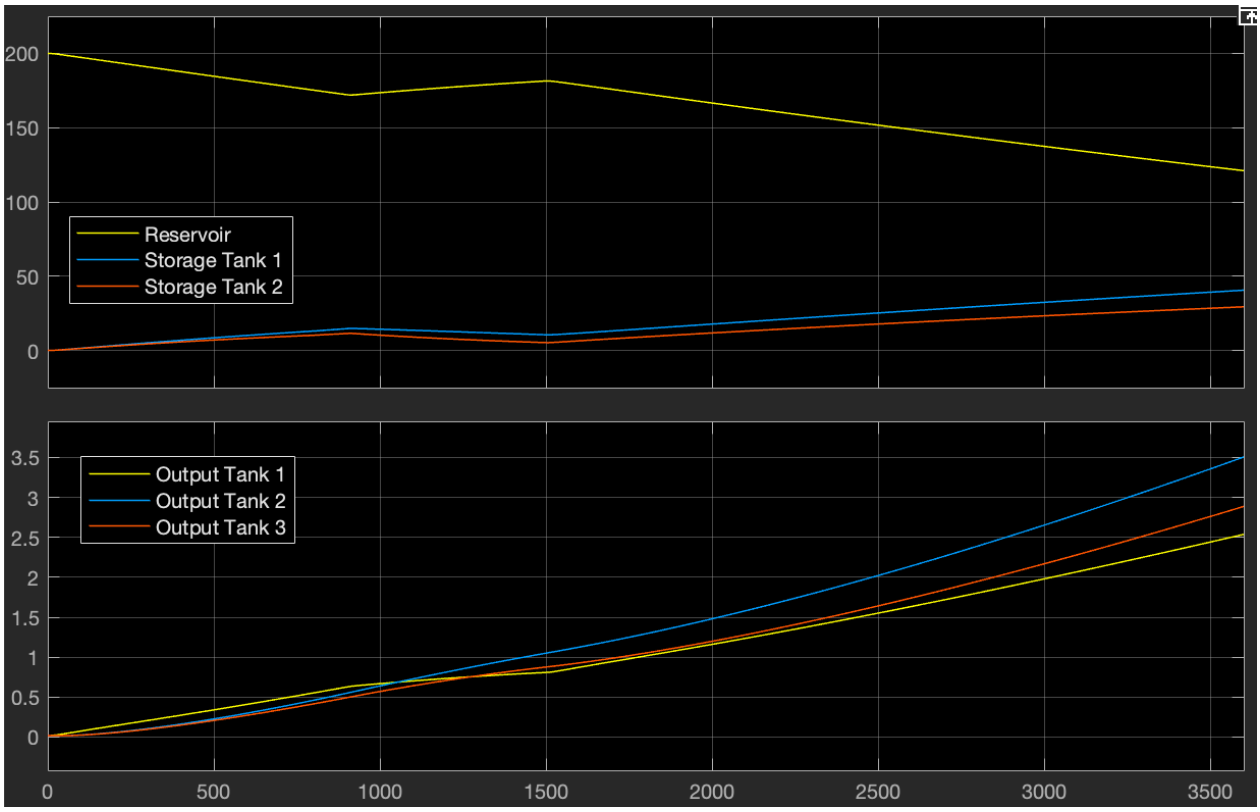


Figure 4.5: Hour 10 with fault

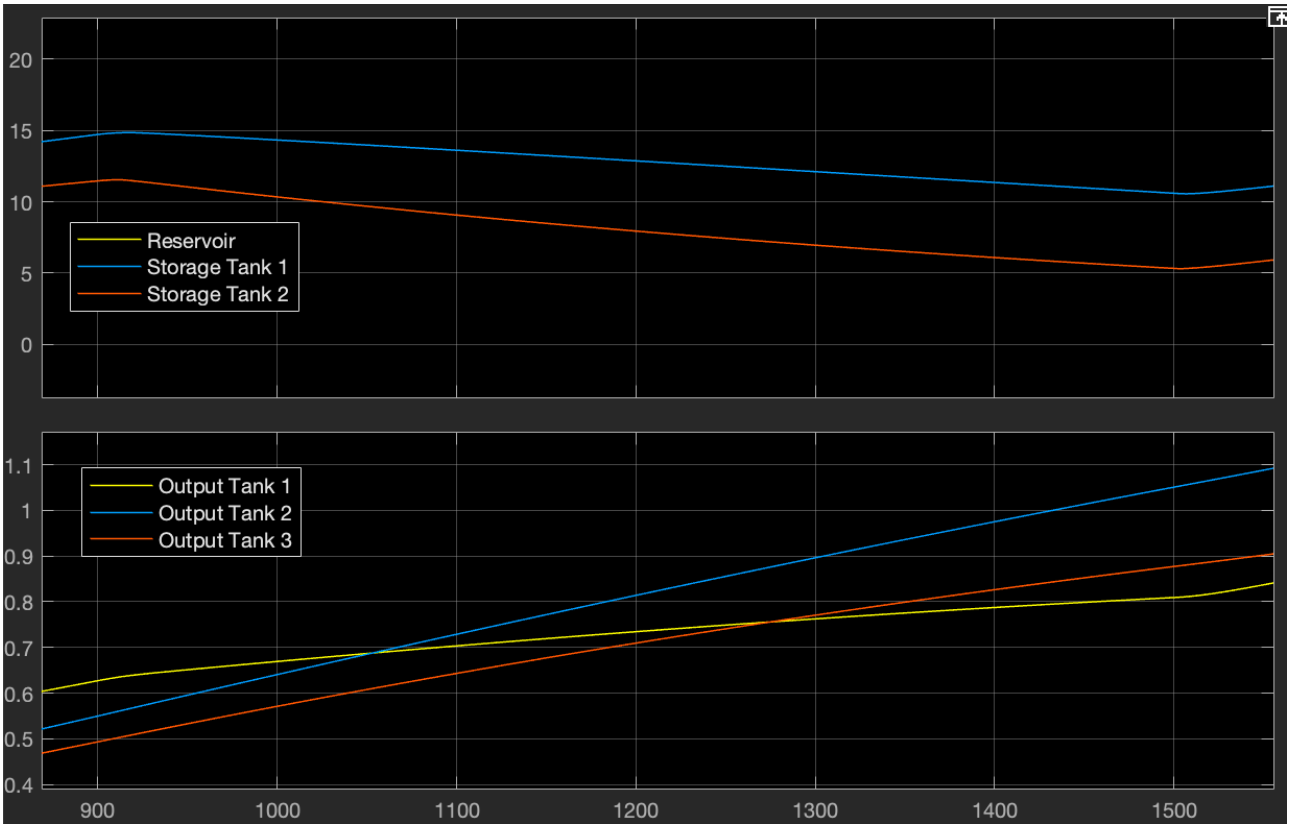


Figure 4.6: Hour 10 with fault during time of fault

The data gathered from Test 1 showed similar results for all hours of the day tested. The trend of the graphs produced were that of the reservoir tank's volume steadily decreasing as the storage and output tanks' volumes increase until the occurrence of the fault. At this point and until the end of the disruption at 1500 seconds, the storage tanks' volumes begin decreasing as the opposite is true for the reservoir. Meanwhile, the output tanks' volumes continue to increase, explaining why the volumes in the storage tanks decrease. The output tanks are still being filled as water has already reached the storage tanks. Moreover, because of the close proximity of the storage tanks and output tanks 2 and 3, their rate of increasing volume does not change, apart from a very minor decrease in the rate of consumption of output tank 3. Output tank 1 however does see a slight decrease in consumption rate as there is not a storage tank close to it for water to flow from and only a small portion of the water which is still in the pipe system flows into it. The reason the reservoir's volume increases during the fault might be attributed to backflow in the system as the pump closest to the reservoir stops functioning, thus, the reservoir's volume increases but at a slower rate than the decrease during optimal running. These effects have been labeled in figure 4.2 and 4.3. Beyond the reduction or complete cut-off of water supply to the output tanks, backflow is a large risk water systems face with very serious ramifications as it can lead to cross-contamination of the water. This occurs if water flows in the opposite direction to where it is intended to, creating a suction which potentially causes water flowing out of a sewage system, or containing any pollutants, to be reversed [25] into the water flowing towards a household or somewhere else where clean water is required. Even though this study is based on simulations of an earthquake, it should be noted that a water distribution system is much more susceptible to backflow in the event of high rainfall and flooding.

For the hour of 03:00 the water demand is second lowest, and figure 4.1 demonstrates a total water consumption of approximately $1.9m^3$. Comparing this to the consumption with a 10 minute fault shown in figure 4.2 where consumption is $1.55m^3$ means the percent change is equal to $\frac{1.55-1.9}{1.9} = -18.4\%$. and an absolute change of $-0.35m^3$. Figure 4.3 allows for a closer look on the tanks to be taken. Before the occurrence of the fault, the gradient, which represents consumption of water per second, for output tank 1 can be calculated by $\frac{y_2-y_1}{x_2-x_1} = \frac{0.08-0.02}{500} = 1.2 \times 10^{-4}$ but after 900 seconds this changes to approximately 5×10^{-5} (calculated from t=1000 to 1200), a 58.3% decrease. As previously mentioned, output tank 3 only had a very minor decrease in rate of consumption and tank 2's gradient remained constant. The time of day with the lowest consumption of water turned out to be 04:00 but the consumption was so low that the fault only caused it to decrease by 3% and the gradient changes were also very minor.

The time of day with the highest water demand is shown to be 10:00 rather than hypothesized 09:00 in subsection 3.4. This is because, as explained in subsection 3.1, the signal generated for each hour of the day starts at the value of the previous hour's water demand, meaning at 10:00 the start of the signal is at the maximum and only decreases by a small amount from 0.01998 to 0.019409 whereas 09:00 starts from 0.0191237 therefore the average demand is higher for 10:00. The overall consumption at 10:00 (figure 4.4) under normal conditions is $11m^3$, around 6 times that of the time of day with the lowest consumption. With the disruption this decreases to approximately $8.8m^2$, a 20% decrease.

When compared to the results for 03:00, even though the percent change is very close, at 10:00 it is still a bigger decrease as well as a much higher absolute fall in consumption of $2.2m^3$. Before the fault, the gradient of consumption in tank 1 is calculated as $\frac{0.62-0.02}{900} = 6.7 \times 10^{-4}$. Figure 4.6 shows the gradient decreased by 70.1% to 2×10^{-4}. Again, as expected the decrease in gradient for 10:00 is higher than at 03:00, which proves that it is much worse for a disruption to occur at times of the day where water demand is higher. This can also be seen by using the data gathered for all times of day to create diagrams presenting the normal load of the water system throughout the day, the losses in the system throughout the day and finally the load against losses. Figures 4.7, 4.8 and 4.9 show these diagrams respectively.

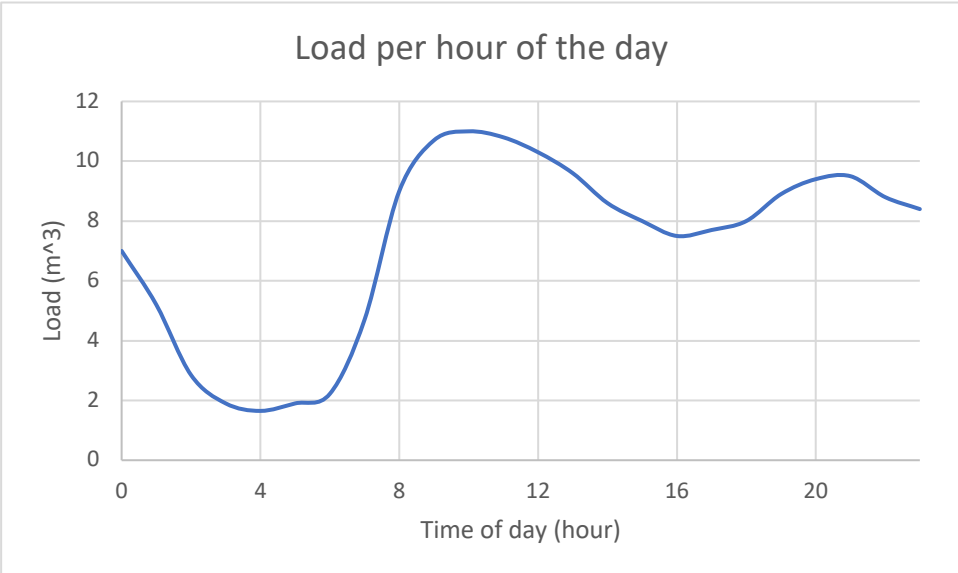


Figure 4.7: Load of water system throughout the day

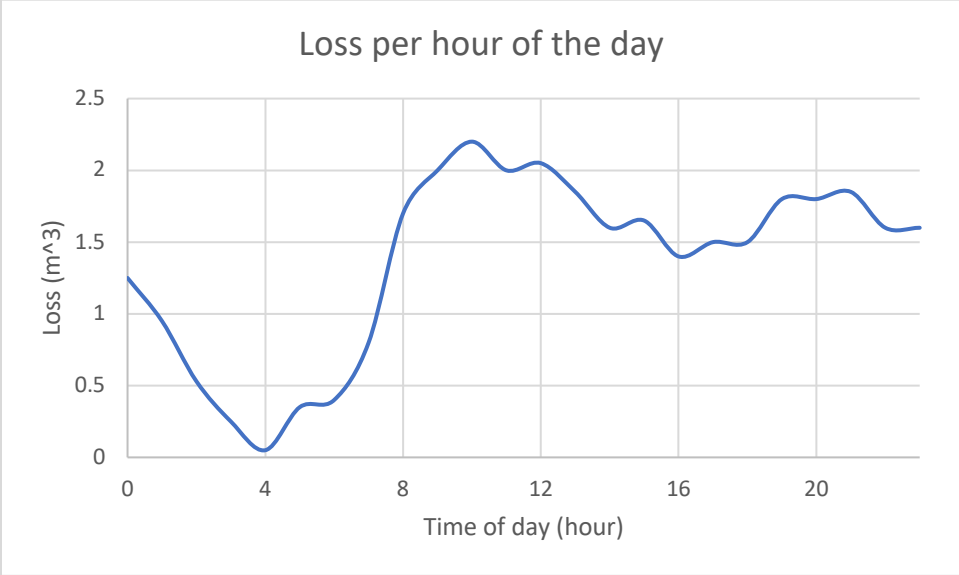


Figure 4.8: Losses in water system throughout the day

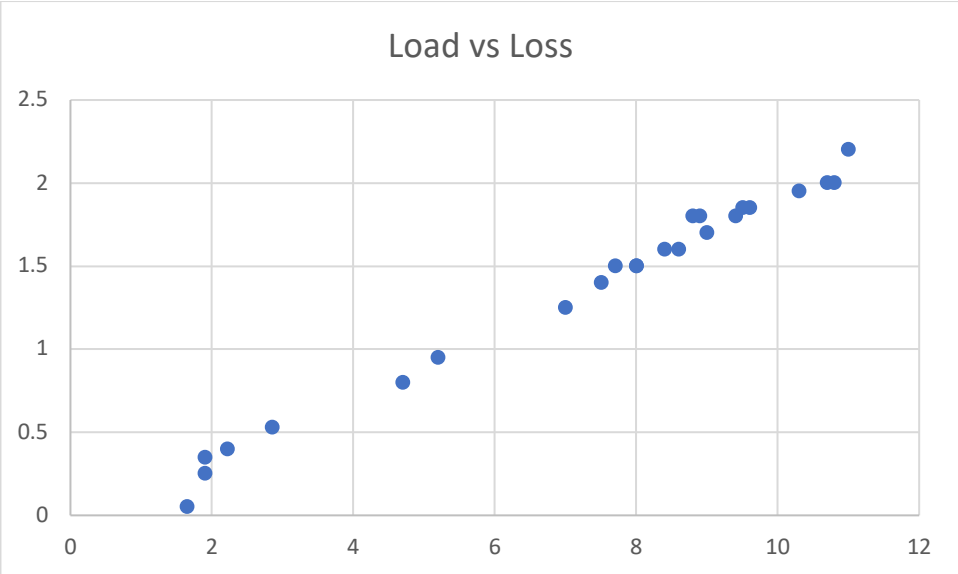


Figure 4.9: Loss against load in the water system

The curves shown in figures 4.15 and 4.16 show very similar patterns the difference being the noise in the figure 4.16. The peak and trough on both graphs are at 10:00 and 04:00 respectively and the gradient changes in the curves occur at the same points, showing the positive correlation between the two parameters. The reason as why the graph showing losses in the system is much less smooth is possibly due to human error when calculating the output volumes in the tanks. The correlation between loss and load is made even clearer through figure 4.17, demonstrating the positive relationship between the two. Again, due to the noise in the losses calculations, the data shown above is not very perfectly linear and has some outlying data but clearly shows the direct proportionality between load and losses.

