# SIMULATION AND ASSESSMENT OF A WIRELESS BINARY WATER PUMPING SYSTEM FOR CONSERVING WATER IN RESIDENTIAL BUILDINGS AND PUBLIC PLACES

BY

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To my beloved parents, sisters and brothers

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| | | |
|---|---|---|
| **CPS** | : | Cyber Physical Systems |
| **WSN** | : | Wireless Sensor Network |
| **WDN** | : | Water Distribution Network |
| **FFPS** | : | Fixed Flow Pumping Systems |
| **VPS** | : | Variable Pumping Systems |
| **VFD** | : | Variable Frequency Drive |
| **TFCS** | : | Total Flow Control System |
| **IPWPS** | : | Identical Pumps Water Pumping System |
| **WBWPS** | : | Wireless Binary Water Pumping System |

# ABSTRACT

Full Name : MOHAMMED MUSTAFA QADRI

Thesis Title : SIMULATION AND ASSESSMENT OF A WIRELESS BINARY WATER PUMPING SYSTEM FOR CONSERVING WATER IN RESIDENTIAL BUILDINGS AND PUBLIC PLACES

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Water is the most valuable natural resource after air. The growing demand is forcing fresh water supplies beyond their natural replenishment rates. Leveraging the advancements in technology and utilizing of smart systems can do significant savings by managing water consumption in the demand side. One of such venues is to match the supply of water to the demands that vary over time. This is achieved by varying the supply of water according to the number of active users on the network. In this thesis, we propose a novel water pumping system that employs wireless and sensor technologies. The proposed combination of wireless and sensing technologies with mechanical systems is energy efficient as well as it saves water by serving it to the users at a consistent and comfortable flow rate. The new system is appropriate for residential, commercial and public buildings. It replaces, the customary single pump by a set of pumps having a binary sequence (1, 2, 4, 8 …) of pumping capacity. This approach facilitates having several levels of output that accommodates variable demands. Additionally, the concept of variable speed pumps for adaptive water pumping based upon user requirements in smart homes is introduced in this thesis. In order to meet the above objectives, simulation models of the newly proposed systems are developed using Matlab. These models are used to assess the operation of the systems as well as the quality of their services. Various simulations replicating real life scenarios are done. The obtained results are analyzed and compared with those obtained by simulating conventional systems such as the single pump and a set of identical pumps. The results show that the proposed systems not only provides significant water and energy savings but also offers an enhanced quality of service to the users. For example, in realistic scenarios of 2.5 and 4.5 average active users in the system, we have observed savings of 50-60% in water and 65-75% in energy.

# ملخص الرسالة

**الاسم الكامل** : محمد مصطفى قادري

**عنوان الرسالة** : محاكاة وتقييم نظام ضخ مياه ثنائي ولاسلكي للحفاظ على المياه في المباني السكنية والأماكن العامة

**التخصص** : هندسة الحاسب الآلي

**تاريخ الدرجة العلمية** : مايو ٢٠١٦

الماء هو المورد الطبيعي الأكثر قيمة بعد الهواء. الطلب المتزايد على المياه اكثر بكثير مما هو متوفر. يمكن الاستفادة من التقدم في التكنولوجيا والاستفادة من الأنظمة الذكية في إدارة استهلاك المياه في جهة المستهلك. ويتم ذلك من خلال التأكد من أن امدادات المياه تتناسب مع الطلب ومن أن المياه تُضخ بمعدل تدفق ثابت ومريح. بالإمكان تحقيق هذه الأهداف من خلال استخدة تقنيات الإستشعار والإتصالات اللاسلكية الحديثة. يعمل النظام المُقترح على أساس تجميع البيانات من جهة المستخدم ومعالجتها ومن ثم أخذ قرارات مناسبة للتحكم في مكائن ضخ المياه مما يزيد في عمرها ويقلل من استهلاك الطاقة. لاحظنا في تجارب المحاكاة التي قمنا بها بأننا نستطيع توفير ما يقرب من ٥٠ - ٦٠ ٪ من المياه و ٦٥ - ٧٥٪ من الطاقة

# CHAPTER 1

# INTRODUCTION

Water is a vital necessity for all living beings and it plays a vital role in maintaining the eco-system of the Earth. Many imperative practices like agriculture, industrial production process and energy production require water as a major input. Water plays a crucial role in sustainable environment management. Due to the rise in the population, increasing usage and wastage of water, water resources are forced beyond their natural replenishment rates. All these factors necessitate us to look for technologies to conserve water which helps in multitude of other problems like water availability, sustainability and pollution reduction. Examples of such technologies include: wireless and sensing technologies and cyber physical systems (CPS). CPS integrates processors, sensors and actuators to affect physical systems like water supply systems [1].

## 1.1 Importance of water conservation in the Gulf region

Saudi Arabia is a country that occupies about 85% of the GCC countries area. It has no permanent fresh water resources such as rivers or lakes and most of its area is covered with desert due to which it receives very low rainfall. A considerable part of the clean water needs in the kingdom is covered by desalinated water [2]. The shortage of clean water is one of the main challenges being faced by the people of kingdom. With the rapid growth in the country's population by 43% in past two decade, there is a rapid increase in demand for clean water simultaneously there is also a significant increase in water wastage in residential buildings and public restrooms. It was mentioned by [3] that Gulf countries are facing serious water scarcity problem and mismanagement of water distribution is one of the reason for this. Even though the countries have invested heavily for water resource management, management of water resources and distribution is not efficient. Excess consumption of water is also a major problem in Gulf countries. It was also mentioned by [3] that UAE and Saudi Arabia use respectively 550 and 250 liters per capita while UK and Germany use only 150 and 127 liters of water per capita. This situation necessitates the utilization of smart technology like WSN and cyber physical systems for improving water conservation in public places and residential buildings.

## 1.2 Cyber Physical Systems for Water Conservation

Cyber Physical Systems was defined in [4] as a new generation of systems with integrated computational and physical capabilities that can interact with humans through many new modalities. The ability to interact with, and expand the capabilities of, the physical world through computation, communication, and control is a key enabler for future technology developments.

Cyber Physical Systems have embedded computing features and communication capabilities. These features of CPS enable them to streamline and manage operation of a physical system. Intelligent physical infrastructures are the most important CPSs which use computing application to have “anytime, anywhere” operation at ease and efficiency. CPS in operating physical infrastructures improves the utilization of the resources, the impact of usage can be assesses and in fact, employing CPS will make us realize the less reliability of the present systems without CPS [5].

It was described by [5] that Water Distribution System (WDS) is an emerging field in CPS. The physical components in water distribution system like valves, dams, tanks, pipelines etc. are integrated with specialized hardware, sensors and energy sources and software to enable efficient water distribution.

CPS and wireless sensor networking can be put to use to distribute safe water to public. For a reliable water distribution system, data like water demand, water usage pattern, quantity requirements, water flow and pressure, water quality parameters are important. This information is critical for making decisions; identifying susceptible areas which need to be concentrated or remedial measures have to be implemented. Sensors which are placed in the physical systems gather the information and send them to the cyber computation system which has complex algorithms. These algorithms will support the decision making authorities to manage the water quantity, scheduling of distribution and check the quality of water [5].

## 1.3 Wireless Sensor Networks for Water Management

Wireless sensor network technology is the latest advancement which has been put to use in water management. Advancements in sensor, wireless communication and embedded technology can be utilized to have efficient water management systems in public water delivery systems. Real-time monitoring of water pipeline network is one of the major applications of Wireless Sensor Network [6]. WSN technology will help in overcoming the challenges in wired communication technology. The WSN system can be adopted at field level and used for constant monitoring of functioning of water delivery system without intervention of human beings.

WSN technology is being put to use in precision agriculture and in automatically irrigating the fields. Irrigation management system in rural areas of Malawi used WSN networking for intelligent irrigation system. Rural areas of Malawi faced severe crunch for water for irrigation purposes. They implemented a system which included WSN, power source using solar devices. The irrigation vales were activated automatically using ZigBee protocol. The system has soil moisture detecting sensors. Data from these sensors were used by the WSN and this information was used to close or open the irrigation pipeline vales [7]. An intelligent reusable, energy efficient WSN sensor based water quality monitoring system integrated with an online portal and sleep scheduling system with the help of sensor nodes was designed and proposed by [8].

## 1.4 Simulation Tools for Water Distribution Networks

There are several water simulation tools such as EPANET [9], PIPEFLOW [10] and SimHydraulics tool of Simulink [11] in the market that will help in the simulation of WDN. The hydraulic simulation tools have become powerful decision making-tools enabling the engineers and the scientist to analyze and manage the WDN with efficiency and accuracy. In this work, we will use SimHydraulics simulation tool of Simulink to simulate the proposed systems. Simulink is an environment that can be used to design simulation models of multiple domains. It supports simulation, automatic code generation, system-level design and continuous test and verification of embedded systems. This software provides actual physical components such as pumps, valves, pipes, tanks and other components to simulate WDN. It helps in predicting the water behavior, calculating flows, pressures and heads, tank water levels.

## 1.5 Problem Statement

Regardless of the technological growth in water purification, water usage control is still very primitive. This causes significant wastage due to the inconvenient adjustment of flow rate. From quotidian life familiarities, it is evident that the users have different water usage habits. They use water according to their habit which leads to a lot of water wastage. For instance, due to the use of manual control taps in the current systems, a user may forget to turn off a tap and leave it in the open state for the whole time even if he is not using the water. There are times during which users do not use water, like when they are applying soap, shaving or adjusting the clothes.

To discuss a scenario, let us consider the activity of washing the face which is a simple day to day activity in the life of every human being. During this simple activity, the user carries out many operations like opening the tap, applying water on his face, going for soap, applying soap, cleaning the face with water and finally closing the tap. We cannot deny the fact that in this simple activity, few operations such as going for soap and applying it does not require water. However, the user still leaves the water tap wide open for the whole time of the activity. This simple activity shows that during half of the activity time, the water is wasted by the user. If this simple activity is carried out by significant number of users, it will lead to significant amount of water wastage.

An investigation of the practices used during the installation of pumps has lead us to the inference that oversizing the pump relative to the actual user demand looks like the best possible solution to supply water. However, this is not the case. In fact this approach causes an additional overhead in terms of water and energy wastage because the bigger the pump the more the wastage. Similarly, what happens if an even smaller pump is chosen? In this case the users will suffer from a loss in the quality of service delivered because the pump is not capable of supporting the maximum number of users. Now, one might argue that a smaller pump can be chosen to exactly match the maximum user demand. But, there will also be water wastage if the number of users is less than the maximum.

Also, from our day to day experiences, it is evident that in the conventional pumping systems, the pump is always in the ON state regardless of the fact whether there are users consuming water or not. This is done to facilitate the supply of water considering the possibility of a user who uses water at any particular instance. This might seem to be the most convenient approach to provide the users with a high quality of service in terms of availability. The pump however, is in the ON state all the time and it thus incurs an additional expense in terms of energy (i.e., power consumed by the pump).

It is very important to stop water and energy wastage during the consumption of water. Trying to tackle all these problems using a fixed flow pumping systems is impossible. Technological advancements such as CPSs and wireless sensor networks need to be leveraged to tackle this issue and to match the water pumping to the dynamically changing user demands.

## 1.6 Need for Computerization

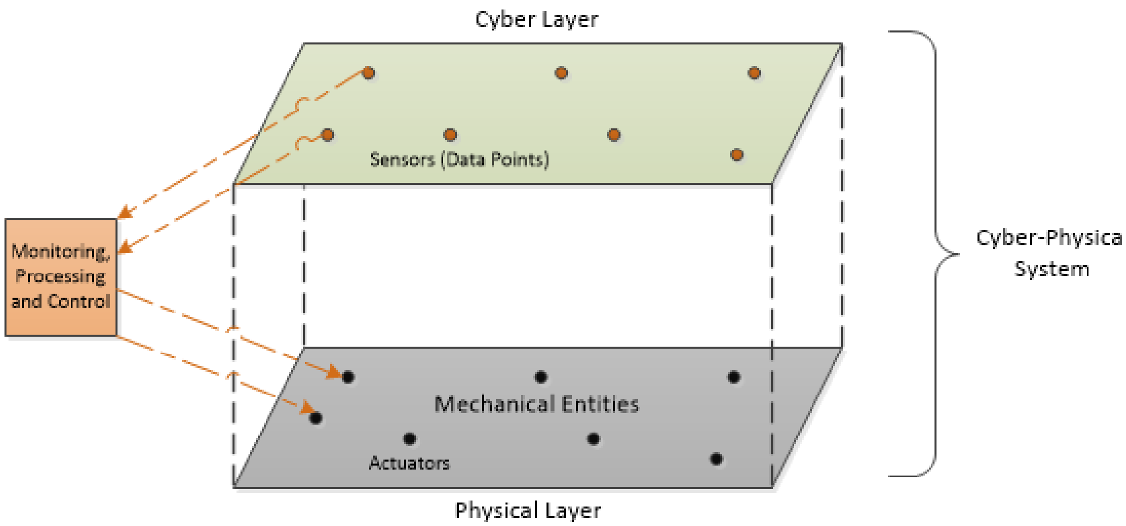


**Figure 1-1 High-Level Representation of Proposed System**

The proposed systems, which provide adaptive pumping, can be described as CPSs which tackle the above stated problems of mechanical tap wastage and fixed pumping. Figure 1-1 shows a high-level representation of the systems. In this figure, the physical layer contains the mechanical entities such as taps, valves and pumps and the cyber consists of sensors such as proximity sensors, flow rate sensors and pressure sensors. These sensors act as data points in the system. They generate data which can be used for controlling the mechanical elements in the physical layer. By controlling the behavior of the elements in the physical layer, the system can be operated in an optimal way.

It should be pointed out that if only the mechanical system used, we cannot obtain the information about the current operational behavior of the system to perform control. For instance, the basic requirement for adaptive pumping is to find out the required flow rate for every instance of time. The required flow rate cannot be determined with just a mechanical tap, because it does not have the capability to gather information pertaining to the user activity. A tap equipped with a proximity sensor is conservatively used for local control to open and close the tap based upon user activity. But, the functionality of such proximity sensors (data points) can be further extended to find out how many aggregated active users are there in the system. Then, based upon this information, the required flow rate can be computed and then utilized for control of efficient adaptive pumping. Therefore, based upon the data collected from the proximity sensors, an additional functionality of global control can be added to the system. Even if we consider the pressure sensor at the pumps, there are limitations like we cannot accurately estimate the exact number of users. For instance, if two users open the taps at the exact same instance of time the pressure sensor will mistake this for just a single user. This control and actuation can be only done if a cyber layer is present to gather the information, process it and perform actuation; hence the need for computerization in adaptive pumping. Since the information gathered from the proximity sensors is used for the purpose of actuation, it is reasonable to say that any change in the proximity sensor data will cause a system behavioral change. The presence of the cyber-layer ensures regulating the correct system behavior and will help in prolonging the lifetime of the system.

## 1.7 Our Approach and Objectives

This thesis proposes adaptive pumping systems, which can be used for water conservation in homes and public places. The customary way to implement a variable pumping system is to use a combination of identical pumps in order to vary the supply. The proposed Wireless Binary Water Pumping System (WBWPS) is a water-conserving, energy-efficient system that matches the supplied water flow to the demand. Adaptive pumping is one convenient solution that will overcome the issues related to fixed flow pumping systems (i.e., conventional pumping systems).

Adaptive pumping, when compared to fixed flow pumping, requires the design of the cyber layer and how it should be interfaced with the physical layer. This is due to the fact that matching the supply flow to the demand cannot be achieved until we have data points in the system to gather information about the current state of the system. And based upon the information gathered we perform some actuation so as to make the system behave in a desired way.

This is a multidisciplinary work in which the design, and working of the WBWPS has been proposed. Also, the design, control and implementation of a water supply system using a Variable Frequency Drive (VFD) for a smart home are illustrated. The different systems are studied under the same conditions and compared to the conventional water supply systems.

The proposed system is expected to save a considerable amount of water when deployed in real environments such as airports, railway stations, hotels and residential buildings. They improve the quality of service by providing water at a more consistent flow rate. A layer of smart sensors will be installed on top of the physical system to provide feedback and control. In the proposed system, the physical system is integrated with a control system and wireless sensor network. It uses proximity sensors, a flow rate sensor and a pressure sensor to control the pumping of water. Controllers have been designed to calculate the optimal flow rate based upon active users in a system. The calculations are based upon readings available from the proximity sensors and flow sensors. The controllers also control the operation of the pumps to release the desired total flow into the serving pipeline.

A VFD equipped pump can change its speed as per the user requirements, for the purpose of adaptive pumping in smart homes. The speed of the pump is changed based upon the information collected from the flow rate and user input. Also, the customary alternative for variable pumping has been implemented using a combination of identical pumps. The systems have been simulated using the physical modeling tools provided by MATLAB [11].

In this thesis, we plan to achieve the following objectives:

- Develop a new system for water conservation in homes and public places by extending the idea mentioned in [39]. In [39], the idea of binary pumps is explained in brief, without any details on the computer control aspects so as to obtain the desired behavior. The idea has been extended to include the controllers and sensor. In this thesis we extend the original idea by approaching the problem from a CPS perspective. This requires designing the cyber layer and its interfacing with the physical layer (Binary pumps and water distribution network). Designing the cyber layer involves selecting the data points and collecting the information from these data points so as to achieve adaptive pumping.

- VFD has not been used for adaptive water pumping in smart homes. We in this thesis introduce the concept of VFD in smart homes to achieve adaptive pumping based upon user requirements.
- Estimate the number of users present in the water distribution network based on monitoring the change in pressure in the main pipeline. This will help in eliminating the proximity sensor and thus reduce the implementation cost. This user counter has been used in conjunction to the VFD approach for adaptive pumping. The proximity sensors are eliminated and just a pressure sensor is used, thereby reducing the cost of implementation.
- Develop simulation models for the above two systems and the existing conventional systems using Mathwork's SimHydraulics simulation tool to estimate quantities like water and energy saving. This will enable us to compare the performance of the newly proposed systems to that of the existing ones.

## 1.8 Thesis Outline

The rest of the thesis is organized as follows. Next, a detailed literature review is provided. Then, Chapter 3 provides detailed information about the system design. The experimental setup is discussed in Chapter 4. The simulation models are discussed in the Chapter 5. After that Chapter 6 describes the results obtained from the simulation. Finally, conclusions and future work are given in Chapter 7.

# CHAPTER 2

# LITERATURE REVIEW

Water conservation and efficient water management have received a lot of attention nowadays. A lot of effort is put into developing smart systems which can better utilize the existing water resources. This section is divided into three subsections. In the first subsection, we present the current works in which the researchers have used Cyber Physical Systems to solve the problems related to water management. In the second subsection, we present the current works in which the researchers have used Wireless Sensor Networks to solve the problems related to efficient water administration and pipeline management. In the last subsection, we gauge the simulation tools which are required for the accomplishment of the proposed work.

## 2.1 Water Cyber Physical Systems

CPS is explained as a smart networked systems with embedded sensors, processors and actuators that are designed to sense and interact with the physical world (including the human users), and support real-time, guaranteed performance in safety-critical applications.

The authors in [1] explained the CPS systems as an integrated behavior of cyber and physical element of a system and it will include computing which will be able to handle complex algorithms, sensing and networking. The components of the CPS will work in tandem with each other to provide safe and reliable water system. It was stated by the authors that CPS can be used for water sustainability [1]. The authors highlighted that CPS can be used for

- Water Quality monitoring of distribution system
- CPS can help public water distribution system to handle emergency situations

Water quality monitoring has become a necessity as pollution is a persistent problem. CPS plays an important role in this area. Water CPS can help us monitor the quality of water at various locations constantly and raise alarm if any contamination happens. The use of Water CPS has not only increased the quality of water distributed for the public but also prevented contaminations. Huge technical advancements in sensors, networking communications, wireless technology, algorithms, computing technologies, threshold parameter monitoring devices and batteries have enables technicians to remotely monitor and evaluated the water distribution system [12]. Two important water monitoring systems mentioned by the authors are Source water quality monitoring and aquatic ecosystem health monitoring.

Water distribution system is vulnerable to leakages, oil spills; biological, chemical, radiological pollution etc., Computing and Hydrodynamic simulation modeling can generate forecast data about the hotspots of leakages, emergencies and pollutions. Computing with complex algorithm can keep track of various parameters and predict emergencies and help authorities to plan to tackle a disaster and take efficient measures.

**Application of CPS for Water Sustainability**

CPS is being used to maintain water sustainability. The water system must be reliable and safe. So it requires automatic real-time monitoring of the water pipelines.

CPS for water distribution system can enable the system to adapt to the environmental factors, prevent pollution and alert failures like leakages. CPS can also enable the water system to repair itself automatically, configure and constantly enable real-time monitoring and ensure there is no wastage due to leakage and prevent pollution of water [13].

Application of water CPS has enhanced the efficiency of the distribution system, provide safe and reliable water to the public and give secured water distribution system. So it can be attributed that CPS can provide sustainable water system. Water distribution system in this current trend needs to gather real-time water quality information, sense the leakage and pollution and have robust networking and communication system and an intelligent computing system which can analyze, monitor and communicate the real-time happenings in the pipeline distribution [14].

**Cyber Physical System and Water Distribution system (WDN)**

Water distribution networks are the trending technology in Cyber physical systems. The physical components of the water distribution system are integrated with the hardware and software which comprises cyber physical system to develop intelligent water distribution [5]. The authors have also mentioned that the aim of WDNs must be to provide reliable and safe drinking water to the people. The WDN system will require many details like water quality, quantity needed and the possible failures of the pipeline, possible contaminations of the water system. These information will help the WDNs will help the administration authorities to attain the main goal of delivering good water to people, maintain the pipeline network, and predict possible locations which may face failures like leakages and WDNs will use these information to take up corrective measures. WDNs will include Cyber physical systems will make use of sensors, collect the threshold parameters, communicate the information to the base station and the computing system will use complex algorithm to analyze the threshold information. The algorithms will be used by the computing component of the Cyber Physical System. The algorithm will give effective decision support system by calculating the quality of water like chemical components and biological components and quantity of water to be allocated. The authors depict a model intelligent water distribution system using CPS and conclude that WDNs in a large distribution system will be more complex [5].

Water Distribution System’s main object must be to provide safe water and also able to locate the leakage or pollution or blockages in the water distribution pipeline system. WDNs will constantly monitor the distribution system and prompt events which require immediate attention. WDS will include static sensors placed at strategic locations in the pipeline network to monitor. WDNs may be an expensive method for governments but it has become an essential one as providing safe water is important [15] [16]. The mobile sensors in the Water Distribution System will monitor more effectively than the static sensors [17] [18]. WDS capabilities are enhanced by CPS [19]. The author has proposed CPS and WDS and called as CPWDS. The mobile sensors used in the CPWDS will move along with the flow of the water inside the pipelines; these sensors will communicate with the static sensors placed outside the pipeline and send data to those static sensors. There are many kinds of algorithms formulated to find a way to have more efficiency in data communication between sensors and extend their lifetime.

**Source Water Quality Monitoring (SWQM)**

Simple Water Quality Model (SWQM) is designed and formulated based on five processes: organic matter degradation, sedimentation, aeration, nitrification and photosynthesis. Based on these parameters and also based on the amount of dissolved oxygen (O2) and Ammonia (NH3), the Cyber Physical system will consider them as parameters. Based on these parameters, CPS will raise an alarm and the WDN authorities will take up necessary actions [20]. The SWQM will act as a crucial parameter to develop algorithm for advance alter system and emergency management system. As water distribution system is prone to many types of pollution, real-time monitoring is very essential. To facilitate real-time monitoring system, WDN uses water monitoring and warning systems in combination with computing, sensors, networking and communication system like Wireless technology. The WDN uses CPS which can intelligent to identify the valuable information from the vast data gathered and transmitted by the sensors. The gathered data will be used for analysis and decision making process. Water distribution systems use Cyber physical systems to collect and analyze data; help in predicting possible emergencies and warn about failures in the water pipeline network. It was reported by [21] that a Smart Water Quality Monitoring System will be able to identify the modifications in the water quality over a period of time, gather information about existing problems in the water quality, predict the future possibilities of water pollution and use other applications like different types of sensors to assess water quality.

SWQMS will give more preference to Quality Assurance (QA) and Quality control (QC) and this must be considered to be more important with more priority. The

SWQMS will also ensure security to the water system to ensure there is no pollution of the network. The SWRMS must be highly fault proof, highly stable and highly reliable. The CPS will take the parameters of the SWQMS as threshold levels which will be sensed by the sensors and transmitted to the computation facility for further analysis and decision making. QA of SWQMS will ensure safety of water to the end user which is the public and the QC will ensure compatibility of the samples taken from different locations along the pipeline [22]. It was also highlighted that despite technological advances in biological monitors and sensor technologies, water quality monitoring system requires more involvement of micro-sensors and nanotechnologies [23]. It was referred that effective water management has become a main topic of discussion in arid regions [24]. The authors have said that sensors are used in irrigation systems and also in precision agriculture [7]. The authors have mentioned about the use of wireless technology, sensors and computational technology to remotely irrigate the field based on the parameters like soil moisture.

## 2.2 Wireless sensor network to solve problems concerning water

A WSN consists of small, energy constrained sensors, which are used to monitor various events and report back to Base Station (BS). There is a growing body of work done in the field of WSNs to conserve water. The evolution of WSNs has led to a cost effective realization to solving such problems. In the recent times many researchers have integrated the WSNs with the Water Distribution Network (WDN) to monitor the water flow, to avoid water leakage and to conserve water in homes and public places. In this section, the current works in which the researchers have used WSNs to solve the problems related to water are presented.

Water conservation programs targeted at large users in the urban areas play an integrated role in reducing the water consumption and wastage. It not only contributes in securing water for individual homes but also in acquiring whole area water supply. According to authors in [25] the water usage can be minimized only when we get a proper knowledge about the water use at a particular site. They suggested that by integrating appropriate water management system with the physical system will give an integrated water conservation scheme that will minimize the wastage of water.

The researchers consider that WSN is one such technology that has emerged over the time in the field of water management system due to recent advancement in sensor, electronics and wireless communication technologies. The authors in [26] presented the challenges faced by the wired based communication system in monitoring the water pipelines. They suggested that WSN technology will overcome the challenges faced by wired communication system. A WSN can be easily deployed in a large field to continuously monitor the events without human intervention. They presented the recent works done in the area of water pipeline monitoring using WSN technology for different scenarios such as underwater, underground and aboveground. Building a smart and efficient WSN for water management system is always a tough task due to many challenges. Some of the challenges are discussed in [27]. According to authors in [27], long network lifetime, network resiliency to natural or manmade disasters and cost of the sensor network are some challenges that are being faced in building WSN for water management system. They suggested some attributes that an ideal WSN should have. The attributes are: multiple levels of QoS, scalable, resilient, fault tolerant and cost effective. To address the above mentioned challenges they proposed a decentralized single-hop architectural framework called AQUA-NET. In this thesis, the proposed water supply system will be designed and simulated considering real time situation. The attributes of an ideal WSN will be assumed. The physical systems proposed in [28], [29], [31] and [32] are a bit close to the proposed work.

Hot water DJ proposed in [28] is a fixture and water flow monitoring system that provides hot water at different temperatures for each fixture based on the requirement. It was designed to save the water heater energy and minimize the energy wastage due to pipe loss. Their proposed system consists of pressure sensors, water flow sensors, hot water tank and a mixer that is installed near to the hot water heater. The mixer is used to mix both hot and cold water running out of the pipes in a proper ratio so that the user receives the water of the desired temperature. The authors conducted experiments in a test home environment for almost six days and compared the performance of the proposed system with the present standard water heater. The results show that they were able to save 10% of water heater energy using the proposed system. The goal is to save water and energy by providing a constant flow rate for large number of users. The integration of the WSN technology and Information Technology (IT) with physical systems has been a major breakthrough in the recent times. This has enabled previously unattainable tasks.

A vibration-based water flow monitoring system was developed and evaluated in [29]. In the earlier work [30], the authors proved the feasibility of vibration sensors in water flow monitoring by deploying and evaluating in a lab setup. In [29], they deployed the system in existing environment and performed a detail study of performance aspects such as sensing sensitivity and stability, model appropriateness and adaptability of system. They also discussed real threats and experiences from the extensive deployment and suggested that estimated water utilization information could provide important information to the users, which will help in saving water. One of the aims of the proposed work is to provide users with in detail information about the consumption of water over a period of time using water flow meters.

B.panindra et al. proposed a Wireless Sensor Network (WSN) based intelligent monitoring system that can be used to monitor the overhead tanks in [31]. The proposed system controls the pumping of water into the water tanks based on the level of water in the tanks. The objective was to detect the scarcity of water and also to control the distribution based on available water source. The system is composed of a WSN coordinator node that monitors overhead tanks and remote nodes that are attached to the overhead tanks. ZigBee wireless communication protocol was used to transmit data from remote node to coordinator nodes. Every overhead tank has one fixed remote node that has a level sensor to measure the level of water, a ZigBee module for communication purpose, a motor pump for pumping water into the tank and a microcontroller that will control the remote node. Proteus Integrated Development Environment was used to simulate the proposed prototype; a three tank model with three level sensors and three motors was simulated to test the proposed monitoring and distribution system. A minimum level of 25% and maximum level of 75% of the capacity of tank was fixed to switch on and switch off the motors respectively to prevent the wastage of water. The system proposed in this paper uses pumps along with variable frequency drives that will control the pump speeds. A wide variety of sensors like water flow sensor, proximity sensor, pressure sensor and temperature sensor have been integrated to make the system efficient.

