Exploring different types of game mechanics based around water flow in pipes

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Abstract

Water flow through pipes in games is a broad topic that involves many interesting game mechanics. There is a sufficient lack of innovative water based game mechanics used in current games available today; when implemented mechanics are often unrealistic, two-dimensional or in the form of a ‘mini-game’ only. Water wastage is also a pressing topic; if the general public were more informed about this problem then it could help save on the demand for water purification.

This project aims to expand upon the core game mechanic of pipe placement in a construction-management simulation game; this is done by allowing the user to control water flow through a piping network of their construction, using it to manage water requirements. The game includes realistic engineering equations which subtlety require the user to consider the basics of fluid mechanics; this is done by the introduction of different pipe sizes and connectors which all affect the behaviour of the water flow. Lastly the game introduces the user to water purification and treatment, teaching them about the processes and highlighting its many stages and complexity.

Acknowledgements

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List of Symbols

A	Area
d	Diameter
h	Height of water tower and contained liquid height
l	Length of Pipe
m	Meters (unit)
r	Radius
s	Seconds (unit)
t	Time
v	Velocity
V	Volume
π	Constant: Pi
ρ	Fluid density

Word Glossary

CMS – Construction management and simulation (game genre).

Demand – The amount of water being requested by the village structures.

Destination Structure – A structure that is receiving water from the pipe network.

DWI – Drinking Water Inspectorate.

FPS – Frames per second.

EPA – United States Environmental Protection Agency.

GUI – Graphical User Interface.

Input Pipe – A pipe that connects to the above ground structure, that will transfer water being provided from a pipe below upwards to the structure.

I/O Pipes – Input pipes and output pipes.

Junction – A pipe that splits the water flow.

MCL – Maximum contaminant level.

MPN – Most Probable Number.

MRDL - Maximum Residual Disinfectant Level.

NTU - Nephelometric Turbidity Unit.

Output Pipe – A pipe that outputs water from the above structure downwards, to be connected to with more pipes.

(Purification) Processor - A stage of the water purification process that appears within the purification facility when bought that will take in water and clean some type of contaminant from it.

Sink – the side of the pipe where water is flowing out.

Source Structure – A structure that is providing water into the pipe network.

Source – the side of the pipe where water is flowing in.

Structure - A building that you can place on the surface (pump, purification facility, water tower, houses, offices and farmland).

TON – Threshold odour number.

Village – A summary of all the houses, offices and farmlands within the world.

Village structure / Village block - Structures that are affected by the incoming water, relative to their demand, that make up part of a village (houses, offices and farmland).

1 - Introduction

Water flow within pipes is an interesting topic that is underexplored within games. The act of placing pipes as a game mechanic has many possibilities; adding context to what pipes are connected to, the types of water transported and means of transportation are all examples. Games involving pipes are usually in the form of a small mini-game, where players rotate and swap pipes, while a slow liquid passes through them; this is a stale format, there's a need for innovation which could bring pipe flow more realistic properties such as: fluid dynamics simulation allowing for a faster paced game format.

Water wastage is a global issue; large quantities of water are wasted in areas of abundance whereas in area of scarcity people suffer, settling for unsanitary drinking water. In the UK, we live with an abundance of clean water and do not consider the processes required to provide us with it. As populations raise so does the demand for sanitary water; preparations are needed in our infrastructure to cope; this begins with our mindfulness of the clean water that we waste.

1.1 - The Plan

The plan is to create a game that is of the construction management simulation (CMS) genre; the game will allow a player to toggle between above and below ground modes. Above ground the player will be able to erect various structures; below ground the player can construct and intricate subterranean piping network comprised of many pipe shapes and sizes. The player will need to link up the structures together with the subterranean piping, thus allowing water to flow between them.

The game will allow the players to obtain the water from a water source using a pump. The player is then taken through the water purification processes; the water can then be stored and/or distributed via piping to the various consumers. The game should simulate the 'rising population' problem by gradually increasing village populations; this forces the player to adapt their in-game water system infrastructure to keep up with the increased water demand.

If consumers are in lack of enough clean safe water, then this will have a negative impact on the varying types of consumer; this could reduce population, lower income and prevent crops from being grown on badly irrigated farmland soil.

1.2 - Aim and Objectives

Project Aim

To explore the interesting game mechanics of water flow through pipes, this is to be done through a fun and engaging water resource management game which will promote water conservation while teaching about water purification, contaminants and the life cycle of water.

Objectives:

1. To make sure to have a comprehensible UI so that it has minimalistic coherent navigation with features like: clear outline of selected tools, tool tips when hovering, current objectives and an in-game help button.
2. To educate the users about the serious problem that water wastage and to inform them about how much effort it put into processing their water so they should be more conservative about the water they use.
3. Research the steps involved to purify dirty water within a facility and simulate the key stages of the process within the game through the form of a purification facility upgrade system. Each stage of the process within the facility should purify the water more and more removing different unwanted impurities from the water.
4. Research the physics behind how water flows through pipes and implement some of the key features into the water flow simulation of the game, this would include things like pipe circumference, water velocity and flowrate.
5. To try and make sure that the game is enjoyable, to do this, a variety of attributes to make it engaging. Randomness of weather conditions and the placement of resources/structures within the world will add replay value.
6. [Stretch Objective] To implement an oil system into the game, like the water mechanics, so this will involve obtaining the oil, purifying it and piping it to its desired destination.
7. [Stretch Objective] To achieve a fluid gameplay experience, previews of structures or pipes should be shown when the player is deciding where to place them, this can be done by showing the object on the centre of the tile that the mouse is pointing on at a deduced opacity, additionally when placing pipes, previews of nearby pipes connecting to the preview pipe will make the game seem more fluid. Secondly the

underground view of pipe placement should be clear: you should be able to see the pipes in the dirt while still showing what structures they connect to in the above ground.

2 - Literature Review

This project is heavily based on all areas of water, and thus is the focus of the literature review. The fields of study relating to water are the fluid mechanics and purification. Fluid mechanics is used here to describe the transportation of water through piping. The methods of purification are explored here which not only describe how water can be purified, removing many types of contaminant but also how those contaminants affect humans if left untreated. Research will also be done into the genre of CMS and other water flow games, this will inform about how to stay within the format of the genre, while getting inspiration from other water flow games. Finally, research will be done into making games enjoyable and educational, as that coincides with my objectives.

2.1 - Water flow within pipes

Implementing a completely 100% accurate fluid mechanics simulation would be extremely difficult, resource intensive, unnecessary in the context of a game and beyond reasonable project expectations. Instead a 'stripped-down' version of fluid mechanics should be implemented to simulate the key features necessary to the game.

2.1.1 - Flowrate

When dealing with water flow within pipes there are near countless factors that come into play; a key factor is flowrate. "The volume flow rate Q of a fluid is defined to be the volume of fluid that is passing through a given cross sectional area per unit time" (Khan Academy, 2015a); the SI units are m^3s^{-1}. One special factor about flowrate is that it remains constant through an open ended but otherwise closed system.

$$Q = constant \quad Q_1 = Q_2$$

(Khan Academy, 2015a)

There are two main forms in which the formula for flowrate is defined, one is in terms of volume ***V***(SI unit is m^3) over time ***t***(SI unit is s), which is what flowrate is effectively based on. The other is rearranged in terms of velocity **v**(measured in m/s) and area **A**(measured in m^2).

$$Q = \frac{V}{t} \quad Q = Av$$

(Khan Academy, 2015a)

Equations four and five are derived from equations one, two and three. These are useful when computing velocity following a change in pipe diameter.

$$\frac{V_1}{t_1} = \frac{V_2}{t_2} \quad A_1 v_1 = A_2 v_2$$

(Khan Academy, 2015a)

2.1.2 - The Bernoulli Equation

To see how different heights and pressures affect the velocity of an incompressible fluid through a pipe continuum, the Bernoulli equation should be used. The Bernoulli equation is a mathematical generalisation of the Bernoulli principal which is defined as: “Within a horizontal flow of fluid, points of higher fluid speed will have less pressure than points of slower fluid speed” (Khan Academy, 2015b). It’s based off the principle of “applying conservation of energy to a flowing fluid” (Khan Academy, 2015b). The common formula for the Bernoulli equation is defined below.

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho g h_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho g h_2$$

(Khan Academy, 2015b)

When water isn’t in a continuum or is at the end of a continuum it is exposed to the atmospheric pressure; in these conditions the pressure is assumed to be at atmospheric pressure (101.325 kilopascals or 1Bar(abs.)) (Encyclopædia Britannica, 2014). When trying to calculate the output velocity from a water tower of a given height, the Bernoulli equation is used. The pressures at the top of the water in the tower and the outlet of the pipe are exposed to atmospheric pressure and thus cancel. The height at the tower base is the gauge height; this renders its value 0m; this leaves only the combined height of the water tower and water tank fill level ***h***. Finally, the velocity of the surface water is 0ms^{-1}. The following formula is derived:

$$\frac{1}{2}\rho v^2 = \rho g h$$

$$v = \sqrt{2gh}\,, \quad h = base\ \ height + liquid\ \ height$$

Formula for output velocity from a water tower

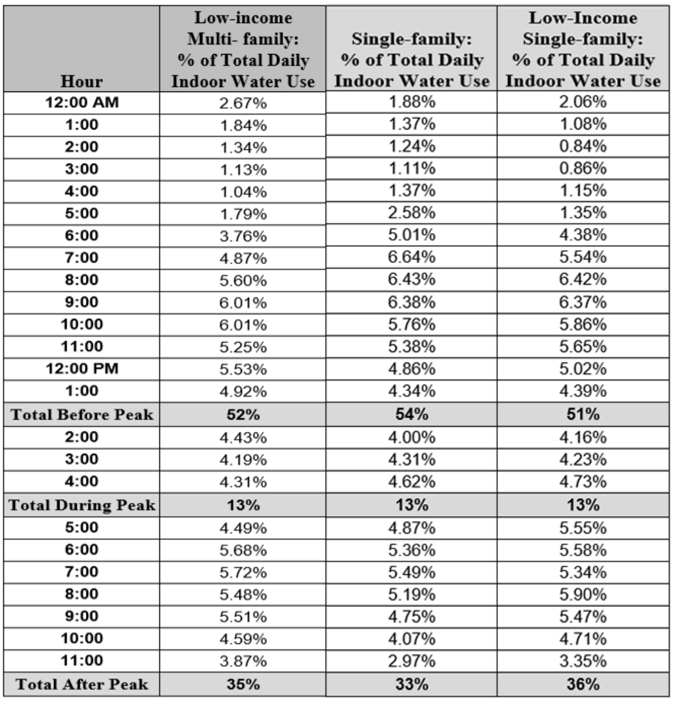
2.2 - Human-Water Interaction

2.2.1 - Water Usage

For the purposes of the game it is necessary to simulate a consumer's water usage and allocate time dependent consumption periods; this introduces overall time dependent usage and peak demand times.