4.2 – Test 2 Data Presentation and Analysis

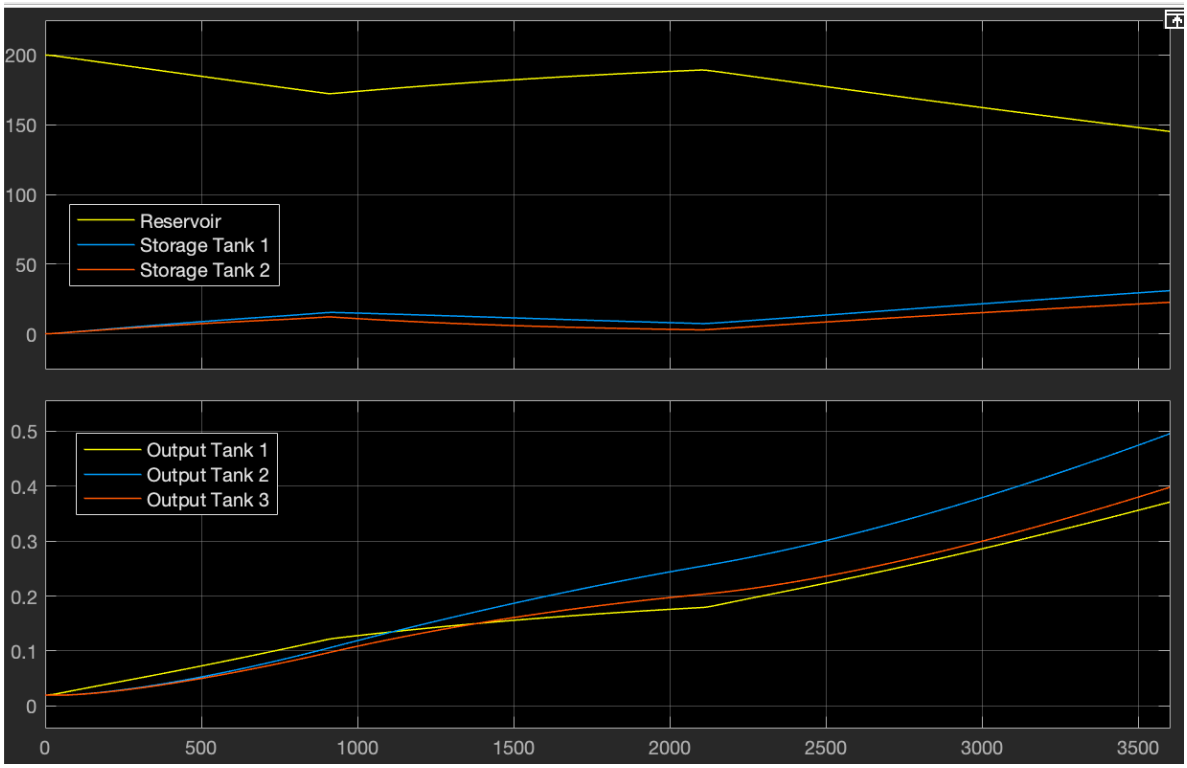


Figure 4.10: Hour 03 20 minute fault

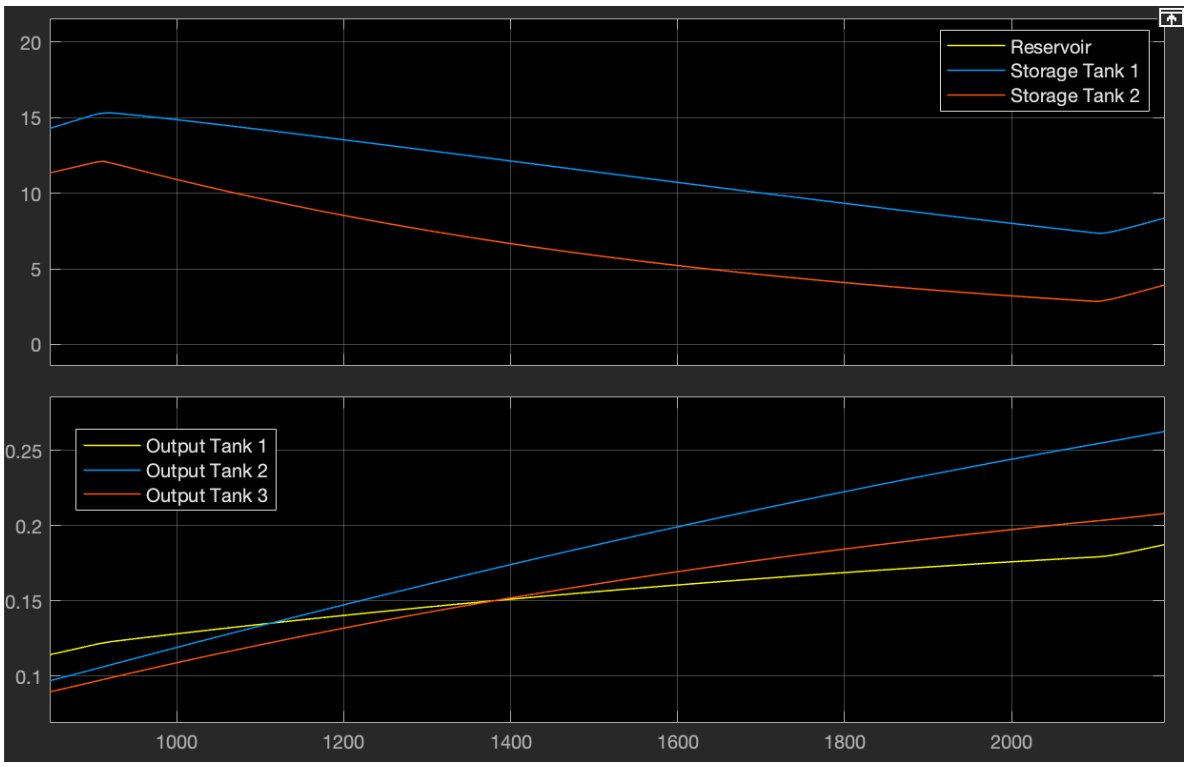


Figure 4.11: Hour 03 20 minute fault during time of fault

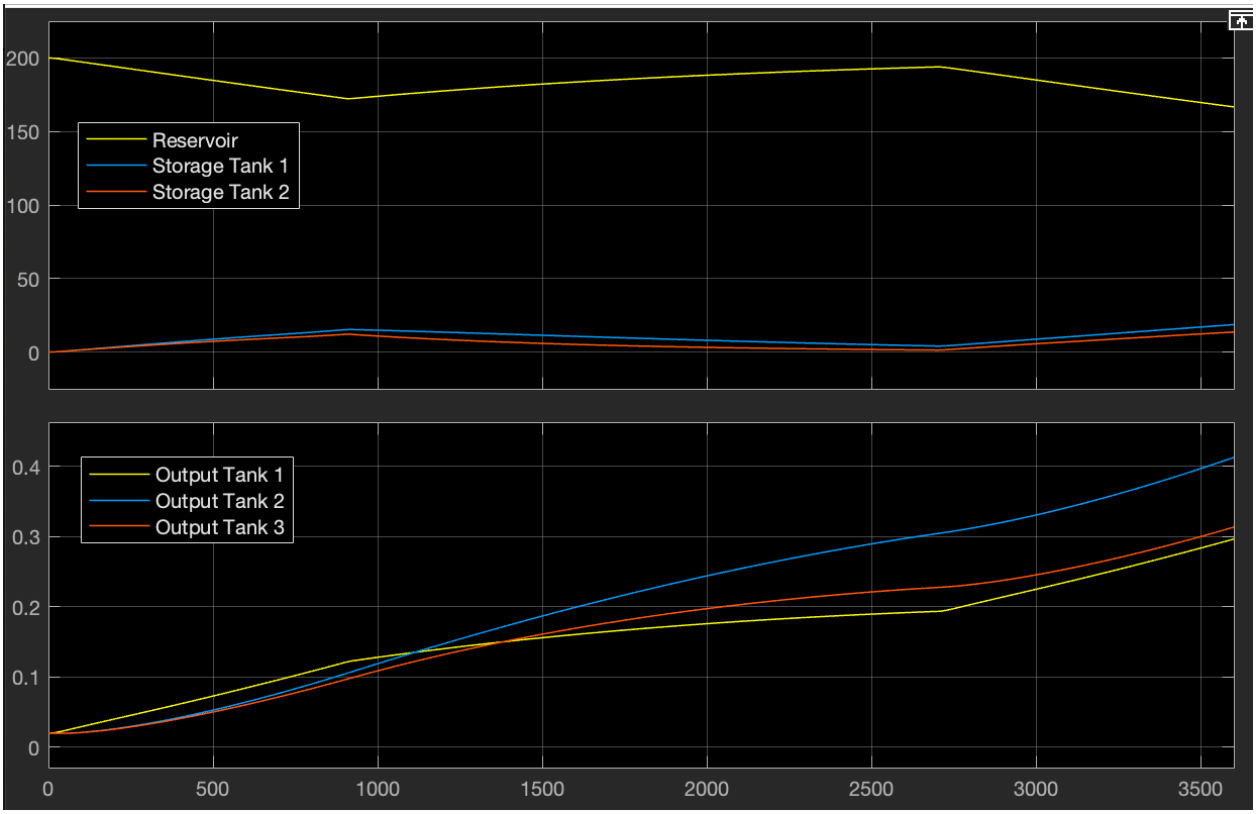


Figure 4.12: Hour 03 30 minute fault

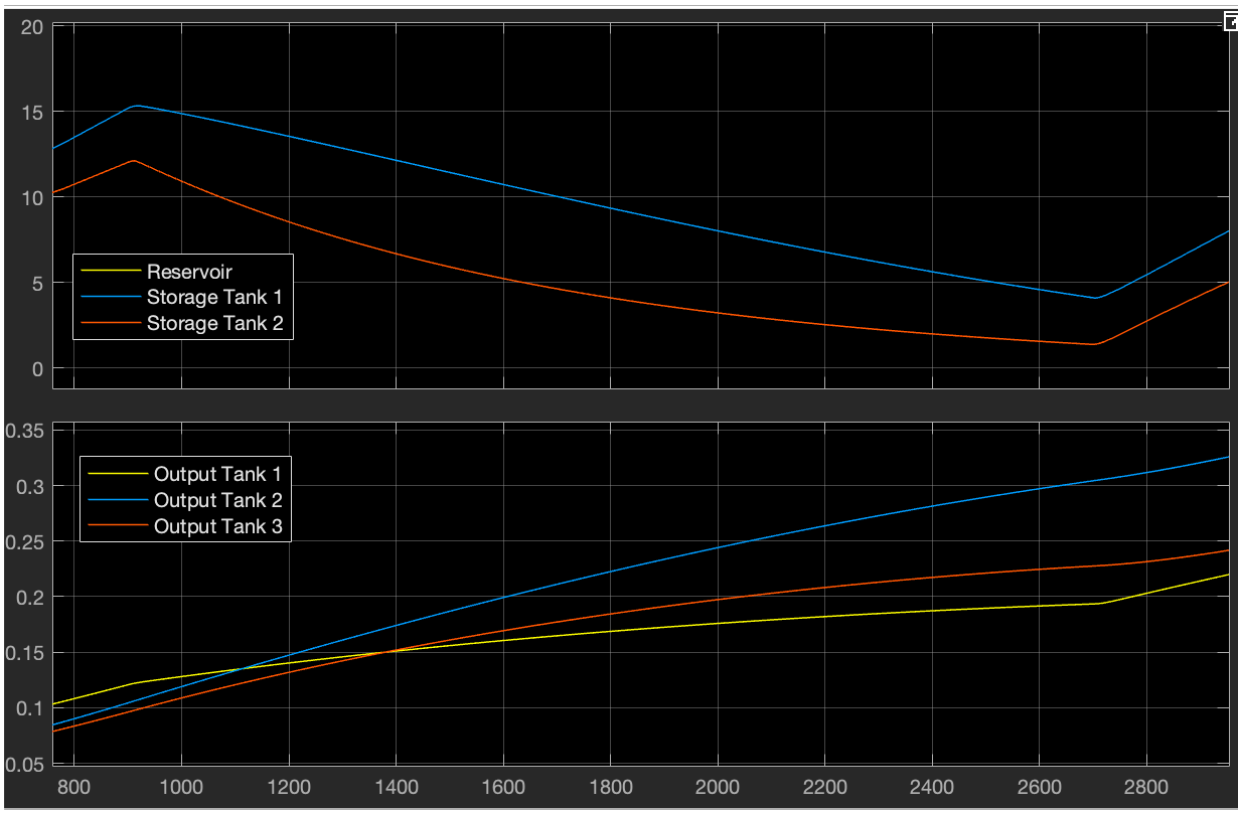


Figure 4.13: Hour 03 30 minute fault during time of fault

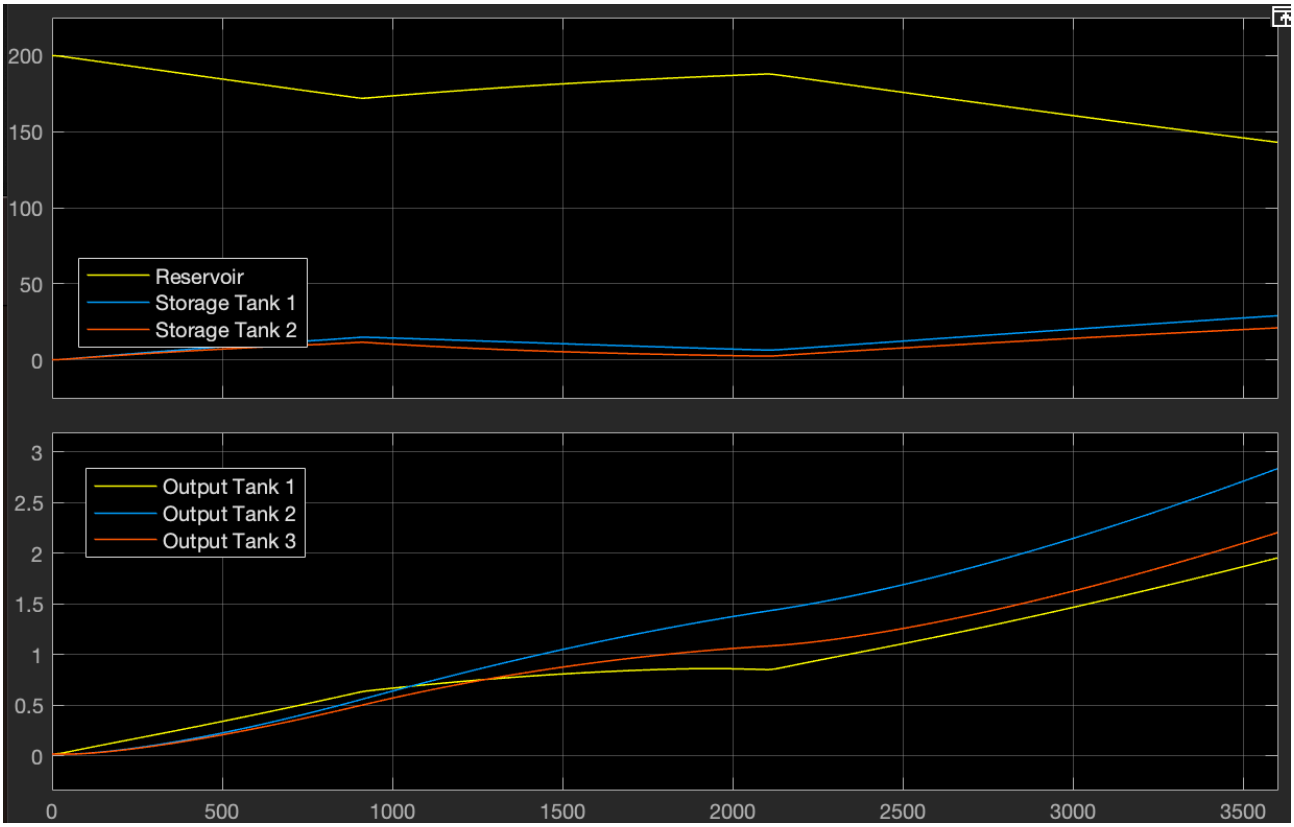


Figure 4.14: Hour 10 20 minute fault

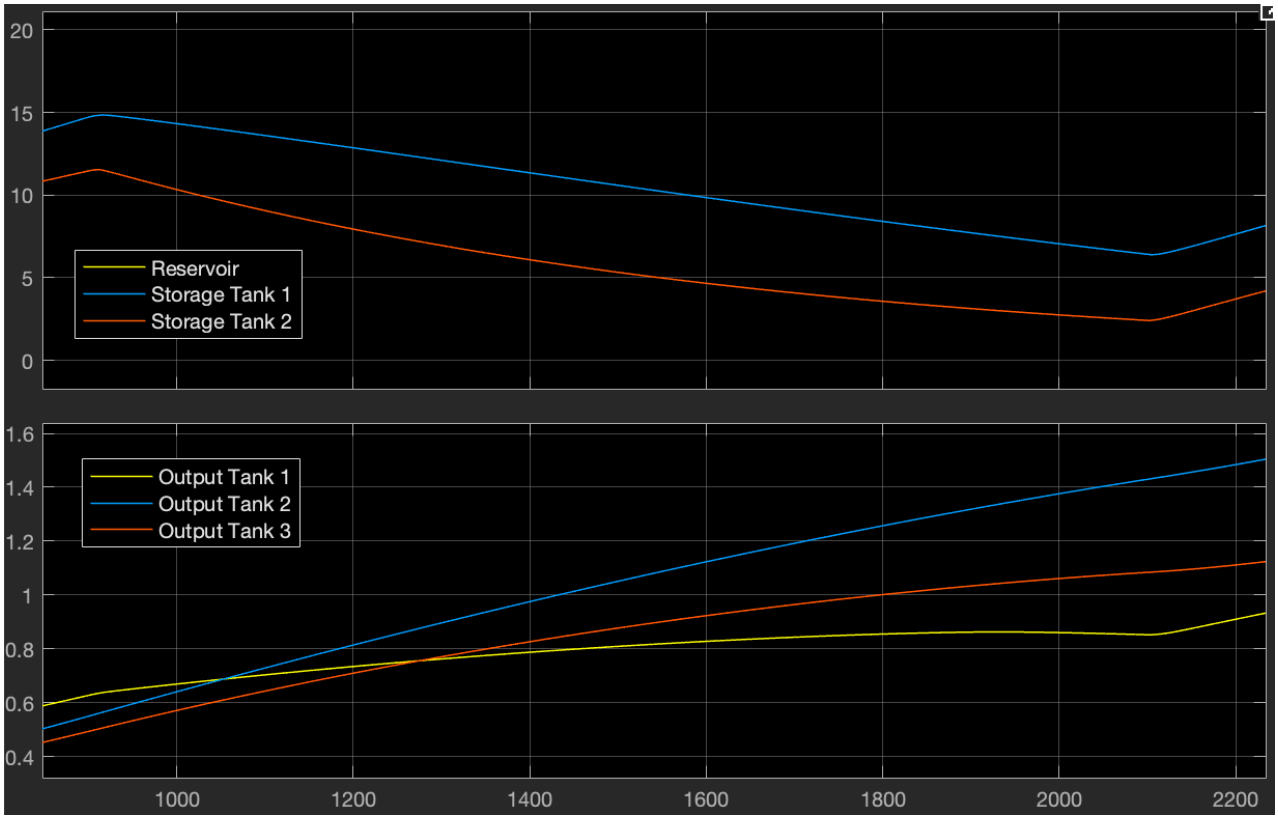


Figure 4.15: Hour 10 20 minute fault during time of fault

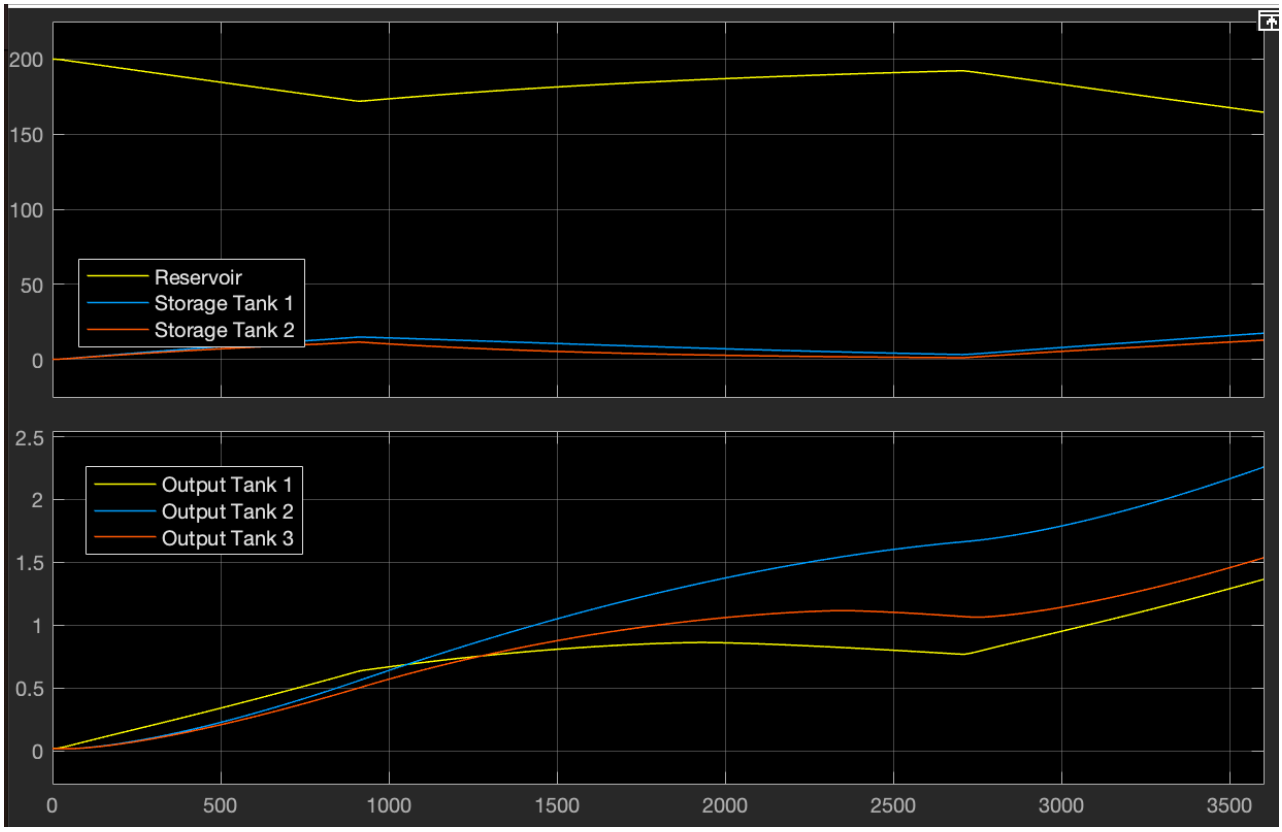


Figure 4.16: Hour 10 30 minute fault

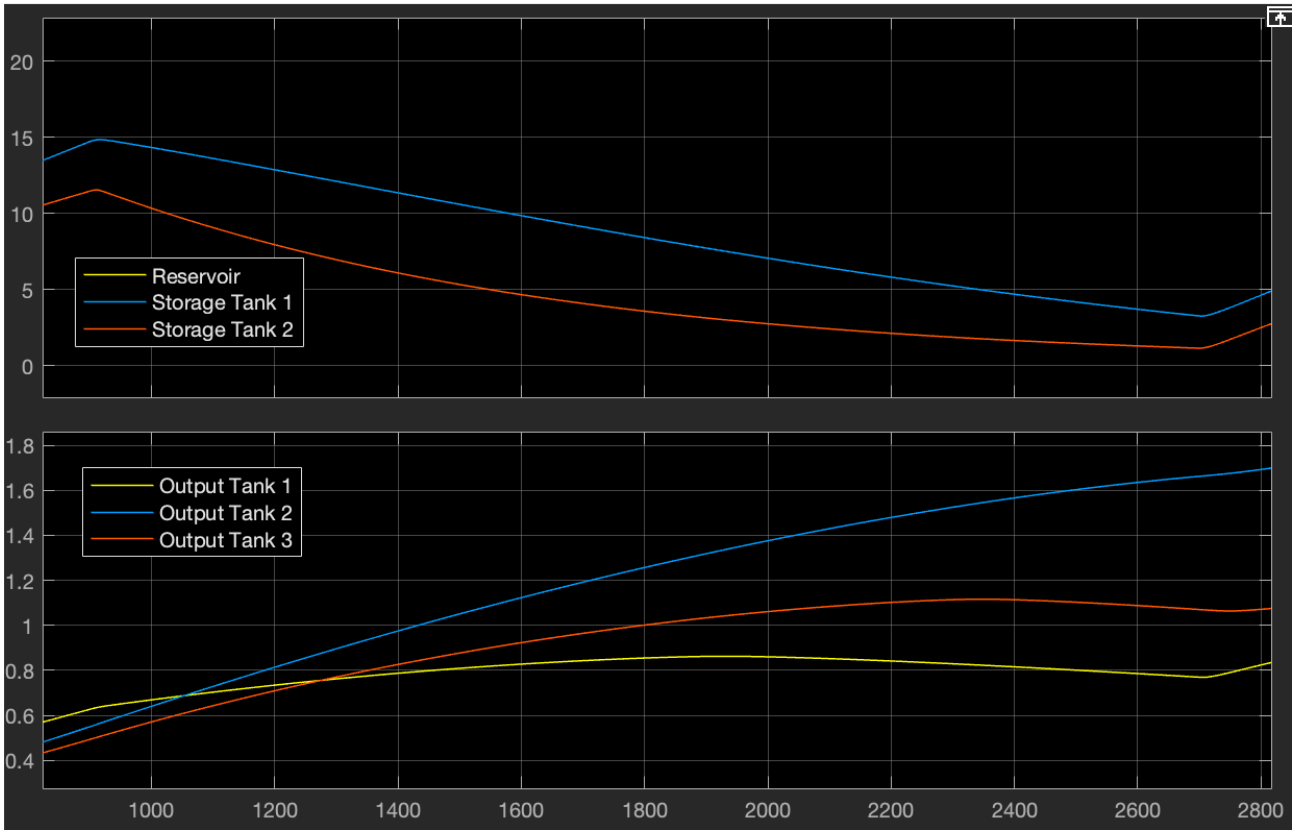


Figure 4.17: Hour 10 30 minute fault during time of fault

Test 2 was conducted to analyze how the timespan of a disruption affects the system. Compared to the figures produced for Test 1, the figures 4.10-4.15 share many similarities such as the curves of the reservoir and storage tanks following the same pattern of increasing until the time of the fault and then decreasing until the disturbance ends. The difference with these parts of the system in Test 2 is that the decrease in volume is much higher by the end of the fault, which is logical. However, a close examination of the different times of day reveals that the graphs for the 03:00 and the 10:00 faults in Test 2 display significantly different curves for the output tanks compared to Test 1.

Figure 4.10 shows the results for a 20 minute fault at 03:00. It demonstrates that the effect of an extended fault period is a reduction in consumption to around $1.26m^3$, which is $0.65m^3$ less than the consumption with no fault and $0.3m^3$ less than a 10 minute fault. The last 10 minutes of the fault had a lower absolute decrease of $0.3m^3$ compared to $0.35m^3$ in the first 10 minutes, and there was a total 34.2% decrease from when the system runs optimally. The calculated percentage changes can also be characterized as the capacity of the system by subtracting the calculated decrease from 1, or by dividing the actual output by the maximum or optimal output. In the case of a 10 minute fault, the capacity utilization is 81.6% whereas it is 65.8% for a 20 minute fault. This indicates that though the system undergoing a disturbance is obviously worse off when the fault lasts longer, the negative effects of the fault slowly become less intense as the fault progresses.

An analysis of the data for the 30-minute fault shown in figure 4.12 further supports this theory, showing that the consumption of water decreased by a further $0.2m^3$ to a total of $1.05m^3$. This is a total decrease from optimal of 44.7% or a capacity utilization of 55.3%. Figure 4.18 demonstrated how capacity of the system decreases with fault duration.

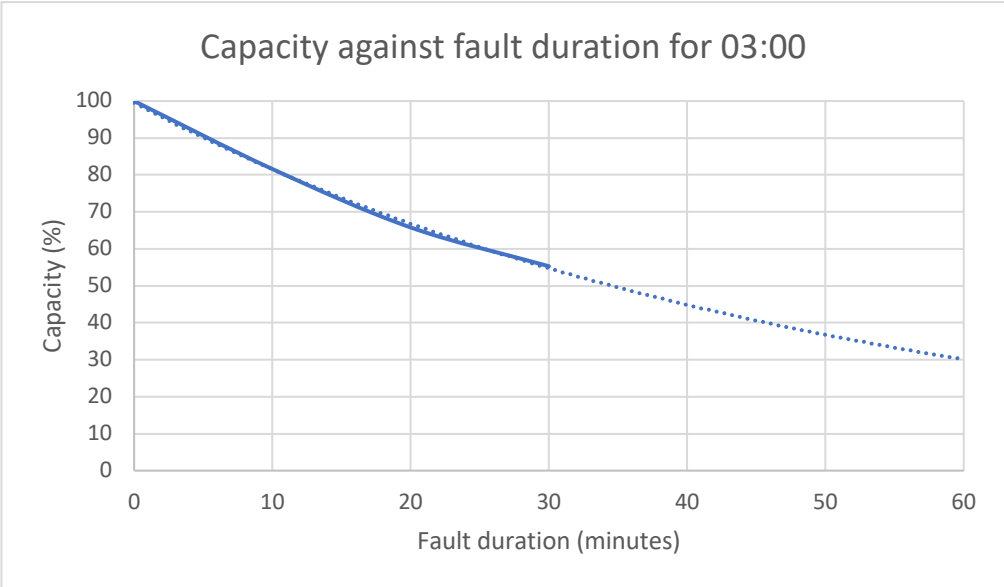


Figure 4.18: Capacity of water system against duration of fault for 03:00

As regards 10:00, Test 2 showed vastly different results than for both Test 2 for 03:00 as well as the figures in Test 1. The big difference lies in the curves of the output tanks. Rather than tank 1 being significantly affected by the fault, it showed the even reaching a point of stabilization where it no longer had an increasing volume. Beyond this, tank 3's gradient also became much less steep (figures 4.14 and 4.15). Even more interestingly, figures 4.15 and 4.17 demonstrate that output tanks 1 and 3 even started to decrease as the storage tanks slowly approach 0. As mentioned previously, backflow is a very big risk in a water system so this is very suboptimal. During the 30 minute fault, even tank 2, which seemed to keep an almost constant gradient in all previous tests started to have a decrease in consumption rate, accentuating the results of Test 1 which shows that 10:00 is the worst time of day for a fault to occur. Looking at the data collected, for a 20 minute fault the total consumption of the system decreased from $11m^3$ to $6.9m^3$ which makes the capacity utilization of the system 62.7%. For a 30 minute fault the total consumption of water in the output tanks equated to $5.2m^3$, thus the capacity is 47.3%. Comparing the capacity utilization between 03:00 and 10:00, it is clear that the effects of a fault are magnified as water demand increases.

It was detected that the storage tanks for the 30 minute faults almost reached 0 but fell slightly short so one more simulation was conducted to test what would happen when this was the case at 10:00. The fault now starts at 600 seconds and ends at 3300 making it a 45 minute fault. The result can be seen below in figure 4.19.

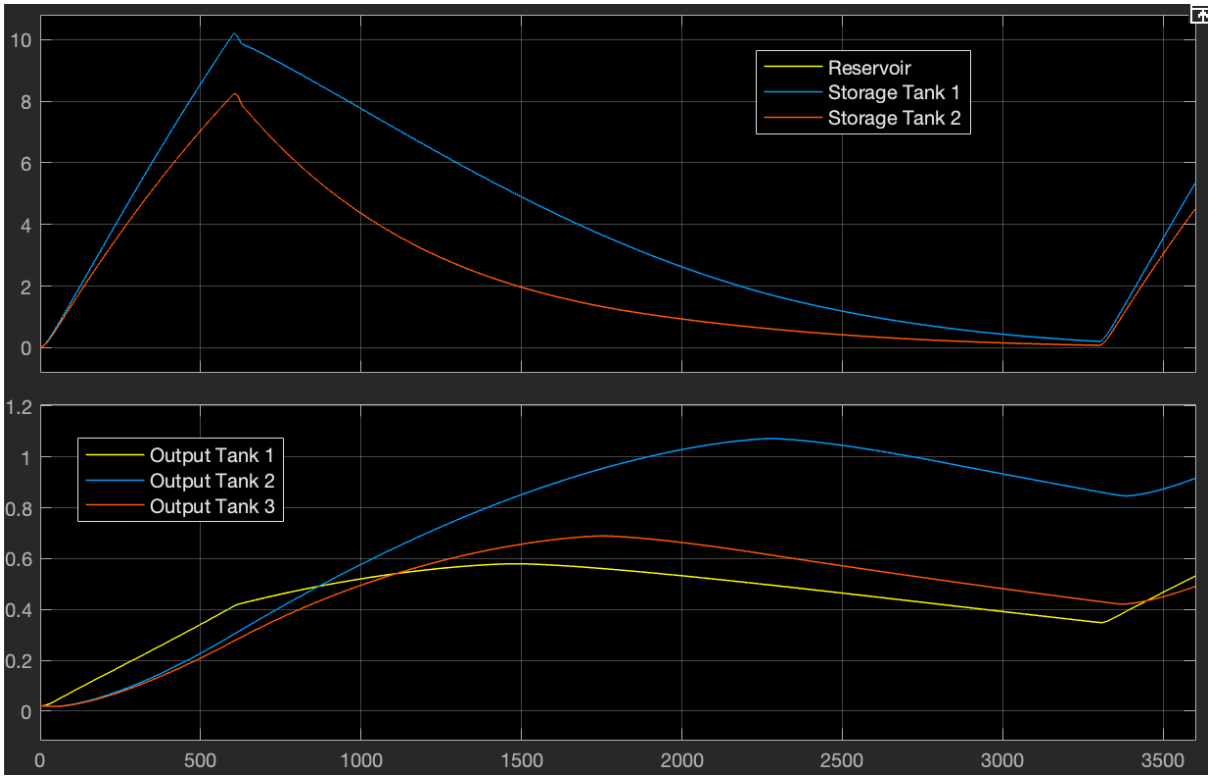


Figure 4.19: 45 minute fault at 10:00

The figure above shows a drastic decrease in consumption to a staggering $1.95m^3$, which makes the capacity of the system 17.7%. This contradicts the theory that the severity and impacts of a fault slowly become less intense throughout the course of the fault. Rather, the intensity of the effects of a fault on a system's capacity seem to decrease for a while until a point where the capacity rapidly decreases. Figure 4.20 demonstrates this. A drop in capacity to such an extent would likely mean the system's performance is below the critical threshold.