The authors in [32] designed, simulated and analyzed centralized water mixing systems for water conservation. The proposed smart TFTCS systems and TCS outperform the conventional system and serve users with thermally stabilized water by reducing wasting due to manual control. The results show that automation can significantly reduce water wastage in homes and public places. TFTCS with electronic valves performed better than the TFTCS with two variable speed pumps. Some of the disadvantages associated with the proposed systems are as follows. The proposed TFTCS with VFD uses the variable frequency drives which are costly when compared to pumps. Also using VFD reduces the lifespan due to operation on multiple frequencies and damages the Pump due to operation of pumps at very high and low speeds. The second approach TFTCS with Electronic Valves uses the electronically controlled valves which are not viable to use in buildings because they are very expensive for common day to day usage.

## 2.3 Simulation Tools

The authors in [33] presented a simulation model for water resource cycle that will help in water resource management as well as water disaster countermeasures. The tool used is GETFLOWS developed by graduate school of engineering, university of Tokyo. One more tool that is popular in WDN is EPANET It can gather data about water quality and quantity of the water thought the water distribution system as reported by US environmental Protection Agency. The authors in [34] used EPANET tool to simulate the water supply network of Hengshanqiao town. Many researchers have also used real time data of WDN into simulation model to analyze the behavior of the physical system. In [35] order to make real-time simulation of WDN, the real-time data such as flow rate, pressure, head of reservoir and pump information was collected every 15 minutes. This data was sent and received in to WDN using object linking and Embedding for process control communication of Supervisory control and data acquisition system. EPANET [36] was also used along with SWMM simulation software to model initial network charging and roof tanks for intermittent WDN.

Simulink and physical modeling tool SimHydraulics provided by MathWorks [11]. Simulink is an environment that can be used to design simulation models of multiple domains. It supports simulation, automatic code generation, system- level design and continuous test and verification of embedded systems. Simulink provides a user friendly graphical editor, solvers for modeling and simulating dynamic systems and customizable block libraries. It is combined with MATLAB, enabling the users to integrate MATLAB algorithms into models and export the results obtained from simulation to MATLAB for detailed analysis. It contains libraries that help in modeling continuous-time and discrete-time systems. The simulation results can be viewed using scopes and data displays. SimHydraulics is physical modeling software that gives us different ways to simulate and evaluate hydraulic power and control systems in the Simulink environment. It includes models of hydraulic components, such as pumps, valves, pipelines, actuators, and hydraulic resistances. These components can be used to model fuel supply and water supply systems. The models developed in SimHydraulics can be used to develop control systems and test system-level performance. The models can be parameterized using MATLAB variables and expressions.

# CHAPTER 3

# SYSTEM DESIGN

In this chapter, the design and operation of the newly proposed systems are presented. The operation of conventional systems is also described. The advantages and disadvantages of each system will be discussed.

## 3.1 Conventional System

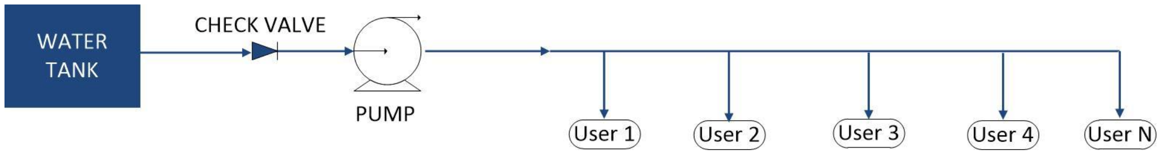


**Figure 3-1 Conventional Systems**

In this section, the design and the operation of the fixed flow pumping system is presented which is very cheap to implement and it requires no micro-controller. The user simply selects the pump of the desired flow rate at the time of installation and leaves it for the remainder of its lifespan. Figure 3-1 gives an overview of the system. It has a single pump that is used to pump the water from the water tank to the users. This water which is at some predefined flow rate, depending upon the selection of the pump, is served to the users who arrive randomly at the taps. In this approach, the users receive water at different flow rates depending upon the number of users in the system but the user has no control to set the flow rate of the water unless a mechanical tap control is provided at the user end. If a mechanical tap is used, the users can manually set the water flow to meet their specific requirements. However, as the pump is operating at a fixed rate, there will be wastage in terms of the power consumed by the pump because the pump is switched ON all the time.

## 3.2 Variable Flow Pumping

An analysis of the practices used during the installation of pumps has lead us to the conclusion that though oversizing the pump relative to the actual user demand might seem to be the best possible fix. It causes an additional overhead in terms of water and energy wastage. This is because the bigger the pumps cause more wastage. Now, one might argue that smaller pumps can be chosen to exactly match the user demand. Yes, it can be done. But, if the pump is selected to match the maximum number of users, then there will be water wastage if there are less than the maximum users in the system. Lastly, what happens if an even smaller pump is chosen? Well, the users will suffer from a loss in the quality of service delivered because the pump is not capable of supporting the maximum number of users.

Also, from the basic understanding of the old-fashioned pumping systems, the pump is in the ON state regardless of the fact whether there are users in the system or not. This is done to facilitate the water supply considering the possibility of a user using water or might use water. Now this might seem to be the most convenient approach to provide the users with a high quality of service (in terms of availability) but the pump being in the ON state all the time incurs an additional expense in terms of power consumed by the pump.

Lastly, from daily life experiences, it is evident that the users leave the tap in the open state for the whole time even if they are not using the water. There are OFF times during the usage where users do not use water, like when they apply soap, shave or adjust the clothes.

It is very important to stop water and energy wastage during the consumption of water. Trying to tackle all these problems using the conventional fixed flow pumping system is impossible. Variable Pumping is the answer to solve these issues. Using variable pumping we can match the pumping to the dynamically changing user demands. To avoid this wastage of water and energy, three Variable Flow Pumping (VFP) techniques are proposed:

- Total Flow Control System with Variable Frequency Drive
- Identical Pumps Water Pumping System (IPWPS)
- Wireless Binary Water Pumping System

## 3.3 Total Flow Control System (TFCS) with VFD

The total flow control system with VFD changes the speed of the pump to match the supply of the pump to the demand. We need to identify the current flow rate and the desired flow rate in the system, to effectively react to the position of the user in the pipeline.

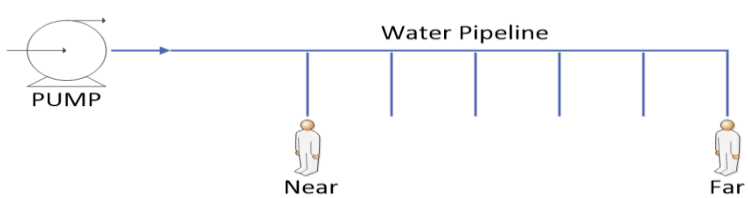


**Figure 3-2 The speed of the pump should be varied in accordance to the location of user because more effort is required by the pumping system to pump the water to a farther distance, overcoming more pipe resistance.n accordance to the location of user.**

It is evident from the Figure 3-2 that depending upon the position of the user the speed of the pump needs to be varied. Without the information about the current flow rate we cannot effectively deliver the required flow rate.

Also, the information pertaining to the current flow rate is vital for the system to react to the different distributions of the same number of user. From Figure 3-3, Distribution 1 will require a lesser speed when compared to Distribution 2. Without a computerized control it becomes very difficult to distinguish between the two scenarios.

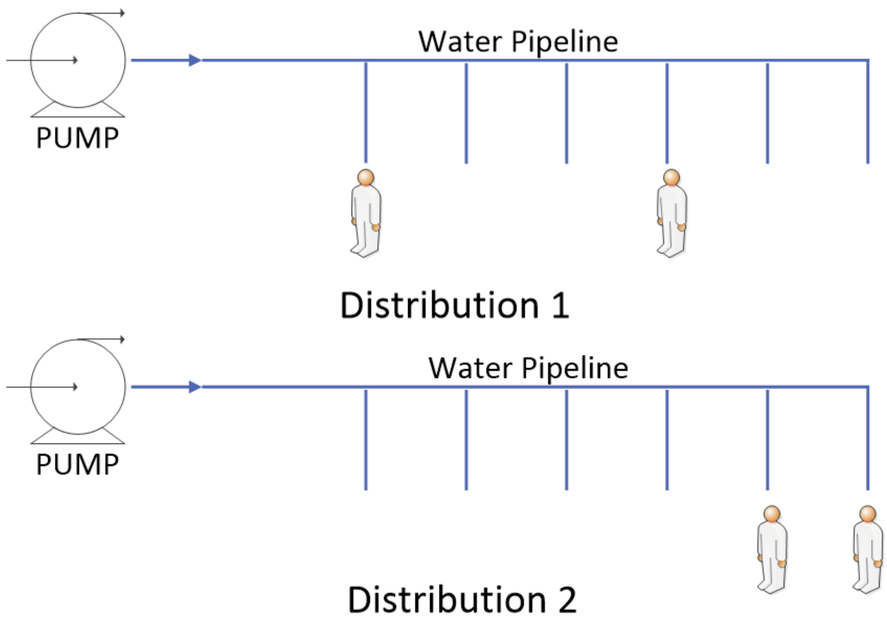


**Figure 3-3 Different distributions of the same number of users. Although there are two users, the speed of pump will be diff in both scenarios.**

The TFCS as shown in Figure 3-4 handles flow rate control along with OFF times at water taps. The system uses proximity sensors to differentiate between OFF time and ON time during the tap usage. The proximity sensor is installed under the tap and only when the user comes close to tap, the water is served. Solenoid valves are installed at each tap and they open only when they receive signal from proximity sensor. This way the water is served only during ON times when user is actually using the water.

In TFCS, the pump is connected to a VFD that controls the speed of pump. The total water demand at taps is calculated based upon the user arrivals. Proximity sensors installed at each tap will help to calculate the total taps open at each point of time. The required flow rate at each tap multiplied by the number of taps open will give the total flow rate. Calculating the required flow rate is done by the Flow Rate Controller (FRC) which sends signal to the variable frequency drives to pump the desired flow rates. By changing the operating speed of the pump to match the water demand, we conserve water and energy. In this system there is a lot of data dissemination from the sensors to the controllers.

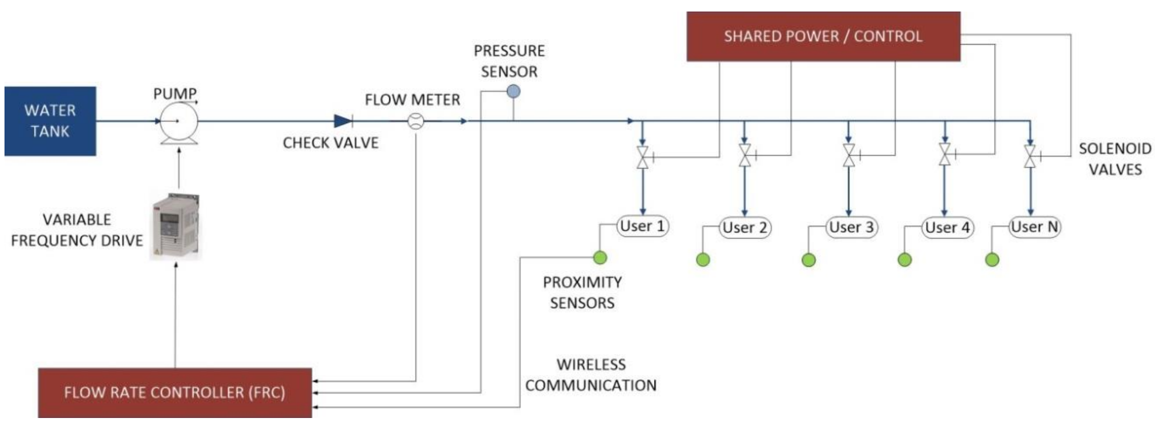


**Figure 3-4 Total flow control system with VFD**

An alternative simple version of the TFCS with VFD has been implemented without the use of proximity sensors (see Figure 3-5). By eliminating the proximity we substantially decrease the cost of implementation. But for monitoring and control purposes we need to find a means to monitor the active number of users in the system. An algorithmic procedure (user counter) that detects the number of users in the system was developed, by processing the information gathered from the pressure sensor placed on the main pipeline. It should be noted that the absolute value of pressure sensor data is not useful by itself to serve this purpose. Rather, the system needs to keep a track of the occurrences of sudden pressure drops and hikes that will aid the estimation of active number of users without the use of proximity sensors.

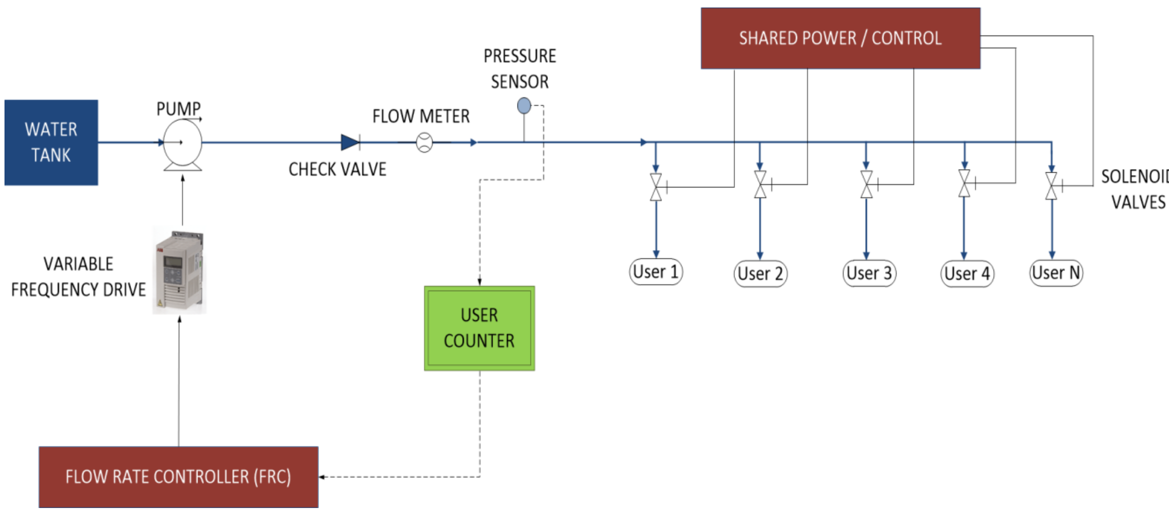


**Figure 3-5 Alternative version of the TFCS with VFD**

## 3.4 Identical Pumps Water Pumping System

In this system, the water distribution network is connected to a combination of identical pumps in parallel. In parallel pumping, more than one smaller circulating pump is installed in a piping system. These pumps are placed parallel with respect to each other. This means that each pump is capable of pumping a portion of the total flow needed at any point in time for an application.

There are several reasons why such an approach of running identical pumps in parallel are considered for comparison with the proposed system. A few of them are [37] [38]:

- Two smaller pumps could be less costly than running one large pump. Because installation often costs less to buy, install, and maintain compared to a single large pump.
- Using parallel pumps to satisfy the demands of a changing flow system.
- Uses less energy

The IPWPS, as shown in Figure 3-6, is our implementation of this approach of using pumps in parallel. We have added the control and sensor network to the combination of identical pumps. The physical system is integrated with a control system and sensor network. IPWPS replaces the VFD and the single pump with a set of smaller identical pumps to control the flow. The check valves are installed to avoid the negative flow of water. The controller tries to operate the identical pumps in parallel so as to deliver the requested flow rate by the system at any point in time.

The proximity sensors, apart from differentiating between OFF time and ON time during the tap usage, also indicate the availability of users by indicating the total taps that are open at each point of time. The required flow rate at each tap multiplied by the number of open taps will give the total flow rate. The flow meters mounted on the pipeline gives the total current flow rate of water in the system. A controller has been designed to calculate the required flow rate based on the proximity sensors readings which are the number of open taps. After calculating the total required flow rate the

Identical Pumps Controller (IPC) intelligently matches water pumped to the user's demand of water. As in this system, there is lot of data dissemination from the sensors to the controller; a sensor network is used to update the IPC controller with the flow rate sensor and proximity sensors data at each point of time

Since the users are dynamically opening and closing taps, the demand of water varies. The IPC matches the current flow rate to the required flow rate by selecting how many pumps to switch ON. By changing the number of operational pumps to match the demand of water we conserve water and energy when compared to the fixed-pump pumping systems.

There drawback to this approach of variable pumping. We cannot exactly match the water pumped to the user demand. The water pumped can be in steps of the pumps selected only. Hence, there will be some amount of water wastage. The detailed working of the designed controller will be discussed in the simulation part.

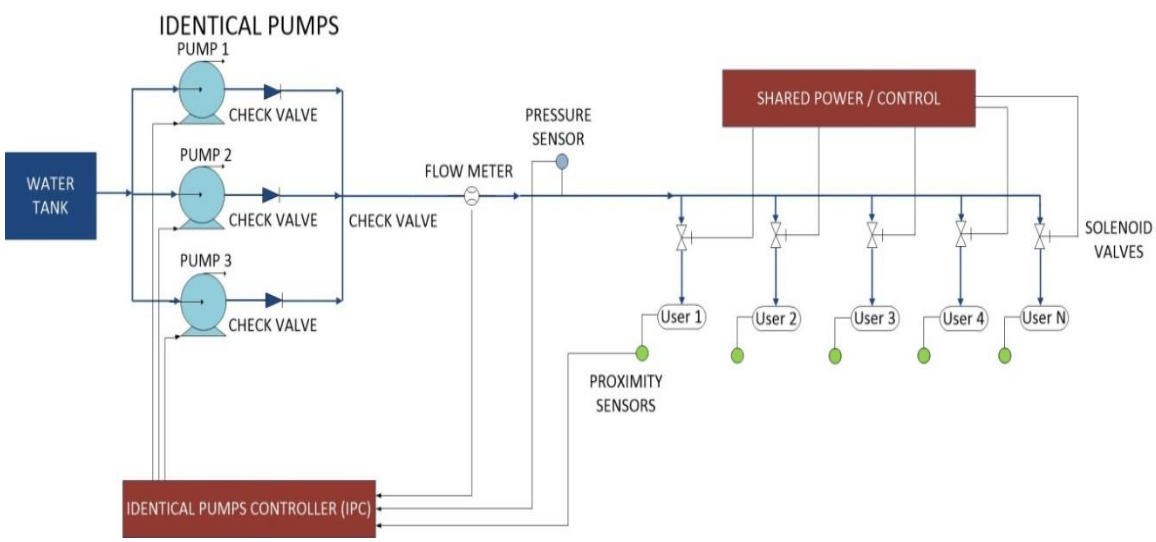


**Figure 3-6 Identical Pumps Water Pumping System**

## 3.5 Wireless Binary Water Pumping System

A CPS can be lucidly understood as a system where the physical process interacts with computational software and hardware. The proposed system is a CPS in which the hardware used is sensors and actuators, wherein the sensors collect data from the physical components and transmit this data in real time to the computational software in order to control the physical components using the actuators.

In order to illustrate the complete design, the proposed system can be explained by dividing them into three sub-systems:

- Physical system,
- Control system and
- Wireless sensor network.

The physical system is the conventional water supply system that comprises water tanks, pipes, pumps, valves and taps. The control system includes the controllers designed to control the pressure of water and the flow rates of water serving the users. The wireless sensor network is the network system, consisting of sensors/ actuators to be mounted on the physical system, which deals transmission of data concerning the underlying physical system. The sensors provide the behavior of the physical system to the control system and also it can be provided to the users via the internet or any local area network.

A disclosure submitted by the patent office to KFUPM [39] states that a binary pump is a novel alternative approach when compared to variable frequency drives.

Binary pump is a collection of pumps whose relative output is the double of the previous pump beginning with the pump with the smallest output as shown in Figure 3-7. The intension of this approach is to generate the desired flow by using the correct combination of pumps and save water. It is also conceivable that the pumps ratios are not factor of two's but are different enough to allow variable pumping by selective on/off of pumps as per demand. This arrangement of motors' combinations also provides energy efficiency in comparison to conventional systems.

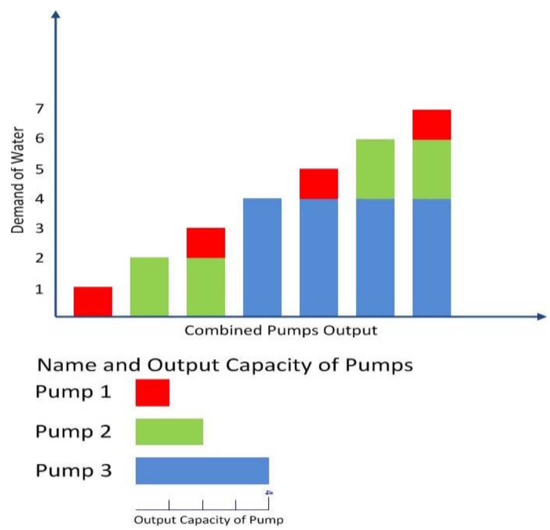


**Figure 3-7 Possible combinations of three binary pumps system**

This system is a novel approach that can be used to substantially reduce water wastage, energy wastage and to provide the users with an optimal quality of service. The Wireless Binary Water Pumping System shown in Figure 3.8 is the physical system designed to conserve water in residential buildings and the multi-user public places such as hotels, airport, railway stations and shopping malls. This system, like the previous system, has a set of pumps, solenoids and sensors such as pressure sensors, proximity sensors and flow rate sensors.

In this system also, the physical system is integrated with control system and wireless sensor network, thereby creating a cyber-physical system. The WBWPS is similar to the IPWPS but it replaces the set of identical pumps with a set of non-identical pumps to accommodate variable pumping. The pumps are chosen in such a fashion such that the pumps in the set of pumps have a binary sequence (1, 2, 4, 8 …) of pumping capacity. The check valves are installed after the individual pumps to avoid the negative flow of water.

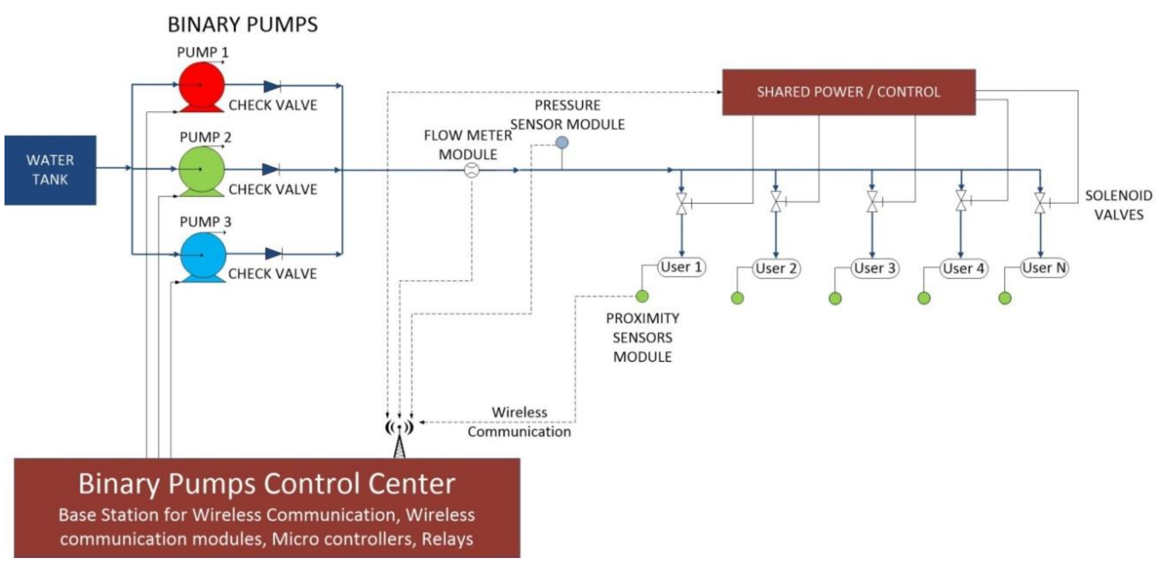


**Figure 3-8 Wireless Binary Water Pumping System**

The water system basically consists of two water pipelines i.e., input pipeline and output pipeline. The water from the water tank goes through the input pipeline to the pumping system. A sensor module in this system consists of a physical sensor, a microcontroller and a wireless communication module. The microcontroller in each of these sensor modules facilitates communication of the readings (collected by the sensors) by leveraging the wireless communication module. The flow rate sensor modules present in the output pipeline detect the flow rate in the system and the proximity sensors stipulate the availability of users. The pressure sensor module helps in understanding the system on the whole. The signals generated by the above mentioned sensors modules will be sent to the Binary Pumps Control Center (BPCC) over a wireless communication medium. The BPCC behaves as the base station for wireless communication. It has various components such as microcontrollers, relays, wireless communication module and antennas to facilitate the communication and processing of the information received from the various sensor modules that exist in this network. The BPCC makes the decision based upon the feedback signals sent by these sensors via the use of the Sensor Nodes. The BPCC decides which pump or combination of pumps to switch ON based upon the number of open taps i.e., active users. The decision made by the BPCC acts as the control signal to the relays and assists in the working of the binary pumps so as to provide water to the users at a constant pressure irrespective of the change in the number of users.

In this work, in order to simplify things we did not simulate a wireless sensor network. We assume getting readings of the input from a WSN to show the proof of concept. Design can happen at different levels. We chose to do it at a high level where we abstracted the underlying physical system. The part of the design is to decide the type of data we need to collect and how the data is fused (processed) at the controller. Then, we determined the actuation needed to operate our system.

There are several advantages of the WBWPS compared to the conventional water pumping systems. Some of them are listed below:

- Water saving by providing water at a stabilized pressure even as the input pressures or the number of users varies
- Improving the quality of service for users by providing more consistent pressure level
- Saving energy by reducing the pumping at higher than necessary rates
- Lower maintenance cost by operating pumps close to their optimal operating range

The previously discussed alternative to this system is the TFCS with the VFD. The electronic components vary the frequency fed to the electric pump to reduce its speed. There is some energy and water savings. But each pump has an optimal operational capacity and its efficiency is degraded if operated at different conditions. Also, one might argue that switching a pump ON/OFF might degrade the pump. But, with the development in pump electronics the effect of the startup current is minimized to almost negligible.

# CHAPTER 4

# EXPERIMENTAL SETUP

In this section the design and the topology of the pipeline system to deliver the water to the users is discussed. The various physical components such as low resistance pipes, t- joints and elbow joins that form the pipeline system are used to create the experimental setup. The specifications of these components are chosen so as to emulate an actual pipeline system with ten users. Also, the specifications of the various pumping systems and pumps specifications in each of the pumping systems in the will be stated.

## 4.1 Pipeline System

The pipeline system, which has been illustrated in Figure 4-1, is divided into two main pipelines which form the backbone of the pipelining system. The branch pipelines provide the water service to the individual users via the use of taps.

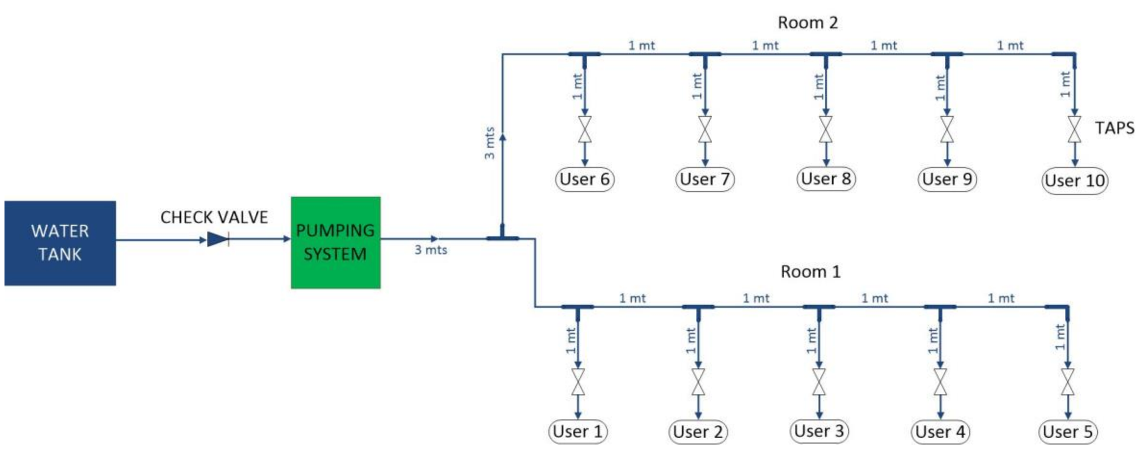


**Figure 4-1 Pipeline Setup for Experiments**

The water is pumped by the various pumping systems mentioned in the previous section into the main pipeline. The main pipeline runs three meters long and has a cross section of three-fourth inch. A t-joint is attached to the main pipeline to split the pipeline into two local circuits to represent two different rooms. This t-joint has a cross section of three-fourth inch for both the main and branch outlets. From the main pipeline the water is served to the individual users via the use of branch t- joints which have a cross section of three-fourth inch for the main outlet and half inch for the branch outlets. The last users in each of the individual circuits are not connected by means of an elbow joint instead of a t-joint. The output of the elbow joint is half inch in cross section. The cross sections of all the low resistive pipes used for the main pipeline is three-fourth inch and the cross section of the low resistive pipes used for branch pipeline to serve the individual users is half inch. The lengths of the pipes to serve water to the two rooms or to each of the individual users are mentioned in Figure 4-1.