2.2.1.1 - Household Usage

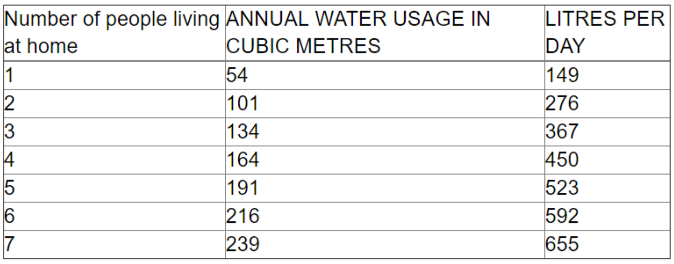
The water usage demand for households will vary dependant on the type of property and the number of residents. I've found three distinct types of property resident categories "single-family, low-income single-family and low-income multi-family" (Aquacraft, 2011, 181), where single-family means one house to one building, and multi-family means many households to one building.



Hour	Low-income Multi- family: % of Total Daily Indoor Water Use	Single-family: % of Total Daily Indoor Water Use	Low-Income Single-family: % of Total Daily Indoor Water Use
12:00 AM	2.67%	1.88%	2.06%
1:00	1.84%	1.37%	1.08%
2:00	1.34%	1.24%	0.84%
3:00	1.13%	1.11%	0.86%
4:00	1.04%	1.37%	1.15%
5:00	1.79%	2.58%	1.35%
6:00	3.76%	5.01%	4.38%
7:00	4.87%	6.64%	5.54%
8:00	5.60%	6.43%	6.42%
9:00	6.01%	6.38%	6.37%
10:00	6.01%	5.76%	5.86%
11:00	5.25%	5.38%	5.65%
12:00 PM	5.53%	4.86%	5.02%
1:00	4.92%	4.34%	4.39%
Total Before Peak	**52%**	**54%**	**51%**
2:00	4.43%	4.00%	4.16%
3:00	4.19%	4.31%	4.23%
4:00	4.31%	4.62%	4.73%
Total During Peak	**13%**	**13%**	**13%**
5:00	4.49%	4.87%	5.55%
6:00	5.68%	5.36%	5.58%
7:00	5.72%	5.49%	5.34%
8:00	5.48%	5.19%	5.90%
9:00	5.51%	4.75%	5.47%
10:00	4.59%	4.07%	4.71%
11:00	3.87%	2.97%	3.35%
Total After Peak	**35%**	**33%**	**36%**

Table 1. House water use table (Aquacraft, 2011)

Water usage from a quantitative perspective varies depending the number of residents per household. Data provided by the Consumer Council of Water shows that the per person water consumption in a household is inversely proportional to the number of residents in that household.



Number of people living at home	ANNUAL WATER USAGE IN CUBIC METRES	LITRES PER DAY
1	54	149
2	101	276
3	134	367
4	164	450
5	191	523
6	216	592
7	239	655

Table 2. (Consumer Council of Water, 2016)

2.2.1.2 - Office Usage

As game needs to implement office structures to provide income and simulate realistic water usages as more people work during the day. As with housing; usage values were obtained. For the purposes of the game however, outdoor office irrigation was not needed, for this reason new percentage values were calculated from the data excluding outdoor usage.

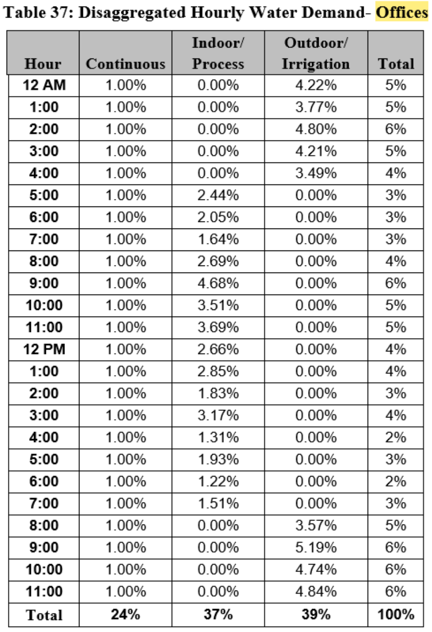
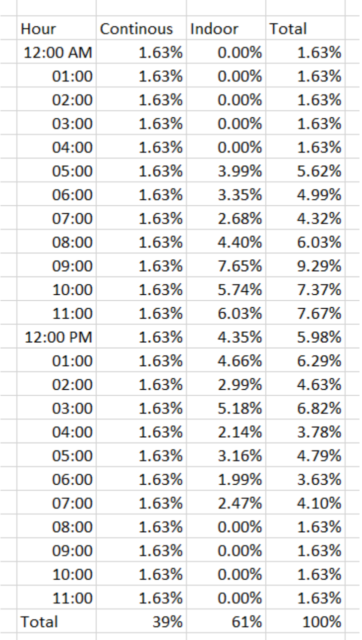


Table 37: Disaggregated Hourly Water Demand- Offices

Hour	Continuous	Indoor/ Process	Outdoor/ Irrigation	Total
12 AM	1.00%	0.00%	4.22%	5%
1:00	1.00%	0.00%	3.77%	5%
2:00	1.00%	0.00%	4.80%	6%
3:00	1.00%	0.00%	4.21%	5%
4:00	1.00%	0.00%	3.49%	4%
5:00	1.00%	2.44%	0.00%	3%
6:00	1.00%	2.05%	0.00%	3%
7:00	1.00%	1.64%	0.00%	3%
8:00	1.00%	2.69%	0.00%	4%
9:00	1.00%	4.68%	0.00%	6%
10:00	1.00%	3.51%	0.00%	5%
11:00	1.00%	3.69%	0.00%	5%
12 PM	1.00%	2.66%	0.00%	4%
1:00	1.00%	2.85%	0.00%	4%
2:00	1.00%	1.83%	0.00%	3%
3:00	1.00%	3.17%	0.00%	4%
4:00	1.00%	1.31%	0.00%	2%
5:00	1.00%	1.93%	0.00%	3%
6:00	1.00%	1.22%	0.00%	2%
7:00	1.00%	1.51%	0.00%	3%
8:00	1.00%	0.00%	3.57%	5%
9:00	1.00%	0.00%	5.19%	6%
10:00	1.00%	0.00%	4.74%	6%
11:00	1.00%	0.00%	4.84%	6%
Total	**24%**	**37%**	**39%**	**100%**



Hour	Continous	Indoor	Total
12:00 AM	1.63%	0.00%	1.63%
01:00	1.63%	0.00%	1.63%
02:00	1.63%	0.00%	1.63%
03:00	1.63%	0.00%	1.63%
04:00	1.63%	0.00%	1.63%
05:00	1.63%	3.99%	5.62%
06:00	1.63%	3.35%	4.99%
07:00	1.63%	2.68%	4.32%
08:00	1.63%	4.40%	6.03%
09:00	1.63%	7.65%	9.29%
10:00	1.63%	5.74%	7.37%
11:00	1.63%	6.03%	7.67%
12:00 PM	1.63%	4.35%	5.98%
01:00	1.63%	4.66%	6.29%
02:00	1.63%	2.99%	4.63%
03:00	1.63%	5.18%	6.82%
04:00	1.63%	2.14%	3.78%
05:00	1.63%	3.16%	4.79%
06:00	1.63%	1.99%	3.63%
07:00	1.63%	2.47%	4.10%
08:00	1.63%	0.00%	1.63%
09:00	1.63%	0.00%	1.63%
10:00	1.63%	0.00%	1.63%
11:00	1.63%	0.00%	1.63%
Total	39%	61%	100%

Left: **Table 3.** Original office water usage table (Aquacraft, 2011).
Right: **Table 4.** tabled based upon indoor & continuous use only

To quantify the size of an office building based upon water consumption an average of approximately **32** litres per employee per day (Ministry of Water and Irrigation, 2011, 9).

2.2.1.3 - Farmland Irrigation Usage

To simulate farmland irrigation within the game, for the interest of growing food for civilians, there's a need to quantify the amount of water used on farmland per acre, on average. "For 2005, total irrigation withdrawals were about 128,000 million gallons per day (Mgal/d), or 144,000 thousand acre-feet per year" (USGS, 2016b).

There is a need to quantify the food demand produced by residents and what percentage of it is met by the farmland in real time; this forces the user to convert one resource, water, into another, food. A study from 2011 shows that the average American ate 1966.3lbs (Toro, 2012), which in kilograms is: 891.89kg, averaging to: 2.44kg per person, per day. Compared to global consumption it's safe to say this is a slight overestimate and that 2kg per person per day is better fitting.

2.2.2 - Contaminants

Large bodies of water maybe host to many contaminants and if consumed by Humans could lead to illness, virus contraction and potentially death. The purpose of this section is to discuss what's naturally found within the water, what makes it safe, and the affects to humans if left untreated.

There are 4 ground water contaminant categories: inorganic, organic, microbiological and physical.

There are many different types of inorganic metals that can be found within groundwater; a harmless example being aluminium ("causing increased turbidity or discoloured water" (USGS, 2016a)) or zinc, the latter of which helps in small quantities: zinc "aids in the healing of wounds. Causes no ill health effects except in very high doses" (USGS, 2016a). Other metals however can have much worse effects on humans, impacting various parts of the body depending on the metal. For example, copper "causes stomach and intestinal distress, liver and kidney damage, anaemia in high doses" (USGS, 2016a). Some of the metals listed that cause bodily harm to humans include: beryllium, cadmium, copper, lead, mercury, nickel, thallium, zinc (at very high levels). Not only do some of these metals effect people, but they can be toxic to plants too, it's important that crops are irrigated with clean water to stop them dying. Of the listed metals, the ones that are toxic to plants include: copper, manganese and zinc. Some of the inorganic contaminants may not cause permanent damage to humans but instead cause temporary discomfort, making people sick and perhaps affecting their ability to work; these contaminants include: barium and sodium (if on a low sodium diet). Fluoride is an inorganic element, its uses include: "Decreases incidence of tooth decay but high levels can stain or mottle teeth. Causes crippling bone disorder […] at very high levels" (USGS, 2016a).