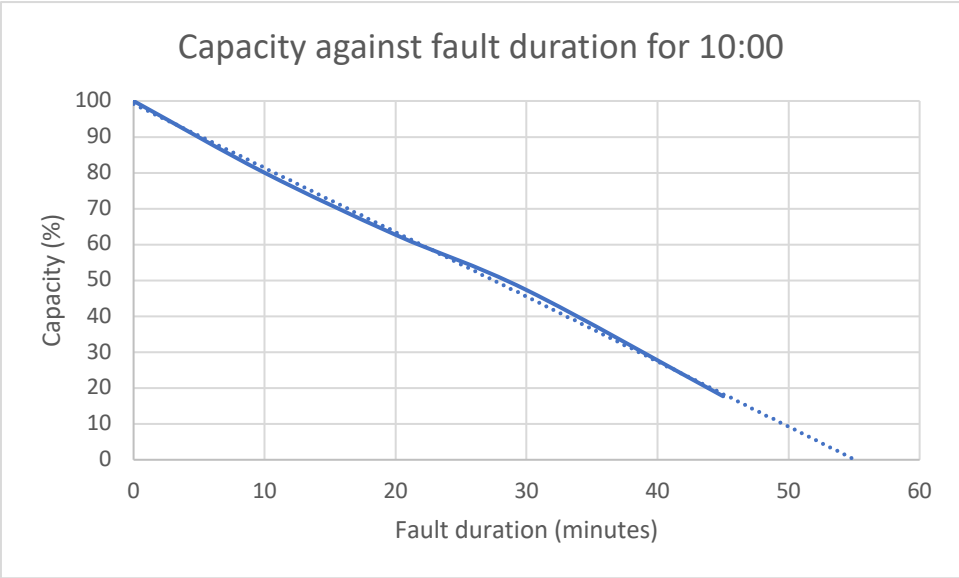


Figure 4.20: Capacity of water system against duration of fault for 10:00

Comparing the trendline seen in figure 4.20 to figure 4.21 which shows the curve of system capacity against fault duration for faults up to 30 minutes demonstrates more clearly how big an impact the extra 15 minutes of the fault has on the system's output.

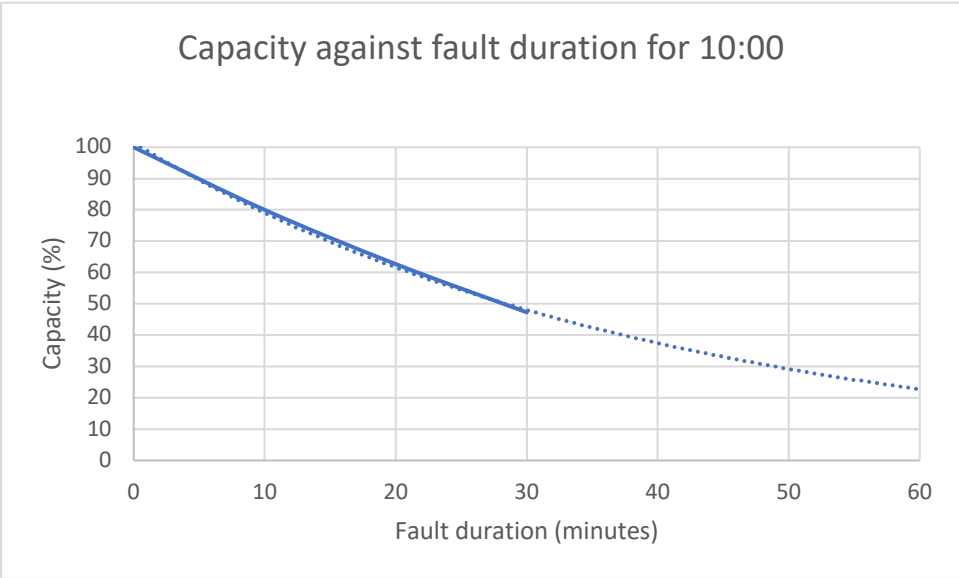


Figure 4.21: Capacity of water system against fault duration (up to 30 minutes) for 10:00

4.3 – Resilience Curves for Both Tests

The last figures produced for the analysis of the interconnected systems were resilience curves, like the example shown in figure 2.1 in section 2.5 of the study. The curves produced were for the data of a 10 minute faults at 03:00 and 10:00 to compare faults lasting the same amount of time, as well as 20 and 30 minute faults at 10:00 to analyze the effects of fault duration. Performance was measured by calculating the change in volume of the output tanks in 200 second intervals and dividing the change in volume when a fault occurs by the change in fault when the systems run optimally.

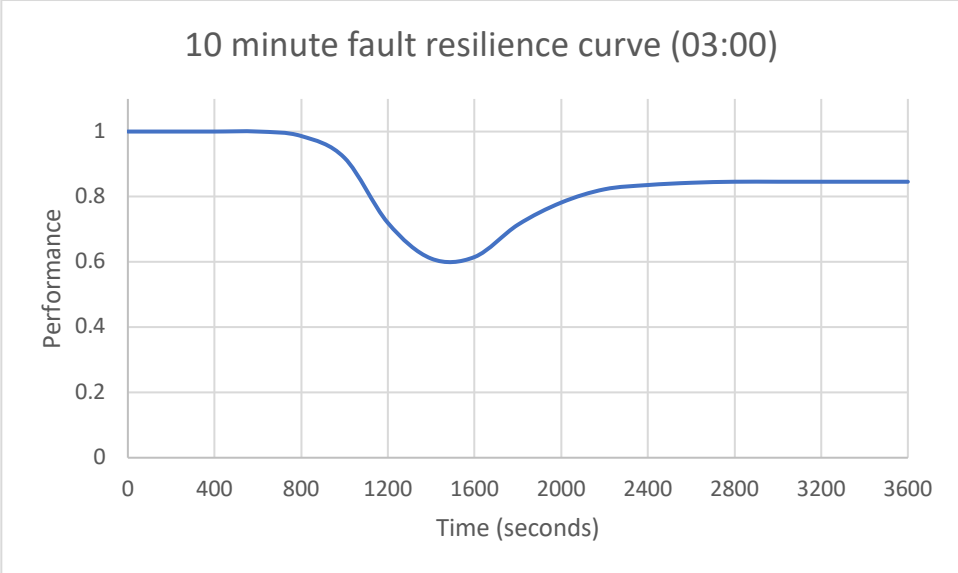


Figure 4.22: Resilience curve for a 10 minute fault at 03:00

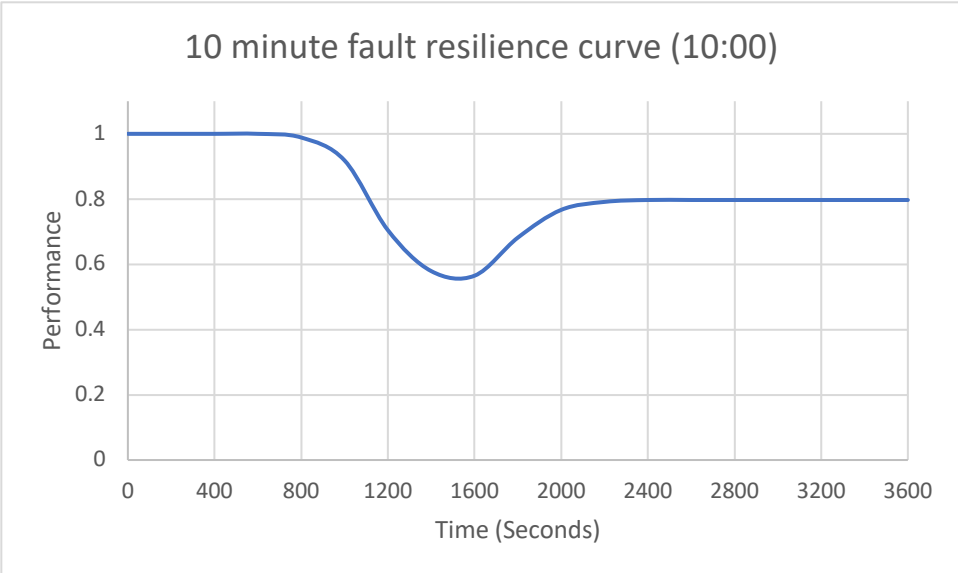


Figure 4.23: Resilience curve for a 10 minute fault at 10:00

Figures 4.22 and 4.23 are almost exactly the same in terms of the metrics listed by Poulin et al. [17] apart from the depth of impact which is only slightly lower by about 5% in the 10:00 fault. This means the cumulative impact on the system is slightly higher for the 10:00 fault. In terms of rate metrics, it seems the rate at which a water system fails and recovers is not dependent on the time of day or water demand.

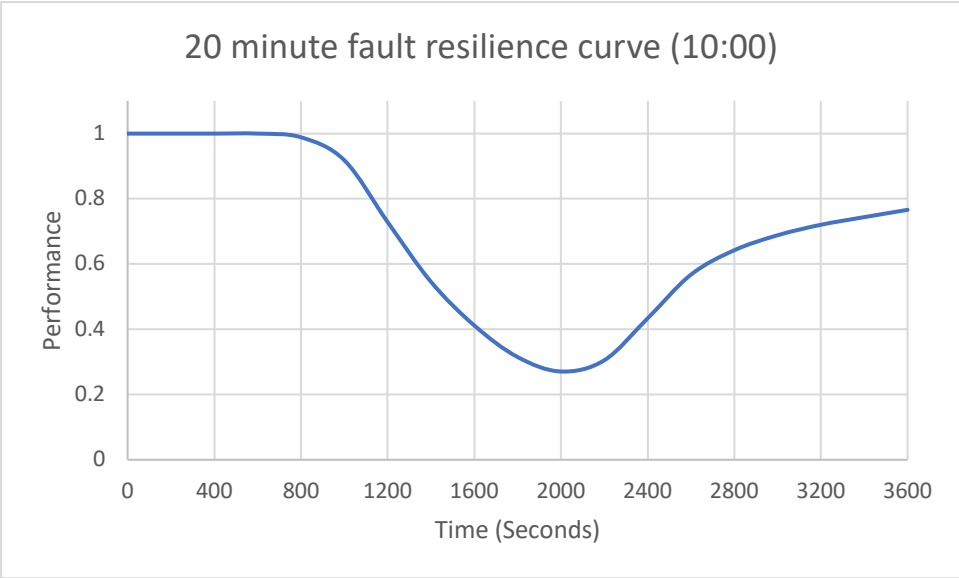


Figure 4.24: Resilience curve for a 20 minute fault at 10:00

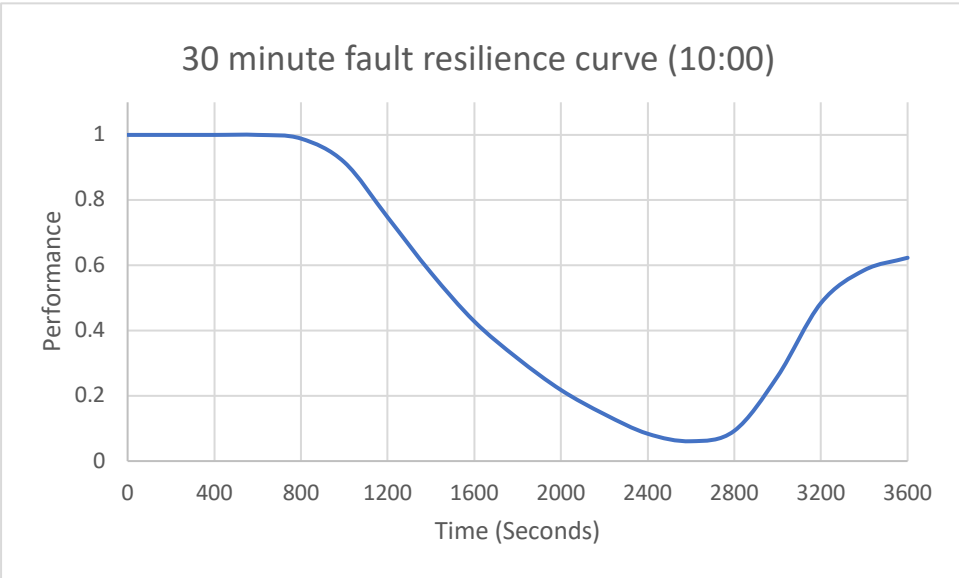


Figure 4.25: Resilience curve for a 30 minute fault at 10:00

Figures 4.24 and 4.25 show very different results to one another. Unlike time of day, fault duration seems to have a much greater effect on the rates at which the system fails and recovers. Figure 4.23 showed the system recovering back to a stable level approximately 700 seconds after it had reached its minimum level of performance, whereas, in the 20 minute fault shown in figure 4.24, around 1500 seconds after the system's minimum performance passed before it began getting close to stabilizing. Finally, though the graph does not show much past time when the disturbance is done, it is safe to assume that the rate of recovery will be even lower. Other than the effects of the rates of failure and recovery, failure duration had a very large effect on the depth of impact, in fact more of an effect than water demand in the given hour as the drastic decreases in performance in figures 4.24 and 4.25 result in a much larger change in depth of impact that what is observed from figures 4.22 and 4.23. Overall, it seems the driving factor when it comes to loss of cumulative performance and other magnitude and threshold-based metrics is failure duration rather than water demand.

Chapter 5 – Conclusion and Evaluation

5.1 – Conclusion

The model of the interconnected water and power distribution system that was created sheds has shed light on the intricate relationship between the two networks. By analyzing the simulations conducted, the effects on the water system as a result of a fault in the power system have been examined providing insight into two main factors – what time of day the fault occurs, and the fault duration. The results for the former indicate that losses in a water distribution system have a directly proportional relationship with the demand for water at a given time of day. In terms of resilience, the performance metrics for the resilience curves for a 10 minute fault were not affected much by water demand in a given hour, meaning the system's ability to bounce back is almost the same for all times of the day.

As regards the latter, namely the fault duration, the results show that longer disruptions lead to higher losses of water consumption. When measuring the performance of the water system under disruptions of different durations, it was found that initially, the rate of performance deterioration slowly decreases until a fault duration of 30-40 minutes. After this point the rate of performance deterioration becomes much steeper, and the capacity utilization of the system diminishes at a drastic rate. In terms of the resilience curves for longer disruptions, the performance metrics – especially the magnitude and threshold-based metrics – are affected much more by fault duration than by the time of day when the fault occurs. In fact, for a 30-minute fault in the modelled water system, the performance reached a minimum of approximately 5% which in a real system would be below the critical threshold.

All in all, the model created for interconnected water and power systems was extremely effective, the results generated were enlightening and the objectives and aim set for the project were met.

5.2 – Evaluation

Although the end product of the project and simulations were successful, there are certain areas which may definitely be improved. The first area for improvement relates to the duration of the simulations. Originally, the simulations were supposed to last 86400 seconds – i.e. a whole day – but there were errors with the fault working for simulation periods this long. If too much time passed without the occurrence of the fault, by the time the disturbance was supposed to happen nothing would change in the system and the output remained the same. This is why one hour simulation periods were opted for. The second aspect of the simulations which could be refined relates to the water pumps. The original plan for data collection included a third test where the order in which water pumps were restored was varied so as to determine which of the pumps has the biggest effect on water consumption, thus indicating which should be the first to be restored in order to maximize resilience. For this reason, three different motors were added to the power distribution system model along with three faults, one affecting each motor. However, it was discovered that a single fault block creates a disruption in all components of the system, meaning only one motor and fault block was required in the power system model. Finally, the last refinement that could be implemented in order to improve the project would be to increase the scale of the water distribution system model as it is relatively small when compared to a real water network. In the future, perhaps further research could be conducted to build upon this project. One area of investigation could be to increase the scale of the water system model; another could be to find a way to restore a single motor during a disruption to allow for the investigation of component importance as a mitigation strategy and a means of improving system resilience.

References

[1] - “Critical National Infrastructure: NPSA.” National Protective Security Authority, 25 Apr. 2023, www.npsa.gov.uk/critical-national-infrastructure-0.

[2] - Lewis, L. P. and Petit, F. “Critical infrastructure interdependency analysis: Operationalising resilience strategies.” Contributing Paper to GAR 2019

[3] - S. M. Rinaldi, J. P. Peerenboom, and T. K. Kelly, “Identifying, understanding, and analyzing critical infrastructure interdependencies,” IEEE Control Syst. Mag., vol. 21

[4] - Schultz, M. T., Gouldby, B. P., Simm, J. D., and Wibowo, J. L. (2010). Beyond the factor of safety: Developing fragility curves to characterize system reliability, U.S. Army Corps of Engineers, Washington, DC.

[5] - Hayward, Keith, et al. “Learning Lessons on Resilient Infrastructure Interdependencies.” The Source, 8 Feb. 2022, https://www.thesourcemagazine.org/learning-lessons-on-resilient-infrastructure-interdependencies/#:~:text=Growing%20interconnections%20and%20interdependencies%20among,exacerbate%20consequences%20of%20a%20crisis.

[6] – Skarvelis-Kazakos, Spyros et al. (2021). “Resilience of interdependent critical infrastructure on behalf of the CIGRÉ C4.47 Power System Resilience Working Group.”

[7] - Roe, E.; Bea, RG; Jonkman, SN; Faucher De Corn, H.; Foster, H.; Radke, J., et al. (2016). Risk assessment and management for interconnected critical infrastructure systems at the site and regional levels in California's Sacramento-San Joaquin Delta. International Journal of Critical Infrastructures, 12(1-2), 143-174. http://dx.doi.org/10.1504/IJCIS.2016.075867 Retrieved from https://escholarship.org/uc/item/7394j8j2

[8] – He, Xian. “Disaster Risk Management of Interdependent Infrastructure ... - Core.” Core, 2019, core.ac.uk/download/pdf/227472335.pdf.

[9] - “Resilience in the Round - Ofwat.” OFWAT, https://www.ofwat.gov.uk/regulated-companies/resilience-in-the-round/.

[10] – Ciapessoni, Emanuele et al. (2019). Defining power system resilience.

[11] – Fluence News Team. “What Is Water Resilience?” Fluence Corporation, 27 July 2021, www.fluencecorp.com/what-is-water-resilience/.

[12] - Vugrin, E.D., Warren, D.E. and Ehlen, M.A. (2011), A resilience assessment framework for infrastructure and economic systems: Quantitative and qualitative resilience analysis of petrochemical supply chains to a hurricane. Proc. Safety Prog., 30: 280-290. https://doi.org/10.1002/prs.10437

[13] – National Infrastructure Commission “ANTICIPATE, REACT, RECOVER.” Nic.org.uk, May 2020, https://nic.org.uk/studies-reports/resilience/.

[14] – National Infrastructure Commission “Technical Annex: Measuring Infrastructure Performance” December 2018, https://nic.org.uk/app/uploads/Technical-annex-Measuring-infrastructure-performance.p

[15] - M. Panteli, P. Mancarella, D. N. Trakas, E. Kyriakides and N. D. Hatziargyriou, “Metrics and Quantification of Operational and Infrastructure Resilience in Power Systems,” IEEE Trans. Power Syst., vol. 32, no. 6, pp. 4732- 4742, Nov. 2017

[16] - F. Meng, G. Fu, R. Farmani, C. Sweetapple, D. Butler, “Topological attributes of network resilience: A study in water distribution systems”, Water Research, Vol. 143, 2018.

[17] - Craig Poulin, Michael B. Kane, Infrastructure resilience curves: Performance measures and summary metrics, Reliability Engineering & System Safety, Volume 216, 2021, 107926, ISSN 0951-8320, https://doi.org/10.1016/j.ress.2021.107926. (https://www.sciencedirect.com/science/article/pii/S0951832021004427)

[18] - Anawat Suppasri, et al. “Cascading disasters triggered by tsunami hazards: A perspective for critical infrastructure resilience and disaster risk reduction”, International Journal of Disaster Risk Reduction, Volume 66, 2021, 102597, ISSN 2212-4209, https://doi.org/10.1016/j.ijdrr.2021.102597.

[19] – Phillips, Tom. “Brazilian Power Cut Leaves 60 Million in the Dark.” The Guardian, 11 Nov. 2009, www.theguardian.com/world/2009/nov/11/brazil-power-cut-rio-madonna.

[20] – Denis, Pierre Charles. “Haiti: The Impacts of the 2010 Earthquake on Water and Sanitation in Port-Au-Prince (#469).” GWP, 2015, www.gwp.org/en/learn/KNOWLEDGE_RESOURCES/Case_Studies/Americas--Caribbean/1Haiti-The-Impacts-of-the-2010-Earthquake-on-Water-and-Sanitation-in-Port-au-Prince-469/.

[21] – McCurry, Justin. “Japan Nuclear Firm Admits Missing Safety Checks at Disaster Hit Plant.” The Guardian, 22 Mar. 2011, www.theguardian.com/world/2011/mar/22/japan-nuclear-power-plant-checks-missed.

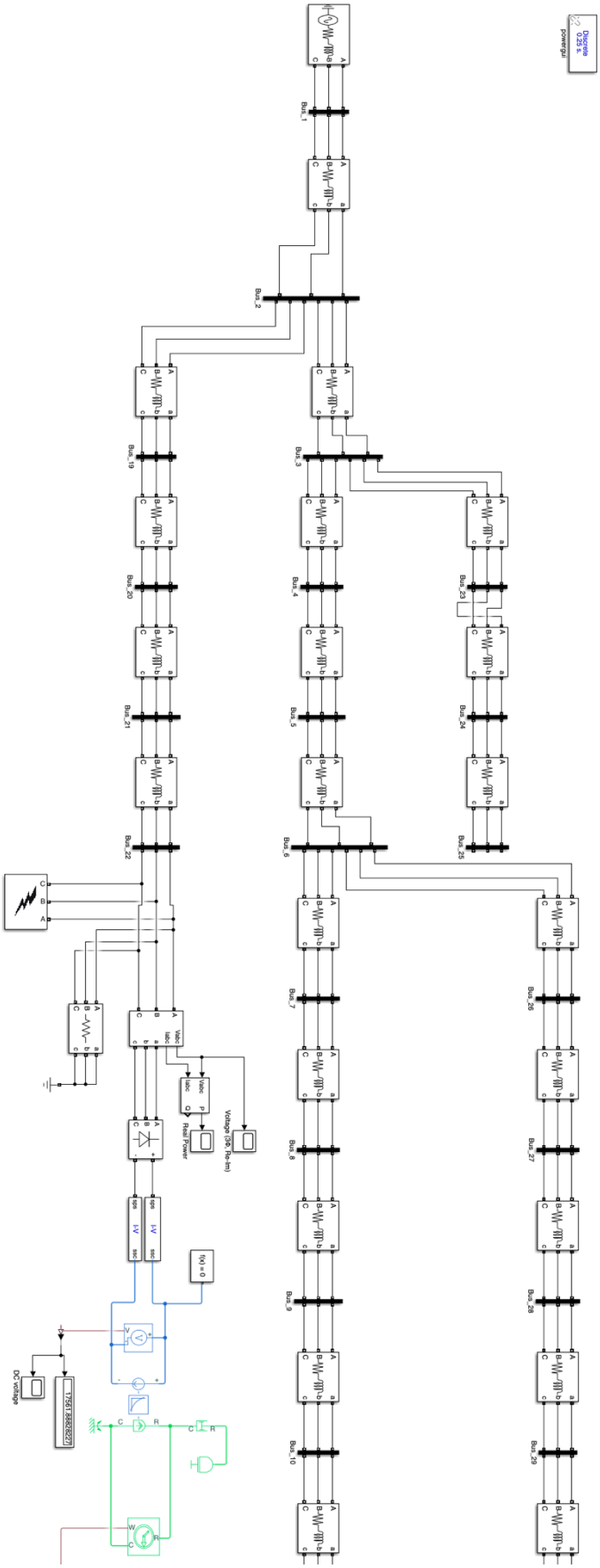
[22] – Parvania, Masood. “Data Sets.” USmart - Utah Smart Energy Lab, 30 Nov. 2021, https://usmart.ece.utah.edu/datasets/.

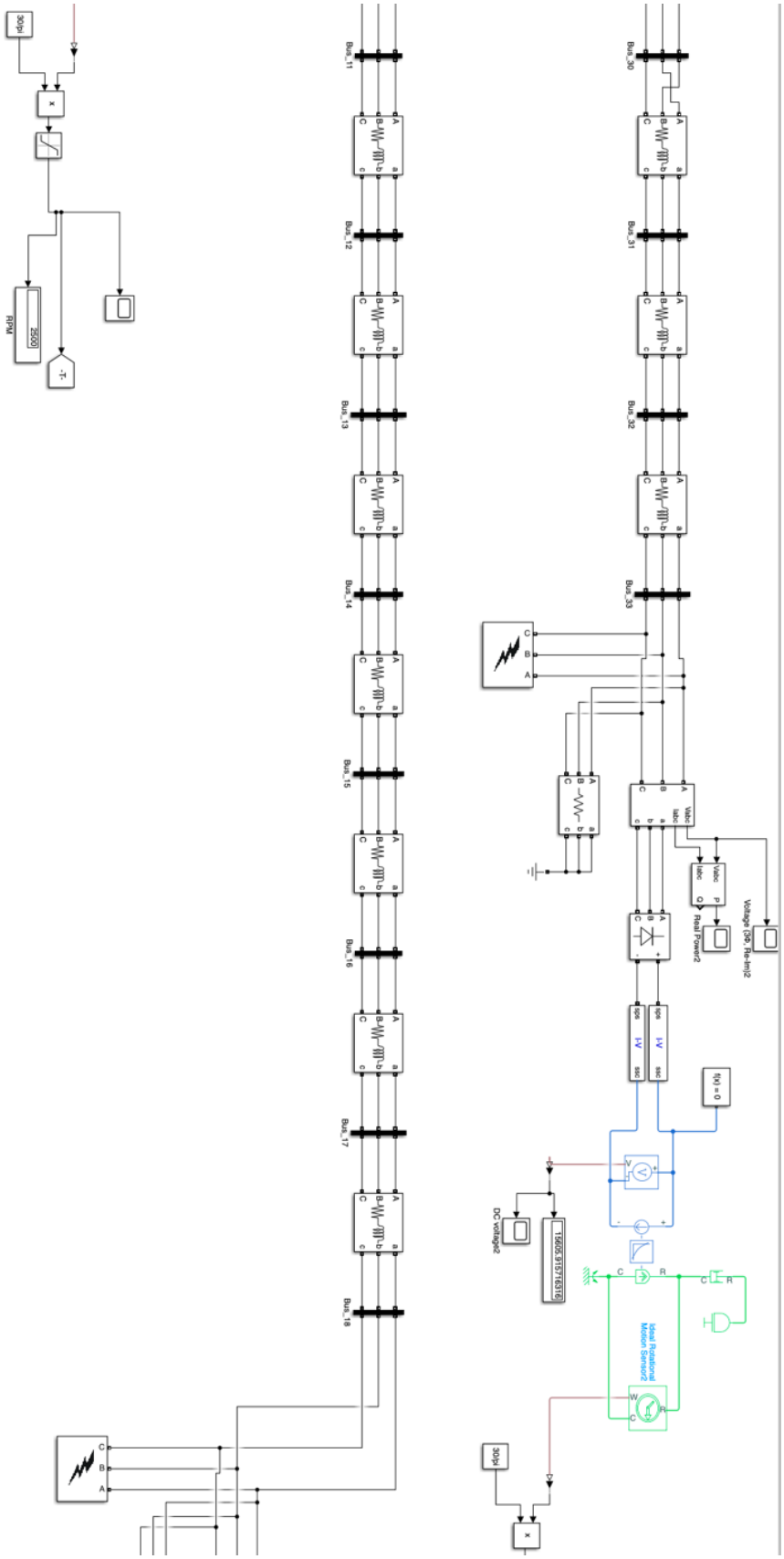
[23] – Simulink team. “Water Supply System.” Water Supply System - MATLAB & Simulink - MathWorks United Kingdom, https://uk.mathworks.com/help/hydro/ug/water-supply-system.html.