## 4.2 Fixed Flow Pumping System

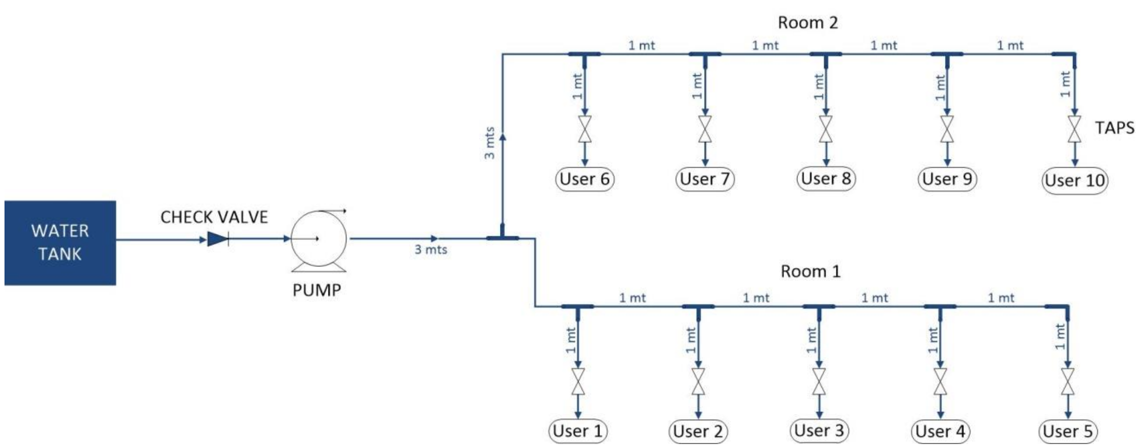


**Figure 4-2 FFPS Experimental Setup**

The pump used in the fixed flow pumping system (conventional) shown in Figure 4-2 is a centrifugal pump which delivers a maximum outflow of 70 liters per minute (lpm) or 18.493 gallons per minute (gpm) and a maximum pressure of 2 Bar or 29 Pound-force per square inch (psi). The power consumption of this pump is calculated to be 0.2345 kWh.

## 4.3 Total Flow Control System using VFD

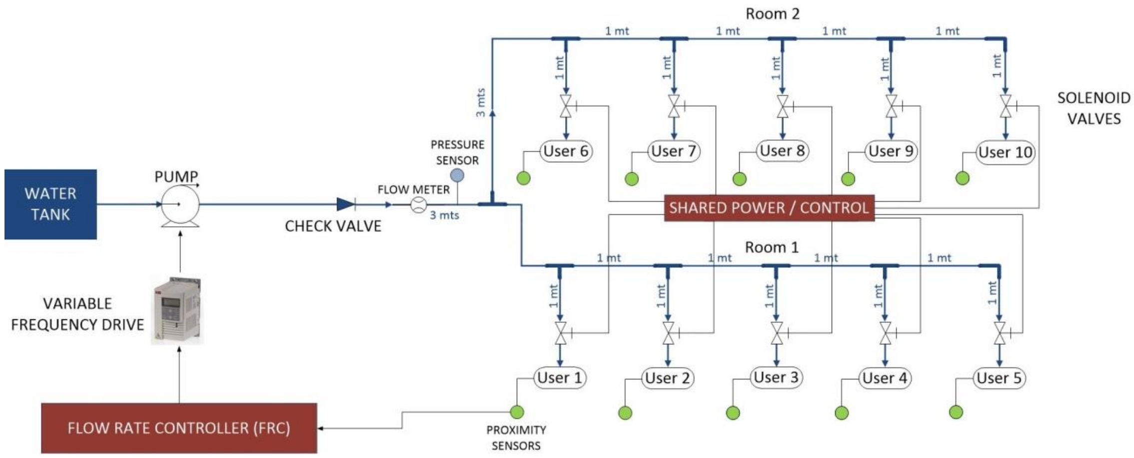


**Figure 4-3 Total Flow Control System using VFD**

The TFCS with VFD shown in Figure 4-3 uses the same centrifugal pump like the previous system which delivers a maximum outflow of 70 liters per minute (lpm) or 18.493 gallons per minute (gpm) and a maximum pressure of 2 Bar or 29 Pound- force per square inch (psi). But, a VFD is used to control the speed (radians per minute) of the pump. Since the speed of the pump varies the power consumption of this pump also varies according to the speed. The power consumption is proportional to the cube of the speed at which the pump is functioning.

## 4.4 Identical Pumps Water Pumping System

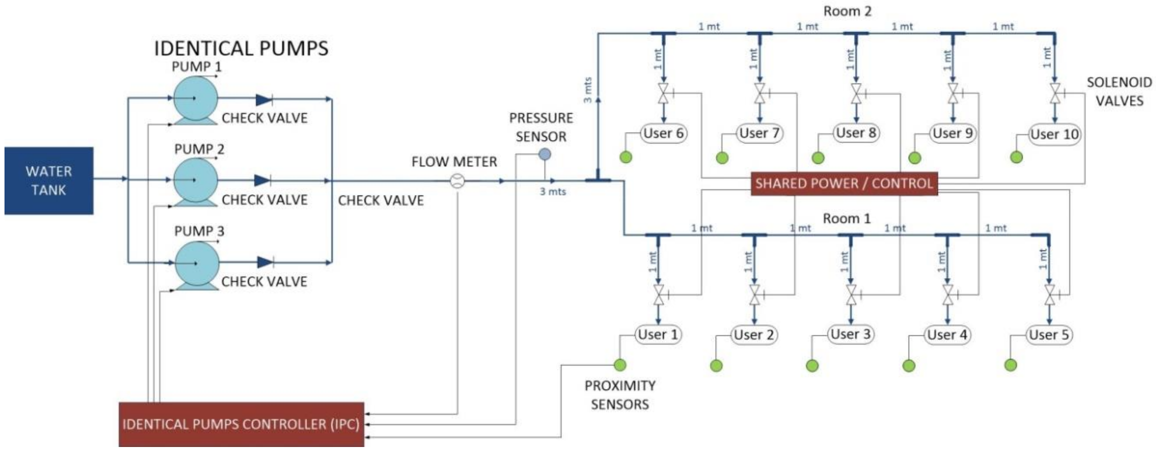


**Figure 4-4 IPWPS Experimental Setup**

The IPWPS experimental setup shown in Figure 4-4 uses a combination of same centrifugal pump like the previous systems but the pumps are smaller in size. Each individual pump delivers a maximum outflow of 25 liters per minute (lpm) or 6.6043gallons per minute (gpm) and a maximum pressure of 2 Bar or 29 Pound- force per square inch (psi). The check valves placed in front of the pumps to avoid the reverse flow have a cross section of ¾ inch. The power consumption of these pumps is calculated to be 0.0781555 kWh each. Also, a combination of 4 pumps has been used wherein the outflow of each individual pump is 18.75 liters per minute (lpm) or 5 gallons per minute (gpm) and a maximum pressure of 2 Bar or 29 Pound- force per square inch (psi). The power consumption of these pumps is calculated to be 0.058625 kWh each.

## 4.5 Wireless Binary Water Pumping System

The WBWPS experimental setup shown in Figure 4-5 uses a combination of centrifugal pump like the previous systems but the pumps different in their output capacities. The first pump delivers a maximum outflow of 11 liters per minute (lpm) or 2.90 gallons per minute (gpm), the second pump delivers a maximum outflow of 22 liters per minute (lpm) or 5.81 gallons per minute (gpm) and the third pump delivers a maximum outflow of 42 liters per minute (lpm) or 11.09 gallons per minute (gpm). The maximum pressure delivered by all of the pumps is 2 Bar or 29 Pound- force per square inch (psi). The check valves placed in front of the pumps to avoid the reverse flow have a cross section of ¾ inch since the pumps are of different capacities. The power consumption of these pumps is calculated to be 0.03685, 0.0737 and 0.1407 kWh respectively.

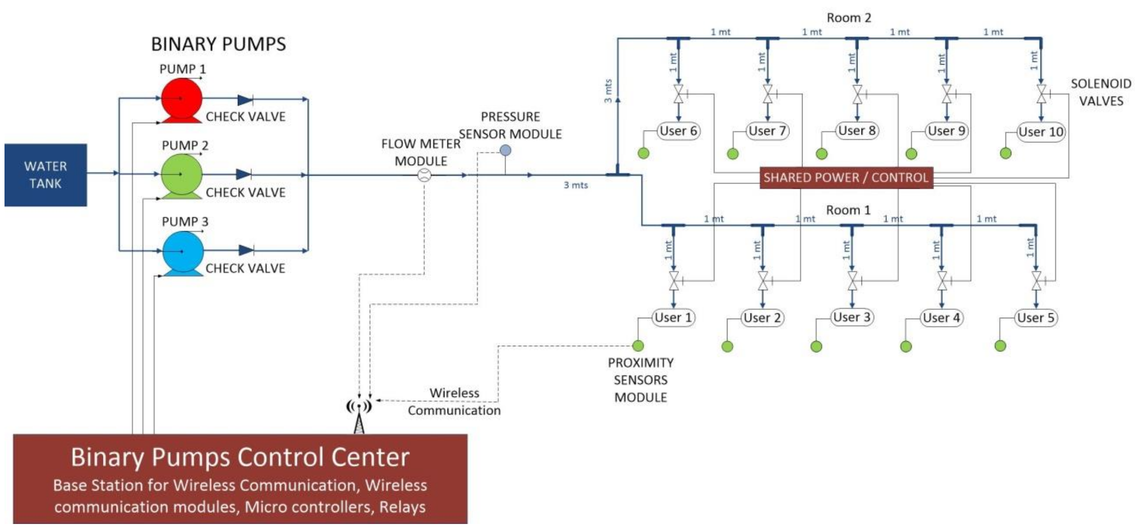


**Figure 4-5 WBWPS Experimental Setup**

Also, a combination of 4 pumps has been tried wherein a smaller pump is added to the above stated combination of three pumps. The outflow of the 4 pumps is 5.5, 11, 22 and 42 liters per minute (lpm) or 1.45, 2.90, 5.81 and 11.09 gallons per minute (gpm) respectively and the maximum pressure delivered by each pump is 2 Bar or 29 Pound-force per square inch (psi). The power consumption of these pumps is calculated to be 0.018425, 0.03685, 0.0737 and 0.1407 kWh respectively.

# CHAPTER 5

# SIMULATION

Physical modeling is a new class of simulation software. It uses “Modelica” a modeling language started in 1997. Wolfram, Mathematica company, only started supporting it in 2011. SimHydraulics has been introduced in Matlab Simulink in 2006. It has been used by a previous MSc student in 2014-2015. The Wolfram System Modeler does not contain all elements needed for this work. This tool does not provide all what we need. For example, customized blocks have to be modeled with an extra effort.

We have also considered PipeFlow but it require a license that is not available in KFUPM. MATLAB is very common in KFUPM and it is easier to obtain support and export data.

As stated previously, the systems designed in the previous section have been implemented using Simulink and physical modeling tool SimHydraulics provided by MathWorks [11]. Simulink is an environment that can be used to design simulation models of multiple domains. It supports simulation, automatic code generation, system level design and continuous test and verification of embedded systems. Simulink provides a user friendly graphical editor, solvers for modeling and simulating dynamic systems and customizable block libraries. It is combined with MATLAB, enabling the users to integrate MATLAB algorithms into models and export the results obtained from simulation to MATLAB for detailed analysis. It contains libraries that help in modeling continuous-time and discrete-time systems. The simulation results can be viewed using scopes and data displays.

A dynamic system is simulated by computing its various states at successive time steps over the simulation time. The information provided by the model of the system is used for the purpose of this computation. A single approach of solving the simulation models does not apply to all the systems. Hence Simulink provides several solvers which are a set of programs. The chosen solvers apply different numerical methods to solve differential equations that represent a particular model.

There are several solvers available in Matlab such as fixed step solvers, variable-step solvers, continuous solvers and discrete solvers. The Ordinary Differential Equation solvers in Matlab solve initial value problems with a variety of properties. The ODE solvers can work on stiff or non-stiff problems, problems with a mass matrix, differential algebraic equations, or fully implicit problems. For the purpose of our simulation we have used ode23t solver which is available in Matlab. This solver can solve differential equations which are pertinent to our simulation.

SimHydraulics is physical modeling software that gives us different ways to simulate and evaluate hydraulic power and control systems in the Simulink environment. It includes models of hydraulic components such as pumps, valves, pipelines, sensors, actuators, and hydraulic resistances. These components can be used to model fuel supply and water supply systems. The models developed in SimHydraulics can be used to develop control systems and test system-level performance. The models can be parameterized using MATLAB variables and expressions.

## Simulation Idea

This simulation will help us to comprehend the working of the proposed systems in a better way. The simulation aims to simulate the various cyber and physical aspects of the proposed systems. Simulating the complete system is done by splitting it into different sub systems. Several simulation models for each of the cases mentioned in the previous chapter have been developed. Firstly, the simulation model for the hydraulic functioning of proposed system is developed by modeling the characteristic behavior of the system. Then, characteristics such as the power consumption of the system were added to the developed simulation model. The sensors and controller sub systems were added, with the intent of providing the behavior of the proposed system. The user activity sub section was added to demonstrate the demand for water in the assumed water distribution network. The aim of the controller subsection is to approximately match the supply of water to the demand to the maximum extent possible. During the simulation, the variable values of flow rates, number of users and total amount of water and energy used will be discovered using Simulink software and MATLAB.

## 5.1 Total Simulation Model Overview

The simulation model of the various systems mentioned in chapter 4 can be represented by Figure 5-1. In order to capture the characteristics of a water usage environment physical modeling has been used. The model has been divided into various sub systems. The Hydraulic Reference system specifies the hydraulic characteristics of the model such as fluid used etc. User activity generator generates the events of users with random predetermined service time associated with each user. The water pumping sub system consists of the various different kinds of pumping systems which correlate to the different systems.

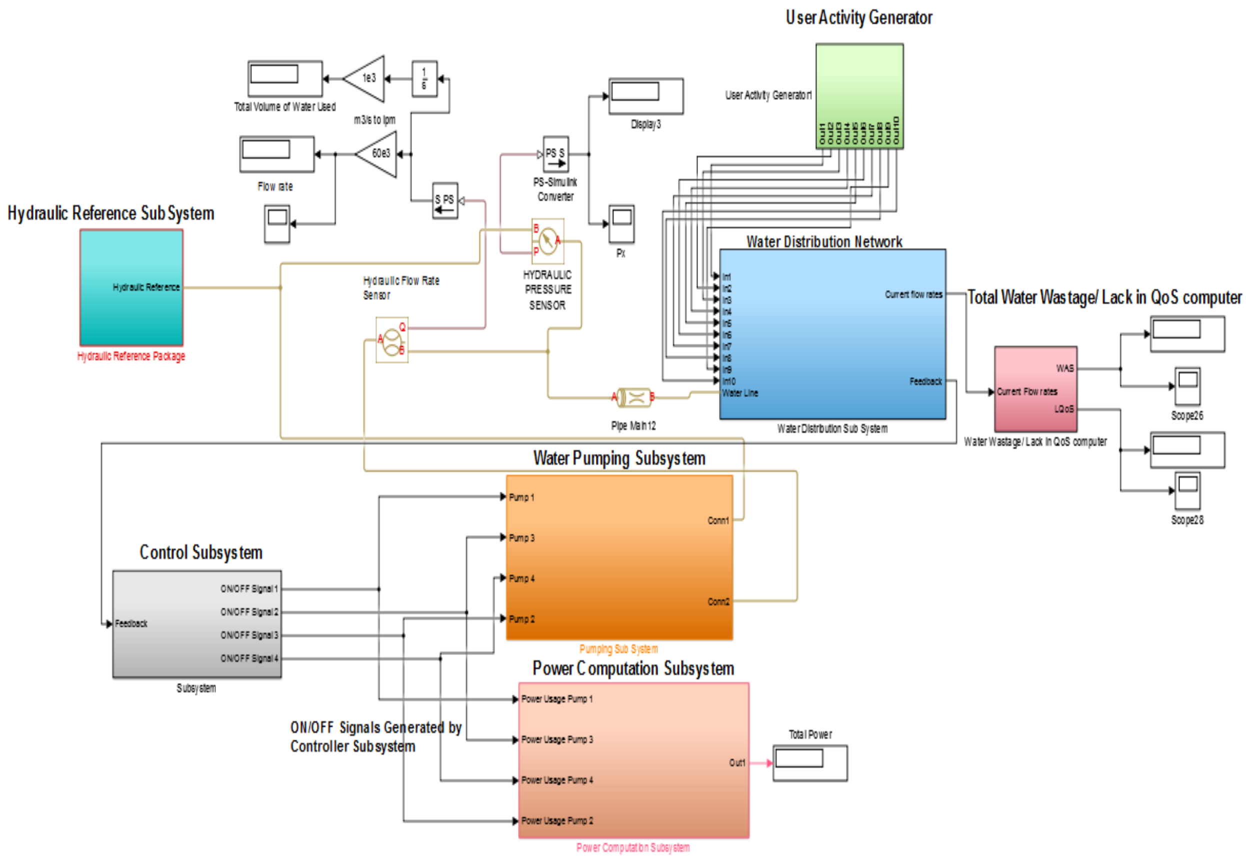


**Figure 5-1 Simulation Model**

The control subsystem based upon the feedback or the number of users present currently in the system determines the optimal functioning of the pumping system. The control subsystem generates the ON/OFF sequence for the pumps in the water pumping subsystem. The power consumption of the pumping system is computed in the Power consumption subsystem. The ON/OFF signals generated by the control subsystem are also used to compute the total power consumption of the pumping system. The water distribution subsystem is used for physical modeling of the pipeline and the tap systems.

The last subsystem which is the Total water wastage/ Lack in QoS computer is used to calculate the deviation of the delivered flow rate from the required flow rate.

## 5.2 Water Distribution Network sub system

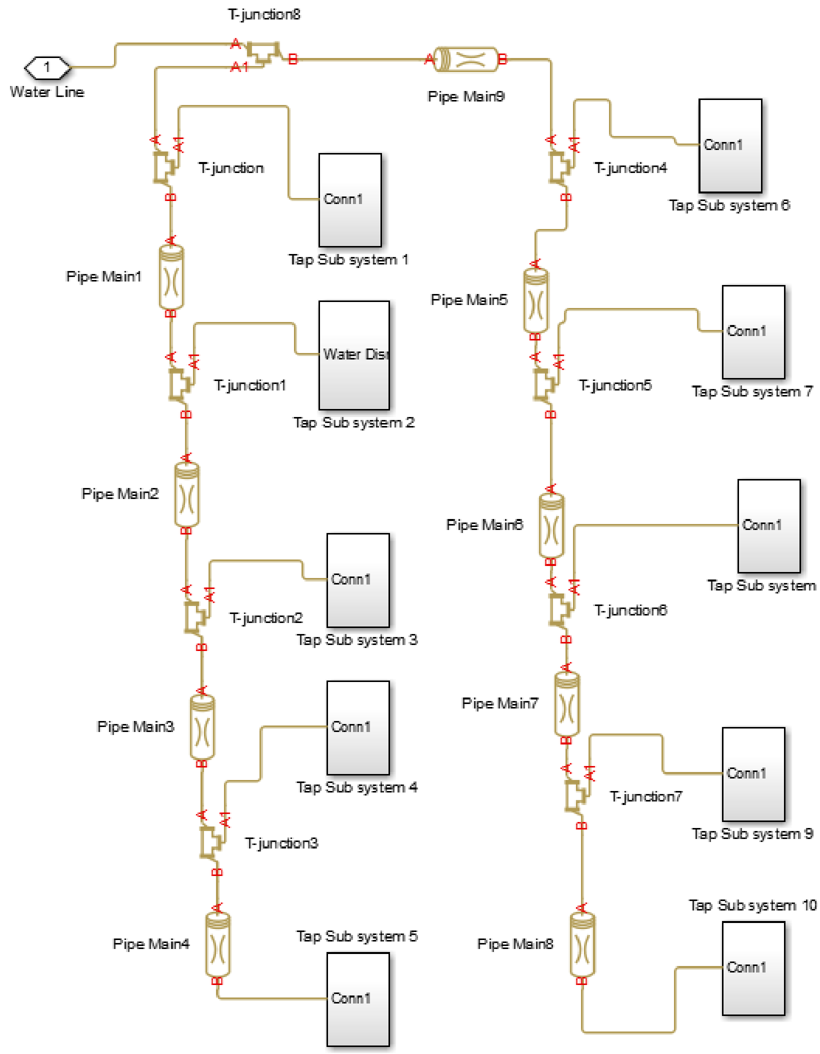


**Figure 5-2 Water distribution network sub system**

The water pipeline and the tap systems have been modeled in the water distribution sub system (see Figure 5-2). Here, the pipeline topology mentioned in Figure 4-1 is modeled using physical modeling in Simulink. The various components such as low resistance pipes, T-junctions and elbows were used to model the physical pipeline.

The input to this sub system is the water flow and the water usage profiles for the different tap systems. The tap sub systems will be described in the next section. The output of this sub system is the flow rate received by each tap and the feedback to the control sub system. The feedback can be either information from the proximity sensors or the information from the flow rate sensors or both depending on the system being modeled.

## 5.3 Tap subsystem

The tap system is not currently available in MATLAB it needs to be modeled with many physical blocks such as resistive pipes, tanks, ball valves, flow rate sensors, pressure sensors, scopes and displays as shown in Figure 5-3. Each physical block used will be discussed in detail in the following sub sections.

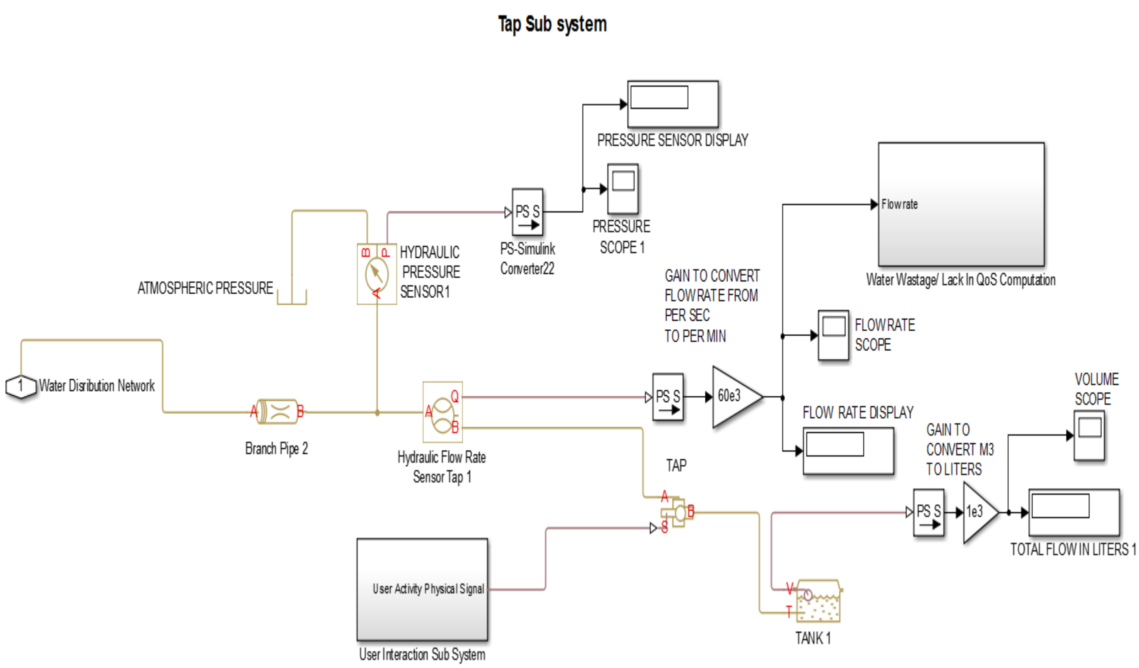


**Figure 5-3 Tap sub system**

The water distribution network connector allows the water to flow from the main pipeline to the various taps. After the water flows through the circuit elements and is used, it will reach the tank collector. Here, the water is stored to compute the total amount of water utilized by each individual tap systems. A hydraulic flow rate sensor and a pressure sensor have been placed at each of the tap to gauge and understand the working of the system. The user interaction subsystem proves the user activity signal generated by the user activity generator for this tap subsystem.

### 5.3.1 Constant head tank

The tank (TANK1) modeled is initially an empty tank that can accept an infinite amount of volume maintaining a constant pressure. The size of the tank is considered to be huge enough to ignore the water level change and pressurization. The tank accounts for the water level elevation considering the tank bottom and the pressure lose in the pipes connected. The pressure loss can be caused by a filter or some other local resistances and it is specified with the pressure loss coefficient. There are two ports: V is a physical signal port and T is a hydraulic port related with the tank inlet. The volume of water in the tank is computed and exported outside through the port V. The flow rate is assumed positive if the water flows from the tank.

### 5.3.2 Valve

The flow control is modeled by a ball valve of a maximum aperture diameter of half inch, similarly to one found on any normal installation. The valve is controlled by the corresponding user arrival signal given to the physical signal port S. There are two hydraulic ports A and B related with the valve inlet and outlet respectively. The water flows from port A to port B. The tap cross section and orifice parameters are shown in Figure 5-4.

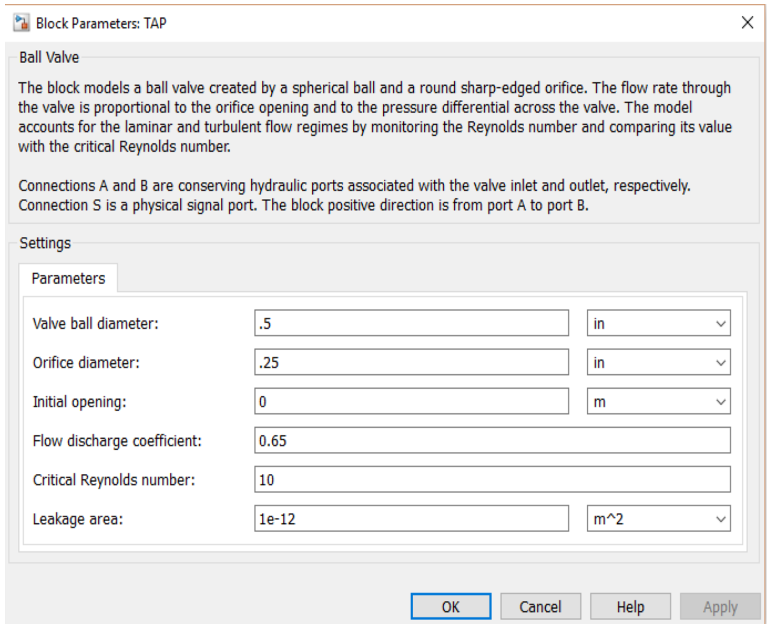


**Figure 5-4 Tap Orifice parameters**

The experimental hydraulic circuit resistance has been implemented using a resistive low-pressure pipe with reasonable values for the model. This block represents hydraulic pipe with both circular and noncircular cross sections. It has two hydraulic ports A and B with positive direction from port A to port B. It is used in simulations that have low-pressure systems and, for this reason, requires specifying the elevation of both ports. The block not only can be used as a pipe itself, but also combination of pipes and local resistances such as fittings, bends, etc., associated with the pipe. The flow rate is considered positive if water flow from A to B. The parameters for the water pipeline system have been mentioned as stated before. The elbow, pipeline and t- junction parameters are as shown in the Figure 5-5.

## 5.3.3 Hydraulic flow rate sensor

Hydraulic flow rate sensor performs as an ideal flow meter, that is, a device that converts volumetric flow rate through a hydraulic line into a control signal proportional to this flow rate. The connections A and B are conserving hydraulic ports connecting the sensor to the hydraulic line. Connection Q is a physical signal port that outputs the flow rate value. The sensor positive direction is from port A to port B.

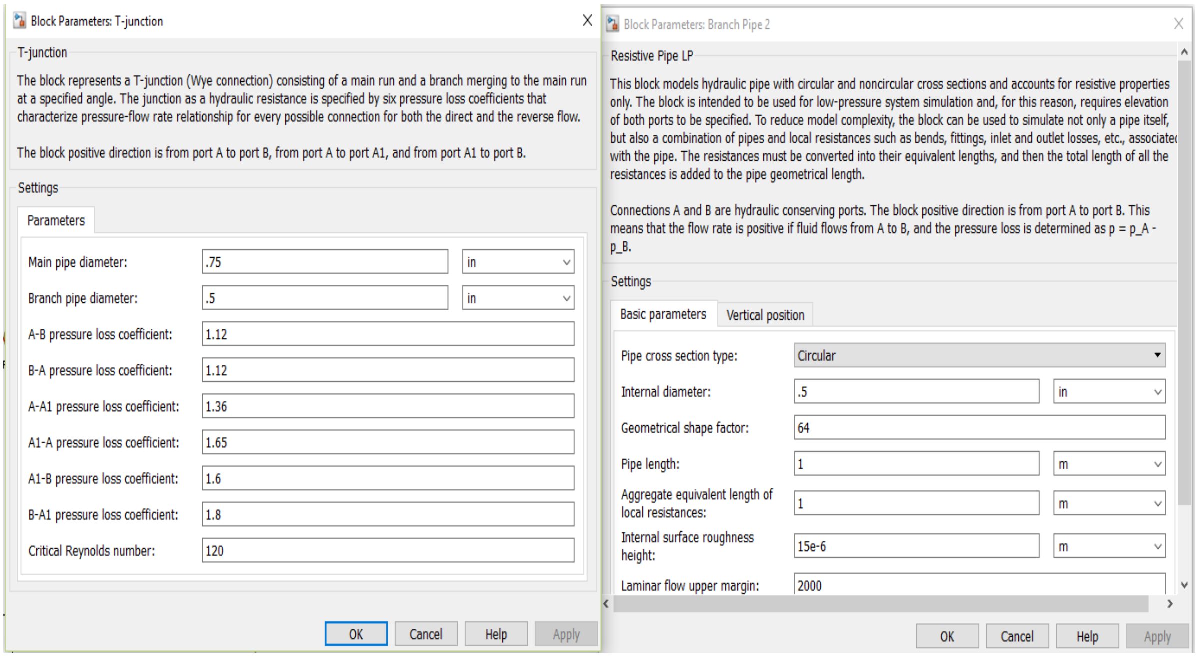


**Figure 5-5 Elbow, Pipeline and T- junction parameters**

## 5.3.4 Hydraulic pressure sensor

Hydraulic pressure sensor denotes an ideal pressure sensor, that is, a device that converts hydraulic pressure differential measured between two points, in the system, into a physical signal proportional to the pressure. The connections A and B are conserving hydraulic ports connecting the sensor to the hydraulic line. The connection P is a physical signal port that outputs the pressure value. The sensor is oriented from port A to port B and measured pressure which is P is the difference between pressure at port A and port B.