Chlorine is an inorganic contaminant and it can be harmful to humans, “Chlorine poisoning can cause symptoms throughout your body […]” (Normandin, 2015). However, chlorine has some good effects too in that it can help remove other contaminants from the water, “Chlorination is effective against many pathogenic bacteria” (Oram, 2014); it can be added to remove other contaminants and will dissipate afterwards when exposed to sunlight, “Chlorine solutions lose strength while standing or when exposed to air or sunlight” (Oram, 2014).

Some organic contaminants mainly consist of “volatile organic compounds, pesticides, plasticizers, chlorinated solvents, benzo[a]pyrene, and dioxin” (USGS, 2016a). These are bad for human consumption and can causes people to be put in a life-threatening state do to various effects including: cancer, liver damage, kidney damage, anaemia, nervous system damage, reproductive damage and more.

Microbiological contaminants like coliform bacteria occur naturally in groundwater, they consist of “Bacteria, viruses, and parasites” and they “can cause polio, cholera, typhoid fever, dysentery, and infectious hepatitis” (USGS, 2016a).

2.2.2.1 - Levels of natural occurrence and safe levels for consumption.

To simulate the real world within the game, research must be done on what the natural levels of contaminant are (to simulate the reservoir contaminant levels), and the level at which the contaminants are safe for human consumption (to be used to control population growth).

There are regulations set by different countries about the ‘safe levels of contamination’; data been collected from United States Environment Protection Agency (EPA) and Drinking Water Inspectorate (QWI for United Kingdom) along with naturally occurring levels of contamination. Below is the table of collected data for only a few key types of contaminant.

Contaminant	**EPA: MCL (mg/l)** (EPA, 2017a) (EPA, 2017b)	**QWI: MCL** (DWI, 2010)		**Natural Levels (mg/l)** (Smethurst, 1988, 22)
Microbiological				
Fecal Coliform & E.Coli	5%*	0	Per/100ml	1700-60,000MPN
Inorganic Chemicals				
Aluminium†	0.05 to 0.2	200	µg/l	-
Arsenic	0.006	10	µg/l	-
Cadium	0.005	5	µg/l	-

Chlorine	4MRDL	-		-
Chloride	-	-		16.7-54
Copper	1.3	2	mg/l	-
Cyanide	0.2	50	μg/l	-
Fluoride	4	1.5	mg/l	-
Iron†	0.3	200	μg/l	0-0.1
Lead	0.015	25	μg/l	-
Mercury	0.002	1	μg/l	-
Nitrate	10	50	mg/l	2
Nitrite	1	0.5	mg/l	0.1
Selenium	0.05	10	μg/l	-
Organic Chemicals				
Benzene	0.005	1	μg/l	-
1,2-Dichloroethane	0.005	3	μg/l	-
Dioxin	$3 \cdot 10^{-8}$	-		-
Epichlorohydrin	0.01% of 20mg/l	0.1	μg/l	-
Heptachlor	0.0004	0.003	μg/l	-
Pesticides	-	0.5	μg/l	-
Trichloroethylene	0.05	10	μg/l	-
Vinyl chloride	0.002	0.5	μg/l	-
Physical Properties				
Colour, Hazen†	-	20	mg/l	30-830
Hardness†	-	-		300-430
Odour†	3 TON	<1 at 25°C	Dilution Number	-
pH	6.5-8.5	-		-
Taste†	-	<1 at 25°C	Dilution Number	-
Total Dissolved Solids†	500	-		415
Turbidity	0.3 NTUs	4	NTUs	-

* "No more than 5.0% samples total coliform-positive (TC-positive) in a month" (EPA, 2017)

† Not a health risk

Table 5. Table of different contaminants, in groups, showing acceptable levels for human consumption from American and British guidelines, along with levels of naturally occurring contaminants.

2.2.3 - Water Purification

There are several steps involved in water purification, a typical purification facility processes the water in the following steps: coarse screens, raw water pumps, raw water storage, fine screens, micro strainers, aeration, pre-chlorination, coagulants, mixing chamber, flocculation, main settling basins, filters, pH correction, chlorine, chlorinators, pure water tank, dechlorination, high lift pumps (Smethurst, 1998, 19).

Coarse Screen are used to stop debris from entering the system, "prevent floating material of fairly large size entering the works." (Smethurst, 1998, 21).

Raw water storage can improve the general overall quality of water, “improvement in quality of a very low grade water can be achieved by storage alone” (Smethurst, 1998, 23).

Coagulants are added to water to group together particulates together, making them easier to remove, “purpose is to assist in the removal of the more finely divided sediment and the colloids” (Smethurst, 1998, 37). The sediments formed in the water because of coagulation is known as a “floc”. Although flocs are formed this doesn’t mean they are joined together, “maybe be fine and require time to coalesce” (Smethurst, 1998, 52). Flocculation can speed up this process using flocculation chambers which help the flocs coalesce, “flocculating action imparted to the water by the gently rolling motion resulting from passing water along a sinuous inlet channel […] proven to be very effective” (Smethurst, 1998, 53). The removal effects of these coagulant-flocculation process take place within the settling basins, “settling basins are dosed with chemicals […] known collectively as coagulants.” (Smethurst, 1998, 37).

Filtration is the next stage of the process to clean the water further, which also benefits from having coagulants in the water, “they are normally operated with coagulants and very often follow settling basins” (Smethurst, 1998, 111).

Aeration is a process that adds oxygen to the water, this helps to remove organic matter with microorganisms, “advantage of the ability of certain microorganisms (including bacteria) to assimilate organic matter” (Condorchem, 2017).

After these stages of the process, there can still be bacteria found within the water, “however not always free from bacteria and other organisms” (Smethurst, 1998, 135). To kill bacteria, chlorine can be added to the water, “when added to water, chlorine reacts […] which is a very powerful bactericide” (Smethurst, 1998, 137). The chlorine leaving the facility should be at a same amount, “0.4mg/l of free residual chlorine […] regarded as safe” (Smethurst, 1998, 141).

2.3 - Games and Simulations

2.3.1 - Construction and Management Simulation as a Genre

Construction and management simulation (CMS) is a genre of game which involves: “two general sets of tools: one for building and one for managing” (Rollings et al, 2003, 418–426). Some of the main features included in CMS games are: “internal economy”, “resources are produced, consumed, and exchanged", "no victory condition" and "world in which buildings or other objects can be constructed" (Rollings et al, 2003, 418–426).

2.3.2 - Bioshock Water Hacking Mini-Game

During the game Bioshock, whenever the player wishes to hack something (turrets, security bots, security cameras, safes or locks) they must complete a water-based pipe flow 'minigame'. The player "must connect input and output of the board, enabling some sort of liquid to flow from one end to another" (Gamepressure, 2008). When the game starts out, all pipes are invisible, the player must click that tile to reveal it, which takes time. Pipes come in 6 basic shapes which are 2 straight pieces (horizontally and vertically) as well as 4 corner pieces. To make the minigame more interesting, they've added 4 additional pieces: overload piece, alarm piece, slowdown piece and speedup piece (Gamepressure, 2008). The game tries introduce interesting game mechanics in the form of special pipes such as: overload and alarm pieces which fail the game, causing different side effects to the full game. Other pipes include: speedup and slowdown pipes which accelerate or retard the water flow.

2.3.3 - Irrigania

Irrigania is a web-based game which "aims to represent water conflicts" (Rollings and Ernest, 2003). The game is based on water as a limited resource, and aims to use it primarily for irrigation processes. The game requires a "certain amount of cooperation within the village" (Rollings and Ernest, 2003), a similar effect to the idea of this project. The game has three types of irrigation types: "rainfed agriculture, irrigation using river water, and irrigation using groundwater" (Rollings and Ernest, 2003), giving the player the decision of how to use the farmland to grow the most crops, using water wisely to produce the most income, to make the game more advanced they add weather conditions, effecting the 'rainfed' outcome; these mechanics give the game unpredictability and randomness.

2.4 - Game Design – Balancing Education and Enjoyment

To make a game educational, while being fun at the same time can be difficult, "The key to success is to reach a balance between fun and learning" (Moreno-Ger et al, 2008). To make educational games effective in teaching the players, they should have some of the following key features: "narrative context, rules, goals, rewards, multisensory cues, and interactivity" (Dondlinger, 2007).

3 - Methodology

The project was developed with an AGILE approach; this was done since when only one feature was added could design decisions be made based where to take the game further. As the main aim of the project was to introduce new interesting game mechanics based on water flow; a waterfall approach was decided against. The waterfall approach would require designing all features at the start; this is very difficult as it's challenging to see how all the designed features would interact with each other. Only when a feature has been designed and implemented could further designs be made based upon that implementation. This methodology meant that if there were limitations early on, changes could be made and then further developments made from those changes, "ability to respond to the changing requirements of the project" (Balaji and Murugaiyan, 2012).

The SDLC pattern was used for each feature implementation to ensure it was implemented and tested fully. The benefits of using AGILE with SDLC is "Easier to test and debug during a smaller iteration" and "Each iteration is an easily managed milestone" (Ragunath et al, 2010). These SDLCs were roughly executed in the order: Grid setup, basic pipe and structures added (pump, water tower, and one size of pipe), pipe flow (without demand/max flowrate), placement object placement system, other pipe sizes and structures added, select object menu, demand added to pipe flow and village structures, contaminants and purification added, finishing touches (objectives, water affecting village structures).

3.1 - Software Development

To develop the game there were a few choices of platform to use such as OpenGL, DirectX, Unity and Unreal Engine. Starting the game with a low-level implementation such as OpenGL or DirectX would have taken too much time to develop, and as the goal of the project was to explore interesting game mechanics this was not desirable. Unreal engine could have worked as a platform, but this would be a better choice to make a polished game. Furthermore, Unity was the game engine that the author was most familiar with; keeping that in mind and for the interest of implementing features a quick as possible without needing to learn more about a game engine, Unity seemed like the best choice.