[24] – Baran, and Wu. “CASE33BW.” Matpower, 16 Dec. 2016, https://matpower.org/docs/ref/matpower6.0/case33bw.html.

[25] – Duffy, Daniel P. “Stackpath - Waterworld.” WaterWorld, 12 June 2018, www.waterworld.com/home/article/14070868/backflow-prevention-methods.

Appendix A


Discrete
0.01 s.
powergui
Bus_1
Bus_2
Bus_3
Bus_4
Bus_5
Bus_6
Bus_7
Bus_8
Bus_9
Bus_10
Bus_19
Bus_20
Bus_21
Bus_22
Bus_23
Bus_24
Bus_25
Bus_26
Bus_27
Bus_28
Bus_29
Vabc
Iabc
Real Power
Voltage (SB, Re-im)
f(x) = 0
DC voltage
17661.8862827


Bus_30
Bus_31
Bus_32
Bus_33
Vabc
Iabc
Real Power2
Voltage (3ph, Re-im)2
f(x) = 0
DC voltage2
Ideal Rotational Motion Sensor2
30pi
Bus_11
Bus_12
Bus_13
Bus_14
Bus_15
Bus_16
Bus_17
Bus_18
30pi
2500
RPM
-T-

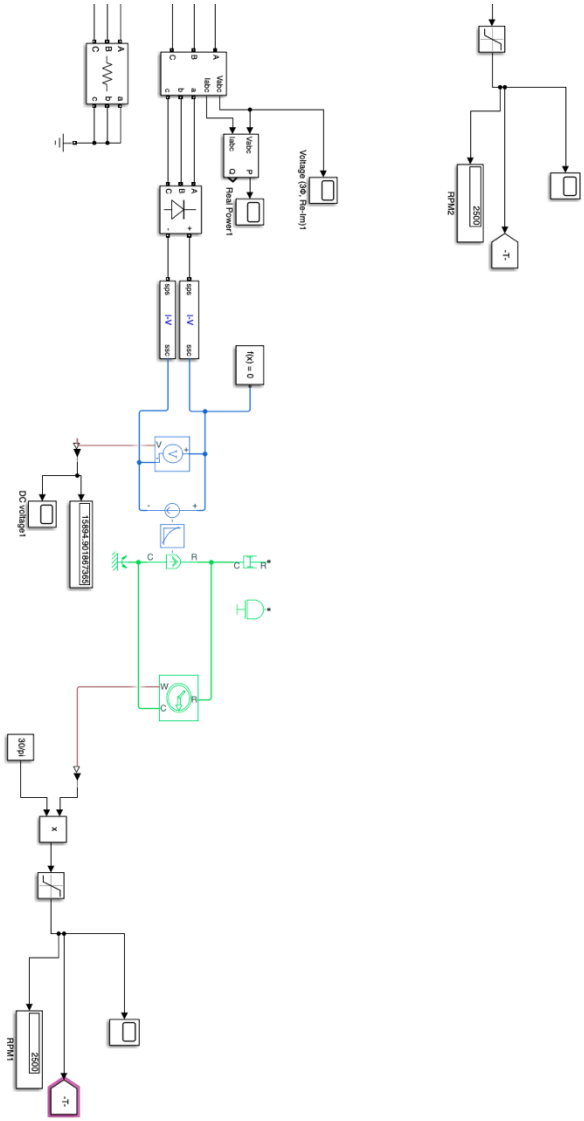
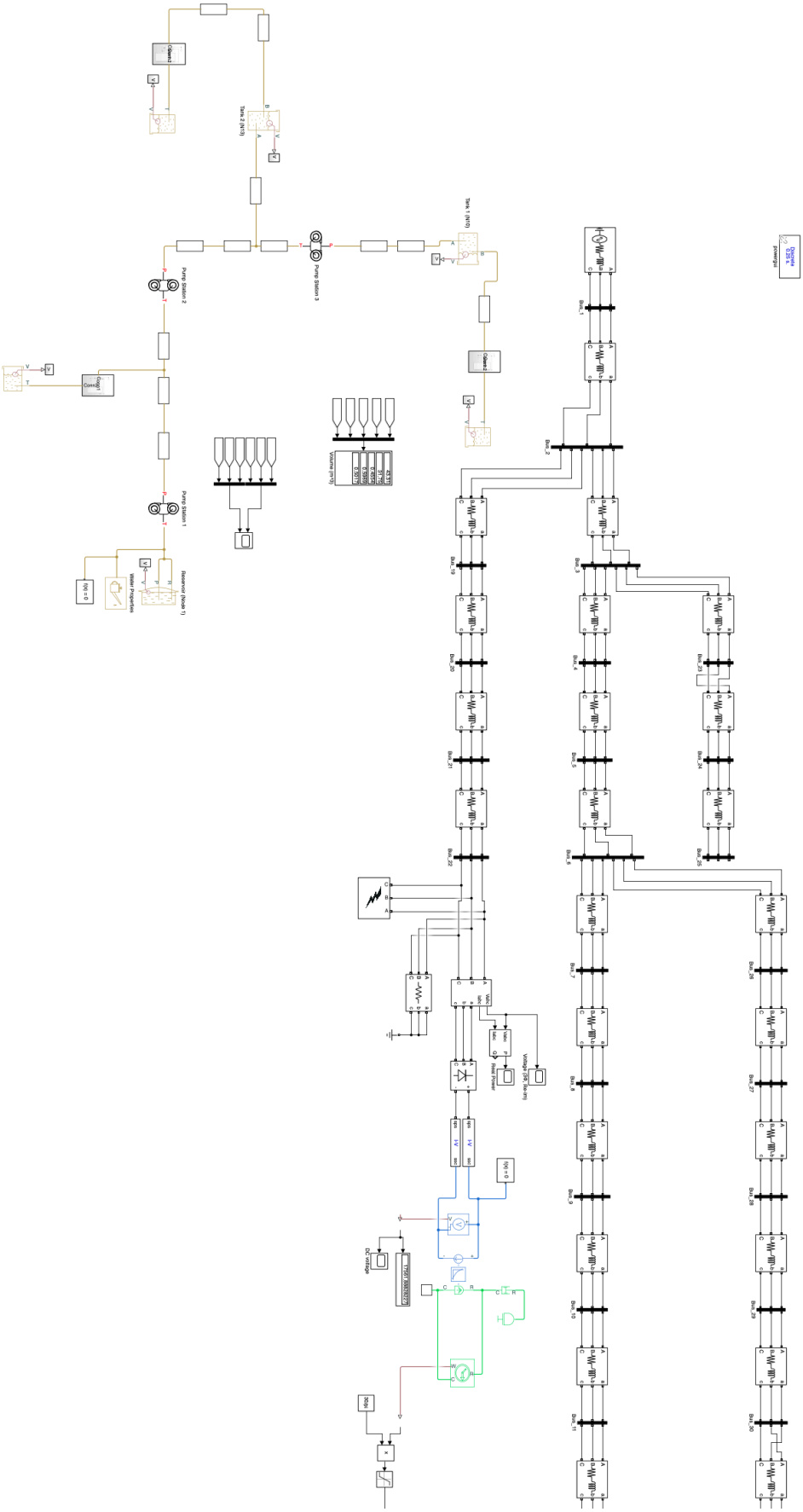


Figure 3.7 Enlarged


powergui
Discrete
Bus_1
Bus_2
Bus_3
Bus_4
Bus_5
Bus_6
Bus_7
Bus_8
Bus_9
Bus_10
Bus_11
Bus_12
Bus_13
Bus_14
Bus_15
Bus_16
Bus_17
Bus_18
Bus_19
Bus_20
Bus_21
Bus_22
Bus_23
Bus_24
Bus_25
Bus_26
Bus_27
Bus_28
Bus_29
Bus_30
Tank 1 (N/T)
Tank 2 (N/T)
Pump Station 3
Pump Station 2
Pump Station 1
Reservoir (Node 1)
Water Properties
Volume (m3)
Fixed Resistor
Voltage Sensor
Vabc
Iabc
Vdc
Idc
Vdc = 0
Vdc = 0
Vdc = 0

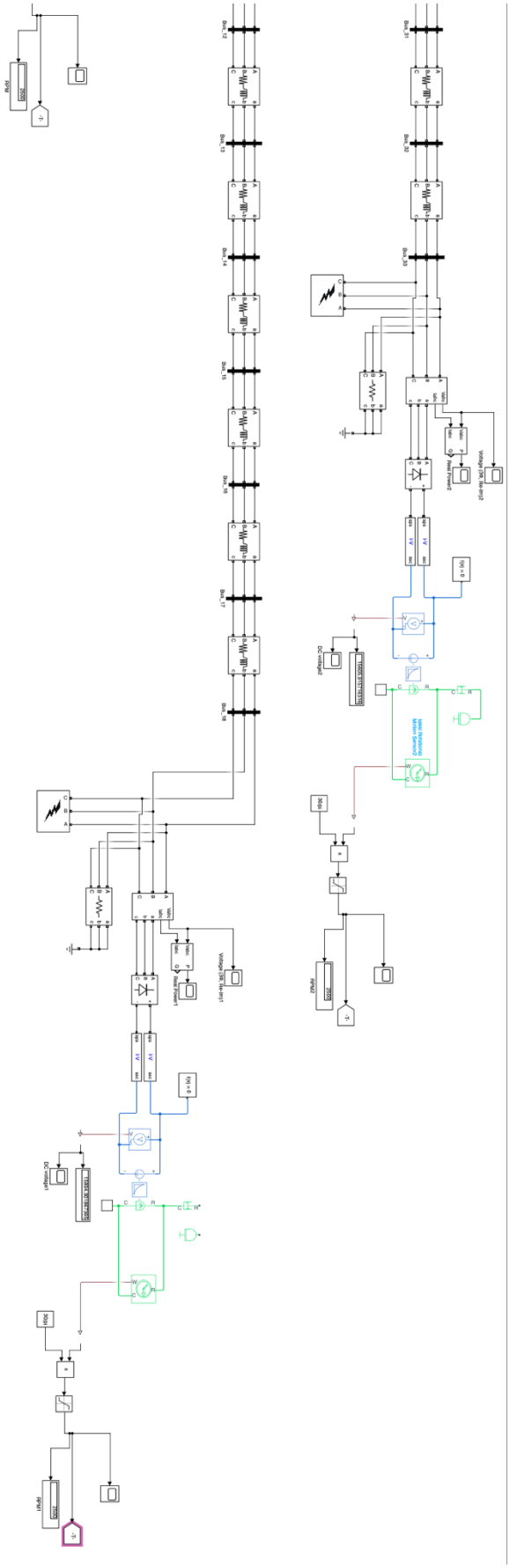


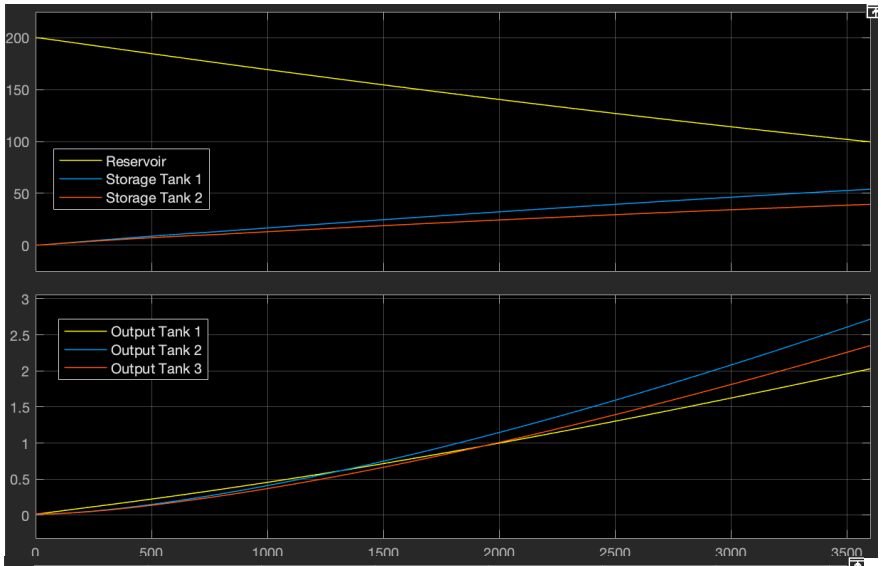
Figure 3.8 Enlarged

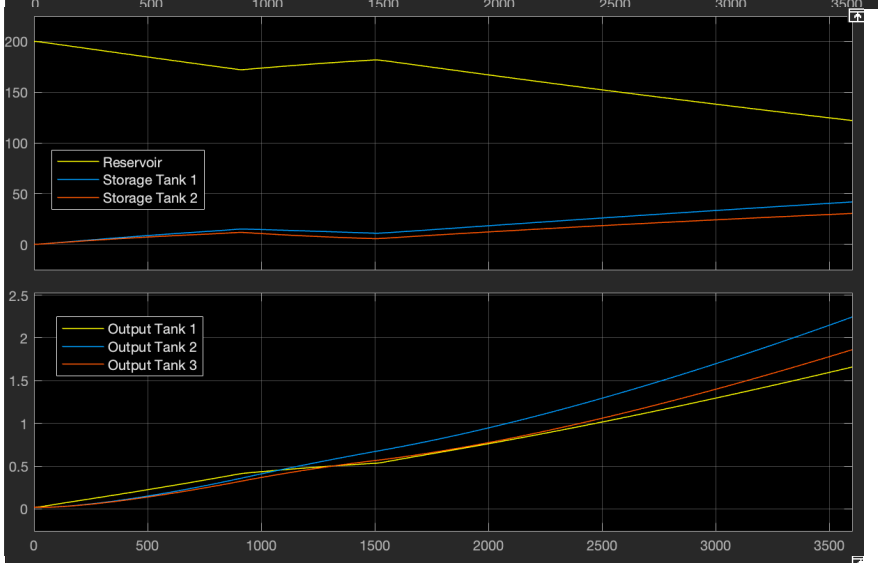
Appendix B

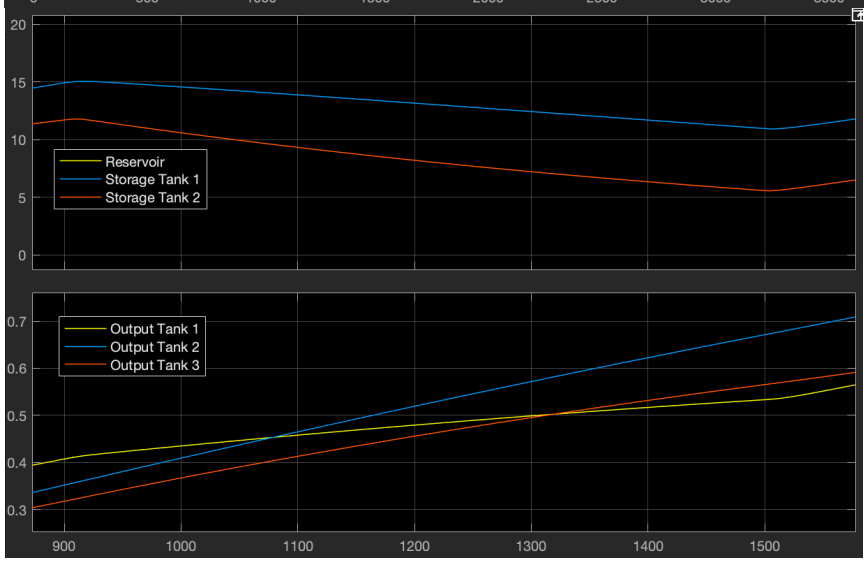
The figures for each hour shown here are in the following order from top to bottom:

No fault (full duration), Fault (full duration), Fault (zoomed in to fault's timespan)