### 5.3.5 User Interaction sub system

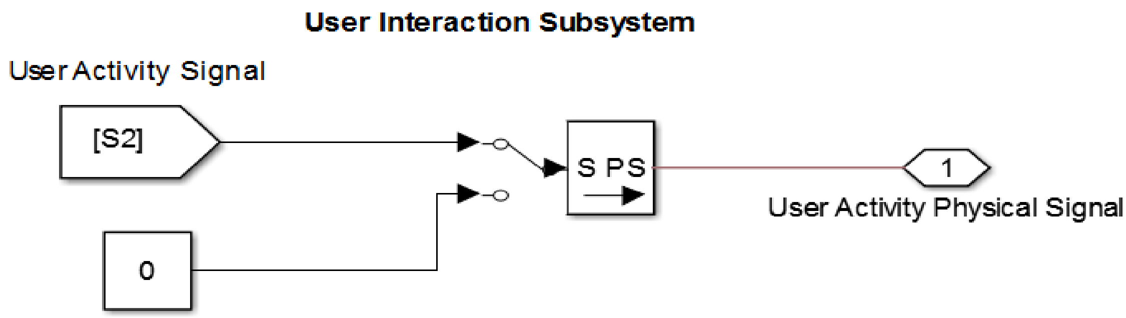


**Figure 5-6 User Interaction Subsystem**

The user interaction sub system comprises of the user activity signal for each of the taps. The user activity signal is modeled based upon the working of the proximity sensors. This signal is an ON/OFF signal which is modeled as either a 1 or a 0. This subsystem is illustrated in Figure 5-6. Also, for testing and analysis purpose a switch has been provided wherein we can switch off the tap permanently by selecting 0 as the input signal. The user activity signal is converted from Simulink input signal to a Physical Signal by the S PS block. This block has three options to handle the input which are you can use it as is, filter input, or provide the input derivatives through additional signal ports. We use the input signal as it is and convert it into the physical signal for the operation of the tap.

The proximity sensors do not come built in; in order to mimic the working of the proximity sensors the code with logic in Figure 5-7 has been employed. The output of the Proximity sensor is either a 0 or 1 which denotes either tap OFF or ON.

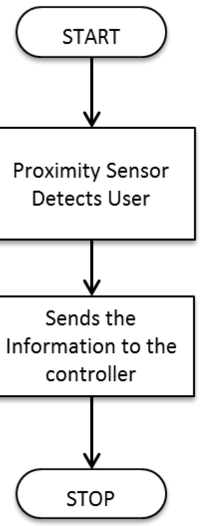


**Figure 5-7 Logic for Proximity sensor**

## 5.4 Hydraulic Reference sub system

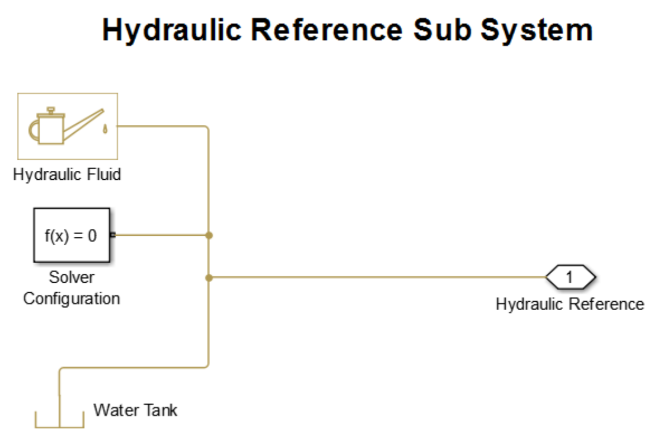


**Figure 5-8 Hydraulic Reference sub system**

The sub system in Figure 5-8 shows the Hydraulic reference sub system where hydraulic sources and the container water tank (also called hydraulic reference) are available. The hydraulic fluid block is used to assign the working fluid to the simulation model. There are various hydraulic fluids available such as water, gasoline, diesel fuel, oil and transmission fluid. The hydraulic liquid used is set to water for the purpose of this simulation, with relative amount of trapped air to be 0.005. The water tank used is used to represent an unlimited supply of water. Another very important component in this system is the solver block, which is responsible for solving differential equations for numerical algorithms applied in any physical system in Simulink.

## 5.5 Total water wastage/ lack in QOS computer sub system

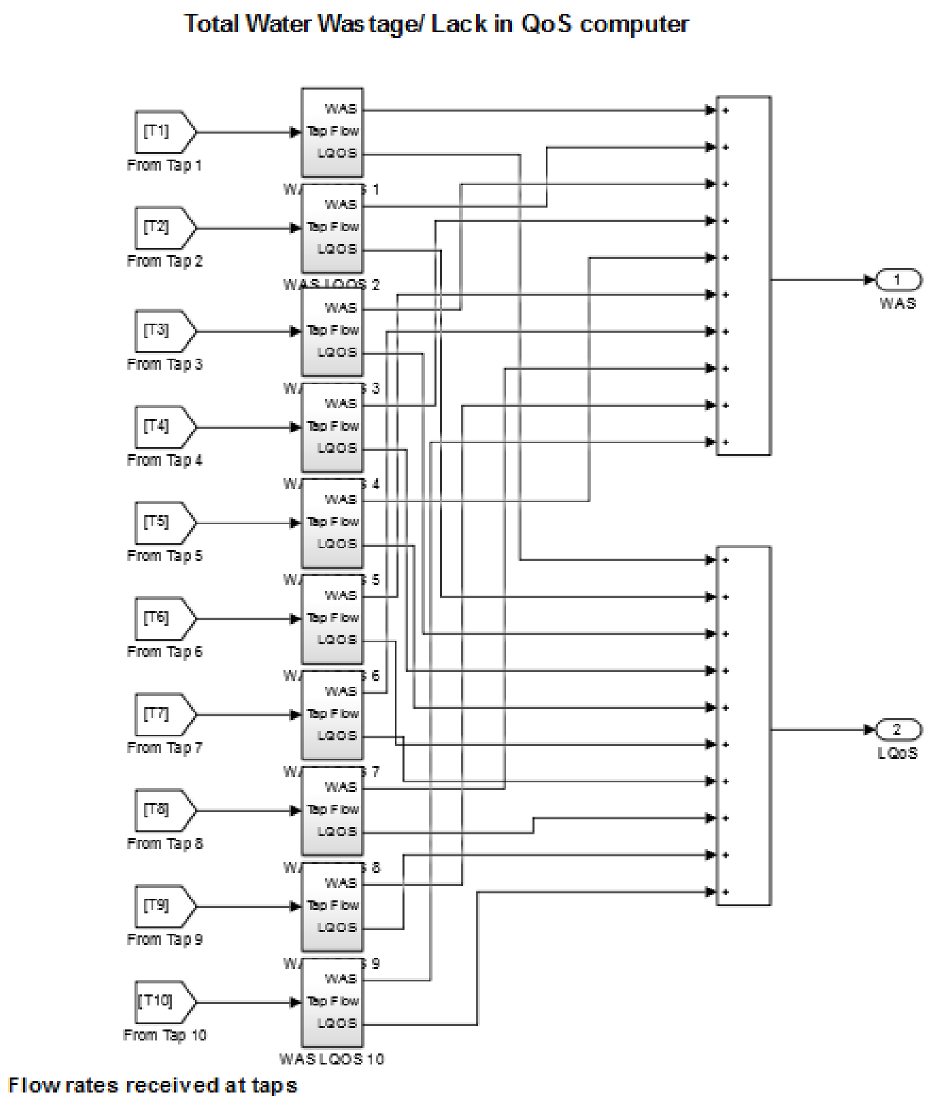


**Figure 5-9 Total water wastage/ lack in QOS computer**

For the purpose of finding out how much water is wasted or how much less amount of water is received at the user end by a system the total water wastage / lack in QoS computer has been modeled (see Figure 5-9). The input to this subsystem the flow rates received by each tap during the simulation time. This sub system has two output ports (WAS and LQoS) which are connected to data elements, scopes and displays for visualization and analysis purposes.

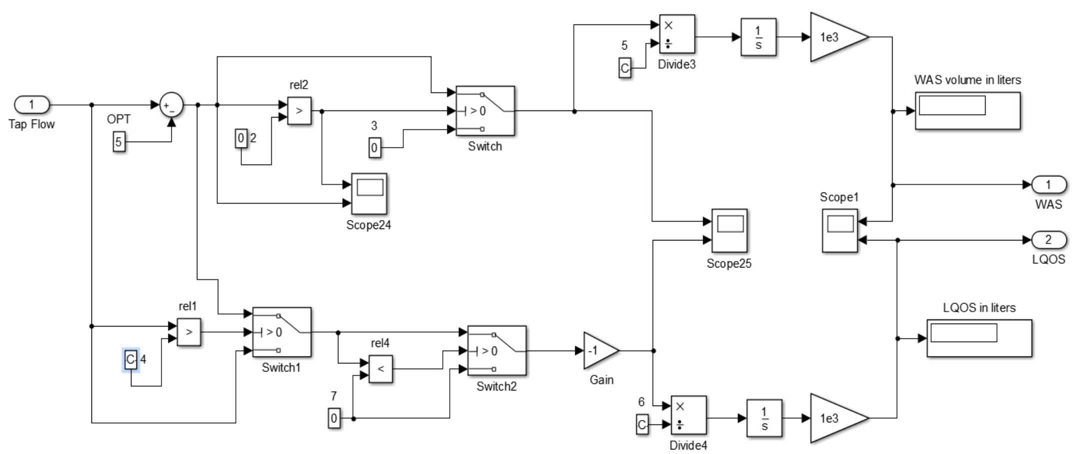


**Figure 5-10 Waste water/ Lack in QOS computation for each tap**

In order to calculate the amount of water wasted or find out the lack in the quality of service received at each of the user taps we designed an automated computer that performs the calculation for the simulated time as shown in Figure 5-10.

To calculate the amount of water wasted the difference from the ideal flow rate at each instance is calculated and after this the water wasted is integrated over the simulation time to find out the total water wasted for one user tap. Similarly to calculate the lack in the QOS, the lack in the flow of the water received is computed which is the difference between the ideal flow and the current amount received. The instantaneous lack in QOS is integrated over the simulation time to find out the total lack in QOS for one user tap.

After obtaining the water wastage and lack in QOS for all the users, finding out the water wastage for the whole system and the lack in QOS the whole system delivers becomes an easy task. Simply summing up the individual water wastages results in the water wastage for the whole system and summing up the individual lack in QOS results in the lack in QOS delivered by the system on the whole.

## 5.6 Control sub system

The control subsystem is responsible for the optimal operation of the pumping systems in the water pumping subsystem. The general idea is that pumping system is made to operate based upon the feedback which is the input to this sub system. The feedback could be the information about the number of users from the proximity sensors, information about the flow rate existing in the pipeline and information about the number of users from the user counter based upon the pressure sensor. Based upon this feedback the controllers for the various systems mentioned in chapter 4 have been developed. The output for this subsystem is the ON/OFF sequence for a combination of pumps or it is the speed (rpm) for the TFCS with VFD system.

## 5.7 Water Pumping Subsystem

SimHydraulics provides us with a simulation platform for modeling mechanical pumps with the desired characteristics. The pumps used for the purpose of our simulation are centrifugal pumps. We need to parameterize the Pump by Pressure Differential and Brake Power versus Pump Delivery.

In order to model the parameters to by a two 1D characteristics P-Q and N-Q, the pump characteristics are computed by using two one-dimensional table lookups [40]. One for the pressure differential based on the pump delivery and the second for the pump brake power based on the pump delivery. The characteristics of the pumps are specified at the same fluid density ρref (Reference density) and the same angular velocity ωref (Reference angular velocity). Affinity laws are used to compute the pressure differential at other angular velocities. The new reference delivery qref is calculated using the equation

$$q_{ref} = q\left(\frac{\omega_{ref}}{\omega}\right) \tag{1}$$

where q is the current pump delivery. At density ρ and current angular velocity ω the pressure differential across the pump is determined as

$$\rho = \rho_{ref}\left(\frac{\omega}{\omega_{ref}}\right)^2 \frac{\rho}{\rho_{ref}} \tag{2}$$

where ρ ref is the pressure differential determined from the P-Q characteristic at pump delivery qref . The brake power is computed using the expression

$$N = N_{ref}\left(\frac{\omega}{\omega_{ref}}\right)^3 \frac{\rho}{\rho_{ref}} \tag{3}$$

where Nref is the reference brake power obtained from the N-Q characteristic at pump delivery qref. The torque at the pump driving shaft is calculated using the expression T = N /ω.

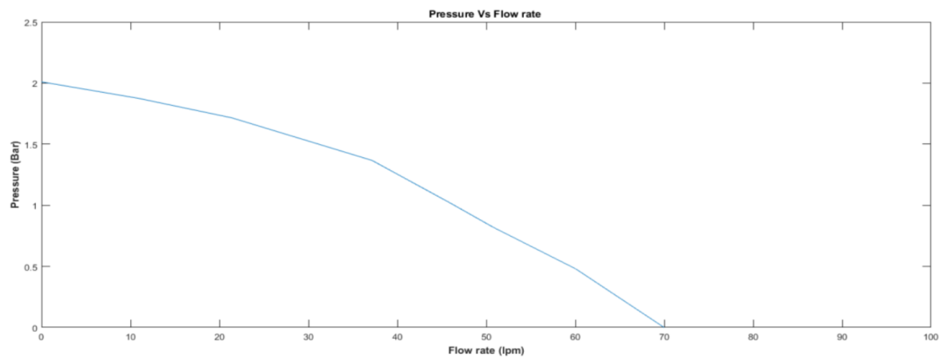


**Figure 5-11 P-Q curve for a centrifugal pump**

The individual water pumping system configurations of the various systems mentioned in chapter 4 will be described in various subsections later on in this chapter. The P-Q characteristics of a centrifugal pump can be represented in the form of a pressure vs flow curve. Figure 5-11 shows a sample P-Q curve generated by a modeled centrifugal pump. In this figure, we see that the pressure is maximum (2 bar) when there is no flow. Also, we notice the pressure is minimum for a maximum flow of 70 lpm.

## 5.8 Power Consumption Subsystem

The power consumption of the various different pumps varies due to the pumping capacities [41]. The power consumption of each of the pumps is calculated using the expression

$$P_h = \frac{QdP}{60000} \tag{4}$$

where $P_h$ is the hydraulic power of the pump (kW), volumetric flow of fluid through the pump(L/min) and dP is differential pressure across the pump (kPa).

Using equation (4) and the time for which a particular pump was operated we can calculate the total power consumption of a particular pump for the simulation time. After we have attained the individual power consumptions of these pumps they can be summed up to find out the power consumption of the pumping system as a whole for the simulation period.

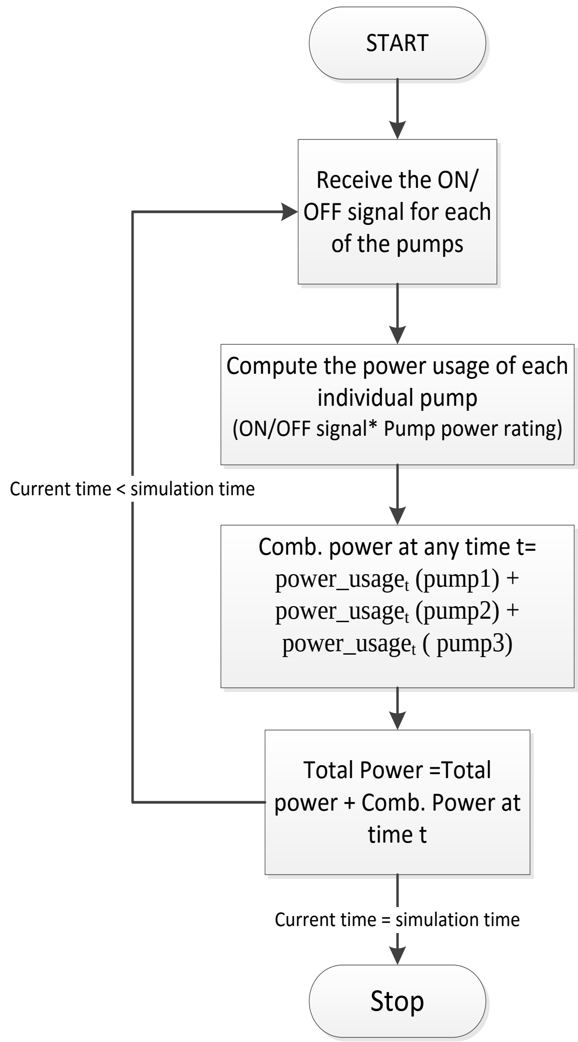


**Figure 5-12 Algorithm to compute the power consumption of the system**

The SimHydraulics tool is used for modeling hydraulic systems, so it lacks the components to compute the power consumed by the centrifugal pumps. The flow chart shown in Figure 5-12 shows the algorithm implemented to compute the total energy consumed by the pumps in the pumping system for the whole simulation period.

The power used by the proposed systems is computed using the same methodology shown in Figure 5-12. If the pump is turned ON it consumes power and if it turned OFF it does not consume any power. The power consumption considered here is the ideal steady state current power consumption since the effect of the startup current is negligible. By simply adding the individual pumps power utilization we can find the instantaneous power consumption of the system as a whole and by integrating the instantaneous power consumption over the period of simulation time we can find out the total power consumed by the system. For better understanding and to investigate the aspect of startup current in the future, the number of times each of the pumps is switched ON/OFF is also computed.

The power consumption of the conventional FFPS and TCFS with VFD system has been computed by an approach which does not follow the algorithm in Figure 5-12. The methodology of power consumption will be described in their respective sub sections later on in this chapter.

## 5.9 User Activity Generator

For the sole purpose of providing a comparison between the various systems random user arrivals are generated with random service time at each tap over a period of five hours. The arrivals are generated according to predefined user profiles which are set for each tap based upon our observations. The user arrivals are less in the first and second hour, increase in the third hour then decrease in the last two hours. The output of this subsystem is the user activity signals which help in running the simulation models. The output of this subsystem is connected to the user interaction subsystem for each of the tap subsystems. Service time is defined as the total time that a user leaves the tap open. We generate the random service times for the user for each tap based upon the predefined user profile..

In order to simplify the task, we assume that the taps are independent of one another. The arrivals are generated according to the predefined user profile for each of the taps. Different mean service times have been allotted to each of the taps. The actual service times generated follow a random distribution around the mean service time.

Three cases of user activity have been utilized for the purpose of comparison amongst the systems mentioned in chapter 4. These three cases have an average number of 2.5, 4.5 and 7.5 users at any point in time in the simulation. It should be pointed out that, we have selected these average points randomly just to have a better understanding of the system as it transitions through the different stages. These usage patterns are not built on real user behavior but to provide a comparison of the systems.

**Table 5-1 Case 1 User Activity Generator Parameters**

| Case 1 | | | | |
|---|---|---|---|---|
| | Arrival Rate (users /min) | Mean Service Time (sec) | Arrivals for 5 hrs Simulation | Total Service Time |
| Tap 1 | 0.13 | 104.74 | 38 | 3980 |
| Tap 2 | 0.14 | 89.21 | 42 | 3747 |
| Tap 3 | 0.11 | 91.76 | 34 | 3120 |
| Tap 4 | 0.11 | 89.09 | 33 | 2940 |
| Tap 5 | 0.10 | 146.00 | 30 | 4380 |
| Tap 6 | 0.13 | 128.08 | 40 | 5123 |
| Tap 7 | 0.10 | 147.74 | 31 | 4580 |
| Tap 8 | 0.09 | 162.86 | 28 | 4560 |
| Tap 9 | 0.11 | 137.65 | 34 | 4680 |
| Tap 10 | 0.15 | 153.78 | 45 | 6920 |
| Total System | 1.18 | 124.03 | 355 | 44030 |

Table 5-1, Table 5-2 and Table 5-3 show the user activity generator parameters which have been used to model these three cases. The events of users are created which help in the simulation of the proposed system are based upon random predefined user profiles for the individual taps. These three cases of the user activity are used in the models of the various systems and the performance of each of these systems is analyzed in terms of water wastage and energy consumption.

In order to test the simulation model dependency upon the user arrivals, two more cases have been simulated to represent the extreme case scenarios. In the first extreme case scenario, we consider there are ten average users all the time in the system. And in the second extreme case scenario, we consider there is only one user always in the system i.e., average number of users is one. A comparison of how the user activity affects the functionality of the proposed system will be shown in the results. The comparison is provided in accordance to the randomized profiles of 1, 2.5, 4.5, 7.5 and 10 average users.

**Table 5-2 Case 2 User Activity Generator Parameters**

| Case 2 | | | | |
|---|---|---|---|---|
| | Arrival Rate (users /min) | Mean Service Time (sec) | Arrivals for 5 hrs Simulation | Total Service Time |
| Tap 1 | 0.20 | 104.74 | 60 | 6320 |
| Tap 2 | 0.26 | 89.21 | 79 | 7027 |
| Tap 3 | 0.26 | 91.76 | 77 | 7040 |
| Tap 4 | 0.29 | 89.09 | 87 | 7780 |
| Tap 5 | 0.15 | 146.00 | 44 | 6420 |
| Tap 6 | 0.21 | 128.08 | 63 | 8015 |
| Tap 7 | 0.16 | 147.74 | 49 | 7180 |
| Tap 8 | 0.16 | 162.86 | 47 | 7620 |
| Tap 9 | 0.19 | 137.65 | 56 | 7720 |
| Tap 10 | 0.21 | 153.78 | 63 | 9613 |
| Total System | 2.01 | 124.03 | 603 | 74735 |

**Table 5-3 Case 3 User Activity Generator Parameters**

| Case 3 | | | | |
|---|---|---|---|---|
| | Arrival Rate (users /min) | Mean Service Time (sec) | Arrivals for 5 hrs Simulation | Total Service Time |
| Tap 1 | 0.44 | 104.74 | 131 | 13700 |
| Tap 2 | 0.51 | 89.21 | 154 | 13710 |
| Tap 3 | 0.44 | 91.76 | 131 | 11980 |
| Tap 4 | 0.48 | 89.09 | 145 | 12960 |
| Tap 5 | 0.32 | 146.00 | 96 | 14040 |
| Tap 6 | 0.36 | 128.08 | 108 | 13850 |
| Tap 7 | 0.33 | 147.74 | 99 | 14620 |
| Tap 8 | 0.30 | 162.86 | 90 | 14680 |
| Tap 9 | 0.34 | 137.65 | 101 | 13940 |
| Tap 10 | 0.26 | 153.78 | 77 | 11890 |
| Total System | 3.64 | 124.03 | 1091 | 135370 |

## 5.10 Fixed flow pumping system simulation

The fixed flow pumping system is implemented as shown in Figure 4-2. It has one water tank that outputs an unlimited supply of water. The pump used in water pumping subsystem is a centrifugal pump with single inlet and outlet as shown in Figure 5-13. The ports T and P are hydraulic ports related with pump inlet and outlet respectively and the third port S is a mechanical rotational port related with the pump driving shaft connected to angular velocity source. If the shaft S rotates in positive direction then the pump transports fluid from T to P. The port P of pump is connected to the pipeline to which the users are connected. The ideal angular velocity source block connected to the port S of pump is used to generate the mechanical rotation, it introduces a velocity differential at its terminals corresponding to the physical input signal. It has three ports, R and C which are mechanical rotational ports and S is the physical port through which the control signal that runs the source is applied. The source is considered ideal in a sense that it is assumed to be dynamic enough to provide specified velocity regardless of the torque applied on the system. The port S is set to 1250 radians per minute (rpm); it is set using trial and error based P-Q delivery vector table to deliver water at a total flow rate of 70 liters per minute (lpm).

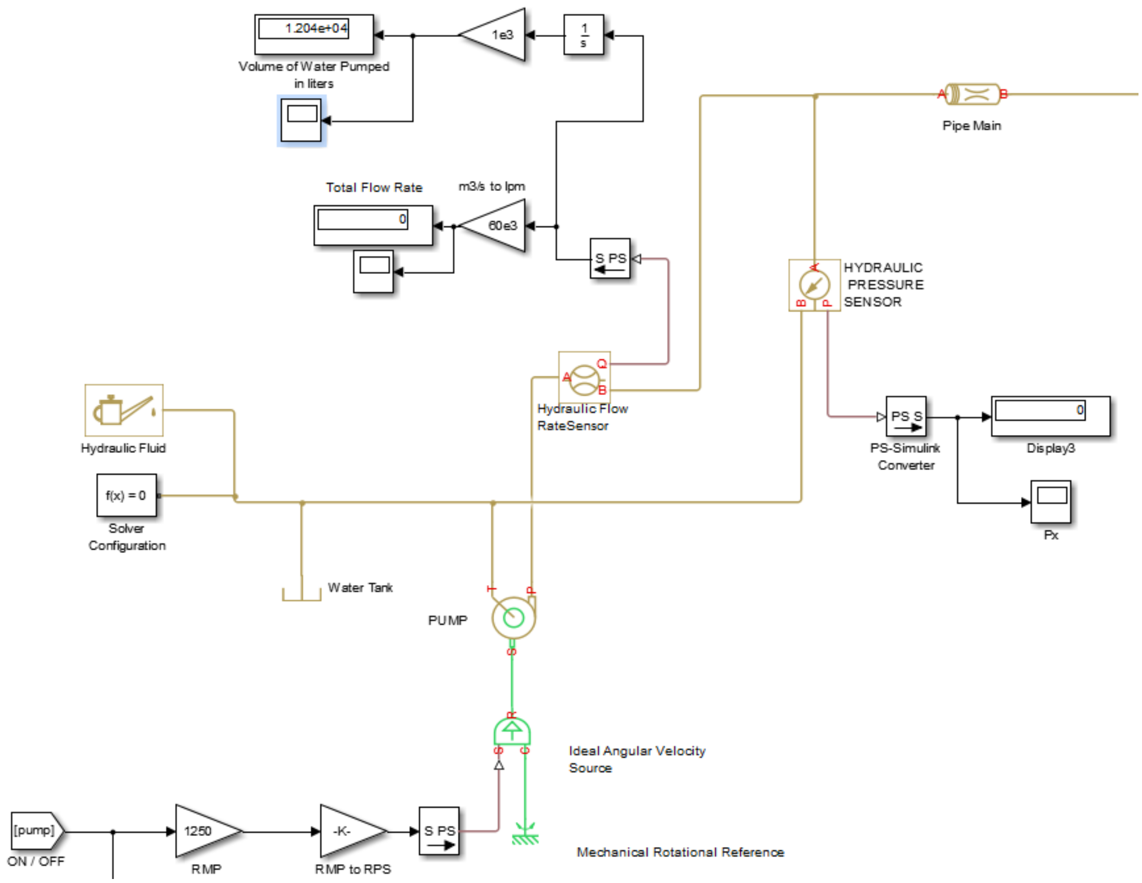


**Figure 5-13 Fixed flow pumping system simulation**

The hydraulic reference subsystem which has Hydraulic Fluid block and solver block is implemented. Hydraulic Fluid block, as stated earlier, is used to assign the working fluid for all components assembled in a particular loop. The loop detection is performed automatically and the block is considered as part of the loop if it is hydraulically connected to at least one of the loop components. This block offers wide selection of fluids to choose from. The custom fluid is assigned with the Custom

Hydraulic Fluid block from the Simscape foundation library. If neither Hydraulic Fluid nor Custom Hydraulic Fluid block is connected to the loop, the default properties of the Custom Hydraulic Fluid block are assigned.

Also, the solver configuration block is used to define solver settings for the simulation model. Every Simulink model needs to have a solver block; in our model we are using the solver block with default settings. The simulation time is 5 hours where users arrive at the taps randomly. The results obtained during simulation are captured using the scope block in Simulink.