One of the benefits of using Unity, rather than Unreal is if the author needs to read up on documentation, then Unity gives you all there is, unlike Unreal, "Unreal or Source which only provide partial documentation for non-paying customers" (Craighead et al., 2008).

3.2 - Research and Evaluation Methods

To assess whether the project is a success or not, there are a few different approaches to take such as: questionnaires, interviews and observations. As the main aim of the project is to explore interesting game mechanics, this should be the focus how the project is evaluated

Observations would allow participants to play the game, and to be able to assess how well they play, and understand the game; this would just be a sign that there isn't enough information given on how to play it, rather than assessing whether the game mechanics are any good.

An interview would get people's opinions, however it would be difficult to quantify their response for certain questions; this is because there's a need to ask how good and interesting the game mechanics are, so it would better for them to write how much they feel rather than trying to interpret how excited their response was.

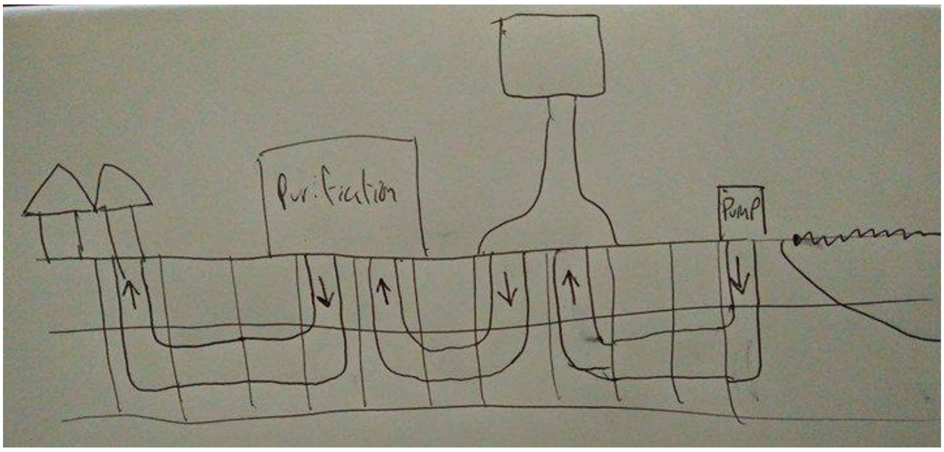
A questionnaire would be more appropriate, as the objective of the research is to try to get them to effectively 'rate' how good certain parts of the game is, a Likert scale should be used, that way it will provide a "degree of accuracy" (Denscombe, 2010). To ensure that people can interpret and understand the questions, the questionnaire will need to "use only the minimum amount of technical jargon" (Denscombe, 2010). The Likert data can then be collected together and summaries to get an average opinion what people think; which wouldn't be as easy or accurate with open questions. The problem with the Likert scale is that it's a form of closed question, this might restrict their opinion on certain parts of the survey. To solve this a final section should be added in an open format, this will allow for "reflect the full richness and complexity of the view held by the correspondent (Denscombe, 2010).

When obtaining participants to complete the survey, ethics will need to be considered, this means not obtaining their name, instead a unique number should be assigned the participant. The participant should also be able to withdraw their submission later if they so wish, by providing their unique identification number.

4 - Design

The game will be developed as a construction and management simulation (CMS) game. Players will be placed into the world, and must build structures and pipes, while keeping track of resources like money, food and most of all water. Like most CMS games, the game will have no victory condition (as aforementioned in the literature review); instead players will be able to build freely and attempt to make the world bigger and better, with sub objectives along the way.

Players must pump water from the reservoir into a water purification facility, from there the various contaminants can be removed ready for the water to be stored within a water tower which will allow enough water to flow during peak times of the day. From there players will need to set up various villages to hold people, that will need jobs for income, and farmland for food, all of which would require a varying stream of clean water throughout the day. Given that the player can provide the correct amounts of water, the populations will be able to grow and expand, requiring a bigger and better water purification and transportation infrastructure.



Planning how pipes and structures will be connected from a 2D perspective

4.1 - General gameplay design flow

The general design of the game is that the player starts with nothing, and they must construct multiple villages, each of which will have certain water demands. Player must provide housing, offices and farmland to the users for them to grow in numbers; this will be based upon the incoming water supply (quantity and quality) and the food generated from well irrigated farmland. The offices that are built will be used to provide income for building, the more water provided to the office, the most efficiently the business can run and the more money they'll get.

Players must obtain the water using a pump, pipe it through to the purification facility to clean the water of contaminants, then store this water into a water tower, this will mean that the system will be able to facilitate peak times of water demand.

As the village population grows new housing, offices and farmlands will be required to accommodate the residents. These new houses, offices and farmlands can be supplied by the same pipeline to a point; when the demand becomes too high the water will reach its maximum flowrate limit, this forces the player to upgrade their infrastructure.

4.2 - Input & Output Pipes

In the real world, pipes aren't '*input pipes*', nor '*output pipes*', they're just pipes. The ideal desired effect would be for users to just can place a vertical pipe and for the game to automatically detect whether it is an input or output based on what they're connected to. Unfortunately, this was not possible, since in the real world although a pipe is still a pipe, they're connected to different parts of the structures and the game would have no way of telling which direction the water should be coming in or going out. This design decision lessens development time but also means users would easily be able to see what the pipe is intended for which helps them grasp the game more easily.

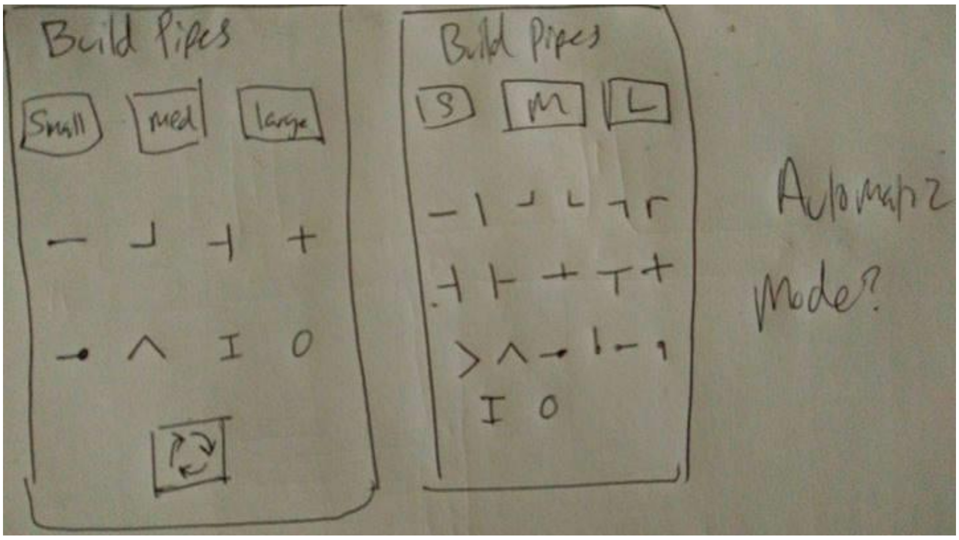
4.3 - Pipe Placement

There are two approached when it comes to user placement of pipes, the first is where the user needs to select a piece and then place that type of piece into the world (manual mode). The other would be just to have a build pipe mode, this way when you click next to a pipe, another pipe would connect to it automatically (automatic mode).

The benefit of having automatic placement is that player would be able to place pipes far faster, which would make the game slightly faster pace, which might increase enjoyment.

The benefit of the manual mode in contrast to automatic is that when placing pipes close together, you have full control of which pipe it connects to, and which one it doesn't, in contrast the automatic placement would make autoconnections whenever possible, even when undesired. For this reason, manual placement was chosen instead of automatic.

There are two types of manual placement, one which has every pipe shape, pointing in a unique direction, the other where it only has the shape, and it can be rotated. To make for a smaller interface, and quicker placement (using a rotate hotkey) I've decided to go for the mode with rotations.



The left side shows manual mode with rotation, the right side shows manual mode without rotations.

4.4 - Player Objectives

The game is of the genre of CMS, this means that the game should have many different objectives that involve building, upgrading and maintaining structures and pipes within the world. Objectives include: building villages (houses, offices, farmland), building the water infrastructure (water towers, pumps, purification facilities), connecting it all together with pipes, upgrading structures, purifying water further, upgrading pipe sizes, raising populations.

Like other CMS games, there should be no win condition for the game (as aforementioned in the literature review) meaning the game should continue for as long as the player wishes to play for. Like most CMS games which add fairly trivial goals, in the context of the game; my game's goals could be to achieve a certain population count, or to achieve a certain high water purity average; these simple milestones are easy to implement.

4.5 - Water Purification and Contaminants

There are many different types of contaminant and impurities that can be found within a body of water (e.g. a reservoir). As the types of contaminant are almost endless, it is necessary to group together key contaminants for the sake of making the game work in a logical way and to not bombard the user with too much data for them to process what's happening. The grouping for this is based off the categories: organic, inorganic, microbiological and physical characteristics (as aforementioned in the literature review).

In the real world when water is being processed, they can sample the water to see what's in it, but in general they don't need to know what the water contains as they know that their rigorous purification process will remove the contaminants. For the purposes of this game, as the contaminant values need to be adapted and specified after each stage of purification, contaminants need to be generalised into groups, and purification processes need to generalise how it adapts those groups, and by how much.

As a list of each group type of contaminant might be a bit daunting to look at, a single purity value was used to summarise the contaminants in a way that will be useful for the player to get a summary and for the game to use as a factor that affects village structures.