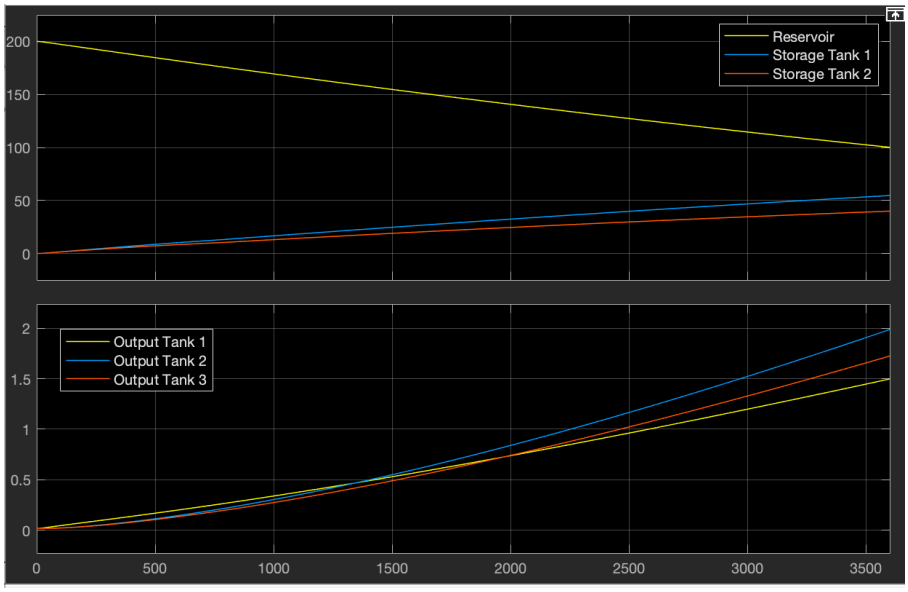
00:00

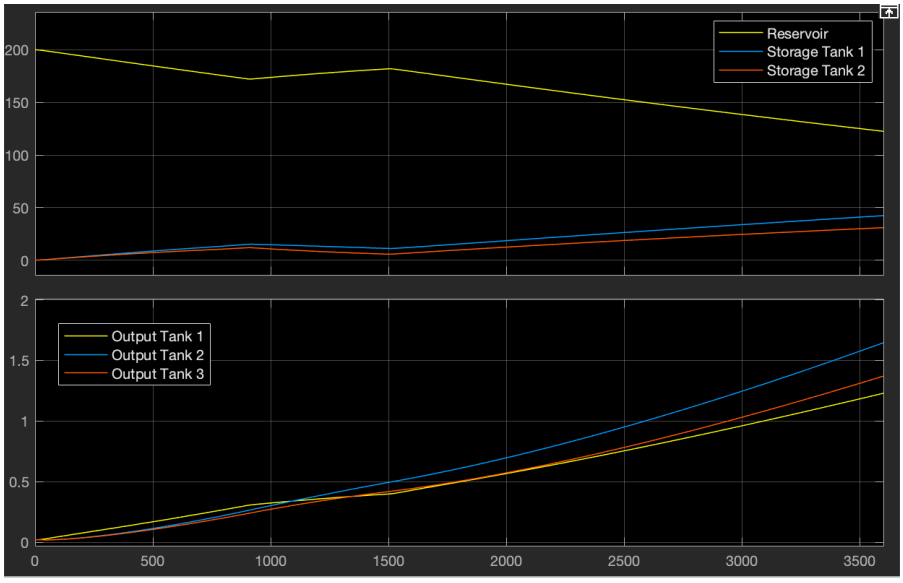


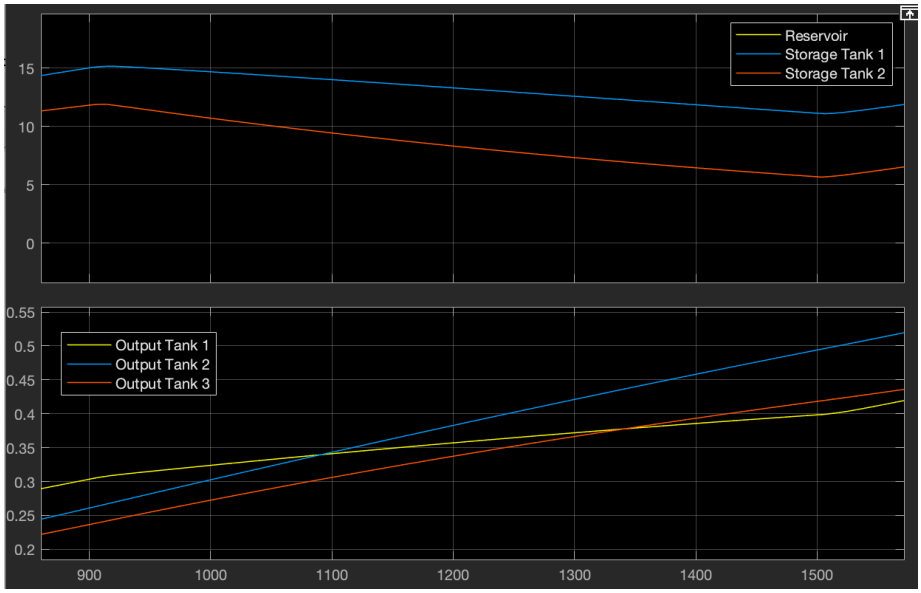




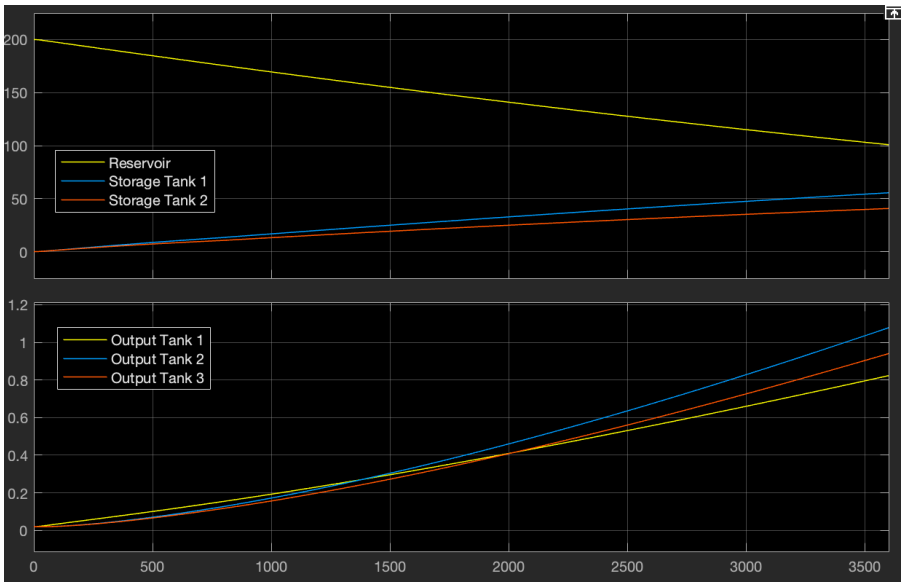
01:00

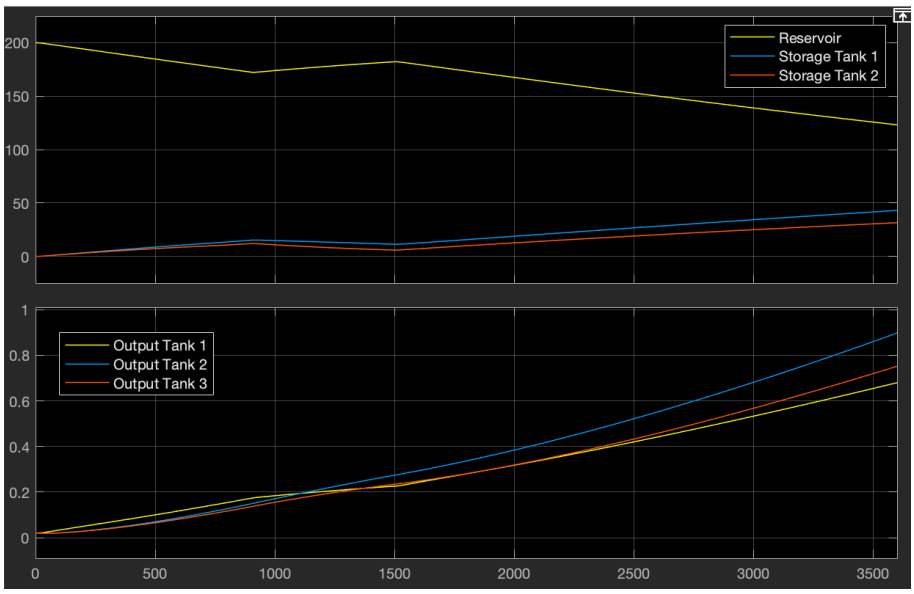

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

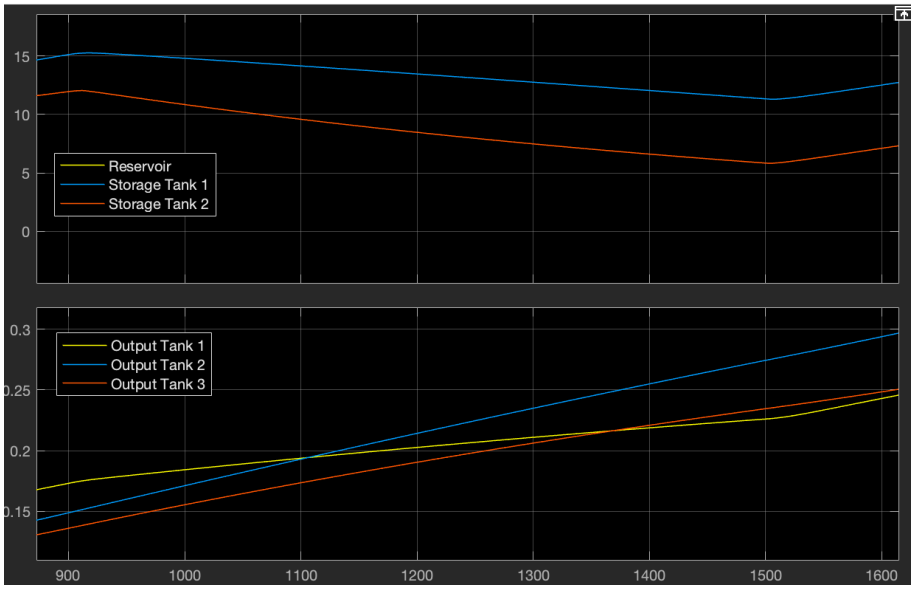

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3


Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

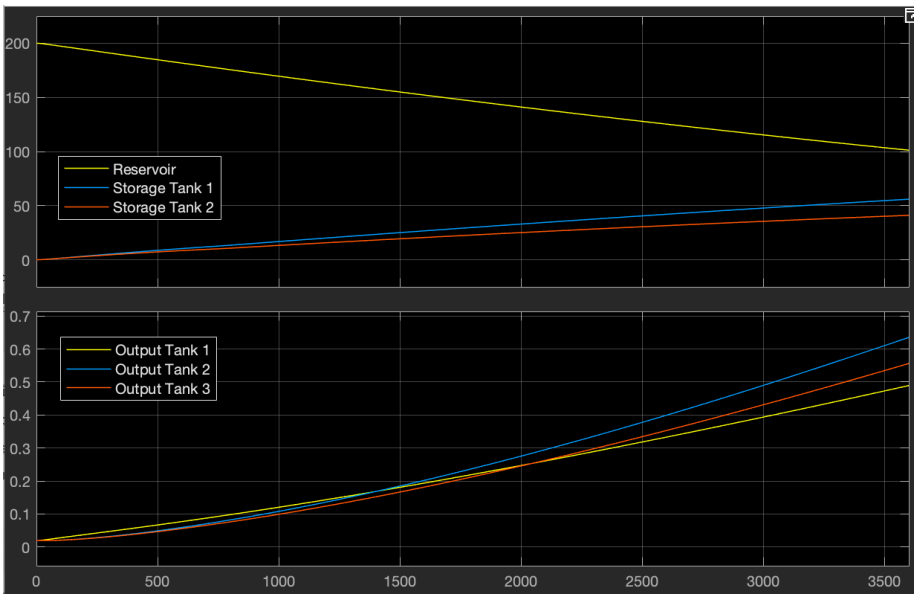
02:00

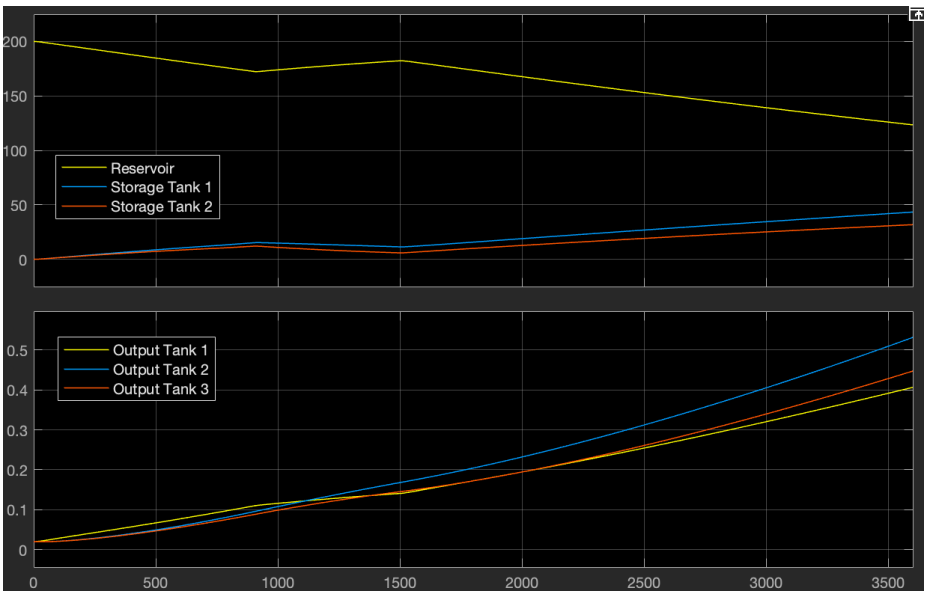

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

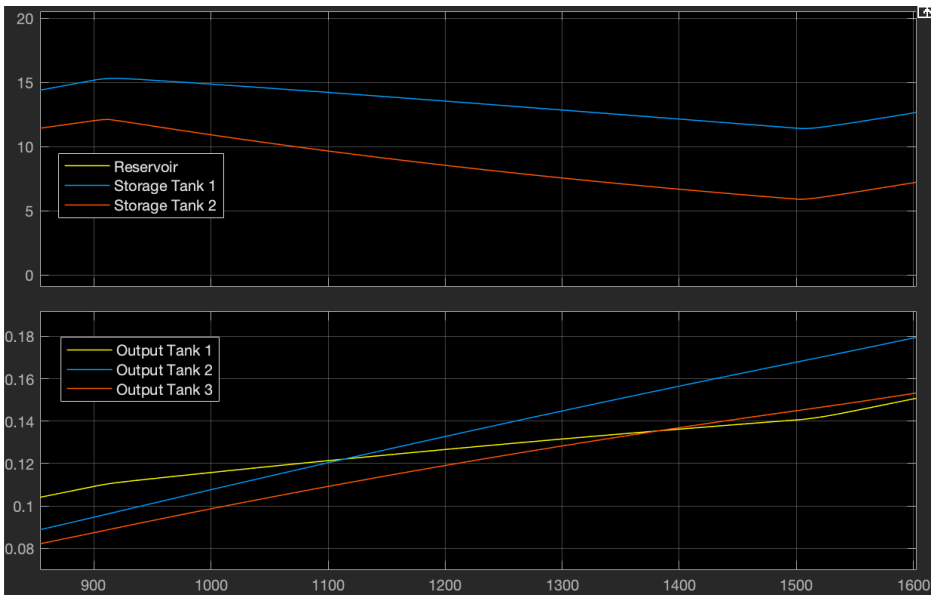

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3


Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

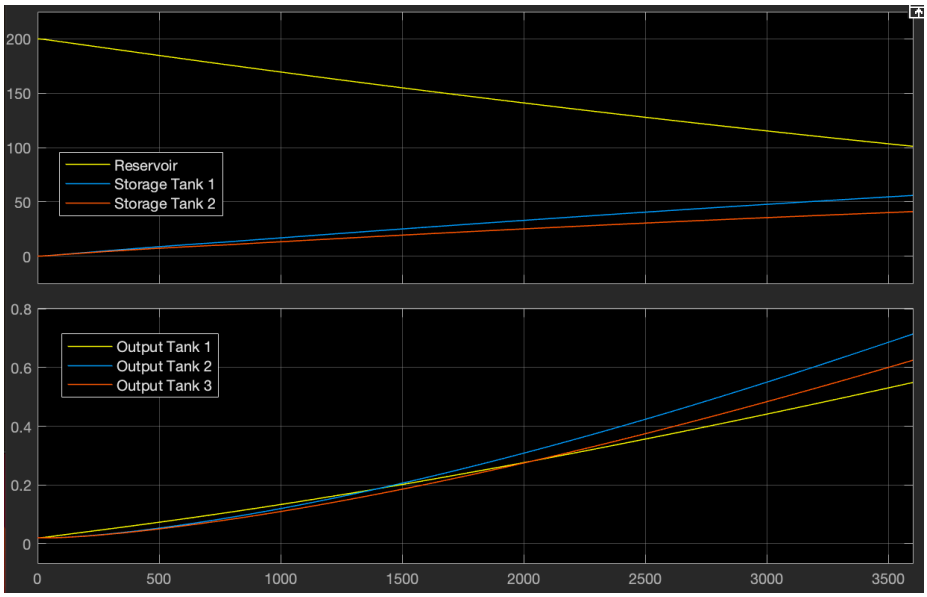
04:00

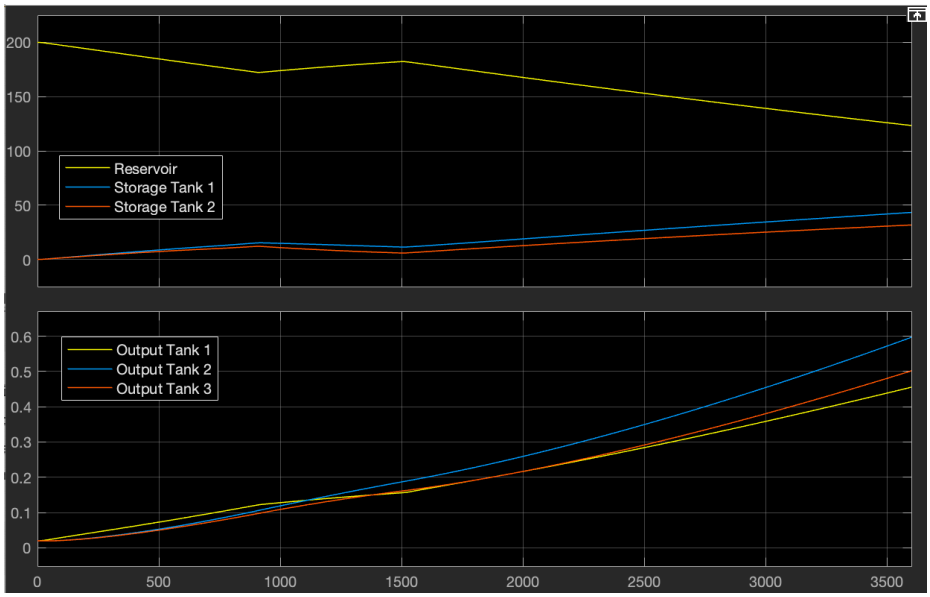

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

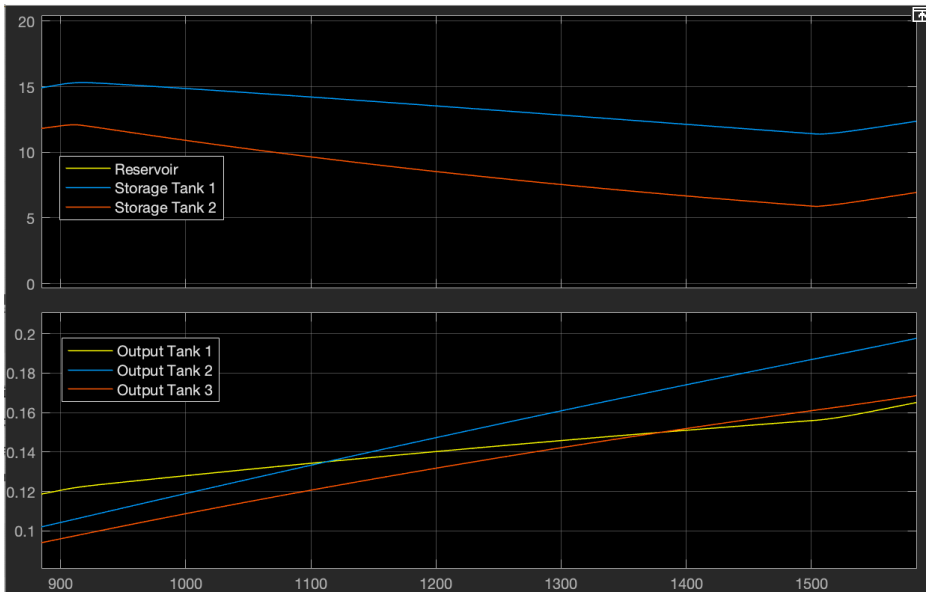

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3


Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

05:00

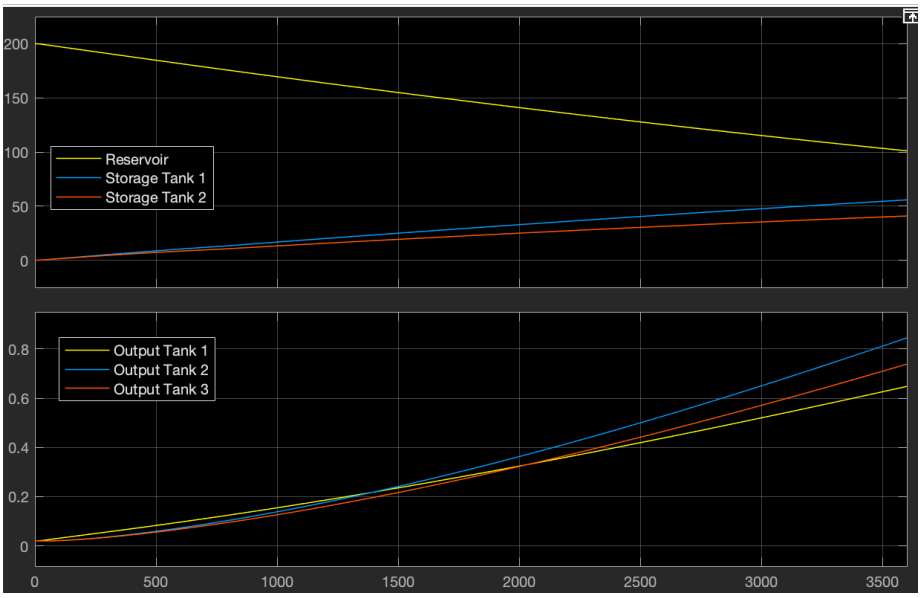

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

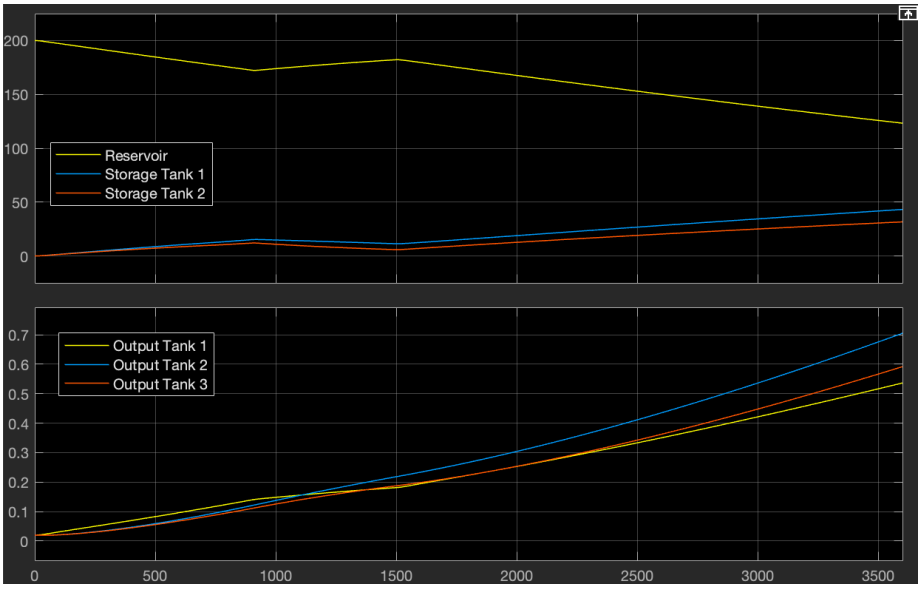

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

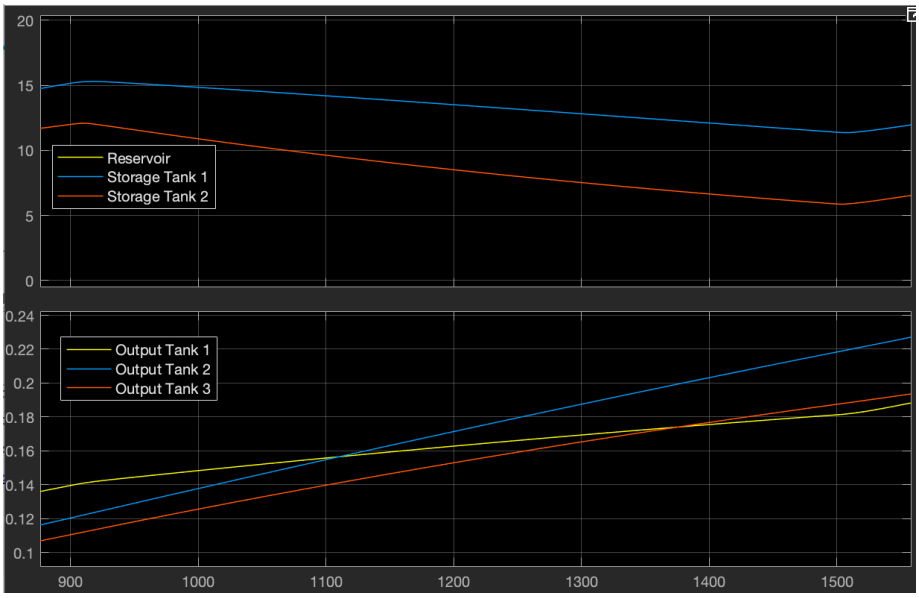

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

x

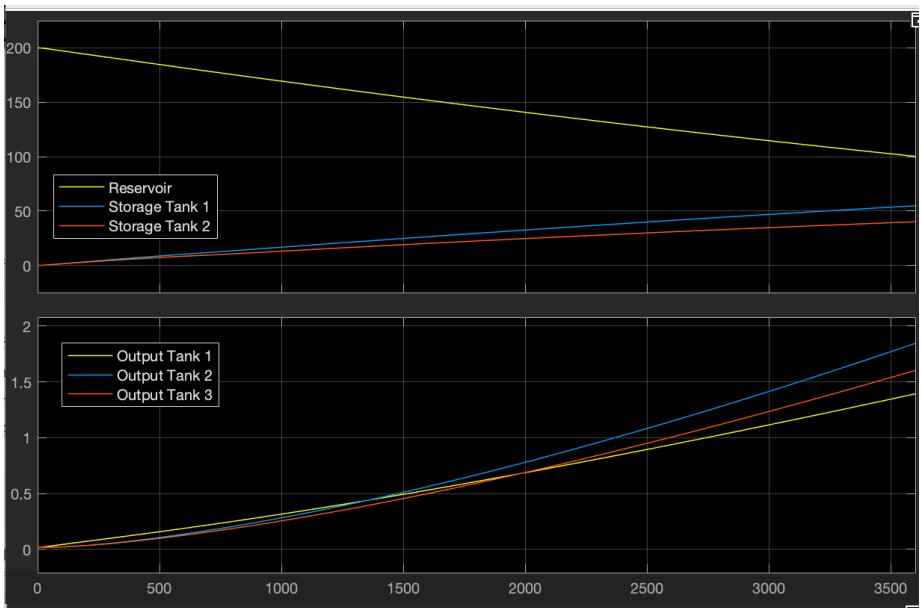
06:00

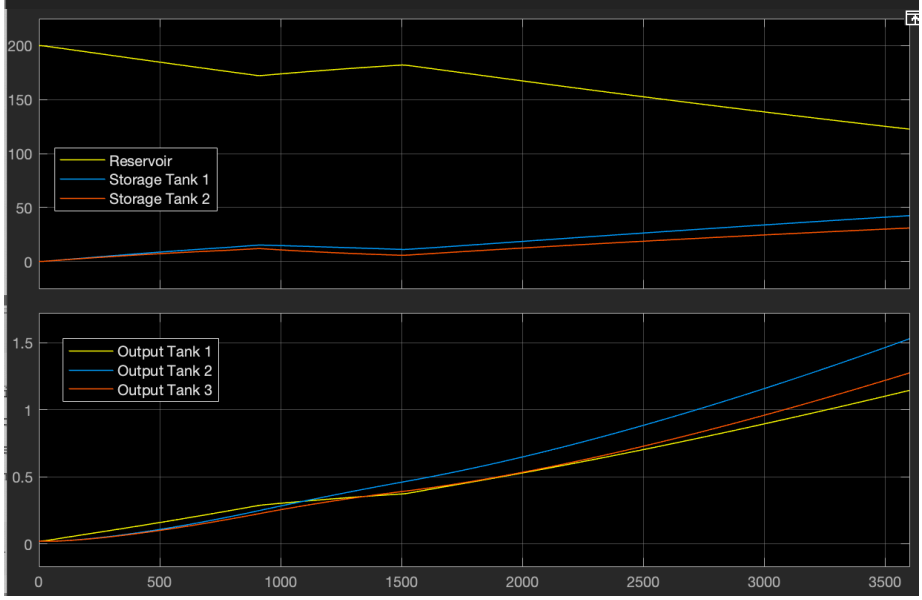

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

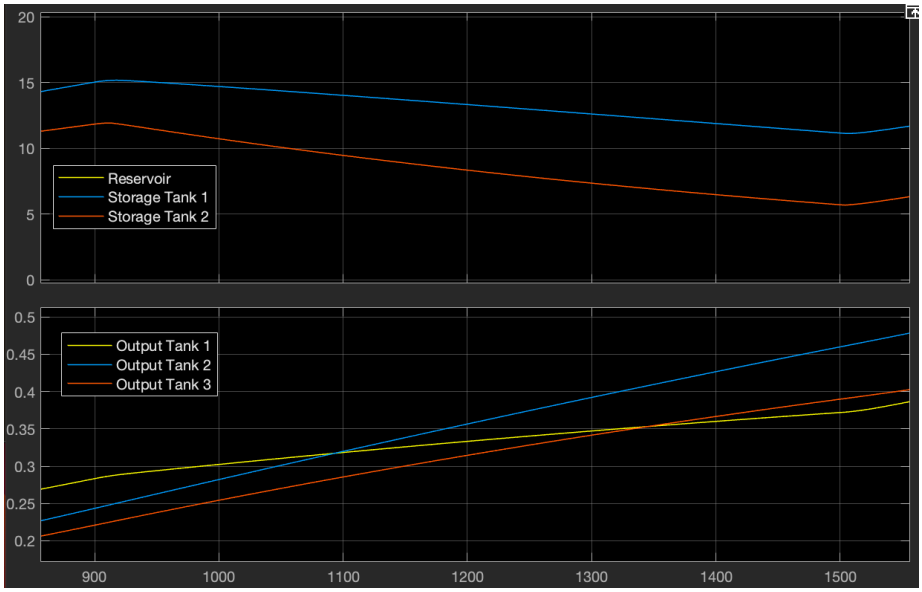

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3


Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

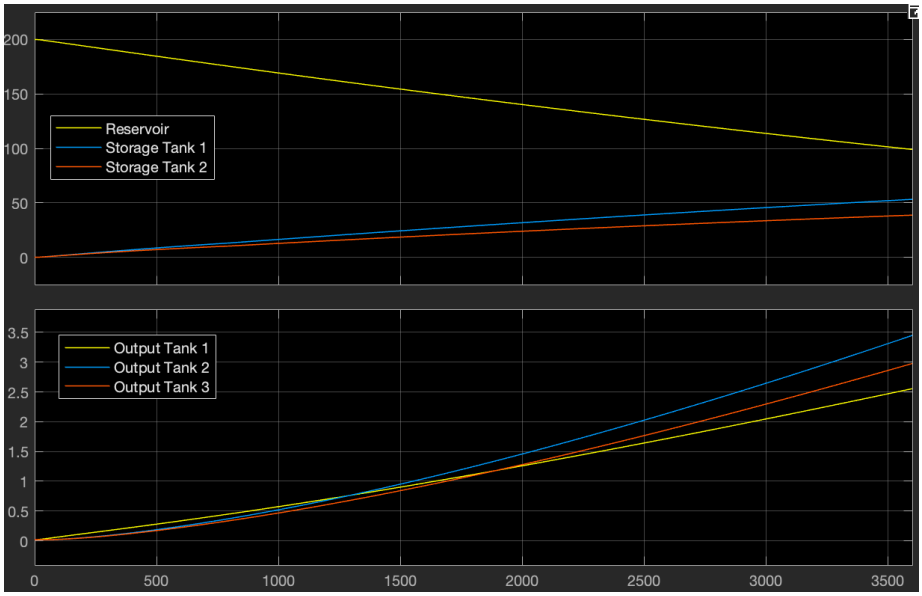
07:00

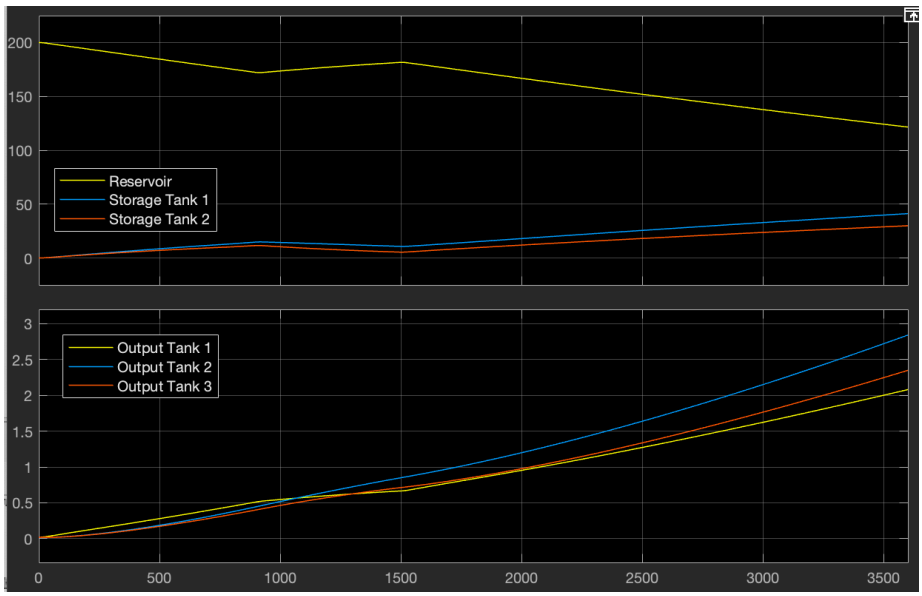

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

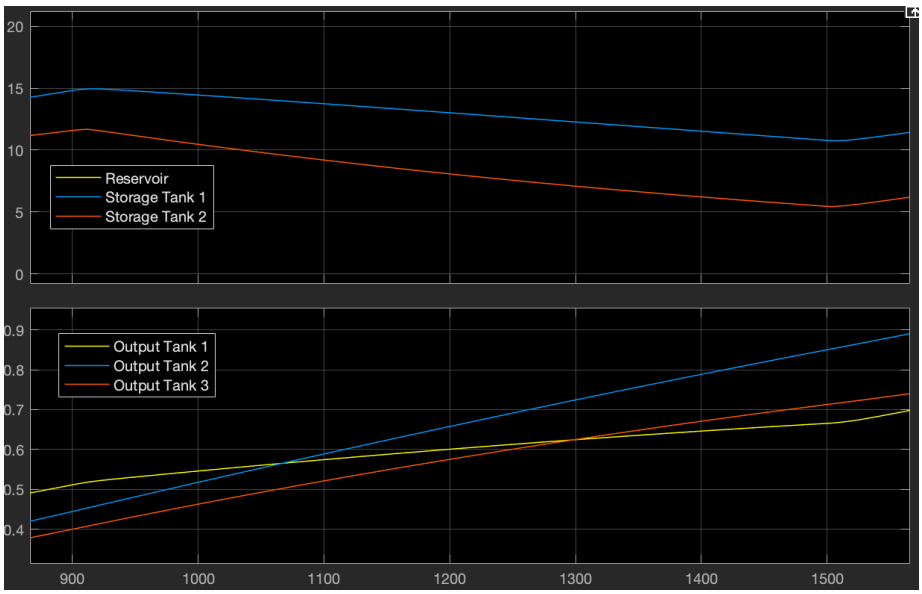