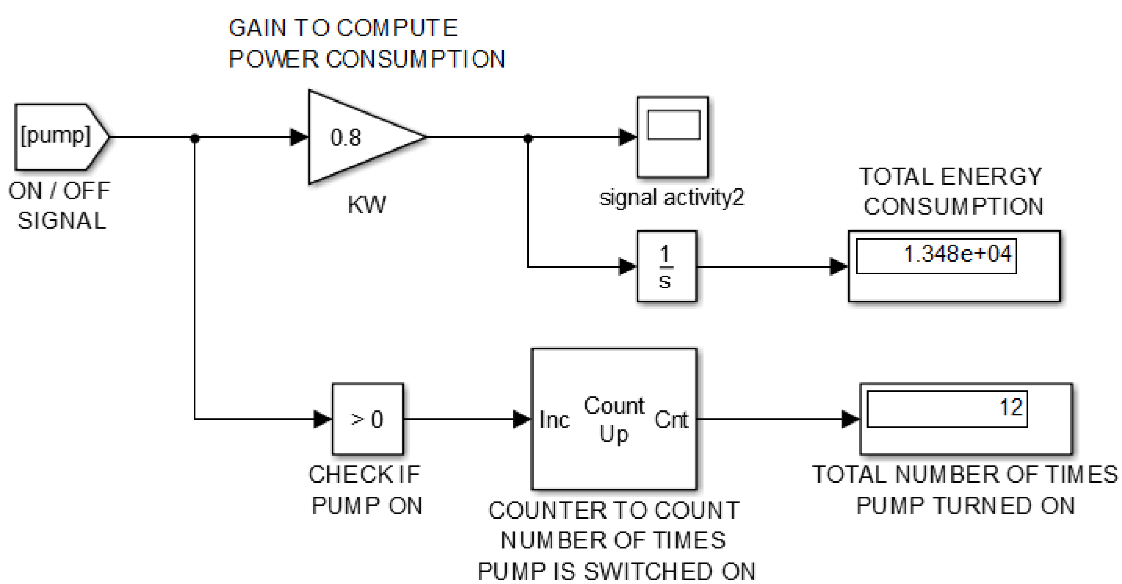


**Figure 5-14 Power Consumption of Fixed Flow Pumping System**

The power consumption of the pump is not calculated by the methodology shown in section 5.8. But, it is calculated by a simple method shown in Figure 5-14. Since there is only one pump, if the pump is turned ON it consumes power and if it turned OFF it does not consume any power. The power consumption of a centrifugal pump is proportional to the size of the pump. The power consumption considered here is the ideal steady state current power consumption. By integrating the instantaneous power consumption over the period of simulation time we can find out the total power consumed by the pump. For better understanding and to investigate the aspect of startup current in the future, the number of times the pump is switched ON/OFF is computed.

## 5.11 Total flow control system with VFD simulation

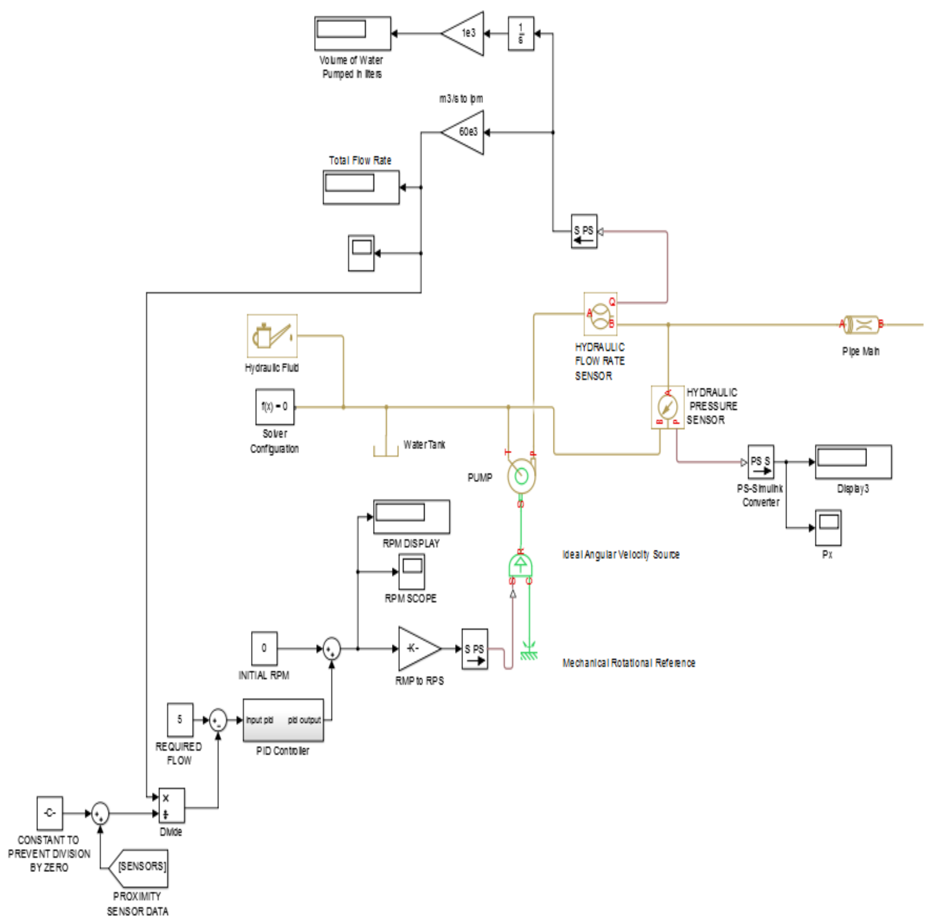


**Figure 5-15 TFCS with variable frequency drive model**

This water pumping subsystem for this model is implemented using the same physical components such as pumps, pipes, valves and taps that are used in the previous system shown in Figure 5-15. Instead of using a fixed flow pump, a variable speed pump that can change speed based on the FRC input is used. The specifications are that the system has to provide approximately 5 lpm to each user that is arriving at the taps. The pumps must provide the total flow demanded at each point in time by the users. Therefore, the variable to control is the total flow. The total flow required in the system can be found out based upon the active taps or the number of users in the system by means of the proximity sensors at each tap. The system should consider the ON and OFF times during the service time at the taps.

The system is actuated by means of a pump that can run at different speeds. The total flow it generates is inevitably the flow being sent through the pipeline and gets divided for each tap. Therefore the task of the control subsystem is to vary the speed of the pump, so that the total flow adjusts to the requirements, which change over time as taps are open and closed. If one tap opens suddenly, the outflow through each tap will instantly decrease. The controller will then react to this change and begin compensating by increasing the speed of pump until the total flow is again equal to the number of open taps times 5 lpm. Similarly, if a tap closes suddenly the outflow through each tap increases; the FRC reacts to this change and compensates by decreasing the speed of pump.

The working of the control subsystem, which is the FRC, is shown in Figure 5-16. The average flow for the number of taps open at that point of time is subtracted from the reference value that the system has to follow, which is 5 lpm. The FRC makes use of the information obtained by the proximity sensors to find out the number of users in the system. The opening and closing signal of taps is provided by the proximity sensor attached to the taps. The controller assumes that the signals from proximity sensors have a value of 0 for negative detection, and 1 for positive detection. Based upon the number of users in the system it calculates the total required flow rate. Also it gathers the information about the current flow rate in the system from the flow rate sensors. Then it computes a difference between the two and based upon the difference it either increases or decreases the speed of the pump.

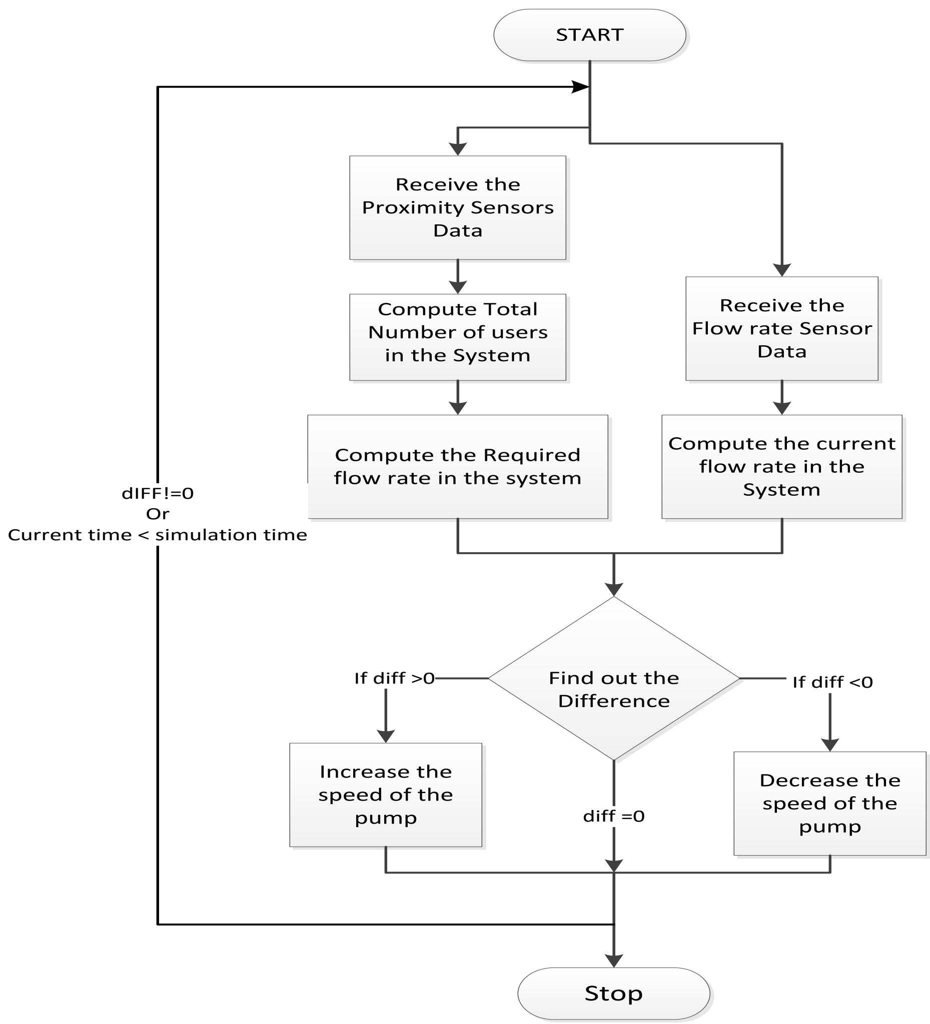


**Figure 5-16 Working of FRC**

The PID block, which represents a microcontroller, is configured so that the response is good as well as the stable. The values have been found by trial and error since no precise performance values have been specified. The signals coming out from the PID block will correct the current speed value of the pump and replace it a value that has been computed by the controller.

For the purpose of this simulation only PI has been used. Effectively, the integral part increases the output signal when the difference between the actual value and the desired value of the control variable is positive, decreases when it is negative, and is zero otherwise. The PID has a higher integral part than proportional part. This makes it react faster to perturbations, but such perturbations are also larger due to the smaller proportional value. The steps mentioned above are compulsory to get the controlled variable to the desired value.

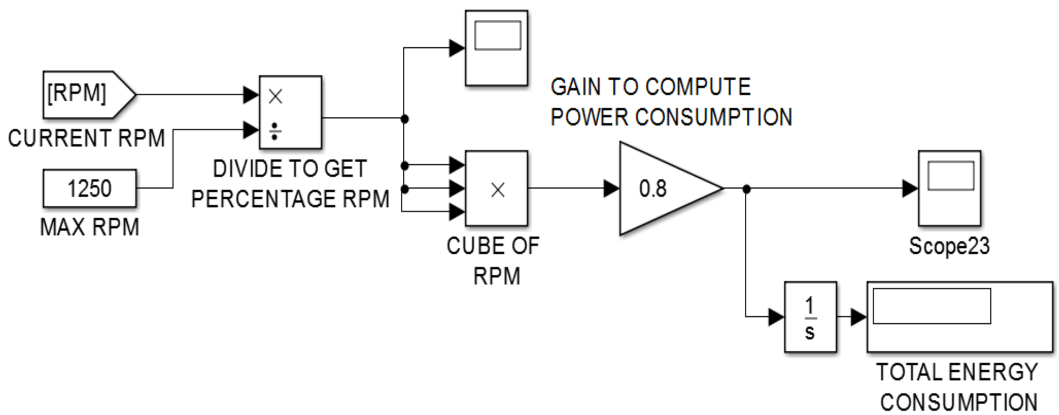


**Figure 5-17 Power Consumption of TFCS with Variable Frequency Drive**

The power consumption of a variable frequency drive is proportional to the cube of the speed at which the pump is operated. The instantaneous power consumption can be calculated by the methodology shown in Fig 5-17. Finding the current RPM and dividing it by the maximum RPM gives the ratio of speeds, cubing this provides the ratio for the power consumption. Multiplying it by a gain equivalent to the power consumption when the RPM is 100% gives the instantaneous power consumption at any point in the simulation. Finally, to find the total power consumption the integral over the simulation time is computed and displayed.

A hydraulic pressure sensor represents an ideal pressure sensor, that is, a device that converts hydraulic pressure differential measured between two points into a control signal proportional to this pressure. The sensor is ideal because it does not account for inertia, friction, delays, pressure loss, and so on. Connections A and B are conserving hydraulic ports connecting the sensor to the hydraulic line. Connection P is a physical signal port that outputs the pressure value. The sensor positive direction is from A to B. This means that the pressure differential is determined as

$$\rho = \rho_a - \rho_b \tag{5}$$

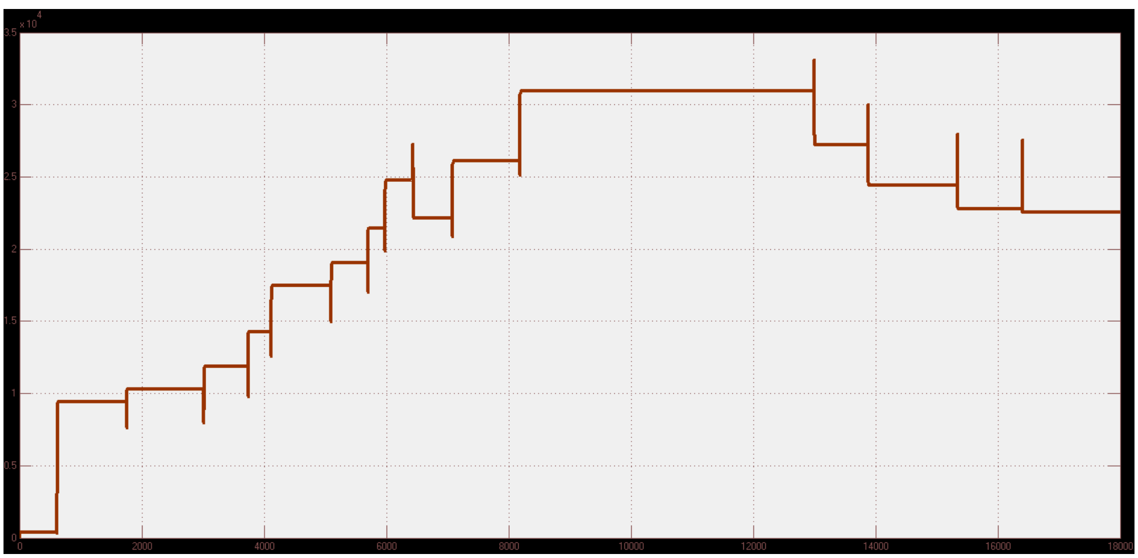


**Figure 5-18 Hydraulic Pressure hikes and drops**

Figure 5-18 represents the pressure output of hydraulic network, the spike wave denotes users activeness or un-activeness. The positive spike represents user has become unactive and negative spike represents user has opened a tap. We see that initially users are arriving regularly so we can see downward spikes only. But after some time we see a spike in the network's pressure indicates a user has become in-active i.e., switched of the tap.

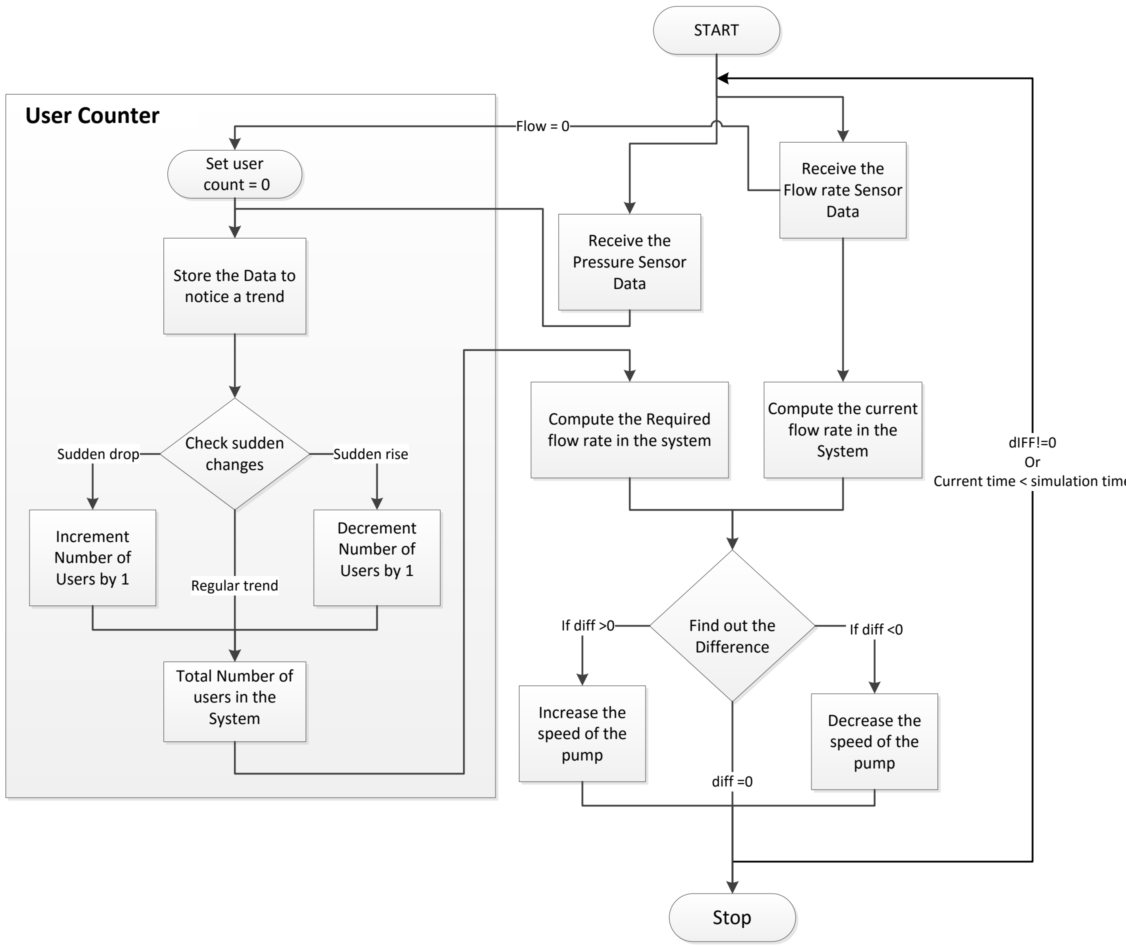


**Figure 5-19 Algorithmic procedure for user counter**

The algorithmic procedure for the control subsystem of the simple version of the TFCS with VFD which has been implemented without the use of proximity sensors is shown in Figure 5-19. The aim is to reduce the cost of implementation by eliminating the use of proximity sensors. A user counter is designed, which is a software based counter that mimics the functionaltity of  proximity sensors for adaptive pumping; it counts the number of active users in the system based upon information gathered from the pressure sensor.

A block diagram representation of user counter shows that it computes the user activeness or inactiveness and provides it for the control. The user counter block finds out number of active users at any point in the system by

1. Initially the number of users in the system is considered to be zero.
2. After receiving the pressure sensor's data the controller stores it to keep track of the changes in the hydraulic line.
3. The current received pressure sensor's value is checked with the previously stored values of pressure. If a sudden drop (compared to the previous trend) is seen in the pressure value means a tap is opened so, a user should be added to the user count. Similarly, if a sudden hike is seen in the pressure value this means that a tap is closed so, a user should be decremented from the user count.
4. The limitation to this approach is that if two users open or close the tap at the same time then it will be counted as a single increment or decrement in the number of users.
5. Hence to avoid the possibility of errors over long periods of time, the user counter is reset to zero each time the flow rate in the system becomes zero, since there are no users.
6. The total number of users at any time in the pipeline is generated by the user counter block which is then used by the controller to control the speed of the pump by determining the required total flow rate in the system.

### 5.11.1 PID controller

A PID block internally has three parts. The proportional part multiplies the input signal by an amount. The integral part integrates the input over time, and then multiplies by the provided gain. The derivative part differentiates the input signal over time. The output of the three parts is then summed up and sent to the block output. In our model only PI has been used. Effectively, the integral part increases the output signal when the difference between the actual value and the desired value of the control variable is positive, decreases when it is negative, and is zero otherwise. Therefore it is important to know which signal goes to which sign in the subtraction block. In short, it acts like some sort of cumulative memory, and it ensures that the error tends to zero as time passes.

## 5.12 Identical Pumps Water Pumping System simulation

The IPWPS system in 4-4 is implemented by adding flow sensors and a control system to the conventional system. The single pump is replaced by a set of identical pumps which have the same output capacities or outflows. These pumps are connected in parallel so that the maximum pressure generated by the system remains the same but the total outflow is the combined output of the pumps as a whole.

The water pumping subsystem comprises of identical centrifugal pump with single inlet and outlet as shown in Figure 5-20. The ports T and P are hydraulic ports related with pumps inlet and outlet respectively and the third port S is a mechanical rotational port related with the pumps driving shaft connected to angular velocity sources. If the shaft S rotates in positive direction then the pump transports fluid from T to P. The ports P of pumps are connected through check valves to the pipeline to which the users are connected. The check valves are placed so as to avoid the negative flow.

The ideal angular velocity source block connected to the port S of pump is used to generate the mechanical rotation, it introduces a velocity differential at its terminals corresponding to the physical input signal. It has three ports, R and C which are mechanical rotational ports and S is the physical port through which the control signal that runs the source is applied. The source is considered ideal in a sense that it is assumed to be dynamic enough to provide specified velocity regardless of the torque applied on the system. The port S is set to 1250 radians per minute (rpm); the size of the pumps is changed using trial and error based P-Q delivery vector table to deliver water at a total flow rate of 25 liters per minute (lpm).

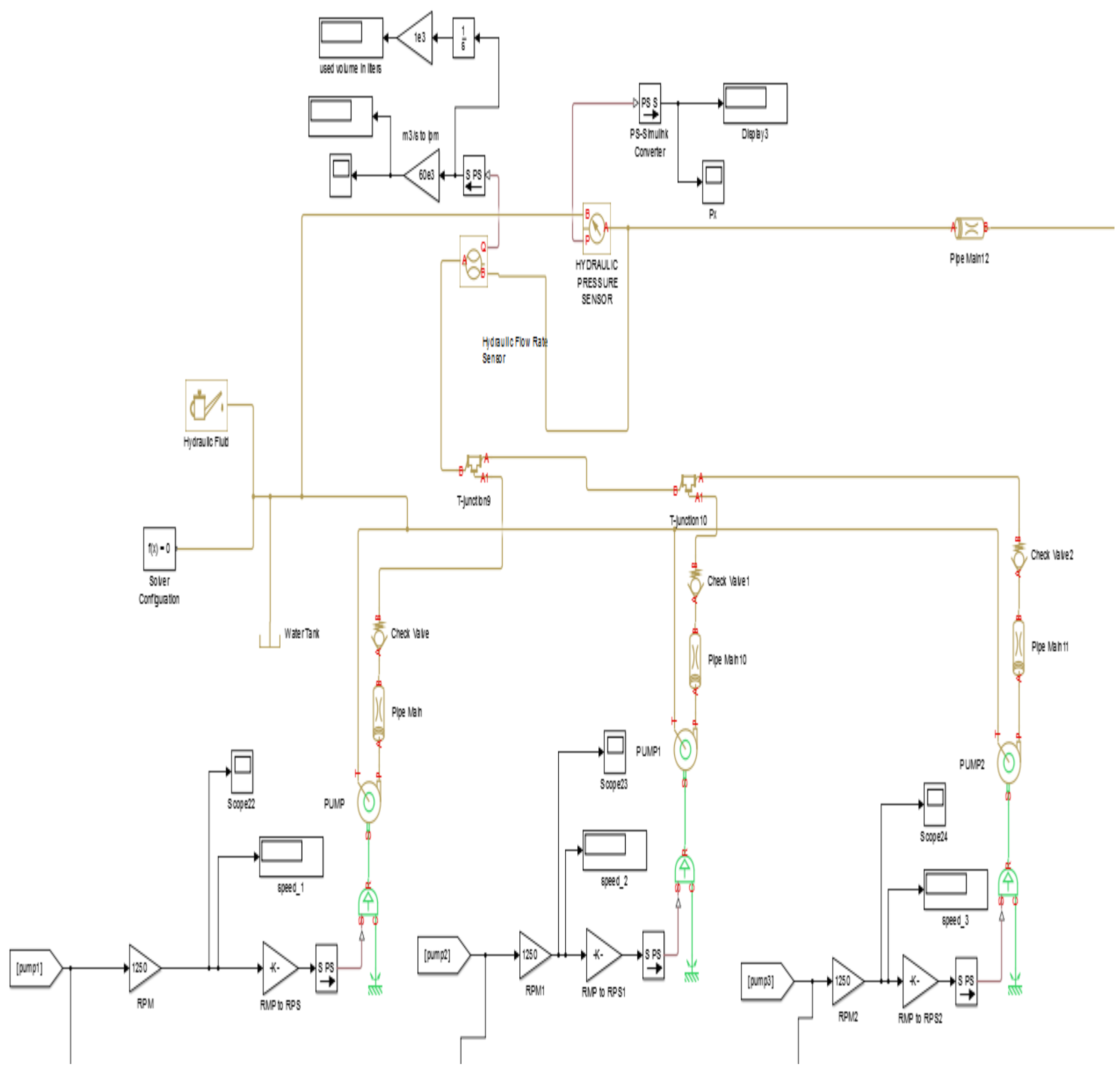


**Figure 5-20 Identical Pumps Water Pumping System with three pumps**

As mentioned in the previous section, the specifications are that the system has to provide approximately 5 lpm to each user that is arriving at the taps. The operation of these pumps must provide the total flow demanded at each point in time by the users. Therefore, the variable that can be controlled is the switching OFF and ON of a single pump or a combination pumps to attain the desired total flow. The requested total flow required in the system can be found out based upon the active taps or the number of users in the system by means of the proximity sensors at each tap.

From the explanation above we can conclude that if one pump can deliver 23 lpm then it can support 4 users since 5 lpm times 4 users gives a total desired flow of 20 lpm. But, this is not the case due to the resistances of the pipeline system; the attained outflow is lesser than the speculated flow of the pumps.

The control subsystem, which is the Identical Pumps Controller, is tasked with the finding out the desired flow rate by the system at any point in time and to intelligently switch ON the number of pumps to deliver at least the requested flow rate. The word at least has been used because we cannot control the maximum flow rate, for example, if we have a single user the IPC according to the logic switches on a single pump whose outflow is 23 lpm. But the desired outflow is 5 lpm and since the smallest outflow which can be attained by using this pumping system 23 lpm the best the IPC can do is to deliver the signal to on only one pump.

Hence, the IPWPS uses the IPC to adapt the minimum flow adequately, in order to output the water such that the minimum demand criteria are met. The IPC is responsible for sending the ON/OFF signals to the individual pumps at any point in the simulation when a user enters the system or when a user leaves the system. The working of the IPC controller is shown in Figure 5-21. When there are zero users the flow should be zero so all the pumps are switched OFF.

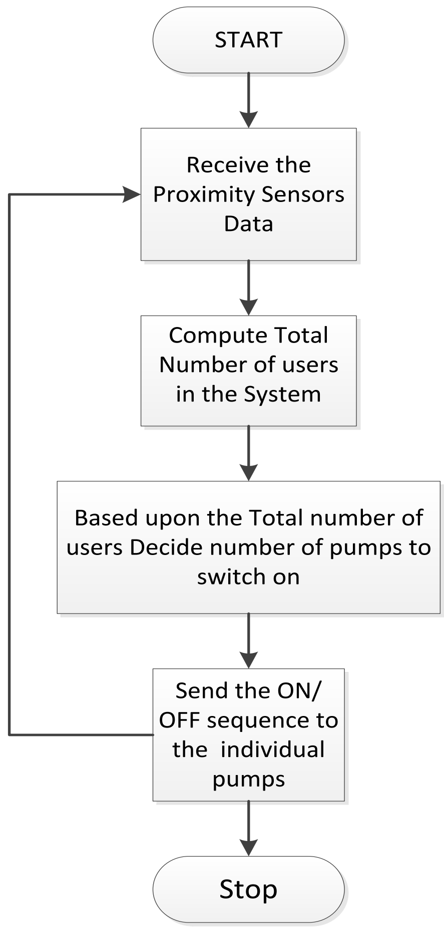


**Figure 5-21 Identical Pumps Controller implementation for IPWPS with three pumps**

Monitoring of the information and performing the control is easier for IPWPS as the controller only needs to decide the number of pumps to on; to match the number of users in the system. Here, the proximity sensors provide us with the number of users in the system. We calculate the total number of users in the system and the required total flow consecutively. First a single pump is switched on if the delivered flow rate is less than the required flow rate then the next pump is switched on. The same case is considered for the vice versa if the difference is the flow rate is more then we switch off one pump. The power consumption of the IPWPS is calculated by the methodology shown in Figure 5-12 which has been explained in the section 5.8.

## 5.13 Wireless Binary Water Pumping System simulation

The Wireless Binary Water Pumping System model as shown in Figure 5-22 is the proposed system. The WBWPS system in 4.5 is implemented by replacing the identical pumps in IPWPS with a combination of binary pumps. The data is communicated wirelessly using GOTO and FROM tags. The pumps in the WBWPS are chosen in such a fashion such that the pumps in the set of pumps have a binary sequence (1, 2, 4, 8, …) of pumping capacity. Similar to the IPWPS, the pumps are connected in parallel so that the maximum pressure generated by the system remains the same but the total outflow is the combined output of the pumps as a whole. Since the pumps are of different capacities check valves are mandatory so as to avoid the negative flow.