4.6 - Economy

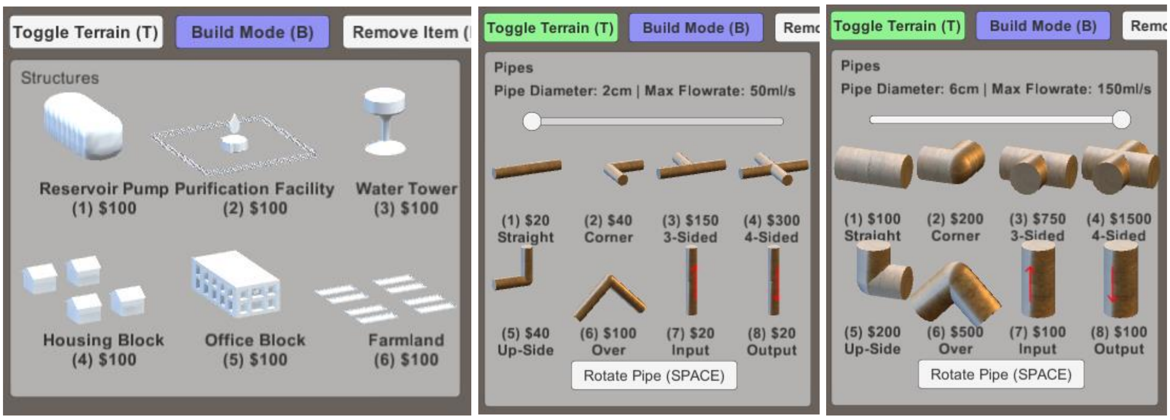
Like most CMS games, the game will have an "internal economy" (as aforementioned in the literature review); players will be given a starting budget which limits their initial build. Money is then acquired via offices; this allows for a more progressive gameplay experience. Money can be spent for the purchase of structures, pipes, upgrades to structures and adding purification processors. Like the real world, pipes that have a corner will be more expensive than a straight piece as it's harder to manufacture, with splitter pipes costing even more. As the game requires you to upgrade pipe diameter to keep up with higher demand, pipes with a larger diameter will cost more.

5 - Implementation

The game was developed with the Unity engine, and in its most raw form consists of two terrains, one on top of the other. Before any other form of implementation, a grid system was developed, consisting of 5 Unity units per tile. Moving the cursor, moved a glowing square aligned to the grid to see where it is. Helper functions were developed that converted from world space to grid space, and vice versa.

5.1 - Building and Pipes

When in the game, the user can switch between two different views, above ground and below ground view. If build mode is selected above ground a build structures menu will appear, while below ground makes a build pipes menu appear. The user can click an item from the menu, making it appear on their cursor, aligned to the grid as a preview of what they’re about to place. Player can also rotate pipe pieces with a button or the Space button to make them face the right direction.



Left: Structure build menu. Middle & Right: Pipe build menu (smallest and largest)

Pipes come in 3 different sizes and 8 different shapes, which can be rotated by 90degree intervals about the vertical axis. The length of the pipes remains constant, even though the width does not. The first 4 pipes work on the lower level, only going horizontal, used for straightforward pipes, bends and splitting. The 5th pipe links horizontal pipes to a vertical pipe. The 6th pipe will go over another pipe, allowing nearby pipes to automatically link up to it. The 7th and 8th pipes are used for inputting and outputting water to the system via structures.

5.2 - Pipe Flow

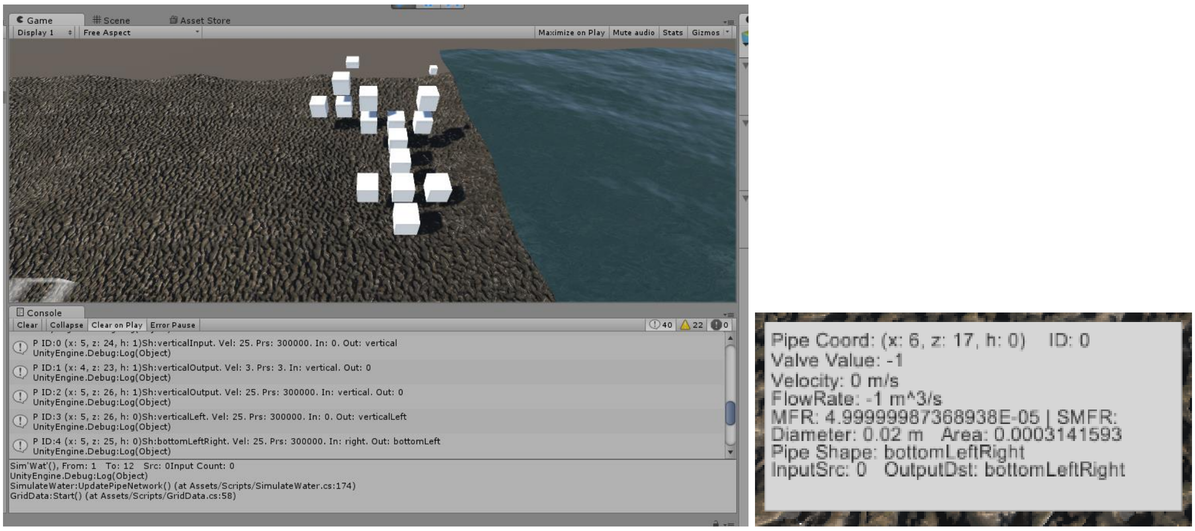
Pipe flow: the transportation of water from source structures to destination structures is the main core mechanic of the game, and so this introduced some large challenges; this was because the player is given full freedom of where they want to place objects and an endless variety of configurations. In addition to that, every new pipe feature added (many different shapes and sizes) resulted in a larger water simulation algorithm that needed to be thoroughly tested during the development process.

Firstly, the pipe network is treated as a separate entity to the structures above ground. A pipe in the middle of the network doesn't need to know the values of structures above, and vice-versa. Links between the two are made via the input/output pipes, they form the bridge between the networks: for each game-tick first all pipe flows are calculated, then all structures are updated.

The basis of how the algorithm works is in a two-step process. Firstly, calculations are made from source structures to destination structures to try and provide as much water as the pipe flow allows. That was originally the only part to the algorithm, until it later had to be updated it to introduce demand. Secondly calculations are made from destination structures sending information about how much water demand there is back to the source structures.

5.2.1 - Ongoing testing and development of algorithm

As this was the biggest challenge of the project, it was essential to try and get this working as early as possible, after the grid system, togglable terrain and placement of pipes, pump and water tower (all with a cube as a prefab) was made. As there was no build menu, pipes had to be placed within the code. Initially pipe values were displayed with a debug command, but this quickly became too difficult to read and understand. A debug hover menu was developed that would appear when the cursor hovers on a pipe, this was to help debug the information contained within the pipes; this later got replaced with a more user friendly hover menu.

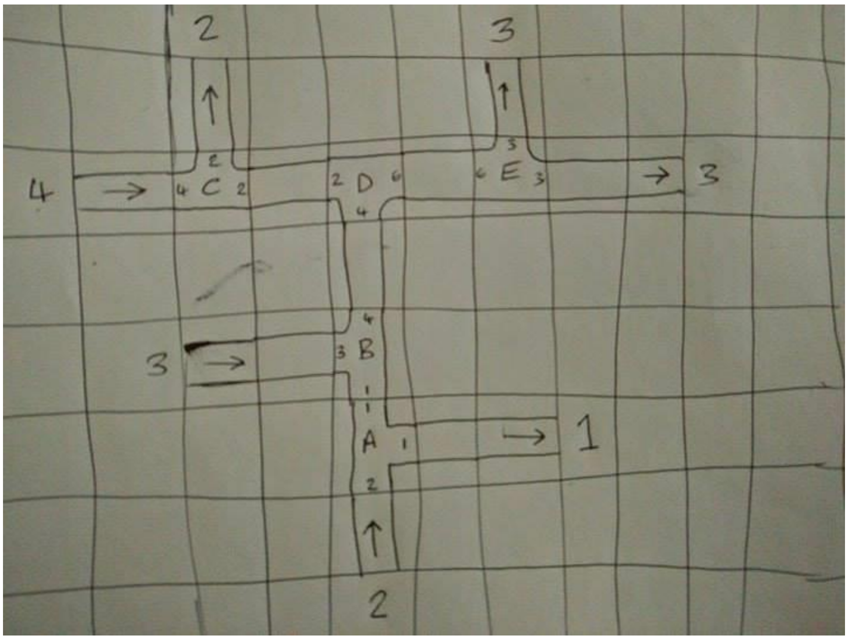


```
P ID:0 (x: 5, z: 24, h: 1)Sh:verticalInput. Vel: 25. Prs: 300000. In: 0. Out: vertical
UnityEngine.Debug:Log(Object)
P ID:1 (x: 4, z: 23, h: 1)Sh:verticalOutput. Vel: 3. Prs: 3. In: vertical. Out: 0
UnityEngine.Debug:Log(Object)
P ID:2 (x: 5, z: 26, h: 1)Sh:verticalOutput. Vel: 25. Prs: 300000. In: vertical. Out: 0
UnityEngine.Debug:Log(Object)
P ID:3 (x: 5, z: 26, h: 0)Sh:verticalLeft. Vel: 25. Prs: 300000. In: 0. Out: verticalLeft
UnityEngine.Debug:Log(Object)
P ID:4 (x: 5, z: 25, h: 0)Sh:bottomLeftRight. Vel: 25. Prs: 300000. In: right. Out: bottomLeft
UnityEngine.Debug:Log(Object)
Sim'Wat'(), From: 1   To: 12   Src: 0Input Count: 0
UnityEngine.Debug:Log(Object)
SimulateWater:UpdatePipeNetwork() (at Assets/Scripts/SimulateWater.cs:174)
GridData:Start() (at Assets/Scripts/GridData.cs:58)
```

```
Pipe Coord: (x: 6, z: 17, h: 0)    ID: 0
Valve Value: -1
Velocity: 0 m/s
FlowRate: -1 m^3/s
MFR: 4.99999987368938E-05 | SMFR:
Diameter: 0.02 m   Area: 0.0003141593
Pipe Shape: bottomLeftRight
InputSrc: 0   OutputDst: bottomLeftRight
```

Left: Pipes and structures placed with cube prefabs, listing debug information below.
Right: Pipe debug hover menu.

Trying to plan how this function was going to run wasn't easy; it required diagrams to be drawn to allow the author to visualise how each stage of process was going to go. Diagrams were used to plan to high priority/low priory implementation of splitter pipes describes in the next section.