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3


Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

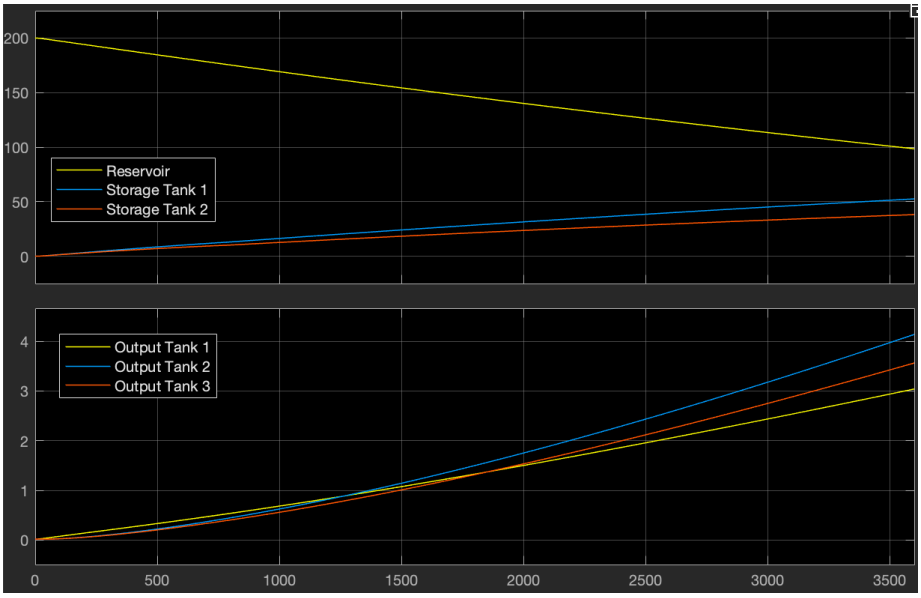
08:00

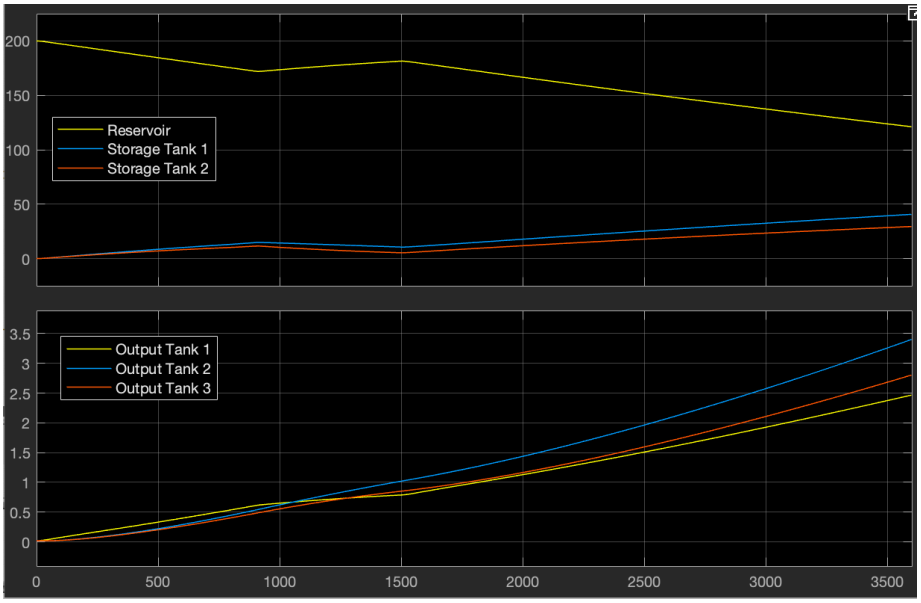

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

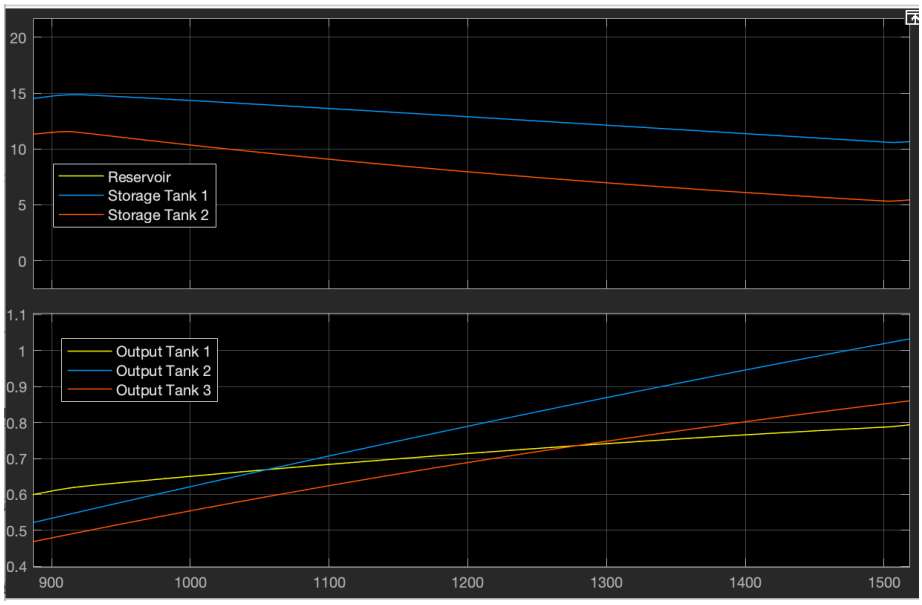

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3


Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

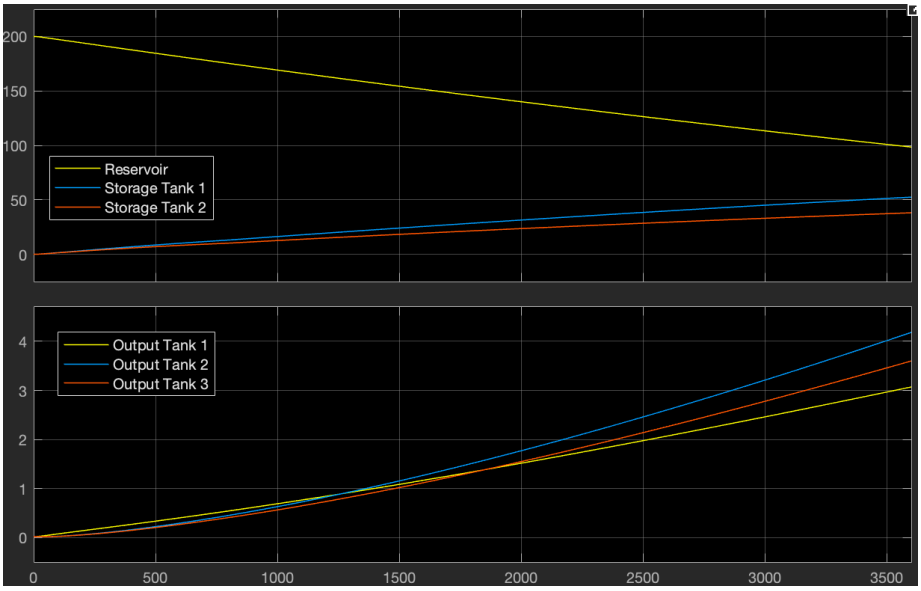
09:00

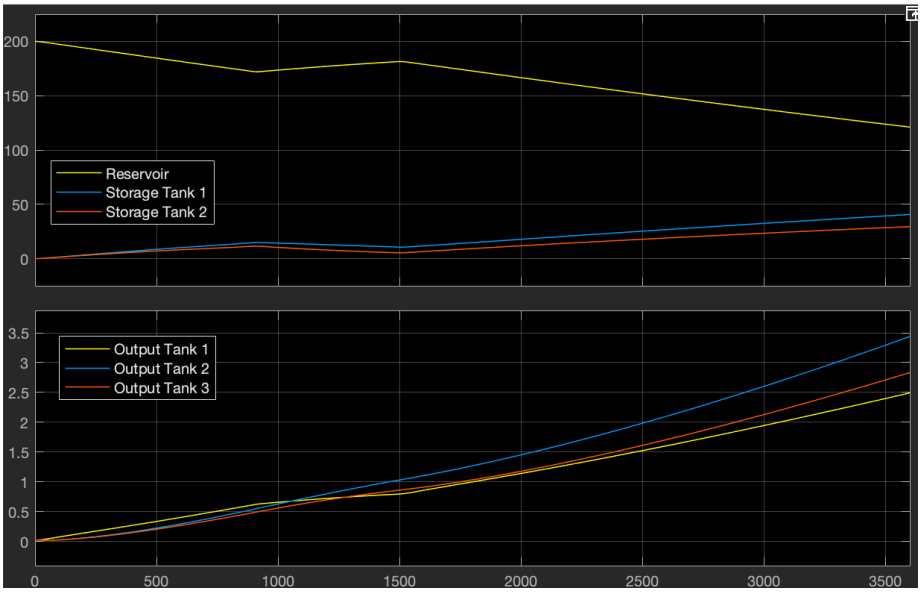

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

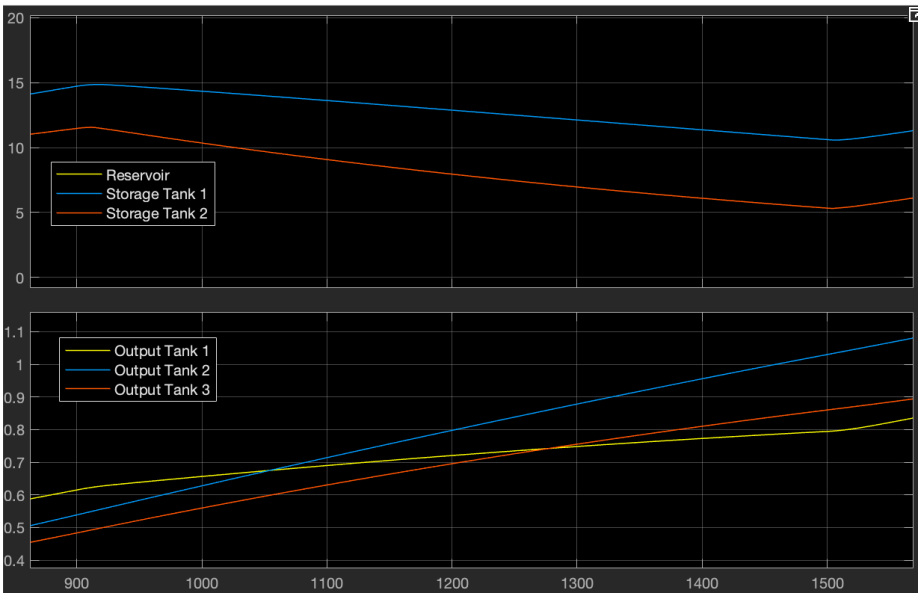

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3


Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

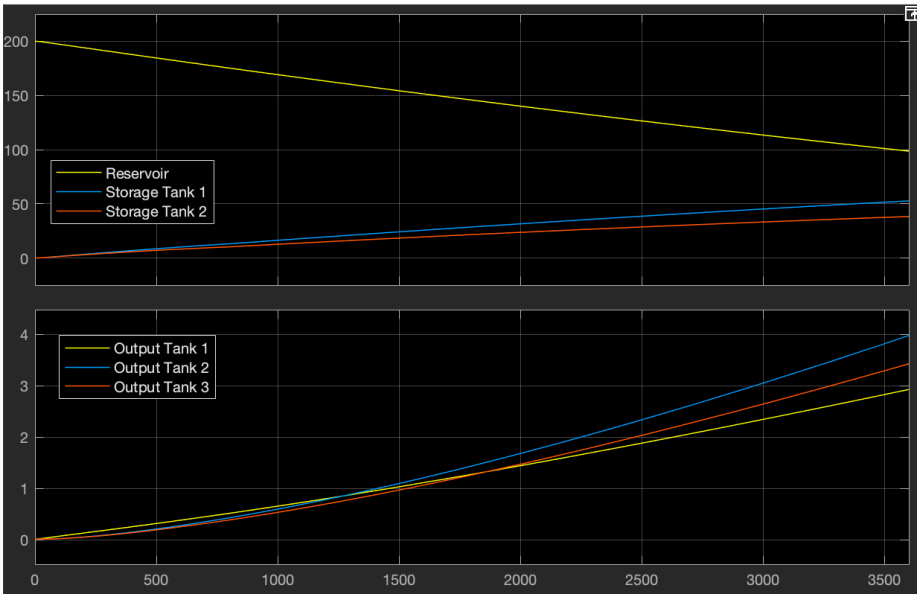
11:00

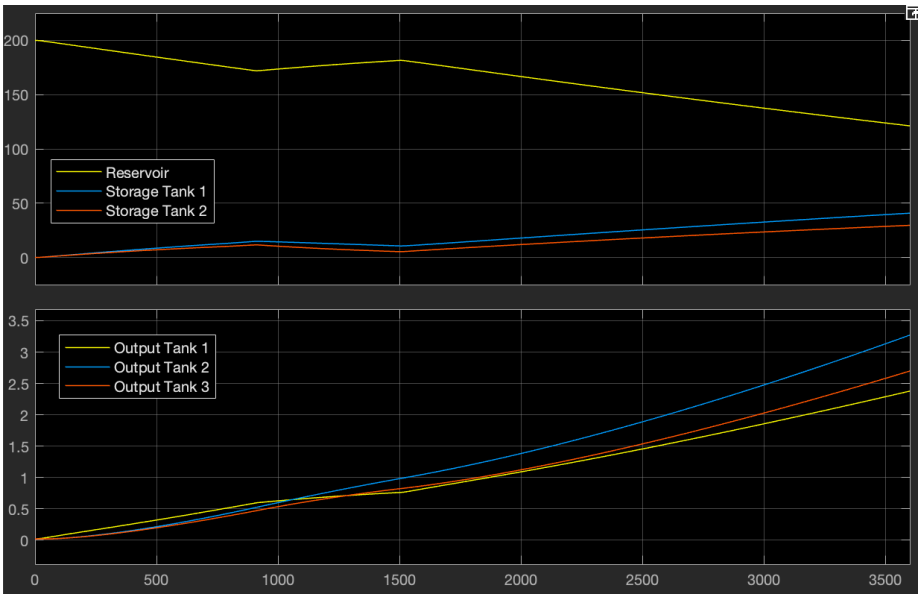

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

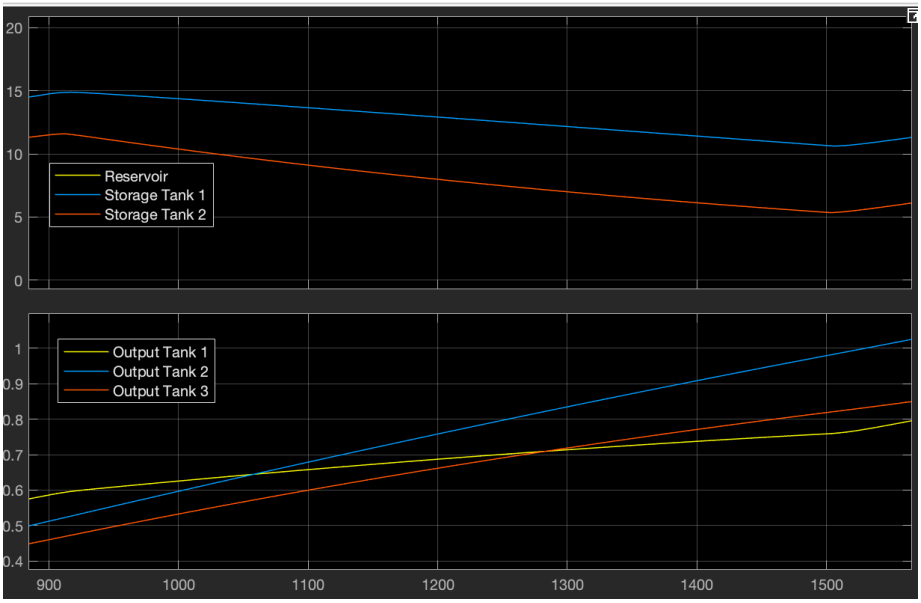

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3


Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

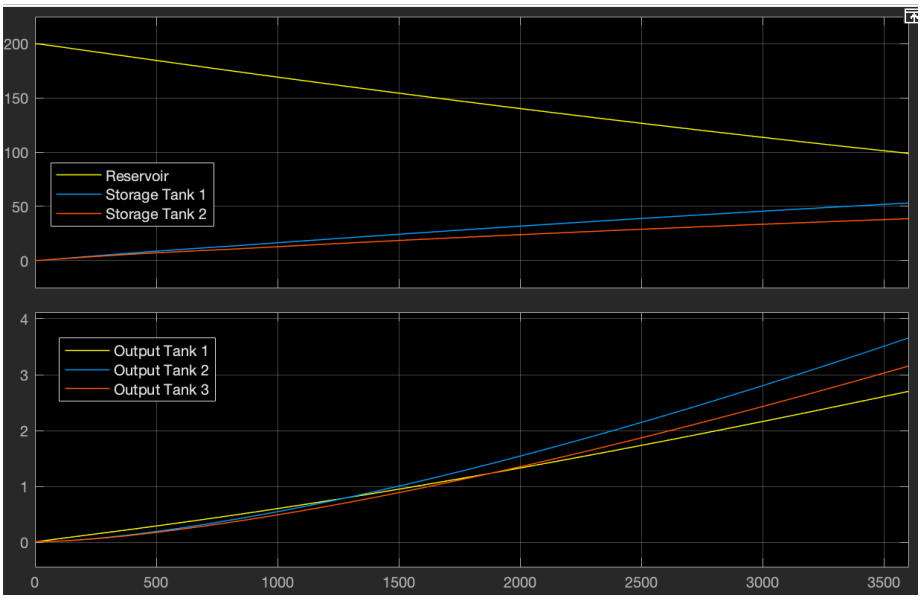
12:00

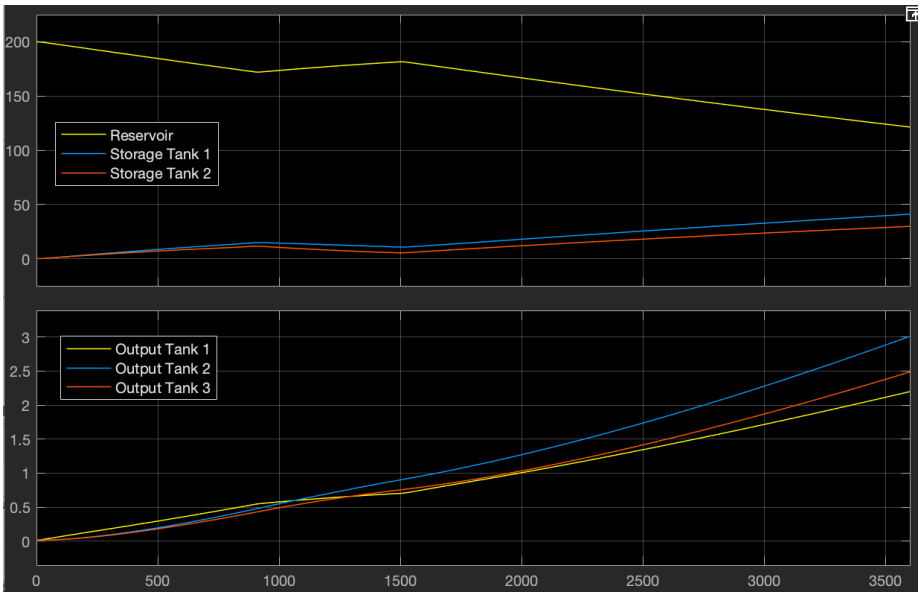

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

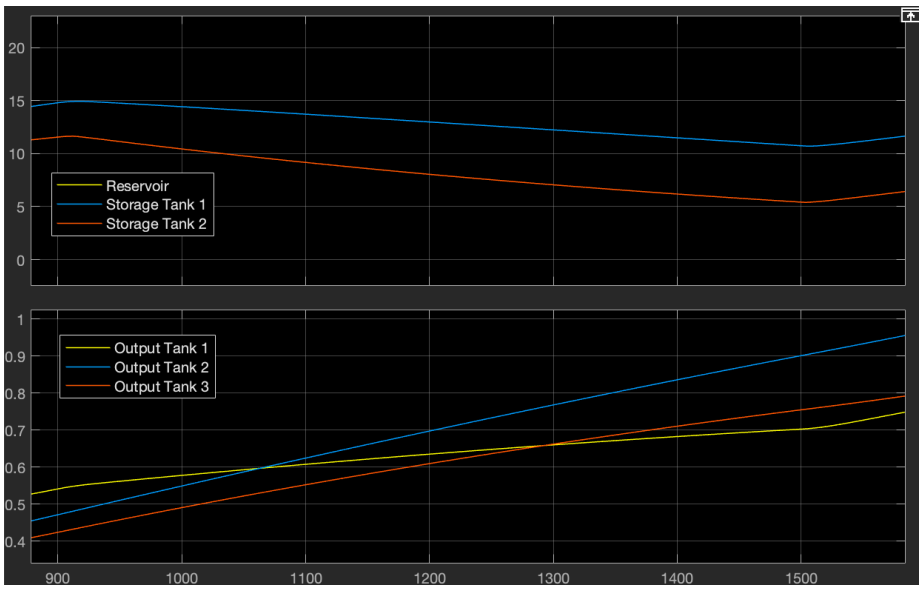

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3


Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

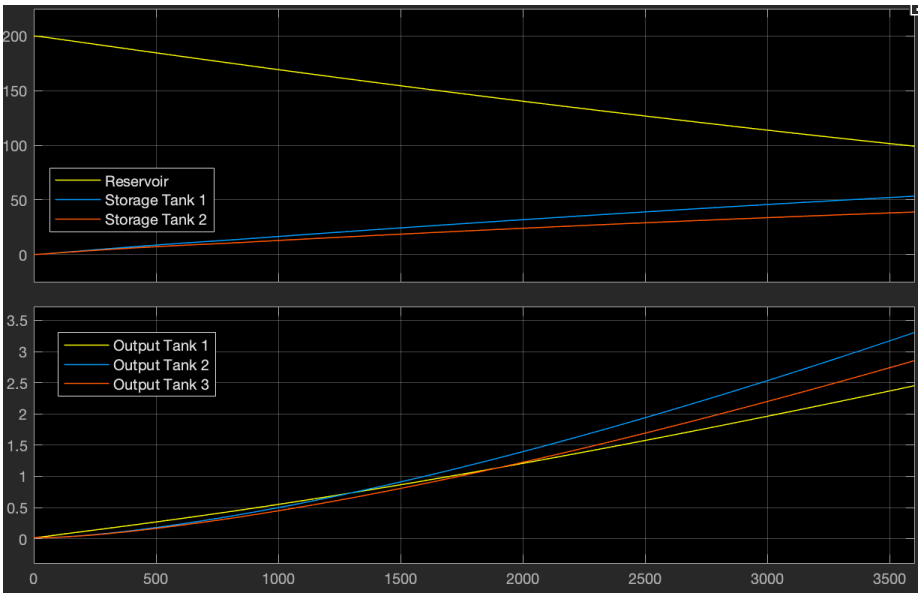
13:00

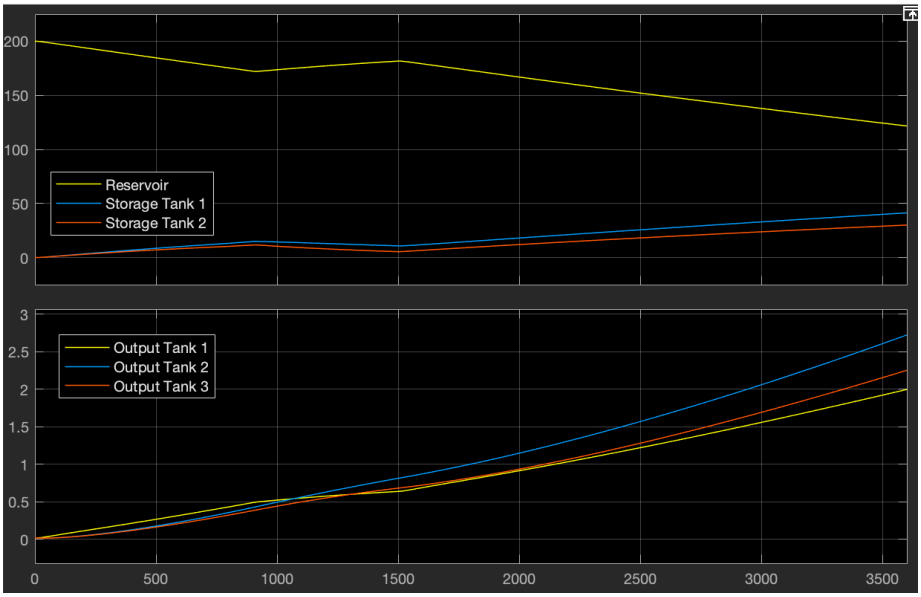

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

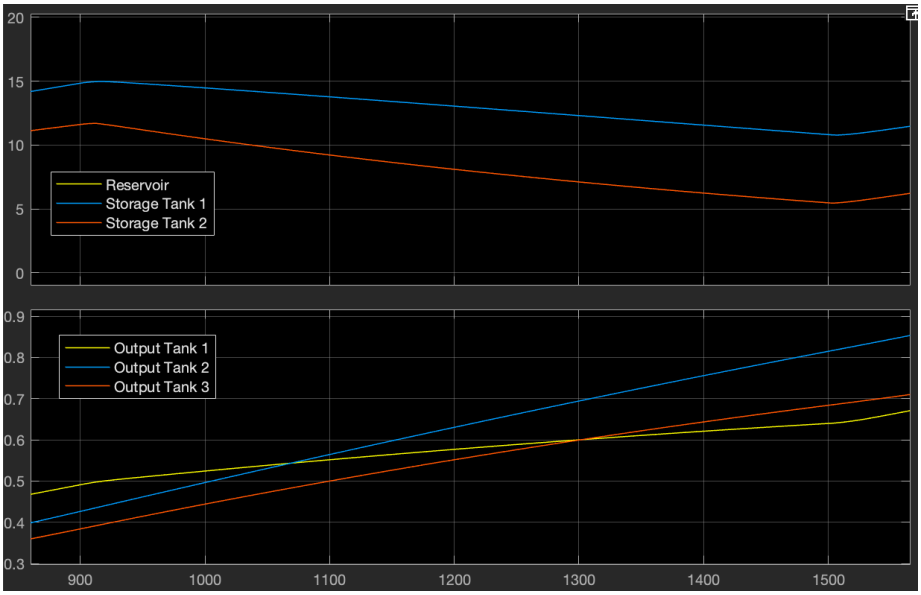

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3


Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

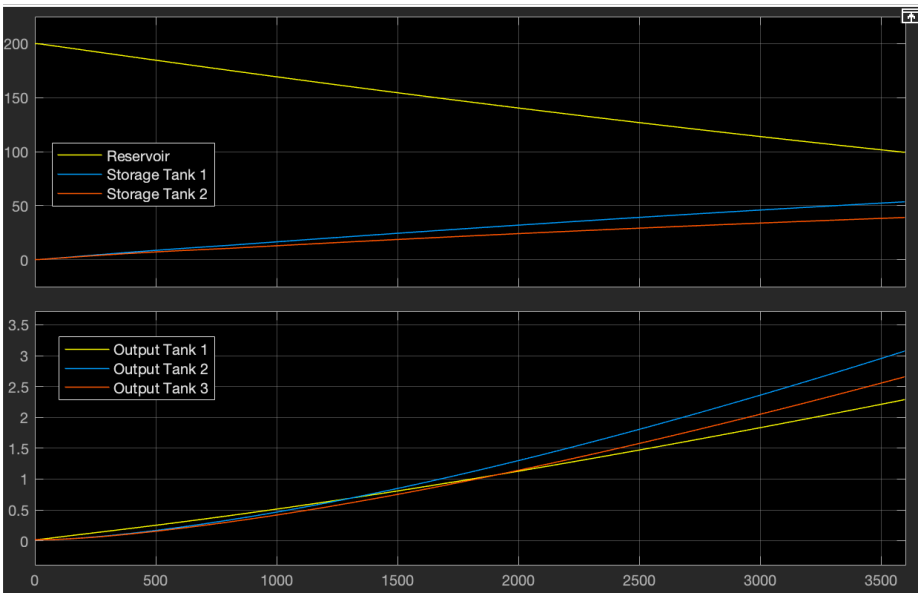
14:00

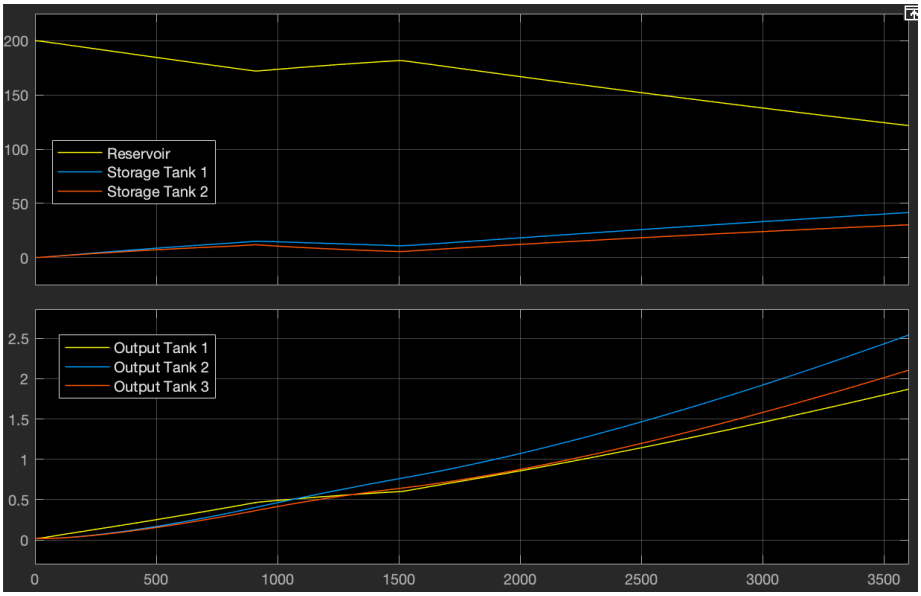

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

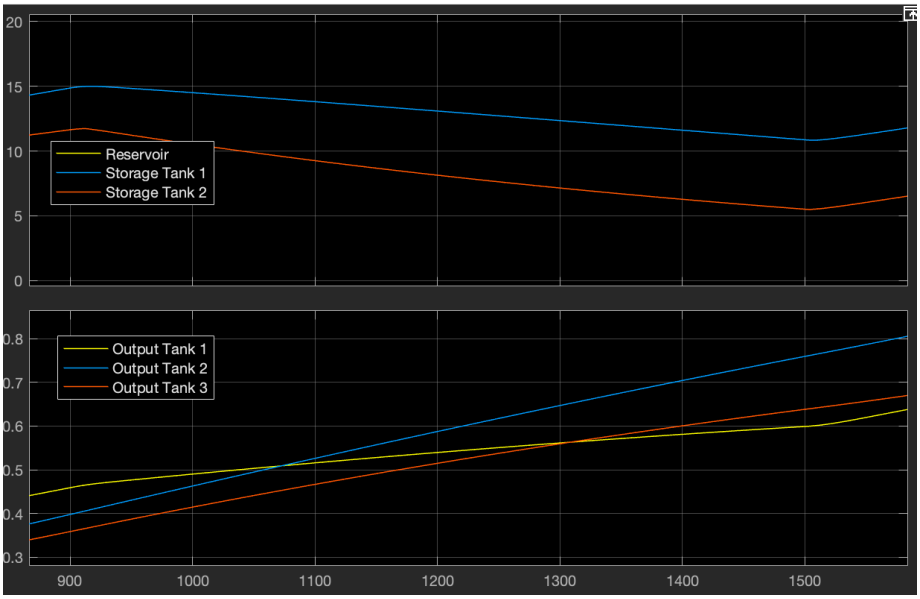

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3


Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

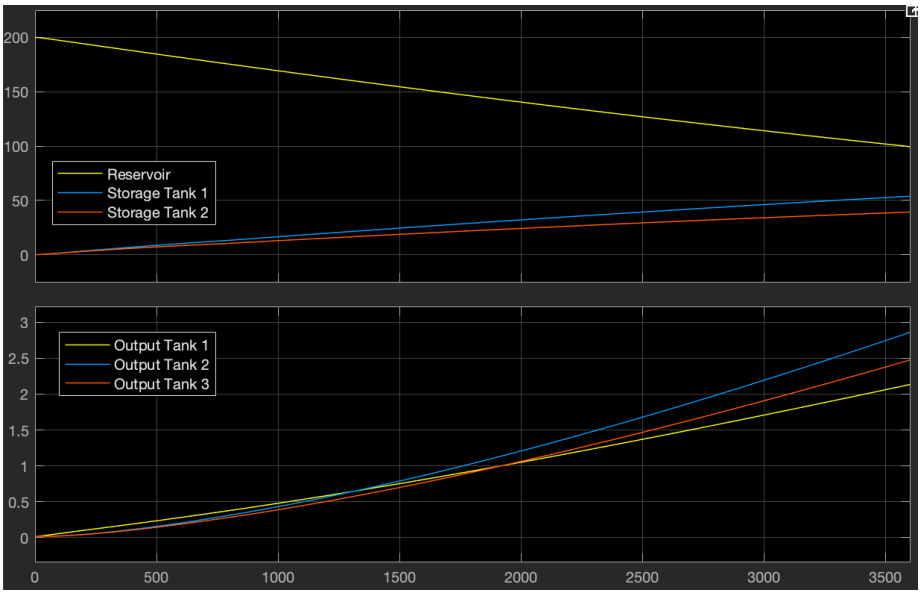
15:00

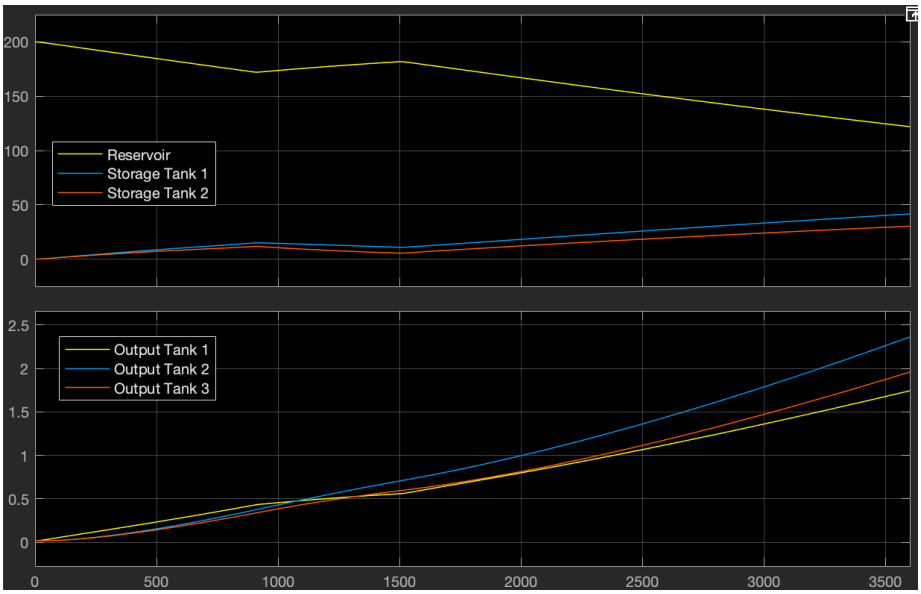

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

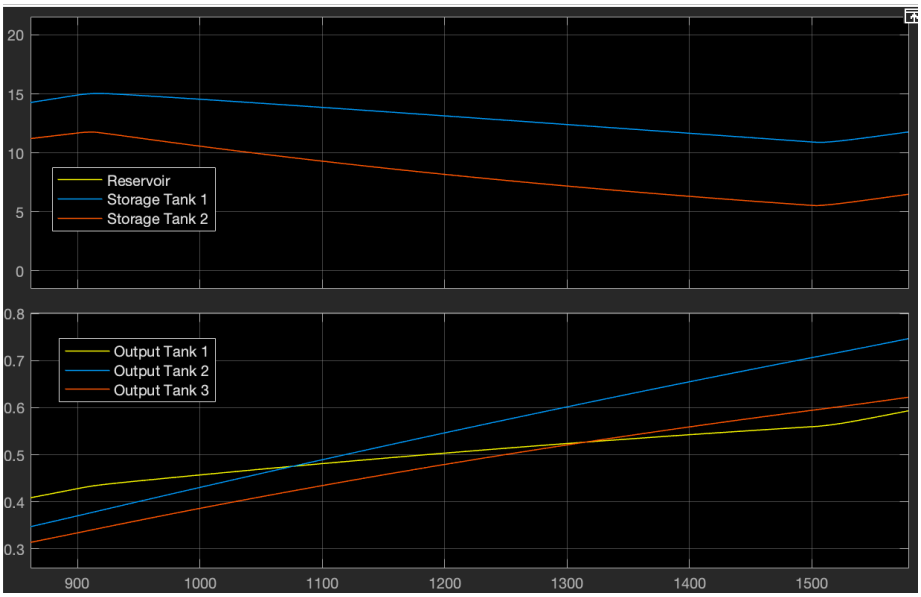

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3


Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

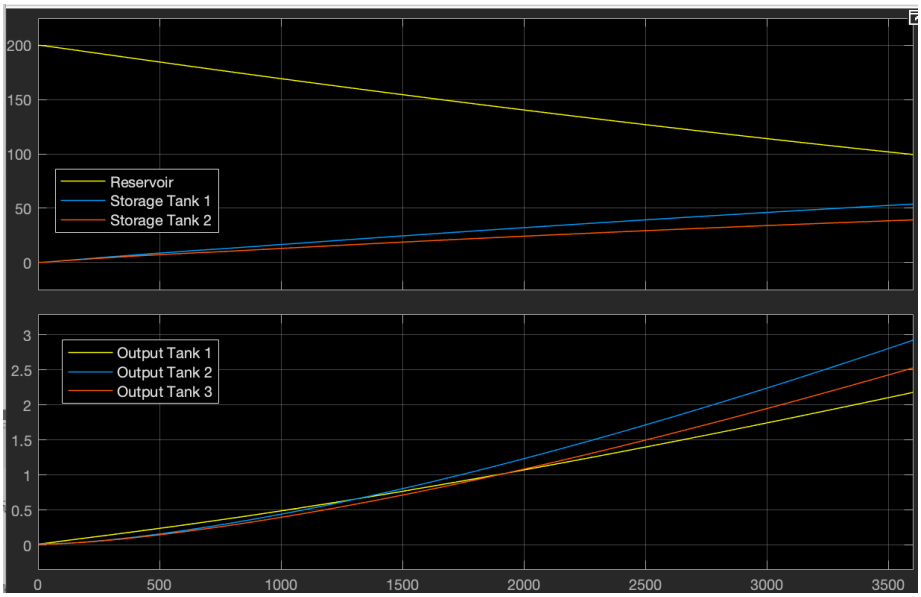
16:00

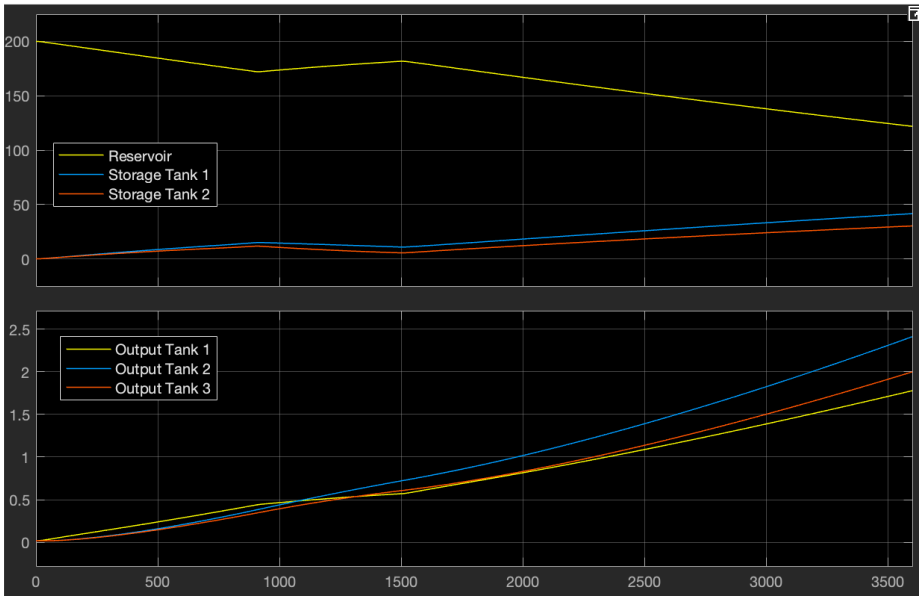

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

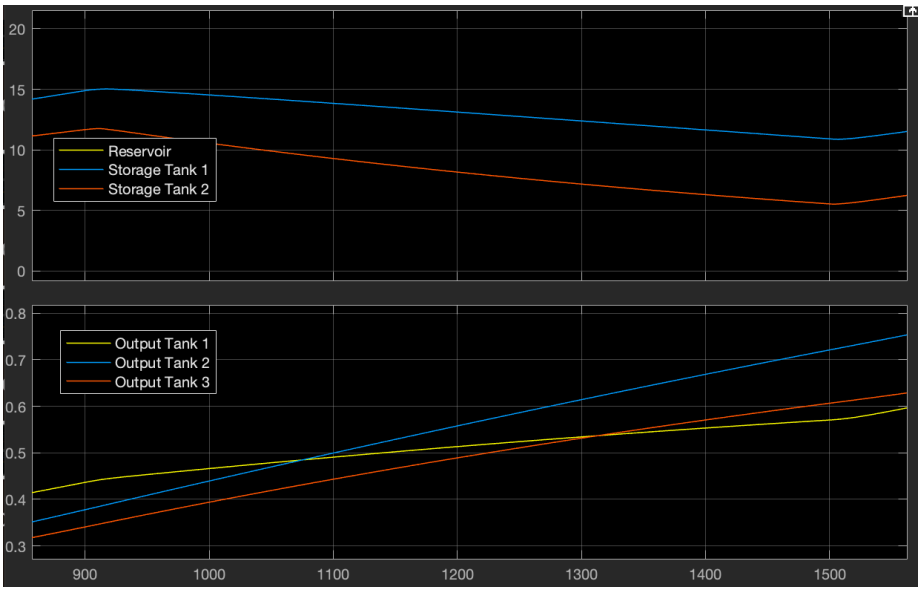

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3


Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

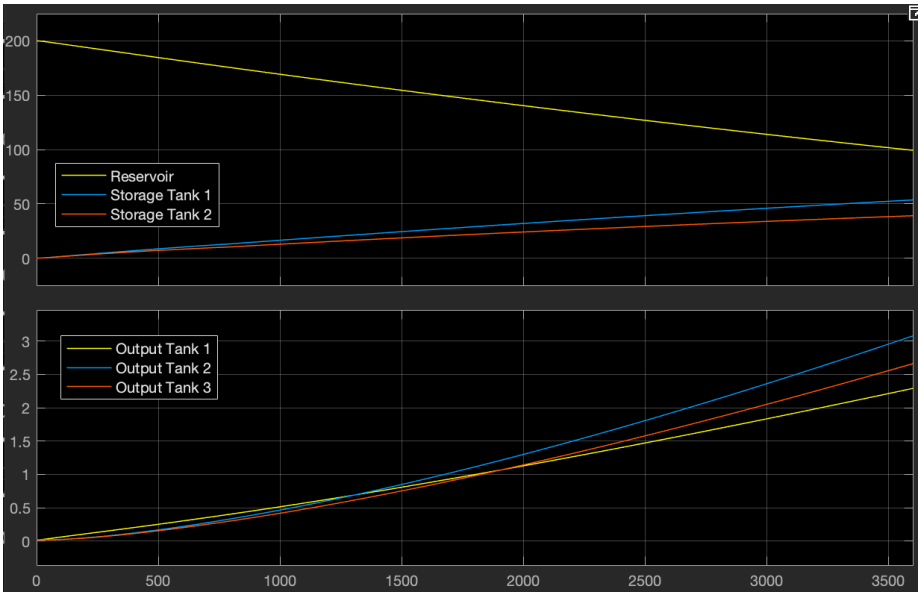
17:00

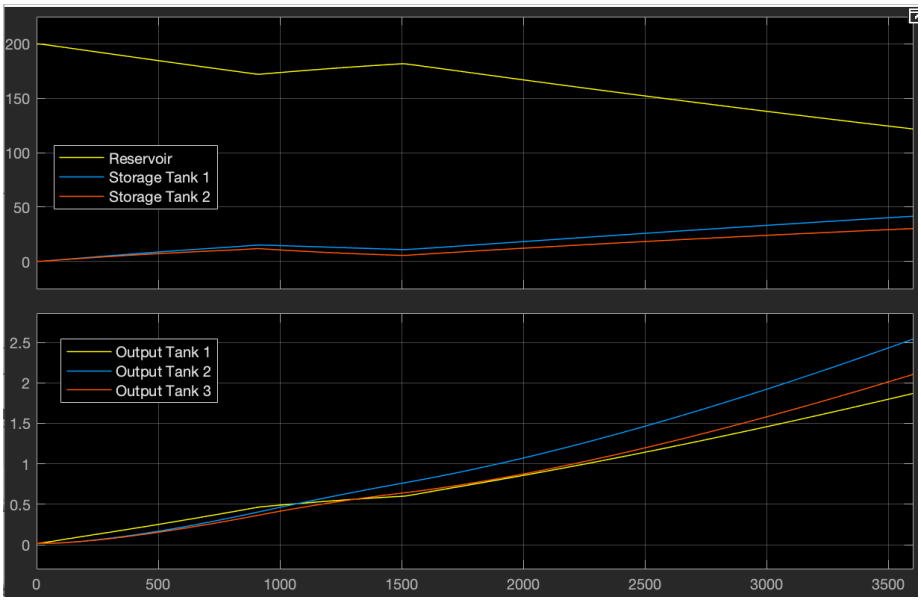

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

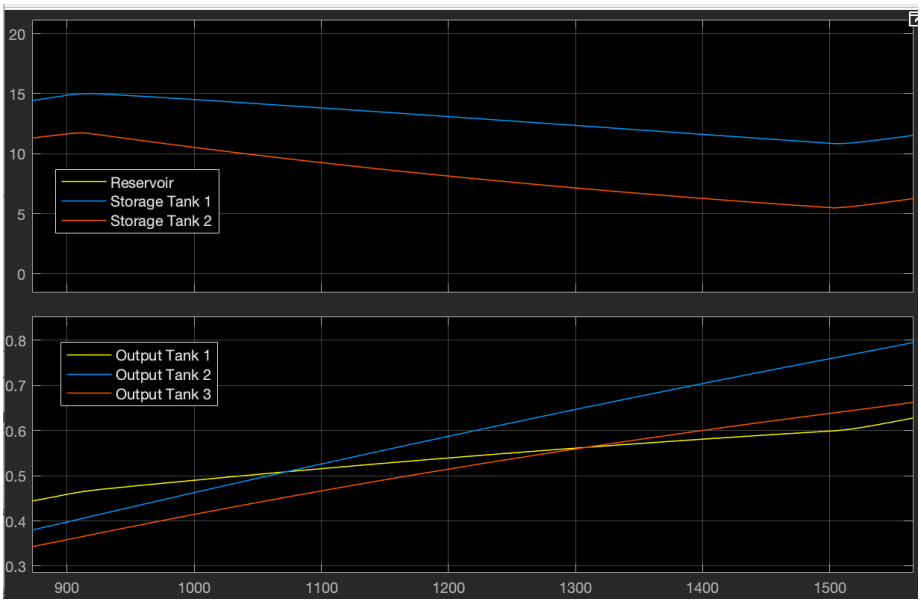

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3


Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

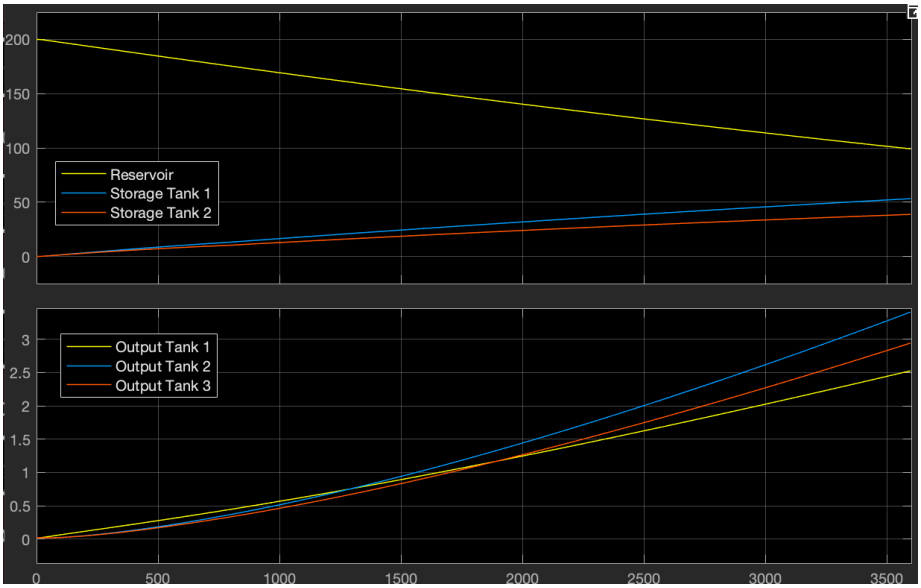
18:00

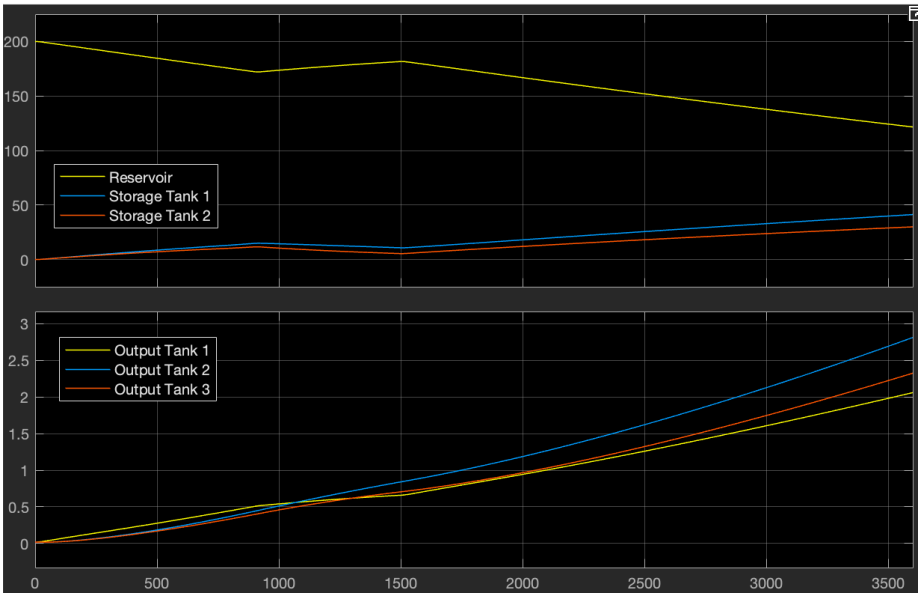

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

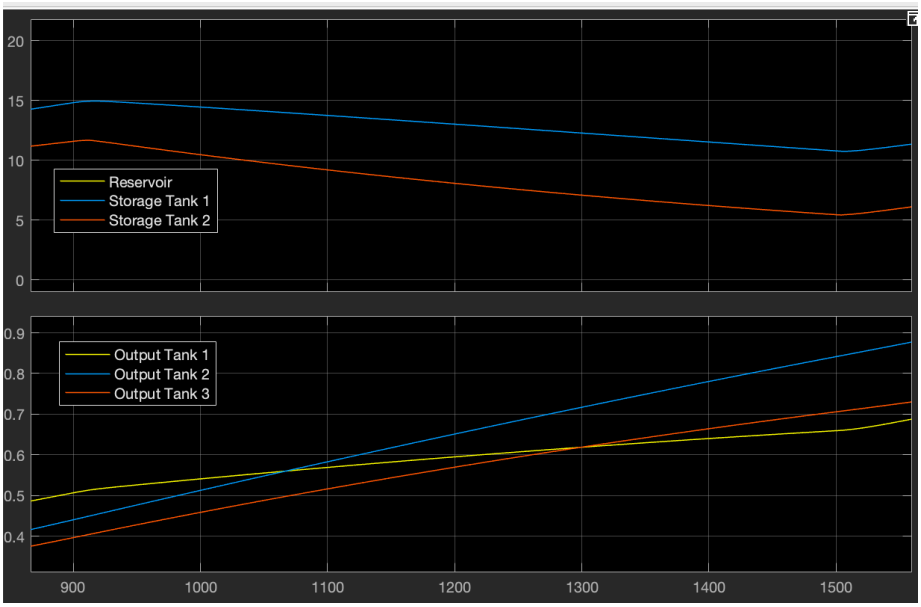

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3


Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

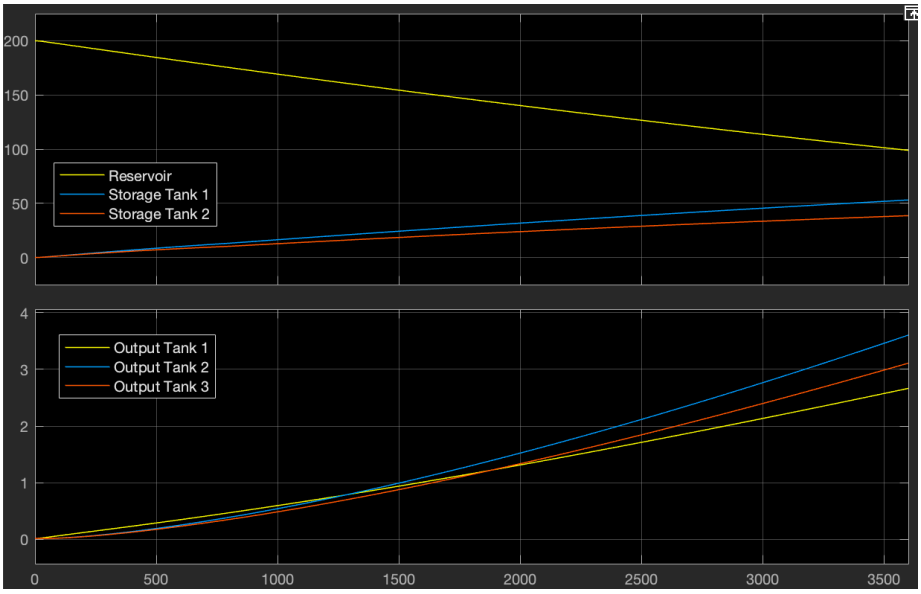
19:00

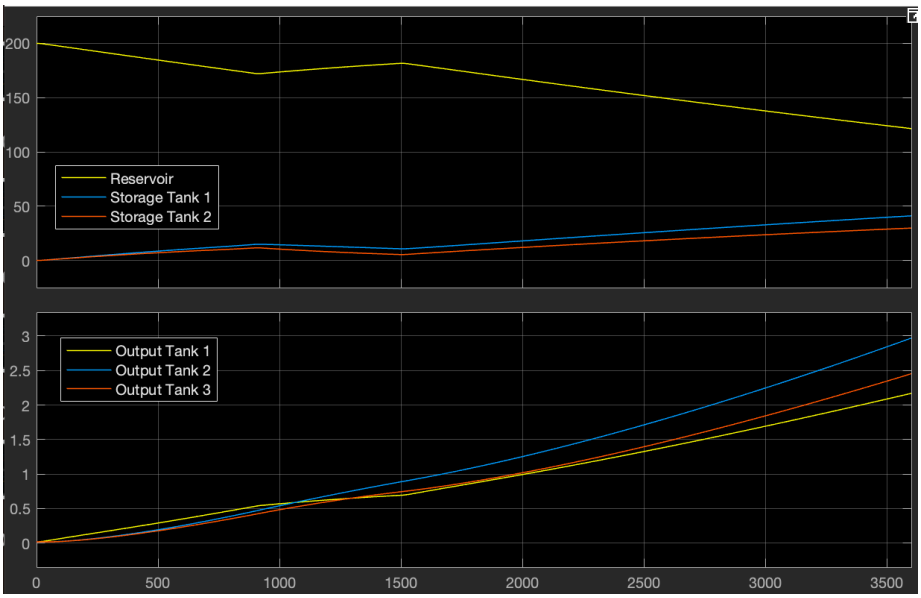

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

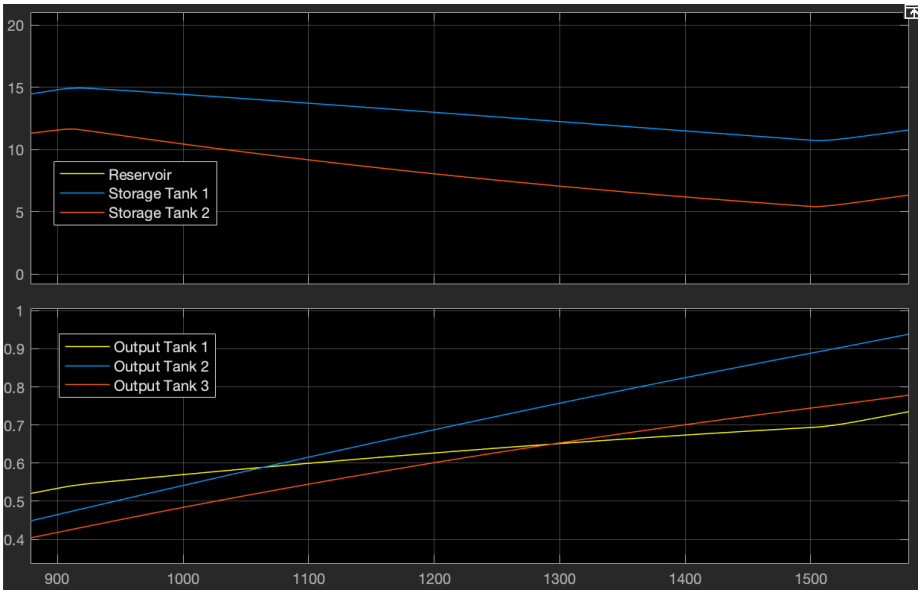

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3


Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

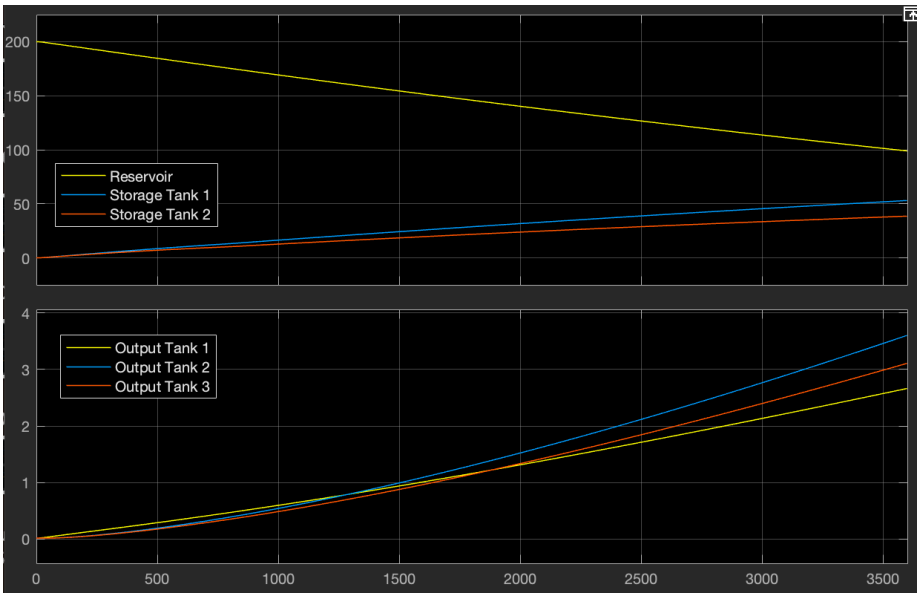
20:00

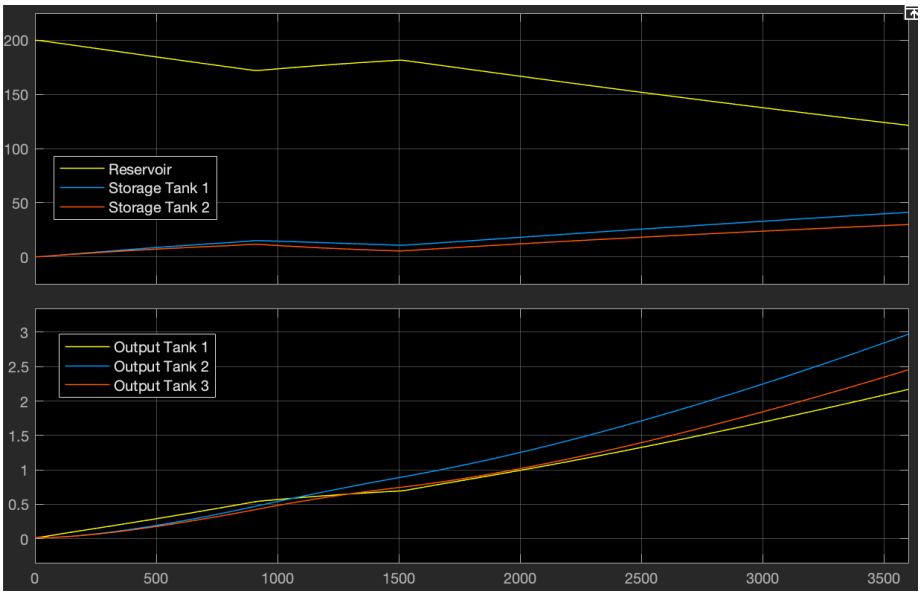

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

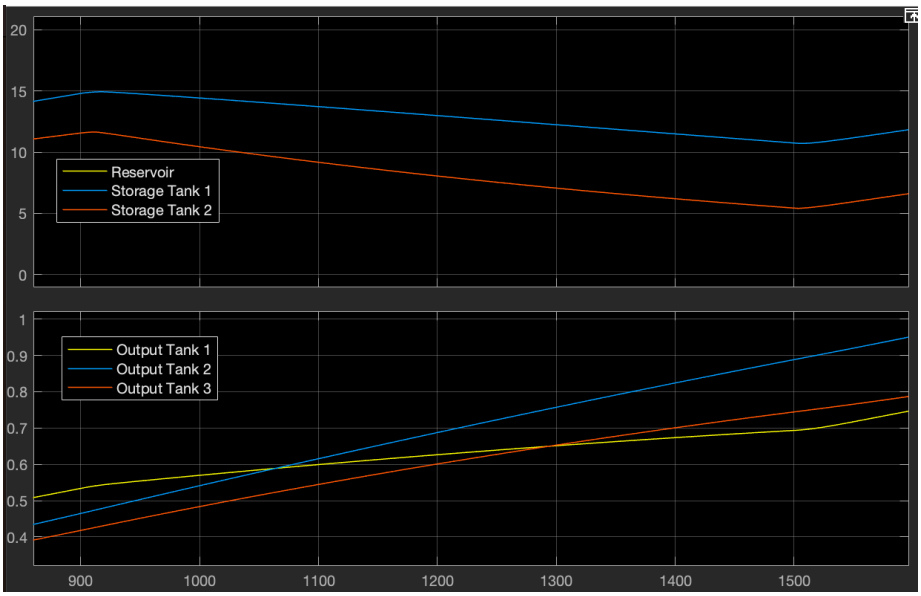

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3


Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

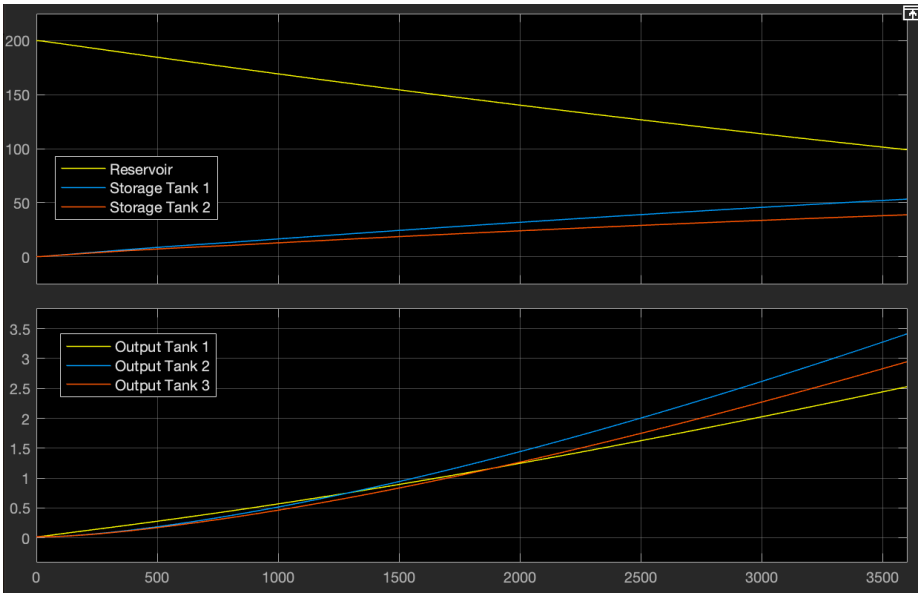
21:00

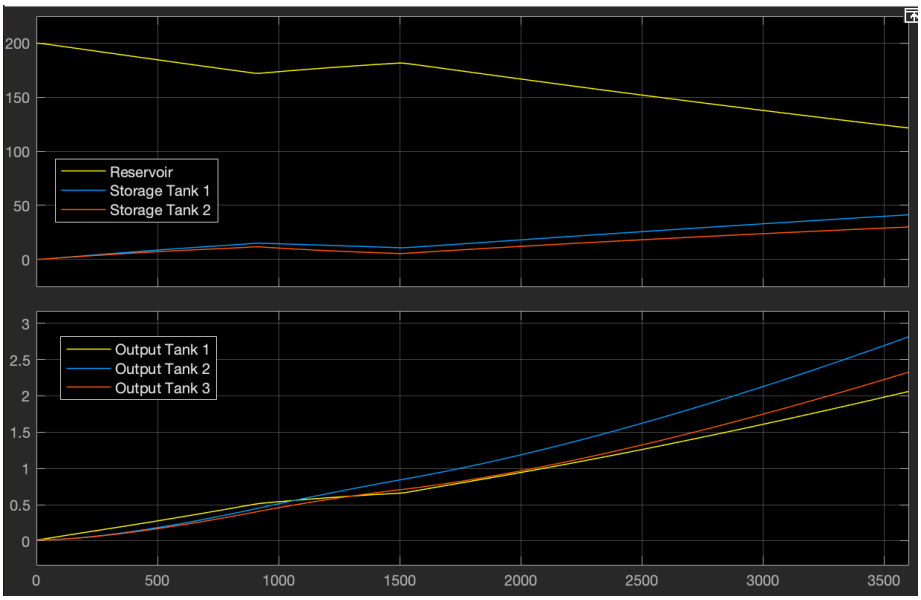

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

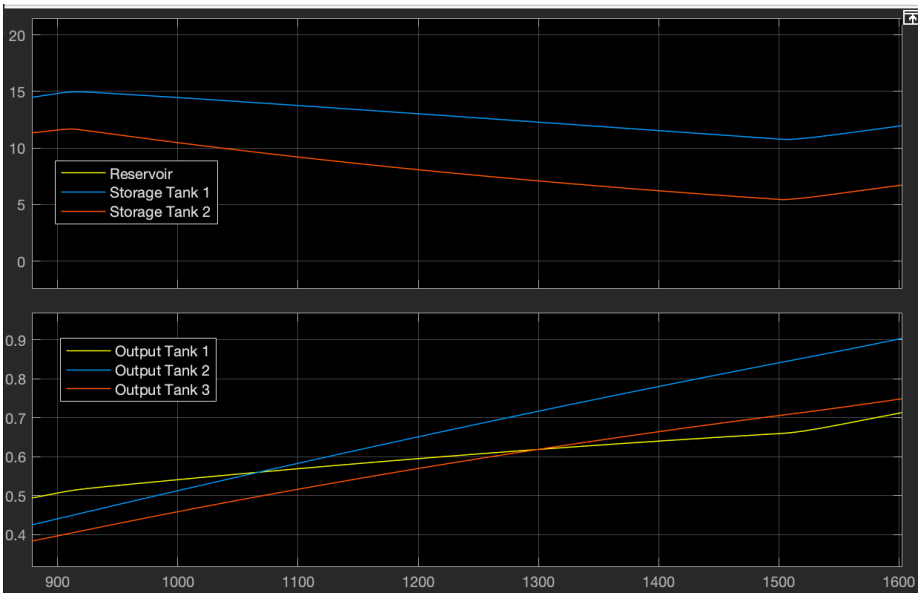

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3


Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

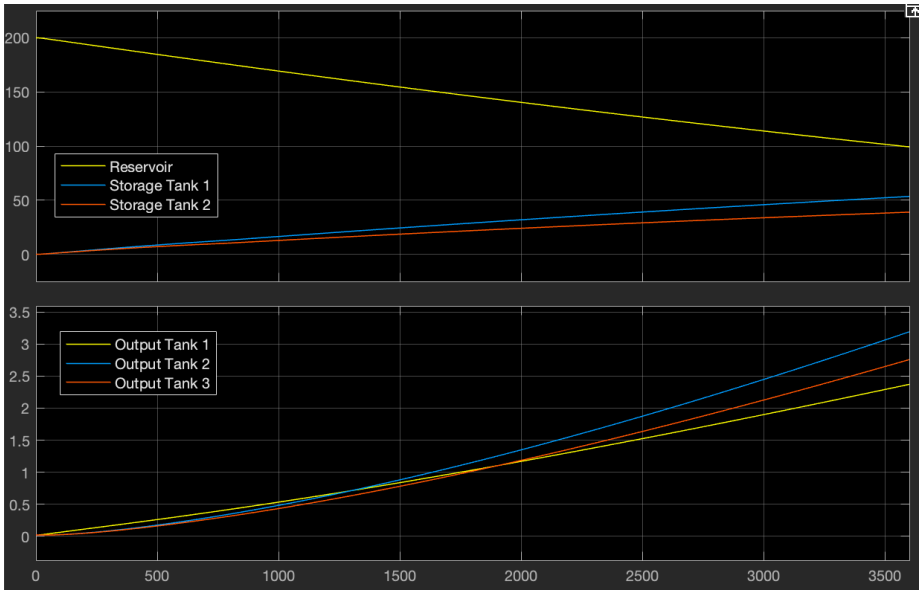
22:00

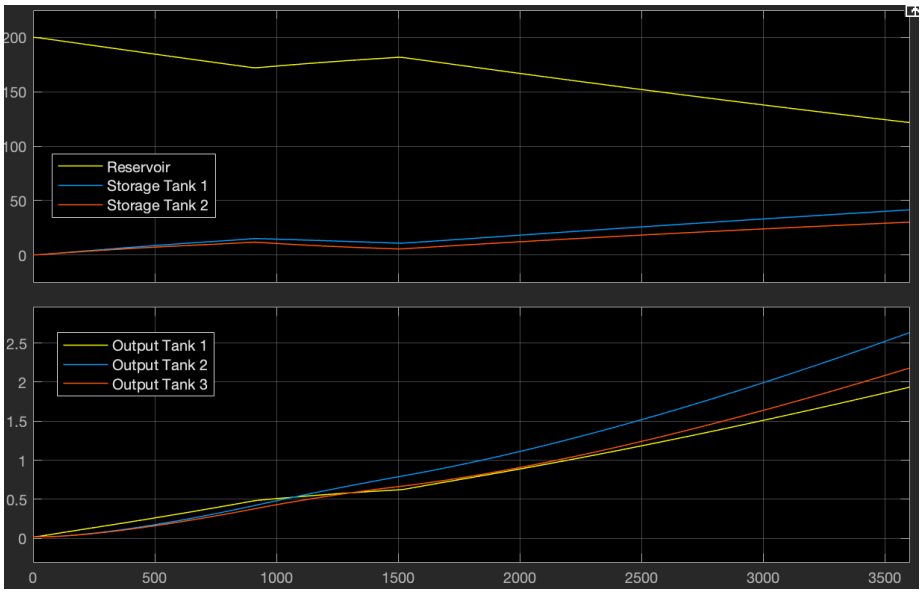

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

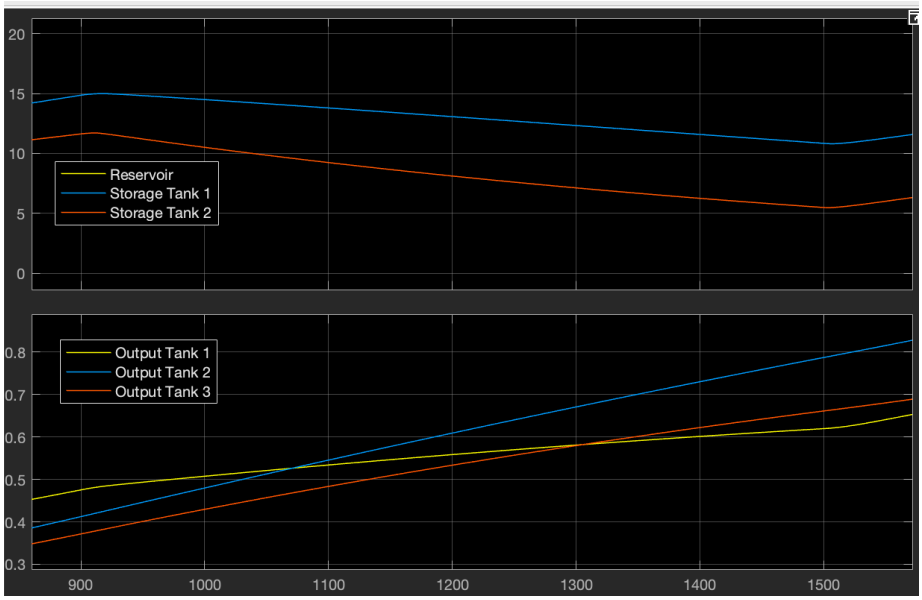

Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3


Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

23:00


Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3


Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3


Reservoir
Storage Tank 1
Storage Tank 2
Output Tank 1
Output Tank 2
Output Tank 3

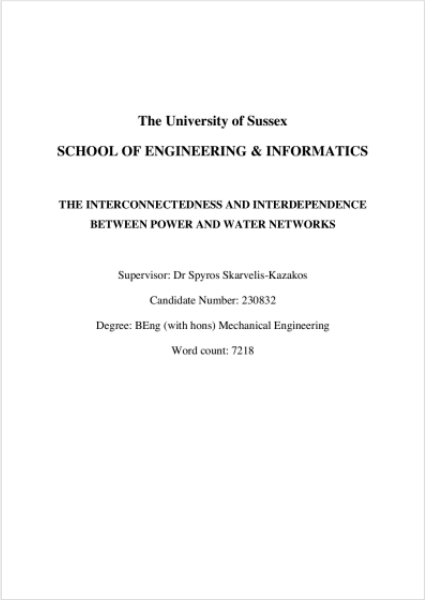
turnitin

Digital Receipt

This receipt acknowledges that Turnitin received your paper. Below you will find the receipt information regarding your submission.

The first page of your submissions is displayed below.

Submission author:	Candidate No : 230832
Assignment title:	Submit a draft file here for checking (1 of 5)
Submission title:	230832 Final Draft
File name:	230832_Final_Dissertation.docx
File size:	9.43M
Page count:	61
Word count:	8,277
Character count:	44,535
Submission date:	16-May-2023 12:12PM (UTC+0100)
Submission ID:	206426302



The University of Sussex

SCHOOL OF ENGINEERING & INFORMATICS

THE INTERCONNECTEDNESS AND INTERDEPENDENCE BETWEEN POWER AND WATER NETWORKS

Supervisor: Dr Spyros Skarvelis-Kazakos

Candidate Number: 230832

Degree: BEng (with hons) Mechanical Engineering

Word count: 7218

Copyright 2023 Turnitin. All rights reserved.

Paper Title	Uploaded	Grade	Similarity
230832 Final Draft	16 May 2023 12:12 BST	--	8%