The pumps used in the water pumping sub system are centrifugal pumps, the size of the pumps is changed using trial and error based P-Q delivery vector table to deliver water at a total flow rate of 11, 22, 42 liters per minute (lpm).

As stated before, the specifications are that the system has to provide approximately 5 lpm to each user that is arriving at the taps. The operation of these pumps must provide the total flow demanded at each point in time by the users. Therefore, the variable that can be controlled is the switching OFF and ON of the pump corresponding to the desired flow or a combination pumps to attain the desired total flow. Analogous to the previous section, the requested total flow required in the system can be found out based upon the active taps or the number of users in the system by means of the proximity sensors at each tap.

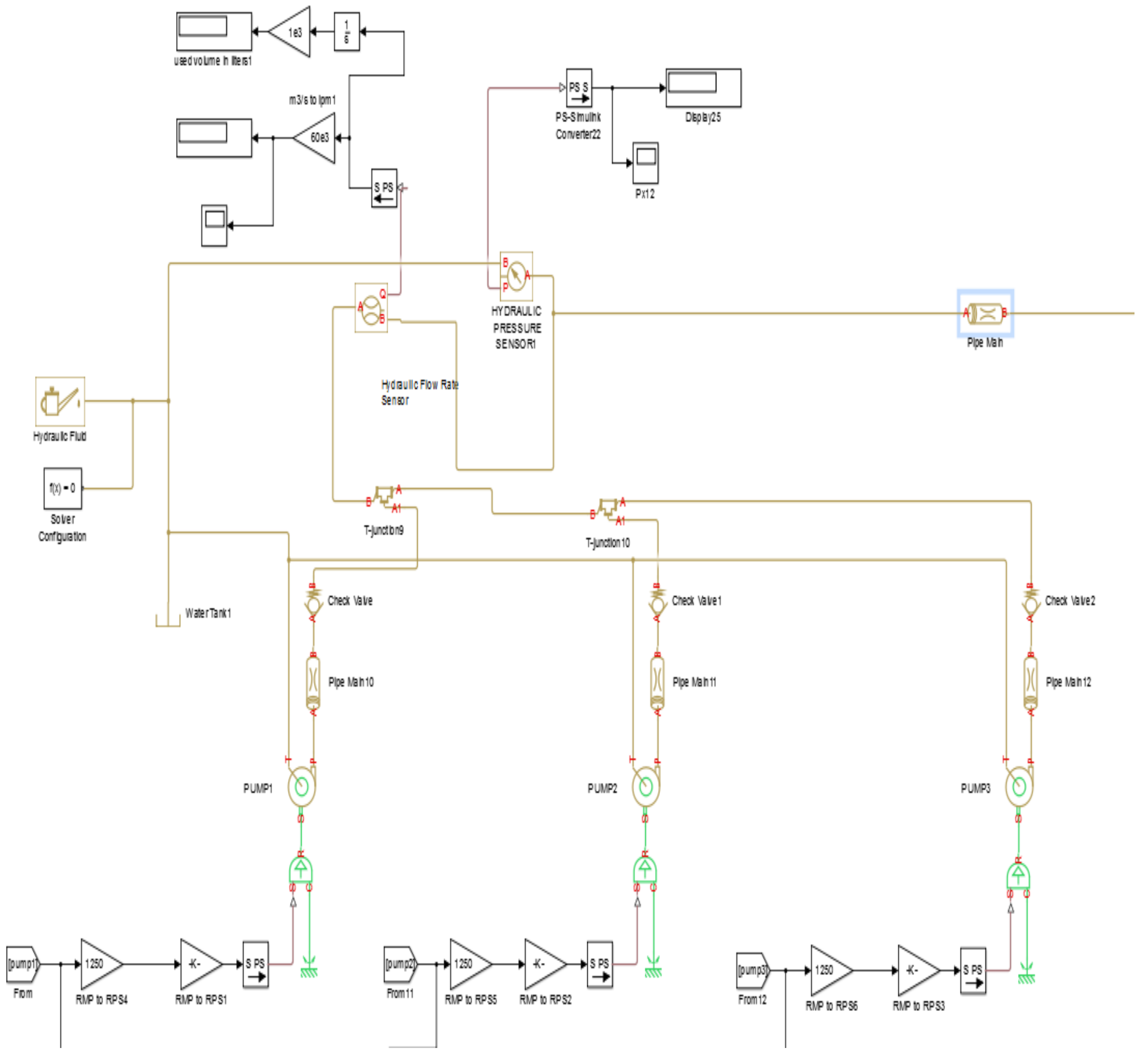


**Figure 5-22 Wireless Binary Water Pumping System with three pumps**

The control sub system, which is the BPCC, is tasked with the finding out the desired flow rate by the system at any point in time and to intelligently switch ON the corresponding pump or a combination of pumps to match the requested flow rate. From a basic understanding, the smallest pump can deliver 11 lpm then it can support 2 users since 5 lpm times 2 users gives a total desired flow of 10 lpm. Now, when a third user enters the system the first pump (11 lpm) should be turned OFF and the corresponding pump, second pump (22 lpm) should be turned ON. Similarly, when there are four users in the system and a new user enters the system then the first and second pump need to be switched ON in combination to deliver the minimum desired flow.

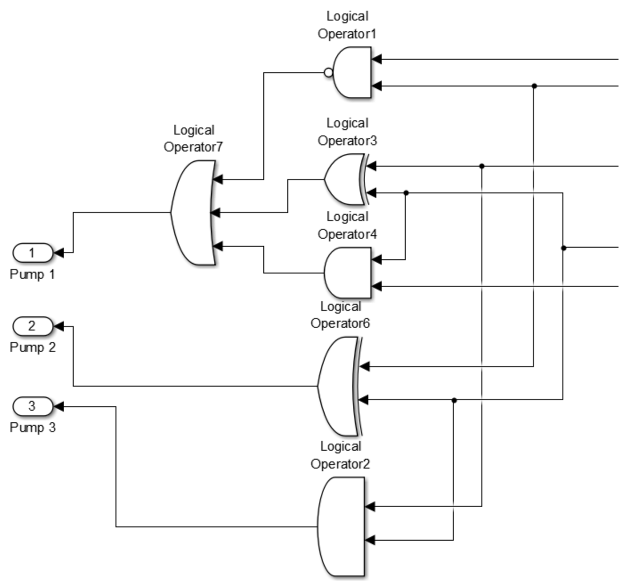


**Figure 5-23 Logic circuit controlling the ON/ OFF signals of the three mechanical pumps**

The successful working of the WBWPS requires the proper functioning of the mechanical pumps to deliver the required amount of water. The mechanical pumps are designed to be made to operate in the desired fashion by the means of a logical circuit taking the processed data after receiving it from the from the proximity sensor as input.

The working of the control subsystem is defined by the flowchart given in the Figure 5-24. The data from the proximity sensors is converted to Boolean type and then the logic circuit is used to create the proper ON/ OFF sequence. The Figure 5-23 shows the circuit diagram for the controller to control the pumps so as to get the desired output accommodating the dynamic user entering the system or leaving the system. Similarly a control circuit for the four pump setup has also been designed. The working of the BPCC is complex when compared to the IPC.

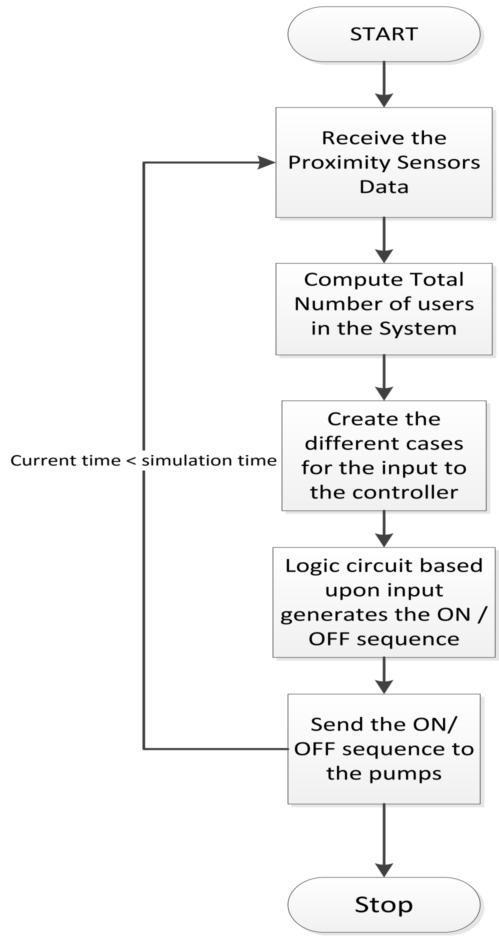


**Figure 5-24 Binary Pumps Control Center implementation for WBWPS with three pumps**

As mentioned earlier, in order to simplify things we do not simulate/build a wireless sensor network. We assume getting readings of the input from a WSN to show the proof of concept. The data communication takes place between the proximity sensors and the BPCC using the FROM and GOTO tags. The FROM and GOTO tags is used to simulate the wireless communication. Also, the BPC sends the ON/OFF signals to the respective pumps using this form of wireless communication. The power consumption of the WBWPS is calculated by the methodology shown in Figure 5-12 which has been explained in the section 5.8. The only difference is the changes in the power ratings since the pumps are of different capacities.

The total flow of the simulation between the various sub systems in the model for this system can be shown in Figure 5-25.

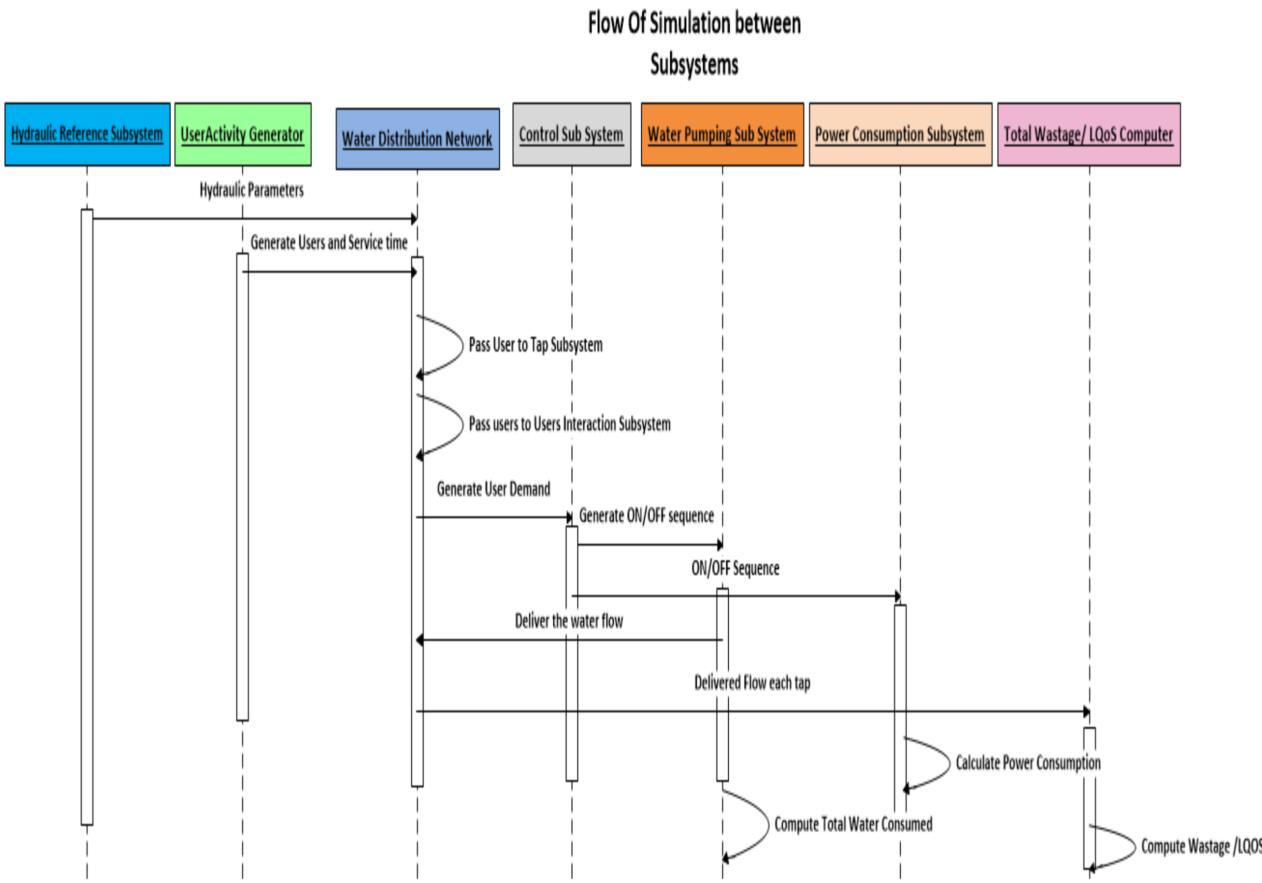


**Figure 5-25 Flow of Simulation**

# CHAPTER 6

# RESULTS AND DISCUSSION

In this section, the simulation results obtained from the systems will be discussed. The systems were simulated for a period of five hours and the behavior of the systems is captured using scope block of Simulink.

## 6.1 User Arrivals

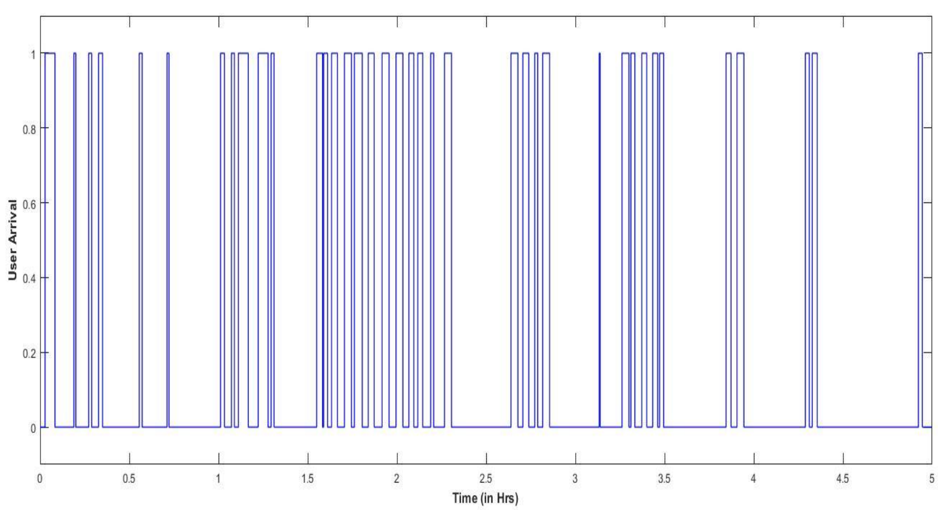


**Figure 6-1 User Arrival for Tap 1**

The user arrivals are simulated in such a way that it should represent real world scenario. The users arrive randomly at each tap and use it for random service time independent of other taps similar to the users in public places such as airports, railway stations and restaurants, etc. In the experiments, ten taps with identical parameters have been simulated; Figure 6-1 represents the users' activity at the first tap respectively. The value zero indicates that the tap is idle with no user and the value one indicates that the user is present and is using the tap.

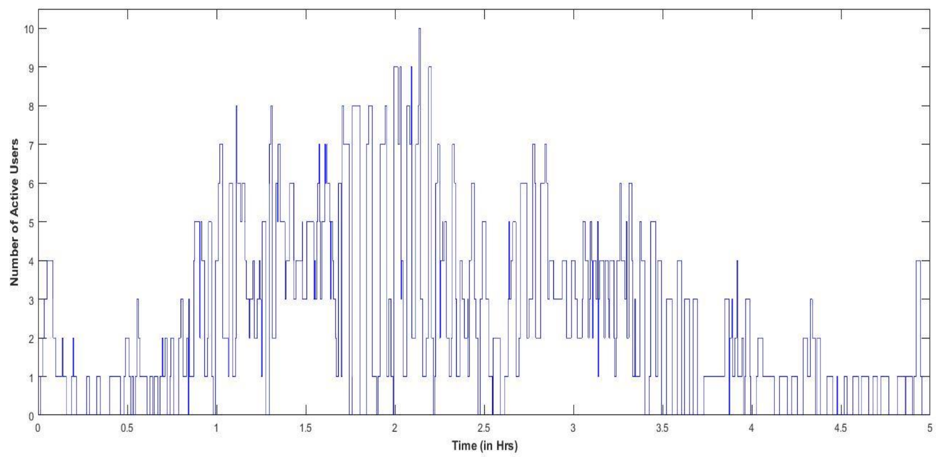


**Figure 6-2 Total number of users with average 2.5 users**

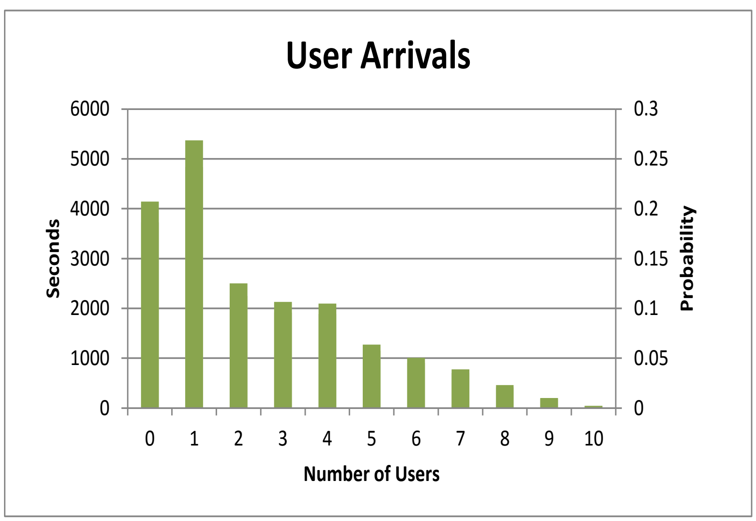


**Figure 6-3 Histogram of user pattern for first case**

The user arrivals have been simulated in such a way as to represent three scenarios, light, moderate and heavy use namely. In the first case the average number of users for the simulated time is 2.5 users and in the second case the average number of users for the simulated time is 4.5 users. And, in the third case the average number of users is 7.5.

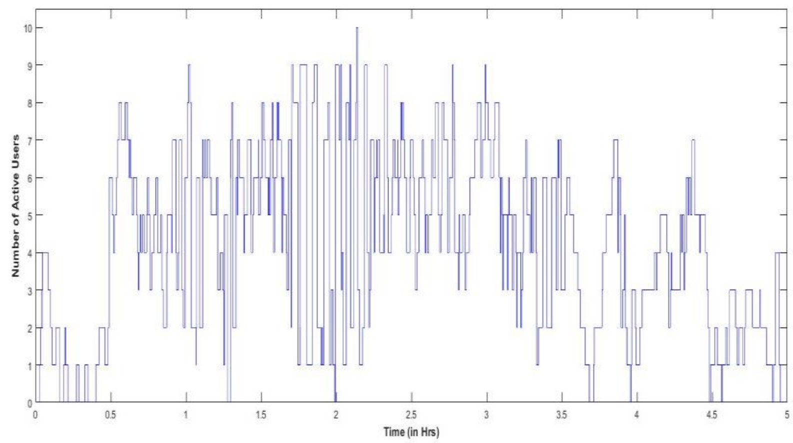


**Figure 6-4 Total number of users with average 4.5 users**

For a better visualization, the combined user usage pattern is shown in Figure 6-2. It shows the total number of users in the system with respect to the simulation time. The histogram of having n number of users at any particular time for this set of user arrivals is shown in Figure 6-3.

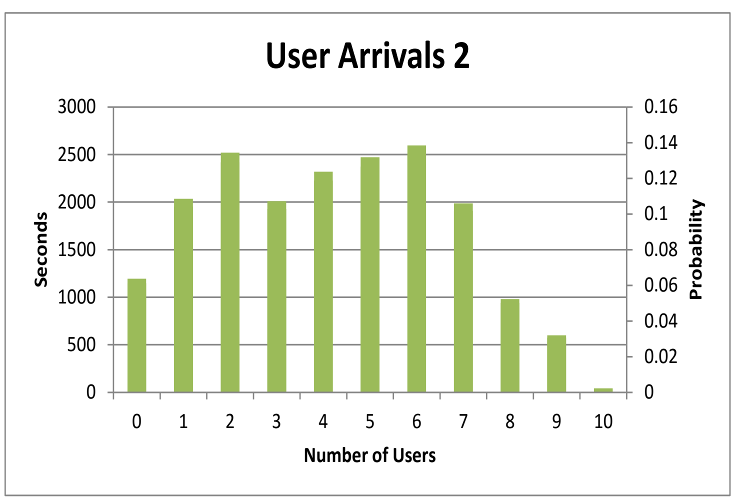


**Figure 6-5 Histogram of user pattern for second case**

As mentioned two more sets of users' arrivals have been simulated to depict moderate and heavy usage. The combined user usage pattern in the system and the histogram for the moderate set of user arrivals can be seen in Figure 6-4 and Figure 6-5 respectively. Also, the histogram for the 7.5 user average is shown in Figure 6-6.

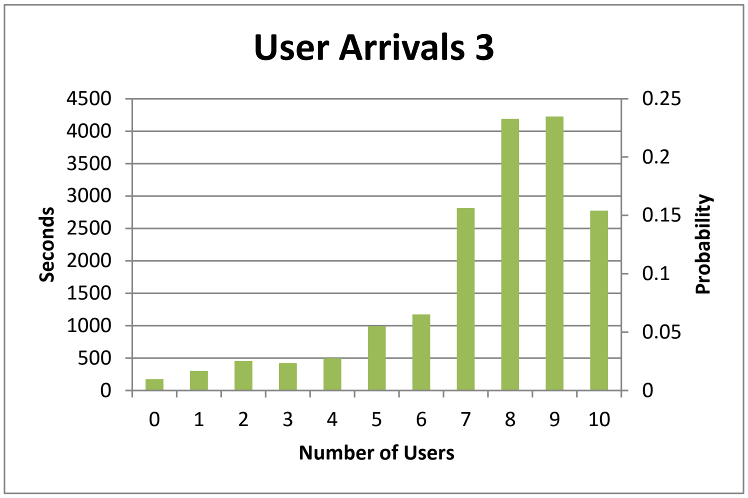


**Figure 6-6 Histogram of user pattern for third case**

## 6.2 Fixed Flow Pumping System

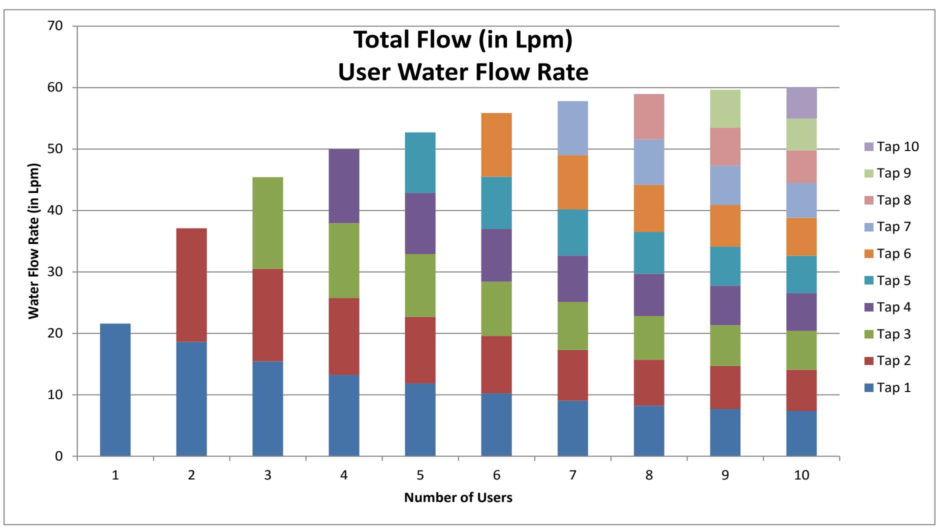


**Figure 6-7 Flow rate for different taps in pipeline**

In this sub section, we discuss the behavior of water flow rate delivered to the taps in the Fixed Flow Pumping System. It is a simple system with no control system to control the flow of water in the pipeline. The pumping system delivers the same amount of outflow into the pipeline irrespective of the number of users. But, due to the position of the taps on the pipeline the users experience different flows rates. The taps closest to the pumping system experience a higher flow rate and consecutively waste a larger quantity of water.

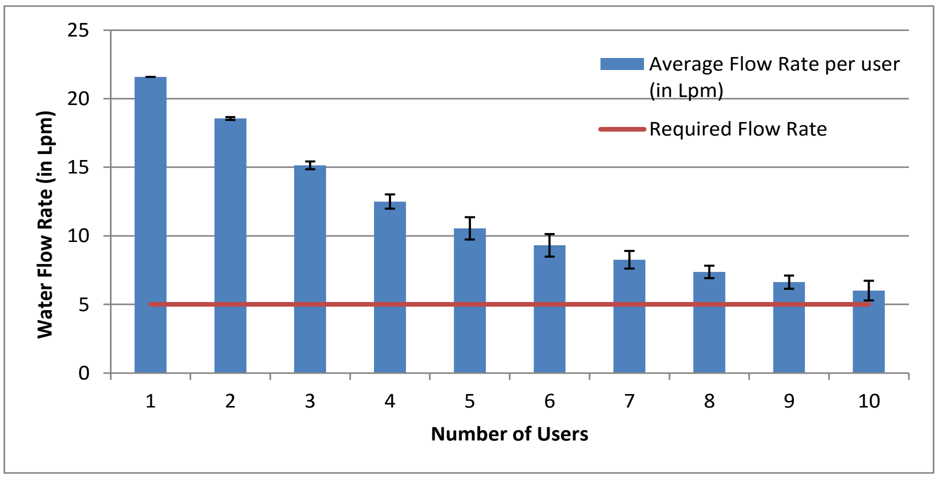


**Figure 6-8 Average Flow rate received per user (in lpm)**

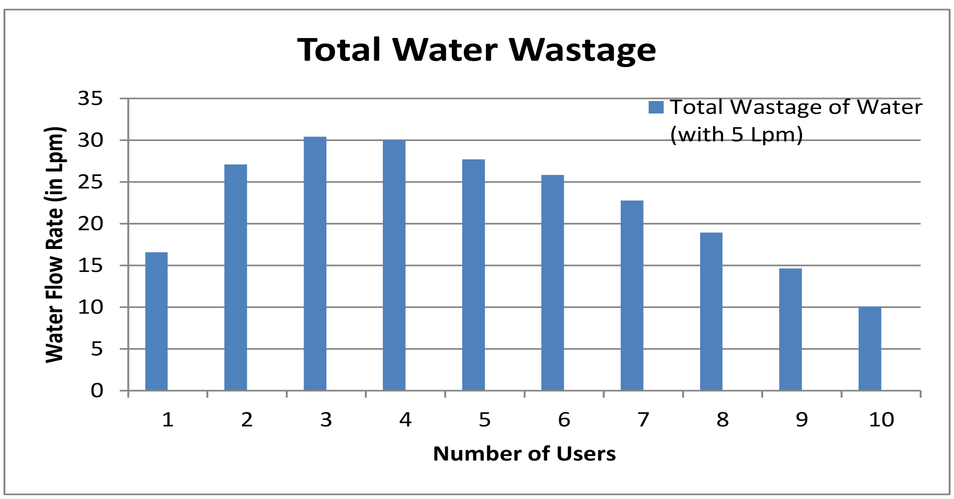


**Figure 6-9 Total Water Wastage (in lpm)**

The graph as shown in Figure 6-7 shows the system serving water to the users at different flow rate due to the pipeline effect. The graph, shown in Figure 6-8 demonstrates the average flow rate received by the taps and the required flow rate taps should receive. Any amount of water delivered above the required flow rate is water wasted. The graph shown in Figure 6-9 shows the total water wastage against the number of users in the system.

Now, we use the user arrivals to mimic a realistic scenario where in the average number of users is 2.5 and 4.5. Figure 6-10 and Figure 6-11 show the flow rate of water delivered to the system; we can see that water is pumped at much larger flow rate. Figure 6-12 and Figure 6-13 shows the amount of water used and wasted by this system; we notice that a substantial amount of water is wasted.