Planning how pipe intersections would be executed

When first implementing this water simulation function in its most basic form, the function had to search for neighbouring pipes to each pipe within the simulation every game loop, and this was happening many times per second. This lead to serve performance decline making the FPS go down. To solve this problem, in the interest of performance purposes, when a pipe is placed into the world it is added to a node list. From there connections between neighbouring pipes are made with an array of links; these links are based on neighbouring proximity and pipe shape to ensure that they are physically connected. This means that when in the main simulation loop a simple index look up of connections can be made, which is better for performance. Similarly, when a pipe is removed, it needs to be removed from the node list and links to other pipes need to be broken.

5.2.2 - Final Algorithm Description

Step 1: Source Structures to Destination Structures

The algorithm works based on one queue and one list, the queue is assigned as high-priority, the list is low-priority. High-priority pipes are pipes that need to be calculated first, these are two-sided pipes as they just pass the information along, simple. Low-priority pipes are three-sided and four-sided pipes as they need to process the mixing of incoming/outgoing water streams. All high-priority pipes are processed until the queue is empty, from then the low-priority queue is then calculated, until another high-priority pipe is added. Low-priority isn’t a queue as they need to be popped off in a certain logical order, based on how many junctions they are from the destination structures to ensure the flow is in the correct direction.

```
While (HighPriority.Count > 0 || LowPriority.Count > 0) {
        Pipe p;
        If (HighPriority.Count > 0)
                p = HighPriority.Dequeue();
        else
                p = LowPriority.RemoveAt(GetNextMultiSidedPipeIndex());
        …
}
```

Code Snippet: Pseudo-code of handling high and low priority pipes.

Before the processing starts, a loop searches through all the structures with output pipes, assigning each to the high-priority queue, then the main loop starts.

All Pipes have a complete status flag applied to them, set to not-complete by default. They will be set to pending if it’s a junction waiting to see if more inputs are coming, and set to complete if they have been fully processed. This ensures flow in the correct direction, preventing cyclic water behaviour, stopping an infinite loop.

Next, it looks at the selected pipe's neighbours, this is done with the node links created when pipes were placed. The current pipe being analysed could either be a two-sided pipe or a multi-sided pipe; regardless if it's selected then it's source(s) have already been defined, such that all remaining sides of the pipe must be sinks. Of those sinks found, they are then sorted in order from largest pipe to smallest pipe, to ensure remaining water is distributed correctly. During this process a summation of the total output area is created to use as a ratio of current pipe area compared to total output area for water distribution calculations.

Next the current pipe sends the water information to its neighbours, from there a list of all sink pipes is created, biggest to smallest. For all the sink pipes in the list, the 'previous pipe' value is assigned to be the current pipe, this is used later in step 2.

Next the amount of water that this neighbour can receive is calculated, this is done by a ratio of the neighbour's area compared to the total neighbours' area by the provided flowrate. If the water can't go into that pipe, due to restrictions, then that water is added to a left-over water variable to be used for another neighbour. If there's still water that can't be accepted by all the neighbours, then the current pipes simulated max flowrate is reduced to match it.

```
…
float outFlowrate = pipe.flowrate * (neighbour.area / totalOutputArea);
if (outFlowrate > neightbour.maxFlowrate) {
        LeftOverWater = outFlowrate – neighbour.maxFlowrate;
        outFlowrate = neighbour.maxFlowrate;
}
…
```

Code Snippet: Pseudo-code for calculating leftover water when flowrate restrictions are applied.

If the neighbour currently has one input stream (from the current pipe) then the flowrate and contamination information is simply assigned to the neighbour. Otherwise the flowrate is added to the current flowrate and the contaminants are mixed as a proportion of the ratio of the input stream areas; this is done with the operator overloading of the contamination class allowing for scaling and addition of contaminants. From there, velocities are calculated based on flowrate divided by areas, this is because flowrate is constant regardless of pipe size which is a fundamental law as seen in the literature review.

The final stage of step 1, is if the neighbour is a two sided pipe its marked as complete and added to the high-priority queue, otherwise it's marked as pending and added to the low-priority list.

Step 2: Destination Structures back to Source Structures

Step 2 is effectively the inverse of step 1, however its computed faster as it's relying on the array of previous pipes created by step 1, but instead of setting the flowrate, you're setting restrictions of flowrate through the pipe system based upon demand of the destination structures and restrictions of pipe sizes. It too works on a high-priority and low-priority system, high-priority pipes are selected from Input pipes and more are added throughout the algorithm process (two sided pipes), low-priority pipes were already assigned in part 1 (multiple output junctions).

The algorithm keeps popping off high-priority pipes, following the previously defined previous pipe indexing to traverse the pipeline in reverse, at each pipe, the simulate max flowrate restriction is applied based upon a ratio of what the source pipes can provided to the current pipe.

Rationale for large function layout

The pipe update function is a large function to make it more efficient on performance. Sectioning off parts of this function that wouldn't be reused elsewhere would not have been any benefit; it would be detrimental as there would be performance overhead for calling the function and many local variables would have to be passes are parameters. Doing that would slow down the game as the function itself is already called within the game loop, and it already has two main nested loops within it just for step one alone, meaning it would been a lot of needless function overhead calls.

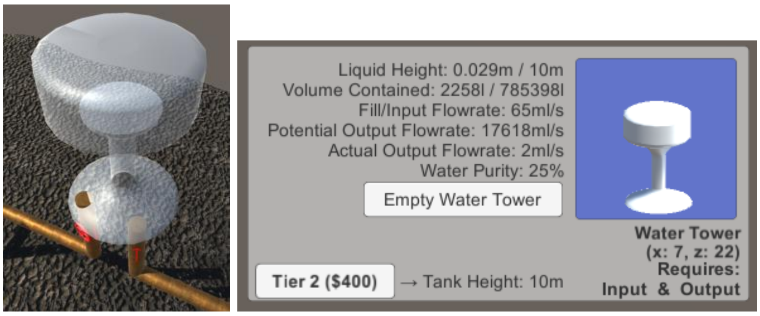
5.3 - Pumps, Water Towers and Valves

Pumps and water towers are treated as a form of storage, because a water tower holds water, and a pump is linked to a giant body of water. The difference being that a water tower can accept an input, while a pump cannot as the input it automatically connected to the reservoir upon placement.

The potential output value for the pump, has just been implemented as a fixed number that works to make the game balanced, allowing for upgrades to increase this amount. The potential output velocity from the water tower is calculated from $\sqrt{2gh}$ as seen in the literature review, from there this velocity is multiplied by the area of the pipe to get the flowrate.


Pump Max Flowrate:
75ml/s
Actual Output Flowrate:
75ml/s
Reservoir Pump
(x: 8, z: 26)
Requires:
Output
→ Max Potential Flowrate: 150ml/s

Left: Tier 1 Pump. Right: Select structure menu for pump


Liquid Height: 0.029m / 10m
Volume Contained: 2258l / 785398l
Fill/Input Flowrate: 65ml/s
Potential Output Flowrate: 17618ml/s
Actual Output Flowrate: 2ml/s
Water Purity: 25%
Water Tower
(x: 7, z: 22)
Requires:
Input & Output
→ Tank Height: 10m

Left: Tier 1 Water Tower, with I/O Pipes. Right: Selected structure menu for water tower.

As they're both treated like storage, when an output pipe is added a valve is attached to the side, this allows the user to restrict how much flowrate comes out of the structure, this is implemented as a percentage of the potential flowrate of the structure. Clicking and dragging on the valve, allows the user to turns the valve, which changes that percent value.


Flowrate: 64.75ml/s
Velocity: 0.0515m/s
Size: Medium (4cm)
Pipe Max Flowrate: 100ml/s
Flowrate Restricted To: 100ml/s
Water Purity: 0%
Valve: 86.33334%
Output Pipe

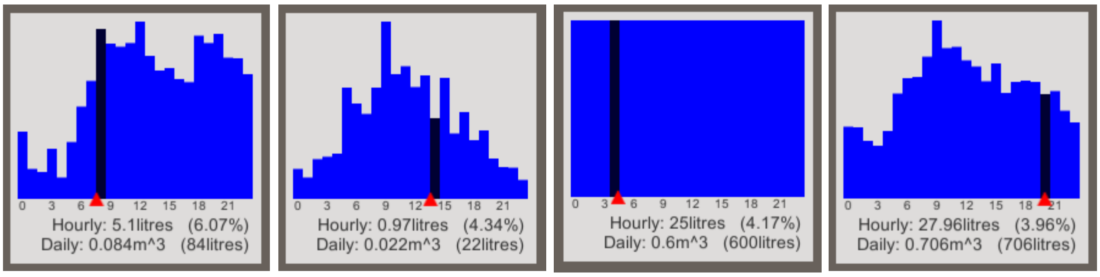
Valve Percent: 86.33334
Max Potential: 75ml/s
Percent of Potential: 64.75ml/s
Max Due To Restrictions: 100ml/s
Resulting Flowrate: 64.75ml/s

Valve game mechanic

5.4 - Water Demand

The water demand was implemented based upon the data obtained during the literature review of water demand requirements; this data was used to generate water usage for three different types of structure: houses, offices and farmland, the first two require a certain amount of water at certain times; however for farmland, although they're typically irrigated at certain times (typically at night), it doesn't *need* to be irrigated at those times, so it excepts an equal amount at all hours of the day.

To implement this a live bar chart was made, one for each building, with a new one being generated every new day for each. The bar chart is generated from a data template which uses the data obtain from the literature review of that specific structure type, this data is in the form of 24 one hour variables that hold the percent of daily use at that hour. It then displaces the data by a certain variance in either direction for each 1 hour piece of data; as it's displaced by a certain variance, all the pieces of data might not add up to 100% exactly, so a function is called to scale the values to make sure they do. As for the quantity of water, this is also done from 3 values obtained from the literature review about amount consumed, again displaced by a variance. From there hourly usage can be calculated by taking a percent of that usage at each hour interval.



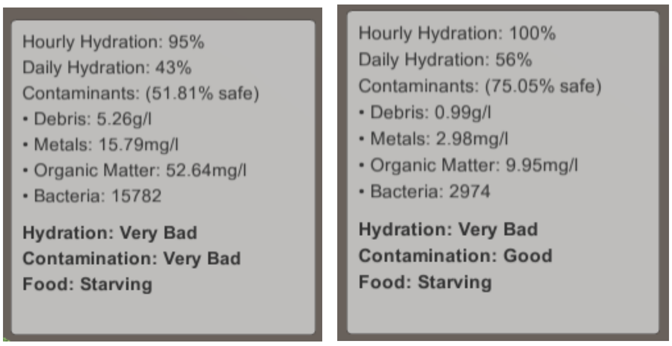
1st: Usage chart from houses. 2nd: Usage chart from offices. 3rd: Usage chart from farmland. 4th Usage chart from village (with one of each village structure).

5.5 - Water Contaminants

To try and implement the different characteristics of water contamination found from the literature review, from there it was put into four groups: organic matter, metals (inorganic), bacteria (microorganisms) and debris. 'Physical traits' wasn't included as a group of contaminant, as it is usually things like: odour, colour, taste and turbidity, all of which don't have any harmful effect on humans. Instead debris was implemented, as a type of contaminant that can be removed by a coarse screen purification process (mainly, also removed slightly by other processes).

The 5th piece of data attached to contaminants is a floc value, this describes how clustered the contaminants are, to allow for a better purification result.

To extract useful information from the contaminants that can be used for effecting village structures and to summarise the data, a purity value can be calculated. For each of the four contaminant types, this compares the value to what is deemed as a safe amount (seen in the literature review), the four results of these are then averages to create one purity value.



Hourly Hydration: 95%
Daily Hydration: 43%
Contaminants: (51.81% safe)
- Debris: 5.26g/l
- Metals: 15.79mg/l
- Organic Matter: 52.64mg/l
- Bacteria: 15782

Hydration: Very Bad
Contamination: Very Bad
Food: Starving

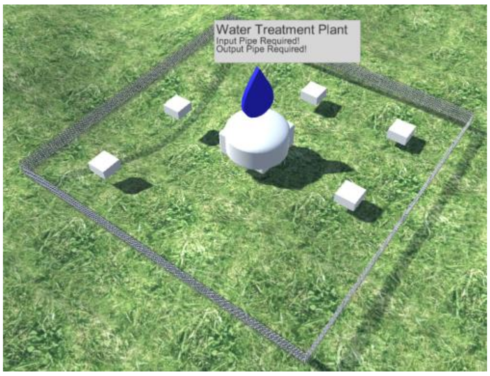
Hourly Hydration: 100%
Daily Hydration: 56%
Contaminants: (75.05% safe)
- Debris: 0.99g/l
- Metals: 2.98mg/l
- Organic Matter: 9.95mg/l
- Bacteria: 2974

Hydration: Very Bad
Contamination: Good
Food: Starving

Left: House incoming water, from “Raw Water Storage”, with processor set to x0.96 purity.
Right: Additional “Coagulation”, “Flocculation”, “Settling basin” and “Filtration” added.

5.6 - Water Purification

Within the game, the users must build a water purification facility, this is a standalone 6x6 tile structure, where the centrepiece is a 2x2 building, with 8 other 2x2 empty spaces around the centrepiece, these extra areas are places the user can buy machines/processors that will treat the water in a different way. The centrepiece alone, water simply comes in and leaves straight after, as there’s no way for water to be processed, unless one of the processors is bought.



Water Treatment Plant
Input Pipe Required!
Output Pipe Required!

Purification facility with 5 of the 8 processors bought

Each processor that is added around the purification facility will remove a different certain aspect of contamination from the water. Some processors help others, for example settling basins and filtration processor work better if coagulation and flocculation are used.

In reality, water purification facilities will only be able to process so much volume of water at one given time; it is for this reason the constrain was added to the facility, allowing the player to upgrade this maximum flowrate with a certain fee. The build also gives the player the ability to focus the energy of purification to either quantity or quality (purity) of water. This allows for maximum customisability of the structure. If quality is set higher, the processors are more effective.

Example of the selected structure menu for the water purification facility, which allow you to but processors.

This implementation of a purification facility treats it like a process, and not storage; this means if the output of the facility is sourced by a pump, and supplying a water tower and the water tower gets full, then the facility can't accept any input from the pump as there is nowhere for it to be stored

Purification Processor	**Effect**
Coarse screen	Removes debris from the water
Raw water storage	Reduces all types of contaminant
Coagulation	Creates flocs
Flocculation	Groups existing flocs, to make more flocs
Aeration processor	Removes organic matter
Setting basins	Reduces all contaminants, better with flocs
Filtration	Reduces all contaminants, better with flocs
Chlorine disinfection	Kills pathogens and anaerobes (bacteria)

Table 6. Table showing effects of each processor, based upon research seen in the literature review

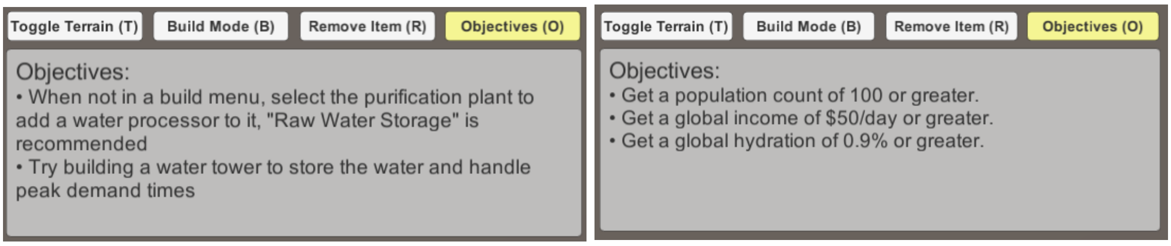
5.7 - Effects of incoming water on village structures

Village structures needed a way to change their effectiveness at their specific job based upon a few different factors, these include: incoming water quantity, incoming water purity and food quantity (houses only). Their specific jobs being: holding and growing residents (houses), providing income to residents (offices) and producing food (farmland). The way in which these factors effect village structures has been implemented differently for houses compared to offices and farmland, this is because you can have a negative population growth, but the game would be too harsh to have a negative income (loss) and it doesn't make sense to have negative crops being grown.

To quantify the hydration factor, a calculation is made every game step to compare the incoming water to what the demand is, this is done until the hour is complete, resulting in a percent of incoming compared to demand, from there the factor is an average of that value for the past 24hours (less if 24 hours hasn't passed).

5.8 - Objectives

To make the game more comprehensible to new users while providing goals for current players, an objective system was added. To begin with, these objectives start out trivial to make sure the player knows what to do, for example to place the required structures and add the necessary pipes to allow water to flow between them. From there, more advanced tasks are given as a form of trivial milestones, achieve a certain population, get a certain income, have an average of 95%+ hydration across the village.



Objectives:
- When not in a build menu, select the purification plant to add a water processor to it, "Raw Water Storage" is recommended
- Try building a water tower to store the water and handle peak demand times

Objectives:
- Get a population count of 100 or greater.
- Get a global income of $50/day or greater.
- Get a global hydration of 0.9% or greater.

Objectives Menu

5.9 - Upgrade system

For each of the structures, when they're first introduced into the world, they appear as Tier 1, structure. From when the structure is selected, there is an upgrade button in the corner of the menu which will allow users to upgrade their structures, for a certain fee.

6 - Testing

During the development of the game, especially the development of water flow, there was many different tests carried out, while developing the algorithm

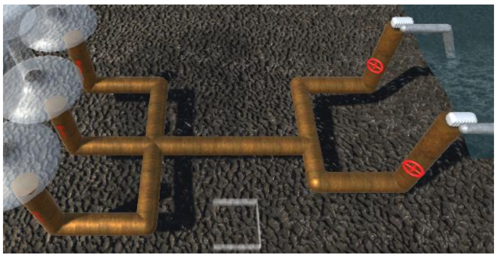
6.1 - Simulation testing of different pipe layout configurations

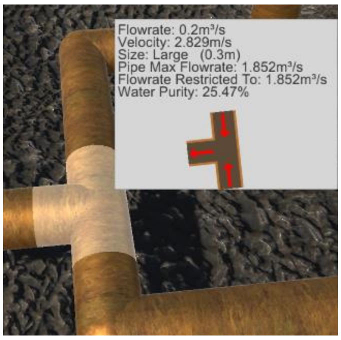
To test if the pipe simulation works, it is necessary to testing various configurations of pipe layout. To begin with, destinations were set to be a water tower, this is because a water tower can accept any amount of water (providing it's not full) as it's not dependant on demand like village structures. Later tests will include village structures to test the demand functionality.

6.1.1 - Test 1: Two pumps feeding into 3 water towers

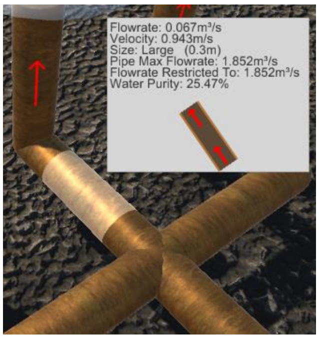
This test uses larger water quantity values than the final game, but the mathematics are still the same

Configuration 1:





```
Flowrate: 0.2m³/s
Velocity: 2.829m/s
Size: Large   (0.3m)
Pipe Max Flowrate: 1.852m³/s
Flowrate Restricted To: 1.852m³/s
Water Purity: 25.47%
```

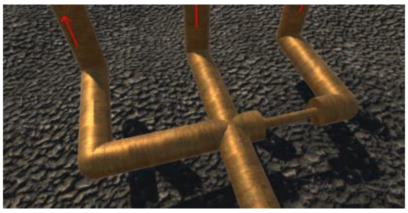


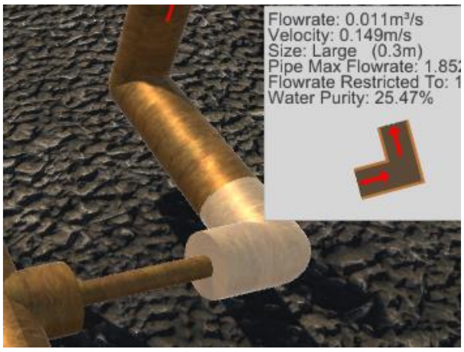
```
Flowrate: 0.067m³/s
Velocity: 0.943m/s
Size: Large   (0.3m)
Pipe Max Flowrate: 1.852m³/s
Flowrate Restricted To: 1.852m³/s
Water Purity: 25.47%
```

Purpose of test: To test splitting and combining of water within pipes

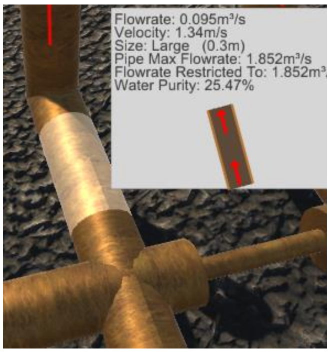
Result: Correct result. Input of 2 * 0.1m^3/s results in each water tower getting 0.067m^3/s, in reality the centre piece might get more water than it neighbours.