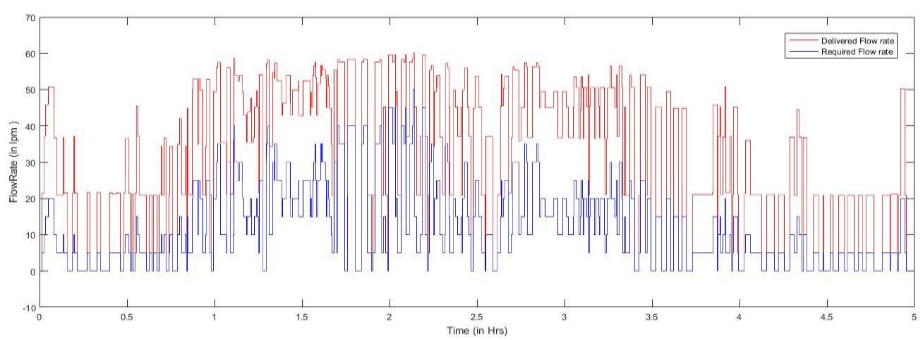


**Figure 6-10 Flow rate for FFPS (2.5 users' average)**

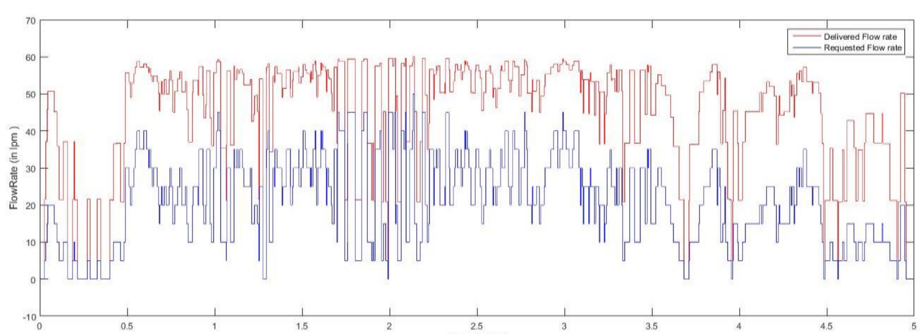


**Figure 6-11 Flow rate for FFPS (4.5 users' average)**

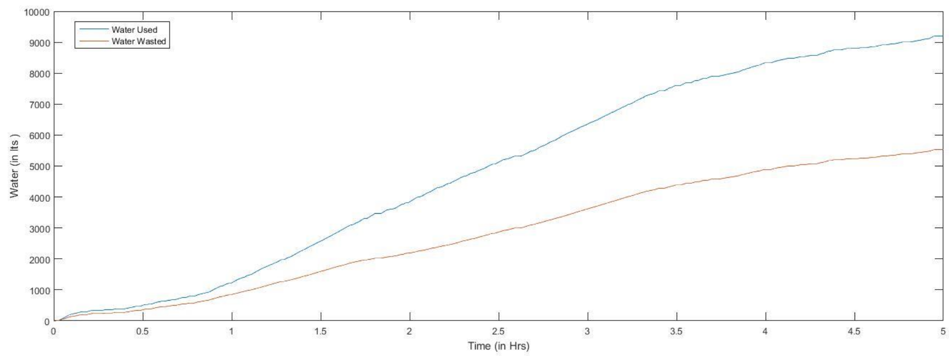


**Figure 6-12 Total Water used by FFPS (2.5 user average)**

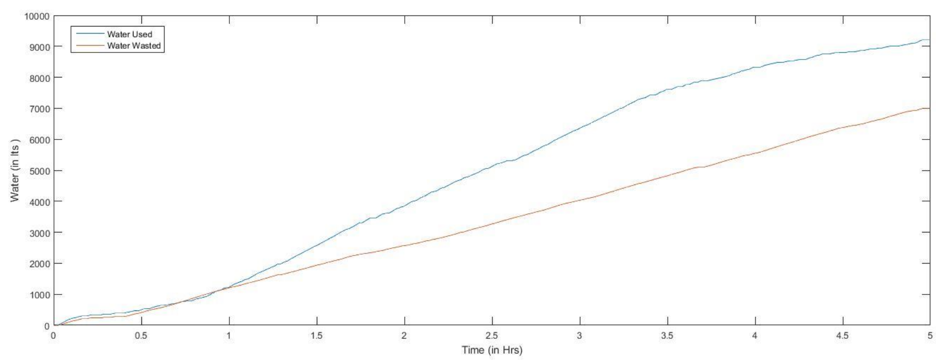


**Figure 6-13 Total Water used by FFPS (4.5 user average)**

From the results we can conclude that there is a lot of water wastage in the fixed flow pumping system since no mechanism to prevent the wastage of water is implemented.

## 6.3 TFCS with VFD System

In this sub section, we discuss the behavior of water flow rate delivered to the taps by the TFCS. The TFCS delivers water as per the users' requirements varying the speed of the pump. The graph shown in Figure 6-14 shows the total flow rate delivered by this system to the taps.

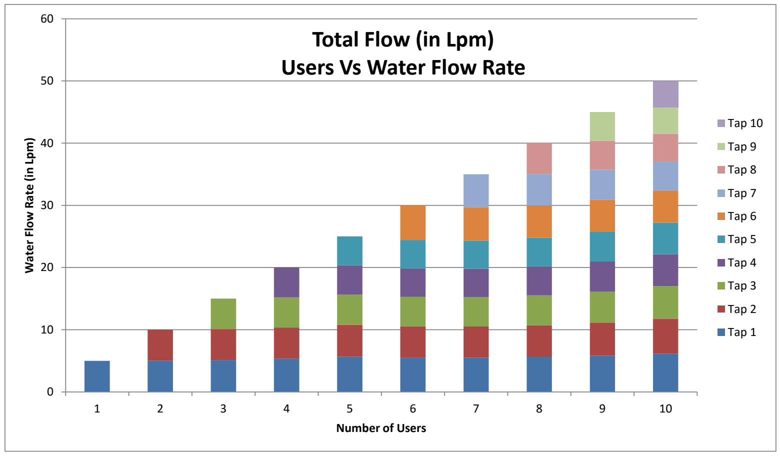


**Figure 6-14 Flow rate for TFCS with VFD (in lpm)**

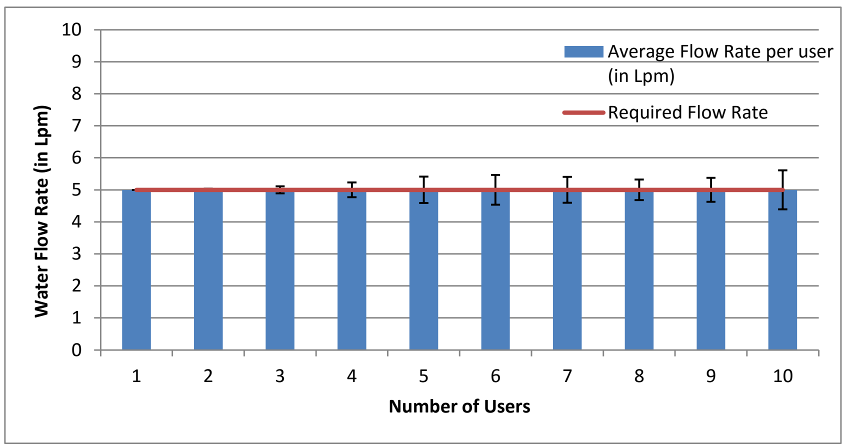


**Figure 6-15 Average Flow rate received per user (in lpm)**

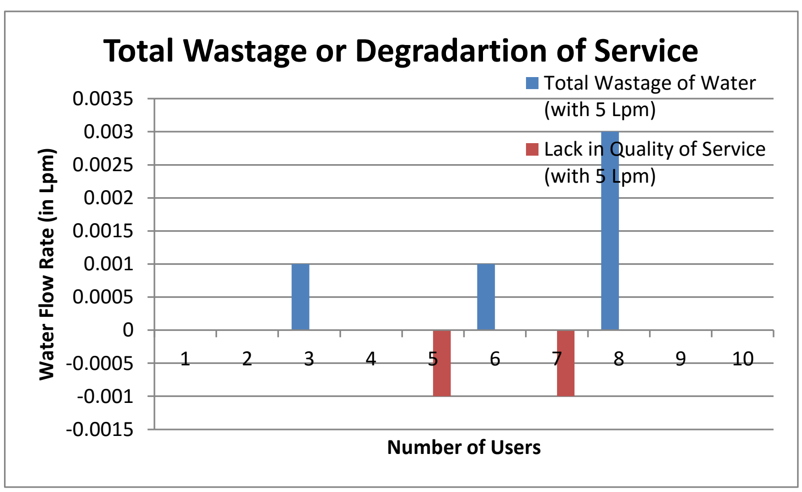


**Figure 6-16 Total Water Wastage and Lack in Quality (in lpm)**

The graph, shown in Figure 6-15 demonstrates the average flow rate delivered by the TFCS with VFD and the required flow rate the taps should receive. Any amount of water delivered above the required flow rate is water wasted. The graph shown in Figure 6-16 shows the total water wastage and the lack in the quality against the number of users in the system.

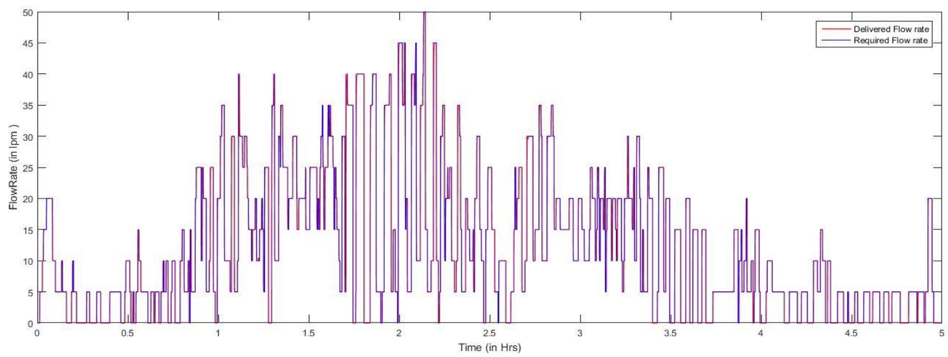


**Figure 6-17 Flow rate for TFCS with VFD (case when average is 2.5 users)**

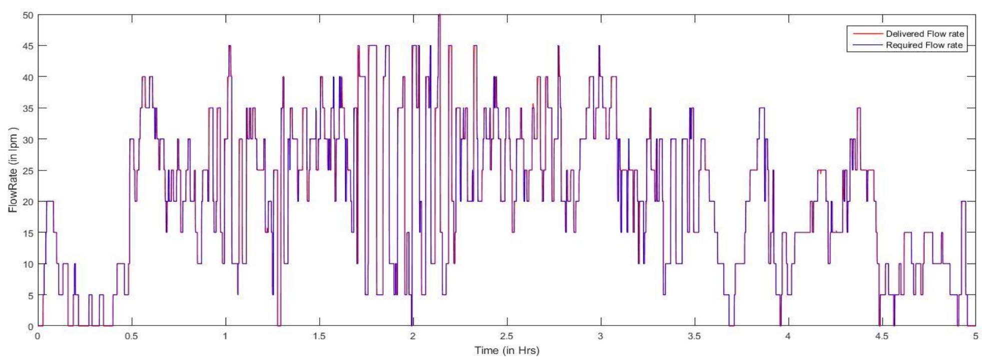


**Figure 6-18 Flow rate for TFCS with VFD (case when average is 4.5 users)**

Like in the previous sub section, we use the user arrivals to mimic a realistic scenario where in the average number of users is 2.5 and 4.5. Figure 6-17 and Figure 6-18 show the flow rate of water delivered by this system; we see that the TFCS with VFD delivers water at an optimum flow rate. Figure 6-19 and Figure 6-20 shows the amount of water used and wasted by this system for the two simulation cases when average number of users is 2.5 and 4.5; we infer from these figures that the water wastage is very less when compared to the FFPS.

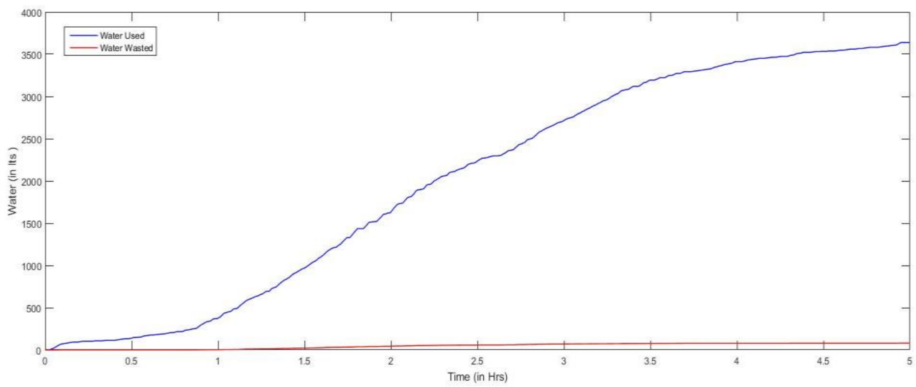


**Figure 6-19 Total Water Used by TFCS with VFD (case when average is 2.5 users)**

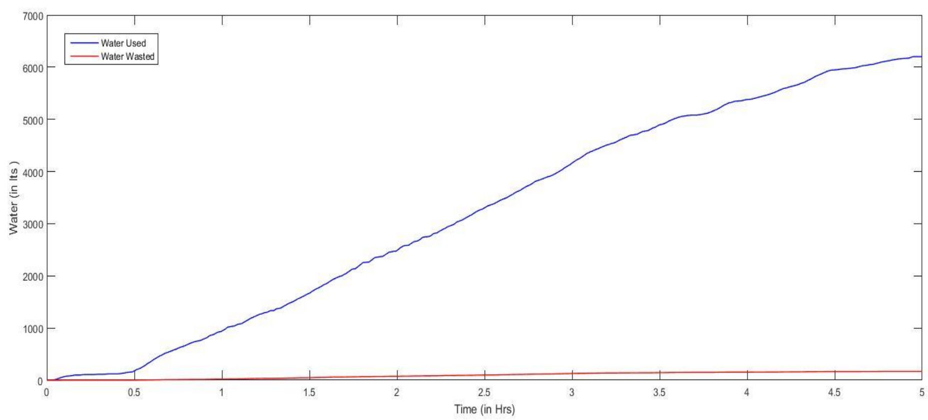


**Figure 6-20 Total Water Used by TFCS with VFD (case when average is 4.5 users)**

## 6.4 IPWPS

In this sub section, we illustrate and discuss the behavior of the water supply flow rate delivered to the taps by the IPWPS. The IPWPS delivers water to the users by switching ON/OFF the number of pumps to match the user demand.

The graph shown in Figure 6-21 shows the total flow rate delivered by IPWPS to the taps. The graph, shown in Figure 6-22 demonstrates the average flow rate delivered by the IPWPS and the required flow rate the taps should receive.

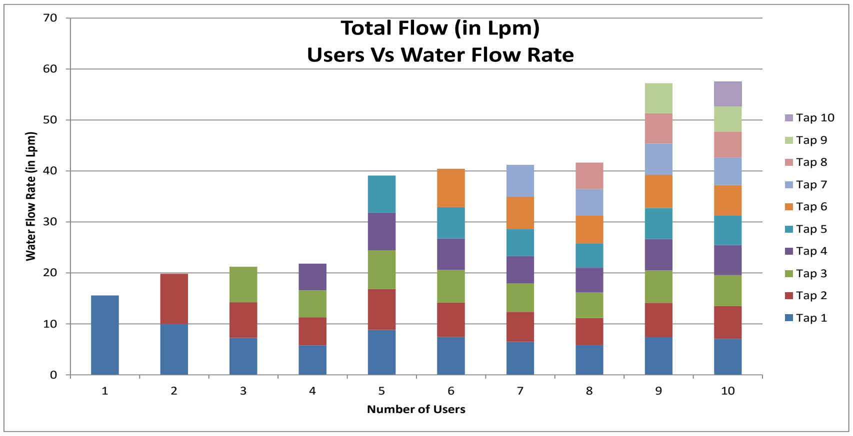


**Figure 6-21 Flow rate for different taps in pipeline (in lpm)**

As mentioned earlier, any amount of water delivered above the required flow rate is water wasted. The graph shown in Figure 6-23 shows the total water wastage against the number of users in the system.

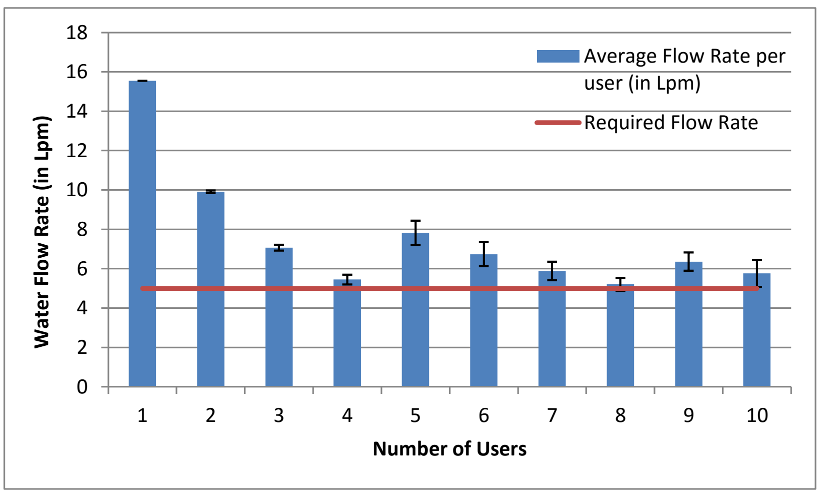


**Figure 6-22 Average Flow rate received per user (in lpm)**

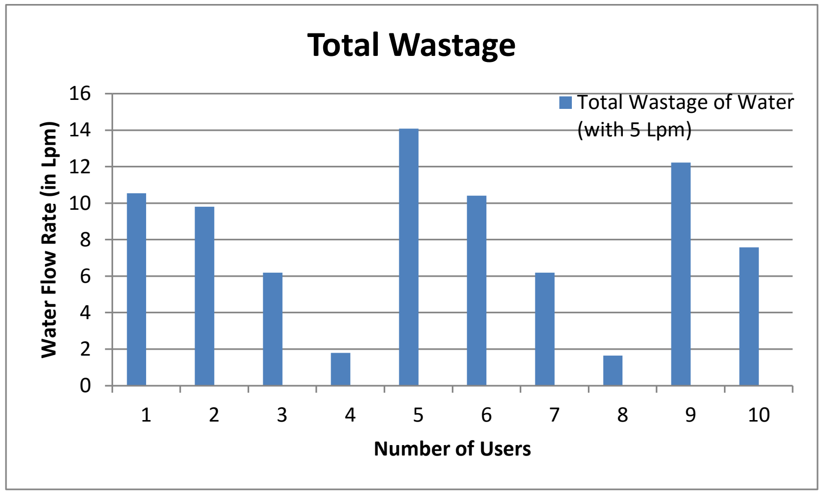


**Figure 6-23 Total Water Wastage (in lpm)**

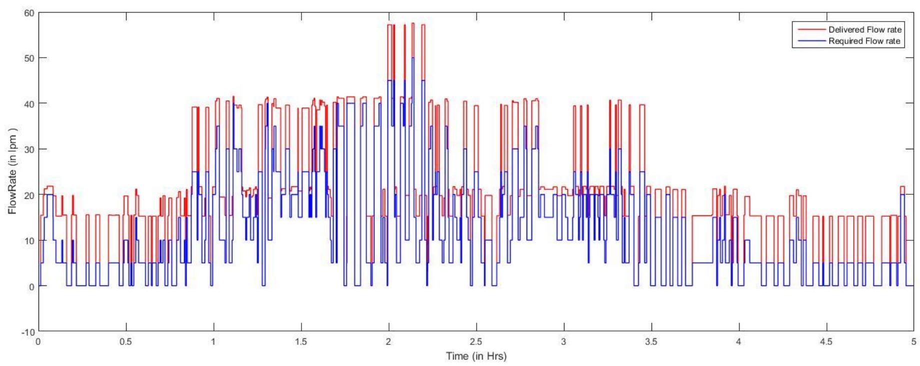


**Figure 6-24 Flow rate for IPWPS (case when average is 2.5 users)**

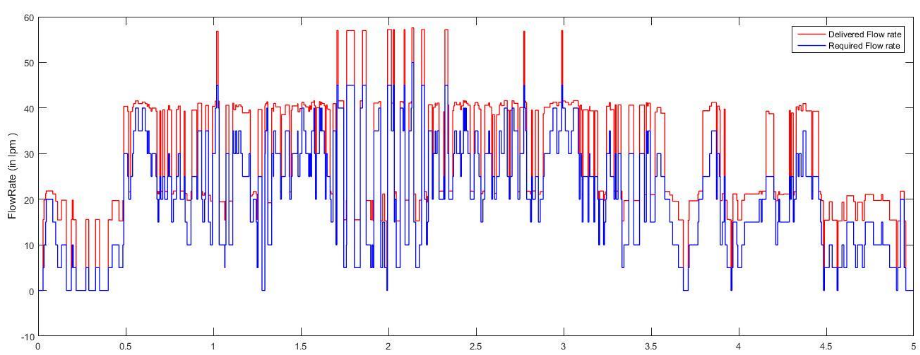


**Figure 6-25 Flow rate for IPWPS (case when average is 4.5 users)**

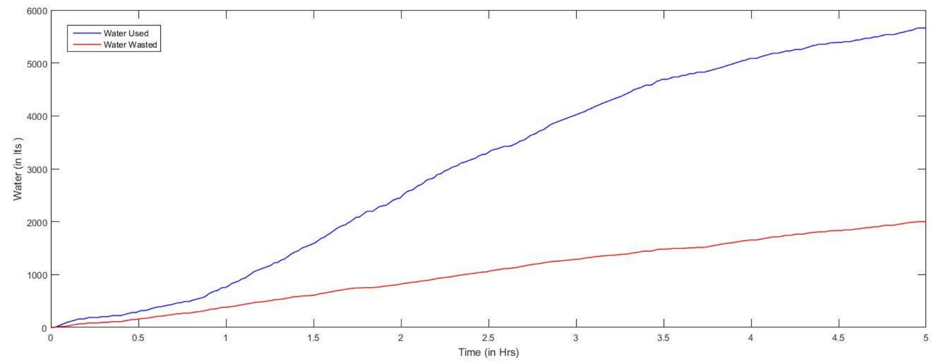


**Figure 6-26 Total Water Used by IPWPS (case when average is 2.5 users)**

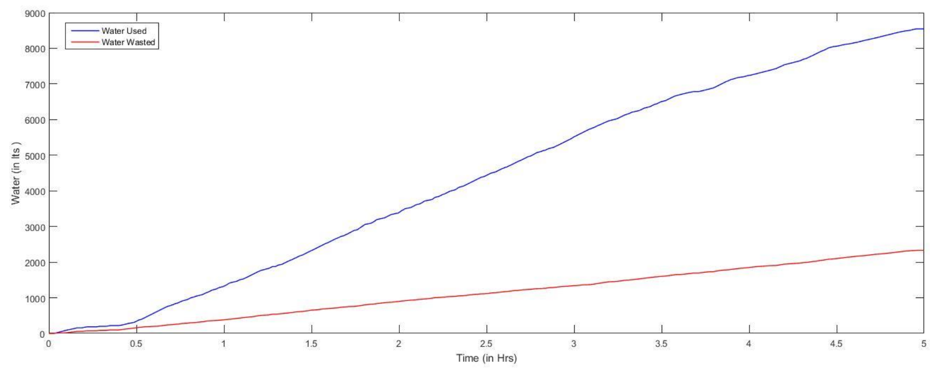


**Figure 6-27 Total Water Used by IPWPS (case when average is 4.5 users)**

The user arrivals, where in the average number of users is 2.5 and 4.5, are used for gauging the water usage. Figure 6-24 and Figure 6-25 show the flow rate of water delivered by IPWPS; we see that this system delivers water at comparatively lower flow rate when compared to the FFPS. Figure 6-26 and Figure 6-27 shows the amount of water used and wasted by this system for the two simulation cases when average number of users is 2.5 and 4.5; we surmise from these figures that the water wastage is lesser when compared to the FFPS.

## 6.5 WBWPS

In this sub section, we describe and discuss the behavior of the water supply flow rate delivered to the taps by the WBWPS. The WBWPS delivers water to the users by logic circuit to switch ON/OFF the correct combination of pumps to match the user demand. The graph shown in Figure 6-28 shows the total flow rate delivered by WBWPS to the taps. The graph, shown in Figure 6-29 demonstrates the average flow rate delivered by the WBWPS and the required flow rate the taps should receive.

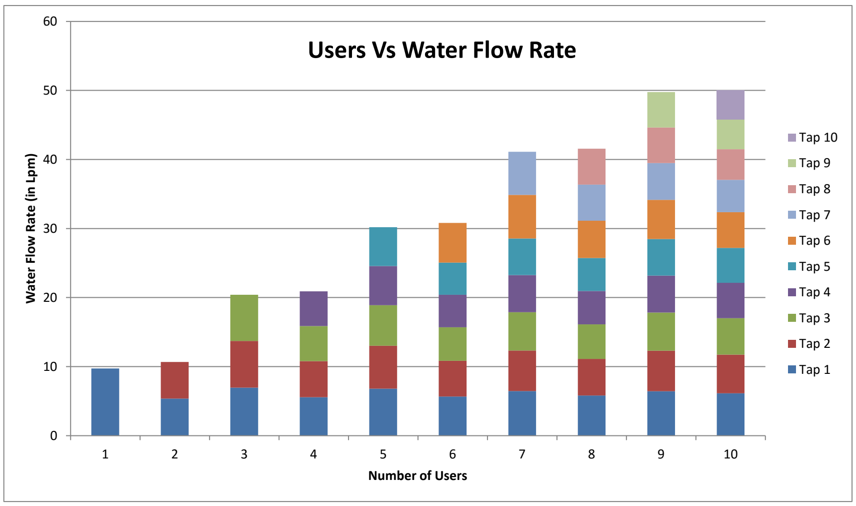


**Figure 6-28 Flow rate in pipeline for WBWPS (in lpm)**

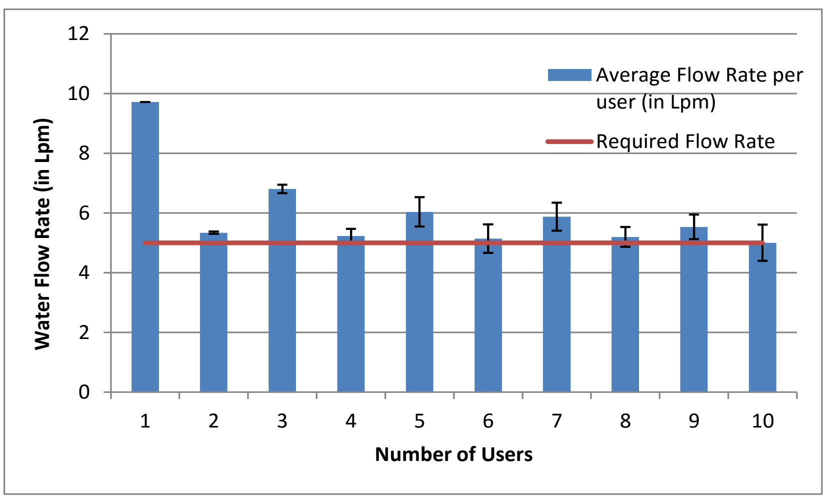


**Figure 6-29 Average Flow rate received per user (in lpm)**

As stated earlier, any amount of water delivered above the required flow rate is water wasted. The graph shown in Figure 6-30 shows the total water wastage against the number of users in the system. The user arrivals, where in the average number of users is 2.5 and 4.5, are used for gauging the water usage.

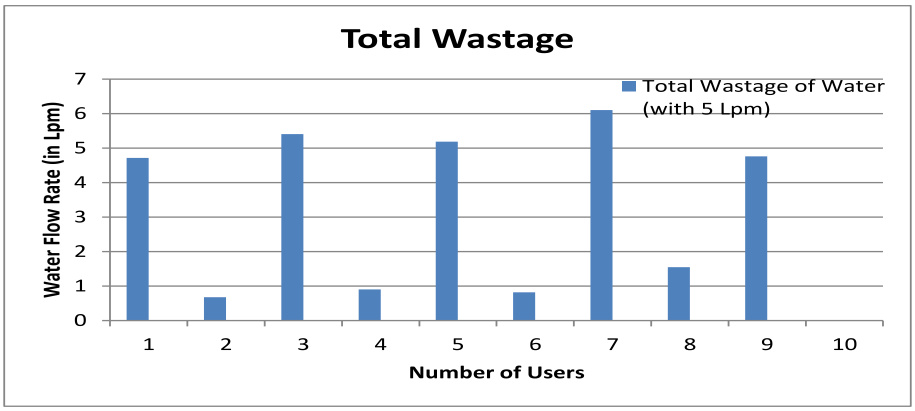


**Figure 6-30 Total Water Wastage (in lpm)**

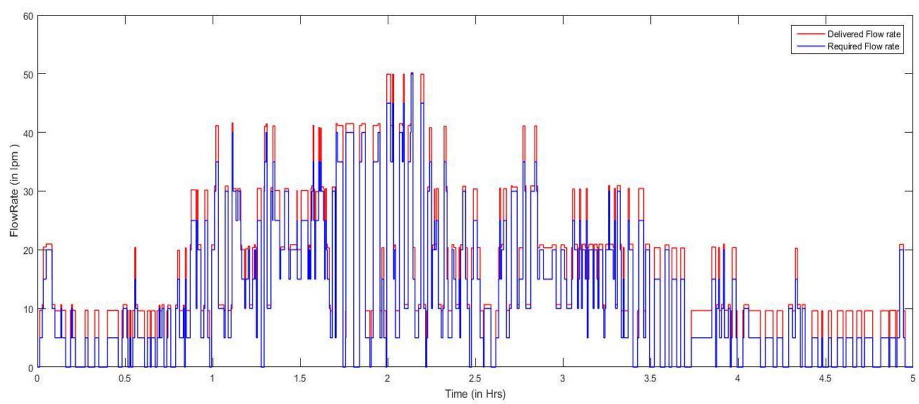


**Figure 6-31 Flow rate for WBWPS (2.5 users' average)**

Figure 6-31 and Figure 6-32 show the flow rate of water delivered by WBWPS; we see that this system delivers water at comparatively lower flow rate when compared to the IPWPS. Figure 6-33 and Figure 6-34 shows the amount of water used and wasted by this system for the two simulation cases when average number of users is 2.5 and 4.5; we surmise from these figures that the water wastage is lesser when compared to the IPWPS.

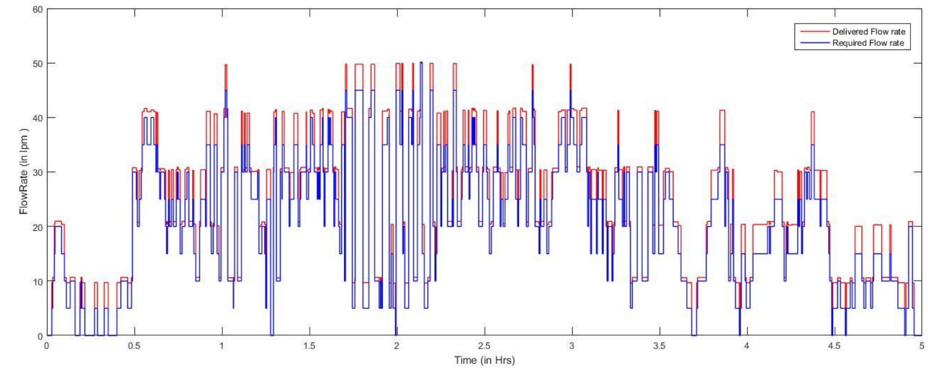


**Figure 6-32 Flow rate for WBWPS (4.5 users' average)**

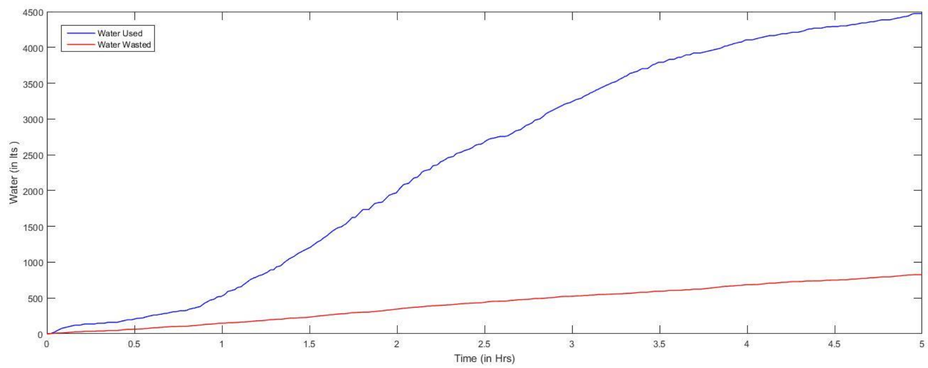


**Figure 6-33 Total Water Used by WBWPS (4.5 user average)**

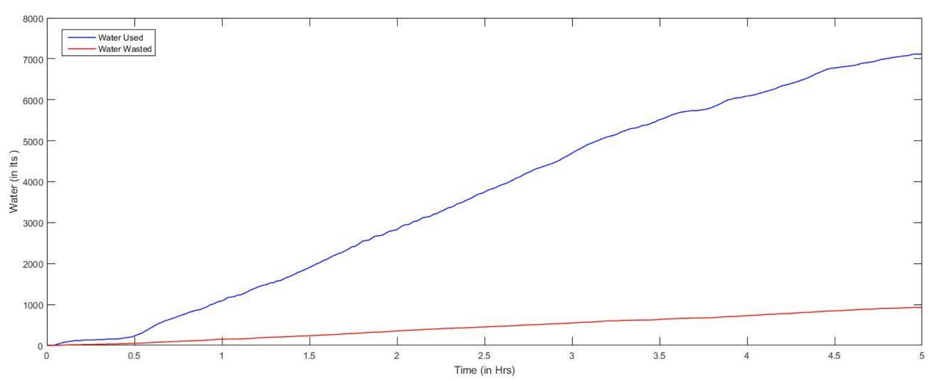


**Figure 6-34 Total Water Used by WBWPS (4.5 user average)**

## 6.6 Comparison

In this sub section, we will compare the results obtained for each of the systems in terms of average flow rates, total water wasted and total flow delivered by the pumping systems.

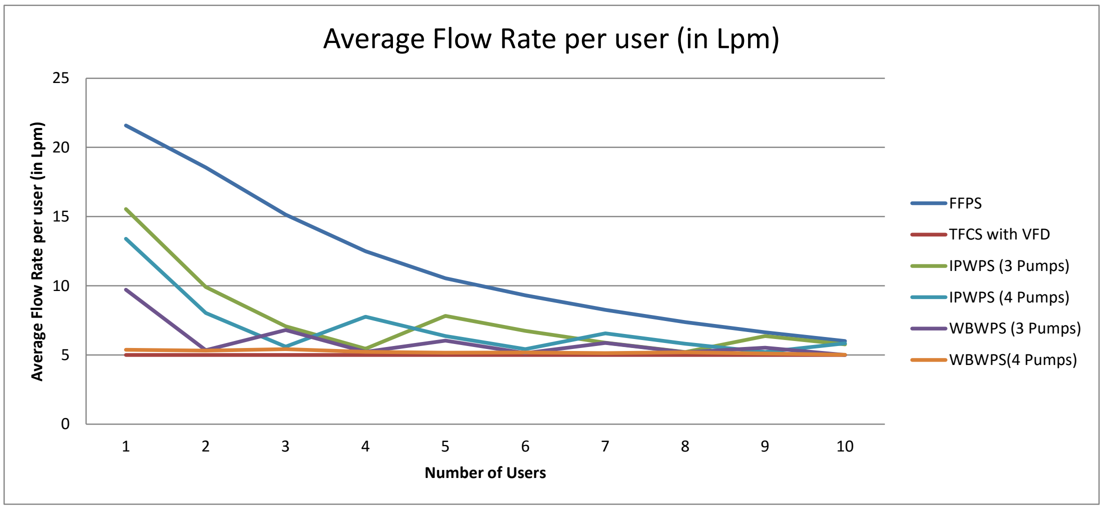


**Figure 6-35 Average flow rate per user delivered**

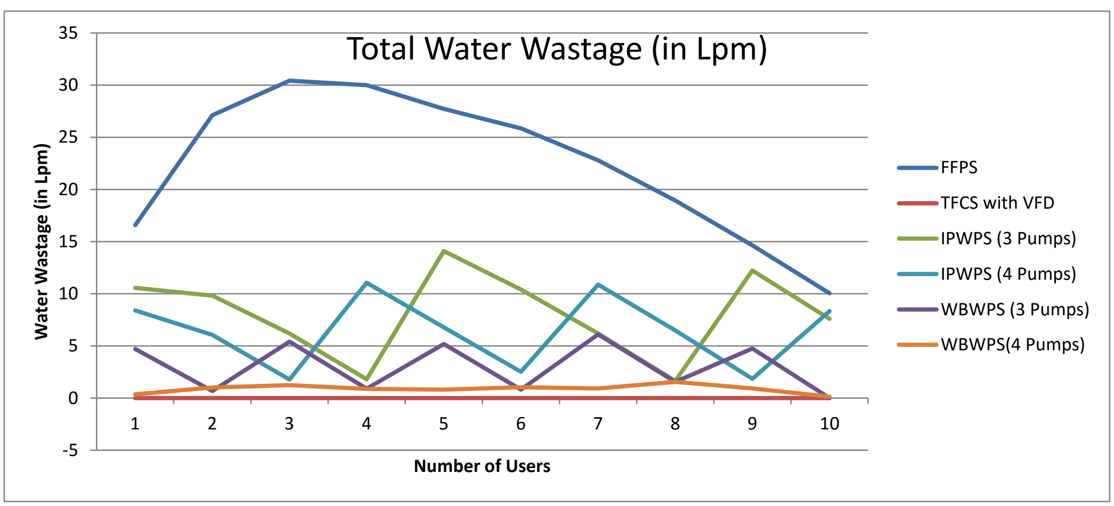


**Figure 6-36 Total water wastage**

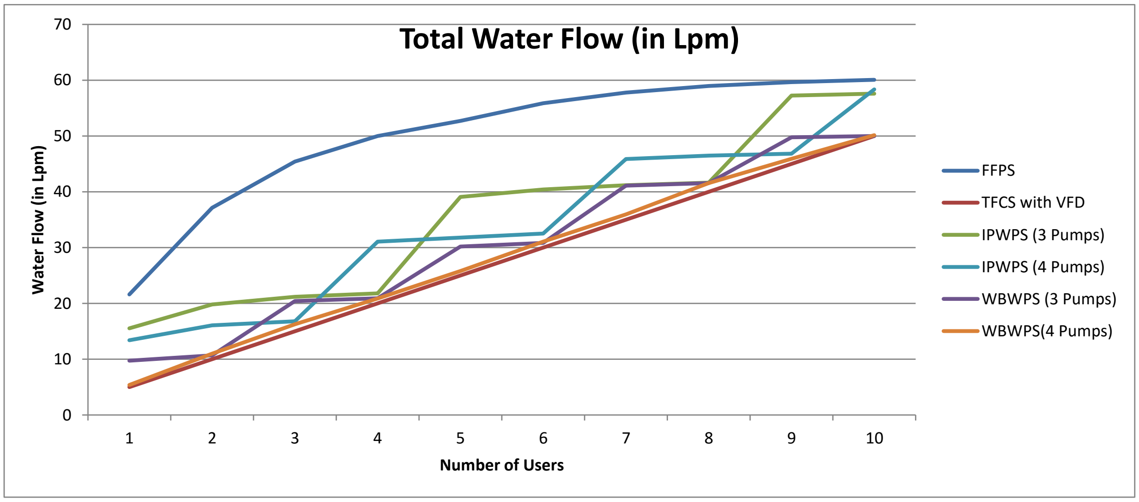


**Figure 6-37 Total flow delivered by systems**

The graph in Figure 6-35 shows the average flow rate per user delivered; the graph in Figure 6-36 shows the total water wastage and the graph in Figure 6-37 illustrates the total flows delivered by the systems.

We can notice that WBWPS and TCFS have the optimal performance in terms of water usage. We also notice a substantial reduction in water wastage by any system when compared to FFPS.

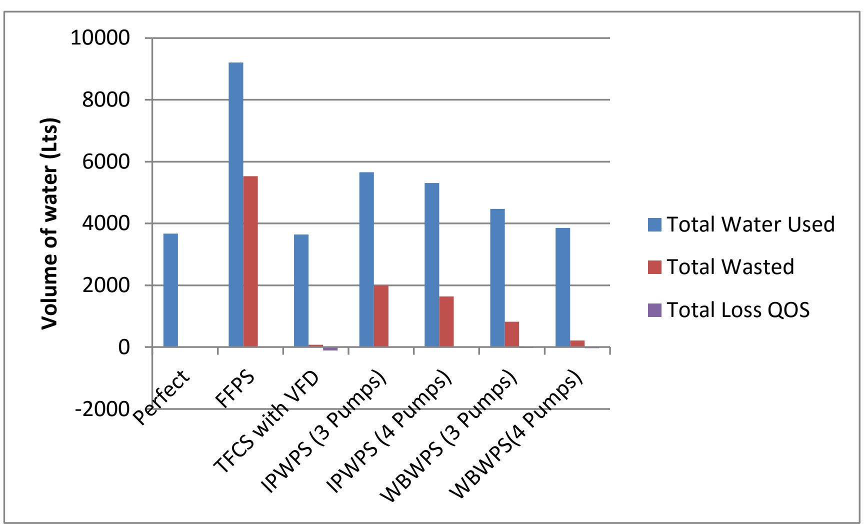


**Figure 6-38 Comparison of Water usage (2.5 user average)**

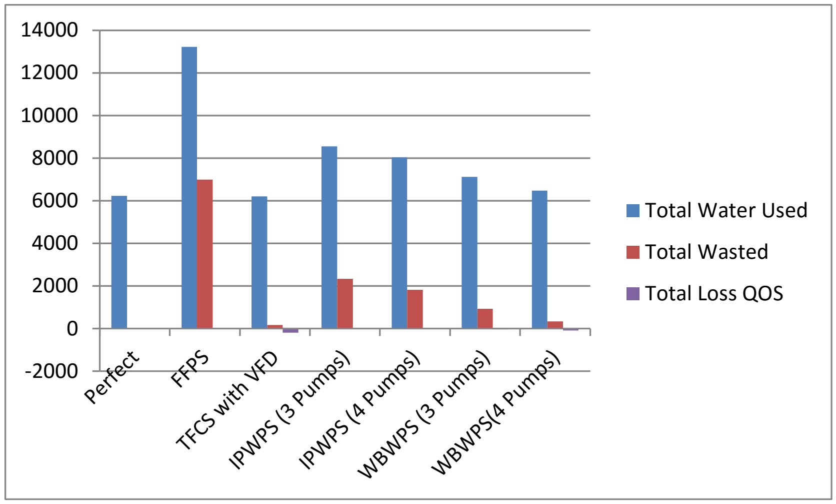


**Figure 6-39 Comparison of Water usage (4.5 user average)**

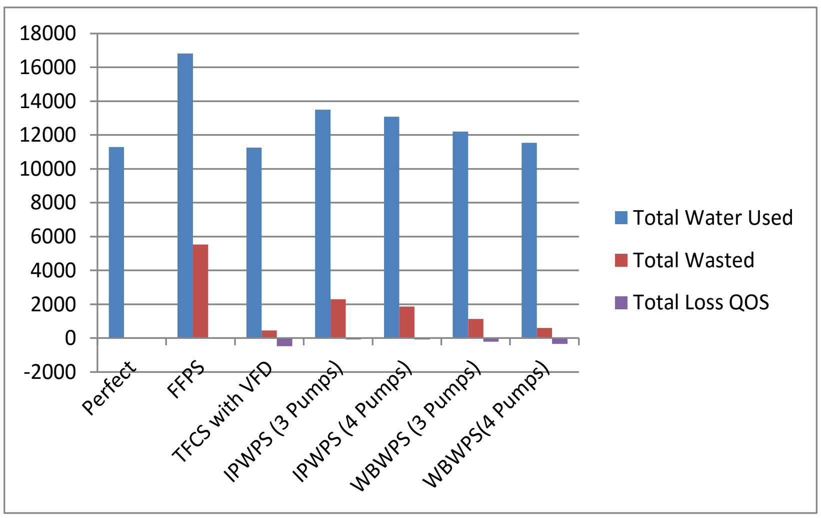


**Figure 6-40 Comparison of Water usage (7.5 user average)**

The graphs in Figure 6-38, Figure 6-39 and Figure 6-40 show the three cases where in the average number of users at any point of time in the system are 2.5, 4.5 users and 7.5 users; here the total amount of water used for these simulation runs is compared. We can derive the conclusion that any form of automation or control by a cyber physical can conserve substantial amount of water.

The graph is Figure 6-41 shows that by using adaptive pumping we can conserve some amount of water at all times; the conservation is high when less than the maximum possible users are using the system. In case of 2.5, 4.5 & 7.5 active valves for WBWPS we observe a saving of 30-60% in water usage.

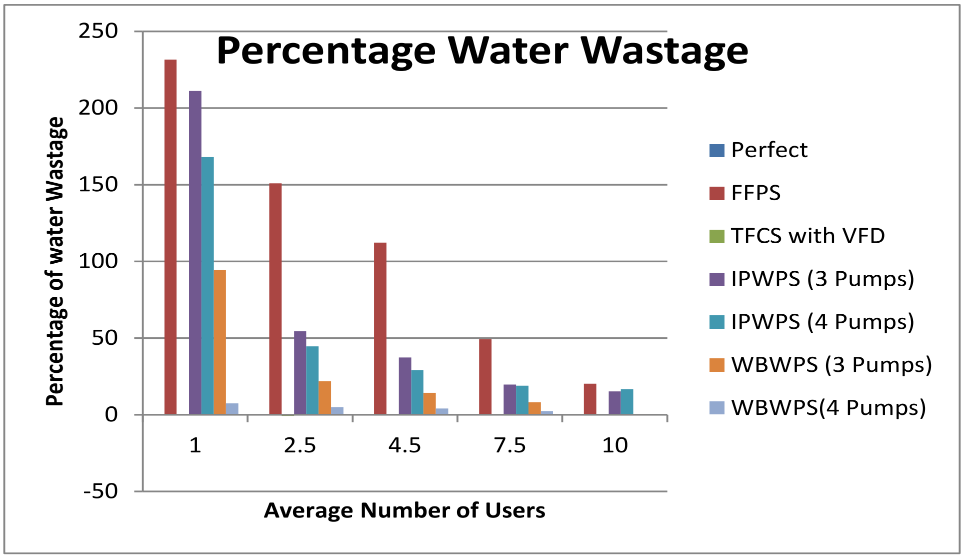


**Figure 6-41 Percentage water wastage vs. average users**

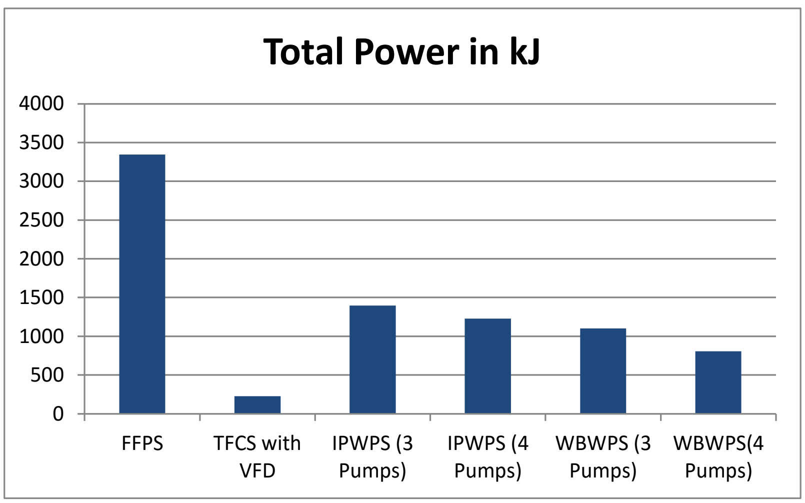


**Figure 6-42 Power consumption for 2.5 user average**

The power consumption for the different systems has been calculated in kJ for the simulation time. Figure 6-42, Figure 6-43 and Figure 6-44 show the power consumptions of the various systems over simulation time. We see that the power consumed for the

FFPS does not change based upon number of users. Also a considerable amount of reduction is seen in power consumed by the other systems when compared to FFPS.

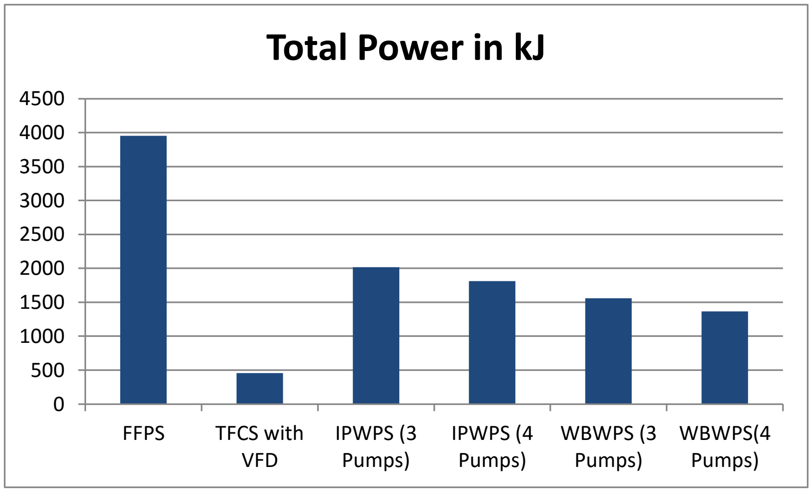


**Figure 6-43 Power consumption for 4.5 user average**

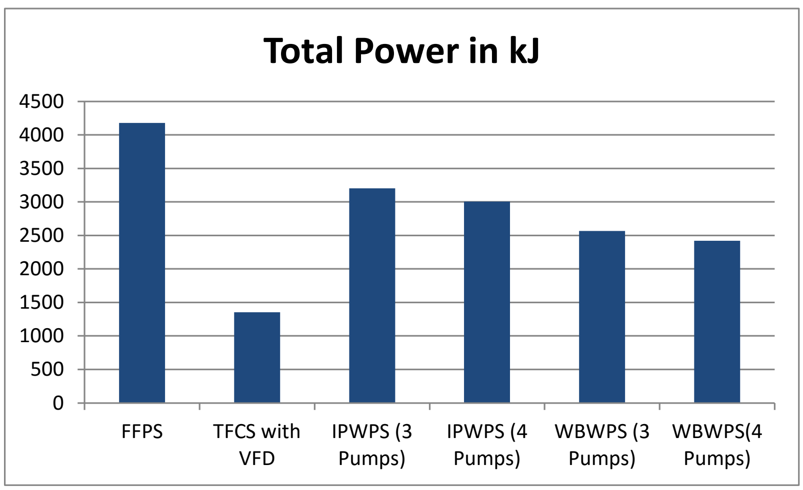


**Figure 6-44 Power consumption for 7.5 user average**

The graph is Figure 6-45 shows that by using adaptive pumping we can conserve some amount of energy at all times; the conservation is high when less than the maximum possible users are using the system. In case of 2.5, 4.5 & 7.5 active valves for WBWPS we observe nearly 40-75% energy savings.

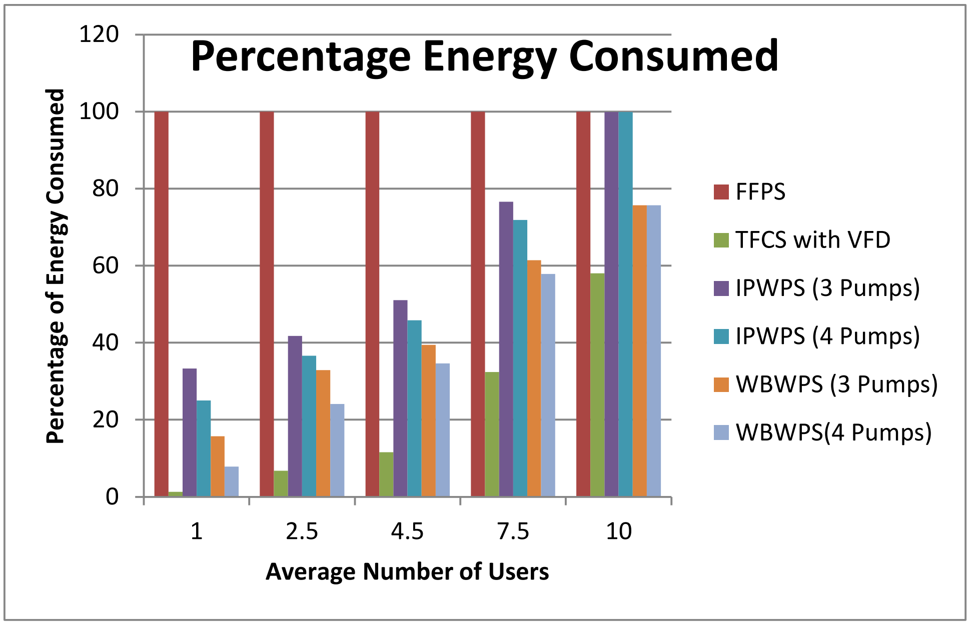


**Figure 6-45 Percentage energy consumed vs. average users**

**Table 6-1 Power Consumption analysis of a university**

| Power Consumption Cost of a University | | | | | | |
|---|---|---|---|---|---|---|
| Pumping System | kJ for 5 hrs | KWh for 5 hrs | KWh for 10 hrs | KWh for 1 year | Annual Cost ($) | Savings($) |
| FFPS | 3347 | 0.93 | 1.86 | 418.38 | 66.94 | 0 |
| TFCS with VFD | 226 | 0.06 | 0.13 | 28.25 | 4.52 | 62 |
| IPWPS (3 Pumps) | 1397 | 0.39 | 0.78 | 174.63 | 27.94 | 39 |
| IPWPS (4 Pumps) | 1226 | 0.34 | 0.68 | 153.25 | 24.52 | 42 |
| WBWPS (3 Pumps) | 1101 | 0.31 | 0.61 | 137.63 | 22.02 | 45 |
| WBWPS(4 Pumps) | 807 | 0.22 | 0.45 | 100.88 | 16.14 | 51 |

**Table 6-2 Water Consumption analysis of a university**

| Water Consumption Cost of a University | | | | | | |
|---|---|---|---|---|---|---|
| Pumping System | Lts for 5 hrs | Lts for 1 Day | Lts for 1 year | Cost per year($) | Savings ($) | Subsdised ($) |
| FFPS | 9202 | 18404 | 4140900 | 11553.11 | 0 | 0 |
| TFCS with VFD | 3640 | 7280 | 1638000 | 4570.02 | 6983 | 2002 |
| IPWPS (3 Pumps) | 5661 | 11322 | 2547450 | 7107.39 | 4446 | 1275 |
| IPWPS (4 Pumps) | 5304 | 10608 | 2386800 | 6659.17 | 4894 | 1403 |
| WBWPS (3 Pumps) | 4474 | 8948 | 2013300 | 5617.11 | 5936 | 1702 |
| WBWPS(4 Pumps) | 3851 | 7702 | 1732950 | 4834.93 | 6718 | 1926 |

Cost Analysis for a University Scenario has been done where in the average users at any point in Time 2.5 and ten is the working hours per day. A typical academic year has 45 working weeks and 5 days a week. The cost of water is 2.79$ per meter cube, cost of power is 0.16$ per kWh and Saudi subsidized cost of water per meter cube is $0.8. Table 6-1 and Table 6-2 show the cost computation for a university scenario.

**Table 6-3 Power Consumption analysis of a mall**

| Power Consumption Cost of a Mall | | | | | | |
|---|---|---|---|---|---|---|
| Pumping System | kJ for 5 hrs | KWh for 5 hrs | KWh for 10 hrs | KWh for 1 year | Annual Cost ($) | Savings($) |
| FFPS | 3952 | 1.10 | 2.20 | 801.38 | 128.22 | 0 |
| TFCS with VFD | 457 | 0.13 | 0.25 | 92.67 | 14.83 | 113 |
| IPWPS (3 Pumps) | 2016 | 0.56 | 1.12 | 408.80 | 65.41 | 63 |
| IPWPS (4 Pumps) | 1812 | 0.50 | 1.01 | 367.43 | 58.79 | 69 |
| WBWPS (3 Pumps) | 1557 | 0.43 | 0.87 | 315.73 | 50.52 | 78 |
| WBWPS(4 Pumps) | 1367 | 0.38 | 0.76 | 277.20 | 44.35 | 84 |

**Table 6-4 Water Consumption analysis of a mall**

| Water Consumption Cost of a Mall | | | | | | |
|---|---|---|---|---|---|---|
| Pumping System | Lts for 5 hrs | Lts for 1 Day | Lts for 1 year | Cost per year($) | Savings ($) | Subsdised ($) |
| FFPS | 13220 | 26440 | 9650600 | 26925.17 | 0 | 0 |
| TFCS with VFD | 6203 | 12406 | 4528190 | 12633.65 | 14292 | 4098 |
| IPWPS (3 Pumps) | 8547 | 17094 | 6239310 | 17407.67 | 9517 | 2729 |
| IPWPS (4 Pumps) | 8039 | 16078 | 5868470 | 16373.03 | 10552 | 3026 |
| WBWPS (3 Pumps) | 7116 | 14232 | 5194680 | 14493.16 | 12432 | 3565 |
| WBWPS(4 Pumps) | 6481 | 12962 | 4731130 | 13199.85 | 13725 | 3936 |

Cost Analysis for a Mall Scenario has been done where in the average users at any point in Time 4.5 and ten is working Hours per day. Malls are usually operational throughout the year (365 days). The cost of water is 2.79$ per meter cube, cost of power is 0.16$ per kWh and Saudi subsidized cost of water per meter cube is $0.8. Table 6-3 and Table 6-4 show the cost computation for a mall scenario.

From the cost analysis performed we can infer that by employing intelligent adaptive pumping techniques we can save a considerable amount of water and energy. The savings for each of these scenarios have been converted to cost in dollars for estimations and analysis purposes.

# CHAPTER 7

# CONCLUSION AND FUTURE WORK

In this thesis, we proposed, designed, simulated and analyzed a novel variable pumping system called the Wireless Binary Water Pumping System (WBWPS) consisting of pumps with binary sequence of pumping capacity (5.5,11, 22, & 42 liters/minute) The various other systems such as the Fixed Flow Pumping System (FFPS, 70 l/min), Total Flow Control System (TFCS) with Variable Frequency Drives (VFD, max of 70 l/min) and Identical Pumps Water Pumping System (IPWPS, 3 pumps of 23 l/min and 4 pumps of 17.5 l/min) have been simulated, analyzed and compared with the proposed system in terms of water wastage and energy efficiency. The FFPS with no sensor and a control system makes no effort to serve the users with desired flow rate. All the variable pumping systems namely TFCS with VFD, IPWPS and the proposed WBWPS outperform the conventional FFPS by reducing water and energy wastage, as well as serving water to the users conforming to the minimum QoS criteria. The results show that automation or eliminating the manual control can significantly reduce water and energy wastage in homes and public places. The proposed WBWPS performed better than the IPWPS in terms of saving both water and energy. The proposed system saves 30-60% water and gives us 40-75% energy savings.

In our future work, we are going to implement the newly proposed systems using Arduino boards, sensors, relays, centrifugal pumps and valves. The physical system will help confirming the simulation results.

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