Configuration 2:





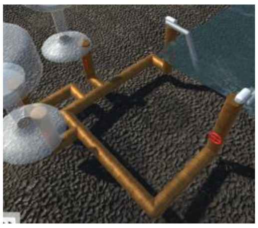
```
Flowrate: 0.011m³/s
Velocity: 0.149m/s
Size: Large   (0.3m)
Pipe Max Flowrate: 1.85
Flowrate Restricted To: 1
Water Purity: 25.47%
```

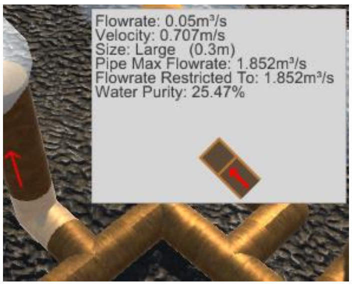


```
Flowrate: 0.095m³/s
Velocity: 1.34m/s
Size: Large   (0.3m)
Pipe Max Flowrate: 1.852m³/s
Flowrate Restricted To: 1.852m³
Water Purity: 25.47%
```

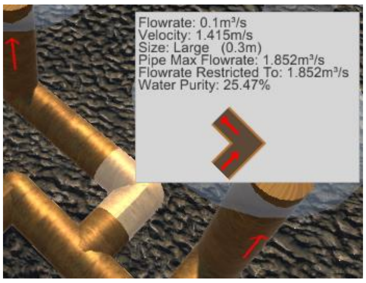
Purpose of test: To test if bigger pipes get more water in the right amount

Result: Correct result. Input of 2*0.1m^3/s results in the thicker pipes getting 0.095m^3/s each while the water through the thinner pipe gets 0.011m^3/s. The thicker pipes are 0.3m in diameter with cross-sectional area 0.0706m^2, while thinner pipes are 0.1m in diameter with cross-sectional area 0.00785m^2. The sum of all three cross sectional areas is: 0.149m^2, so the proportion that the thicker pipe gets is 0.0706/0.149 = 47.38%, while the thinner pipe is 0.00785/0.149 = 5.26%. Multiplying those percent by the input amount (0.2m^2/s) confirms the result are correct.

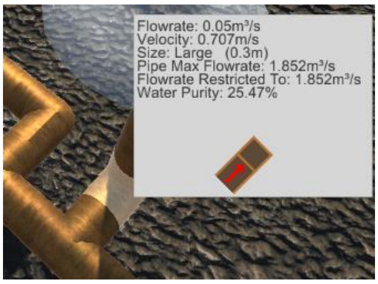
Configuration 3: 



```
Flowrate: 0.05m³/s
Velocity: 0.707m/s
Size: Large   (0.3m)
Pipe Max Flowrate: 1.852m³/s
Flowrate Restricted To: 1.852m³/s
Water Purity: 25.47%
```



```
Flowrate: 0.1m³/s
Velocity: 1.415m/s
Size: Large   (0.3m)
Pipe Max Flowrate: 1.852m³/s
Flowrate Restricted To: 1.852m³/s
Water Purity: 25.47%
```



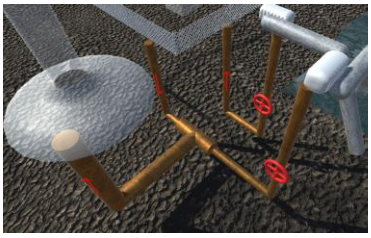
```
Flowrate: 0.05m³/s
Velocity: 0.707m/s
Size: Large   (0.3m)
Pipe Max Flowrate: 1.852m³/s
Flowrate Restricted To: 1.852m³/s
Water Purity: 25.47%
```

Purpose of test: To see if the order of splitting effects the water flow

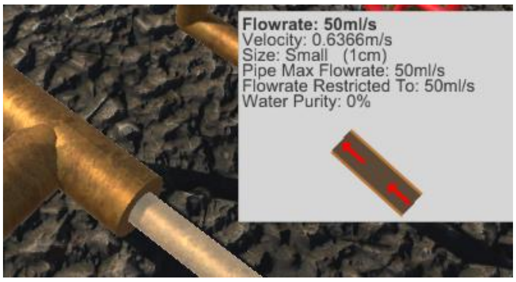
Result: Acceptable result. The sum of inputs (2*0.1m^3/s) do in-fact equal the outputs (0.05+0.1+0.05m^3/s) however the sizes of those is debateable, in reality they wouldn't all be the same as some pipes will have more of a directional bias over compared to others, given no demand restrictions.

6.1.2 - Test 2: Mixing of contaminants

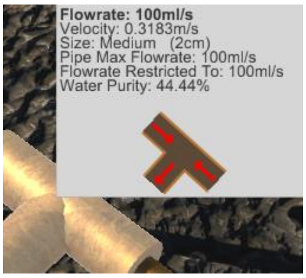
Configuration:



Flowrate: 50ml/s
Velocity: 0.6366m/s
Size: Small (1cm)
Pipe Max Flowrate: 50ml/s
Flowrate Restricted To: 50ml/s
Water Purity: 86.41%



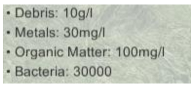
Flowrate: 50ml/s
Velocity: 0.6366m/s
Size: Small (1cm)
Pipe Max Flowrate: 50ml/s
Flowrate Restricted To: 50ml/s
Water Purity: 0%



Flowrate: 100ml/s
Velocity: 0.3183m/s
Size: Medium (2cm)
Pipe Max Flowrate: 100ml/s
Flowrate Restricted To: 100ml/s
Water Purity: 44.44%

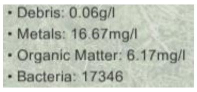
Purpose of test: See if contaminants are mixed correctly

Result: Correct result. Reservoir:



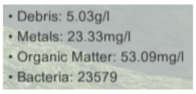
- Debris: 10g/l
- Metals: 30mg/l
- Organic Matter: 100mg/l
- Bacteria: 30000

Purified:



- Debris: 0.06g/l
- Metals: 16.67mg/l
- Organic Matter: 6.17mg/l
- Bacteria: 17346

Mixed:

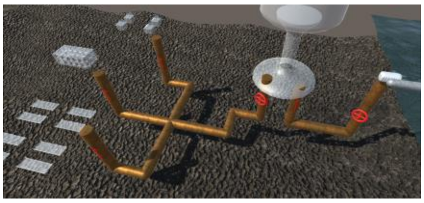


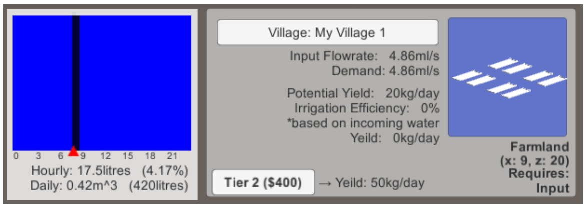
- Debris: 5.03g/l
- Metals: 23.33mg/l
- Organic Matter: 53.09mg/l
- Bacteria: 23579

The contaminants are all mixed in half, except for bacteria, which is nearly half, this is because the purified bacteria count fluctuates, and therefore so does the resulting mixed count. The purity percent isn't the average of the two input percent as the percent is roughly based on a comparison of naturally occurring levels compared to a safe amount, and not zero-based.

6.1.3 - Test 3: Demand

Configuration:

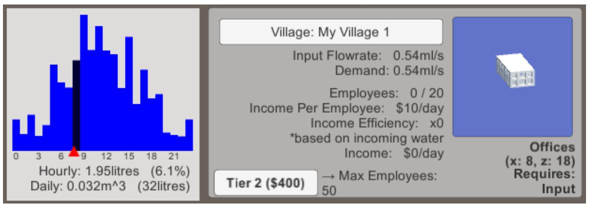




Hourly: 17.5litres (4.17%)
Daily: 0.42m^3 (420litres)

Village: My Village 1
Input Flowrate: 4.86ml/s
Demand: 4.86ml/s
Potential Yield: 20kg/day
Irrigation Efficiency: 0%
*based on incoming water
Yeild: 0kg/day
→ Yeild: 50kg/day

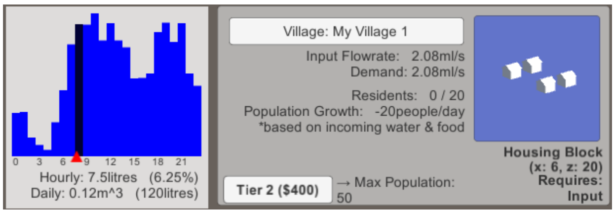
Farmland
(x: 9, z: 20)
Requires:
Input



Hourly: 1.95litres (6.1%)
Daily: 0.032m^3 (32litres)

Village: My Village 1
Input Flowrate: 0.54ml/s
Demand: 0.54ml/s
Employees: 0 / 20
Income Per Employee: $10/day
Income Efficiency: x0
*based on incoming water
Income: $0/day
→ Max Employees: 50

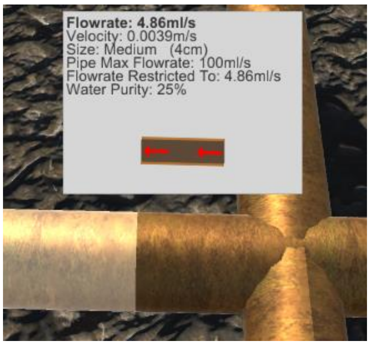
Offices
(x: 8, z: 18)
Requires:
Input

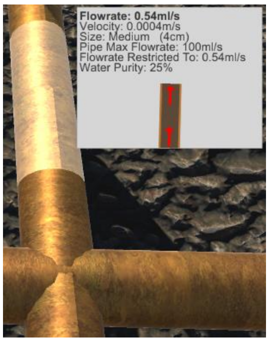


Hourly: 7.5litres (6.25%)
Daily: 0.12m^3 (120litres)

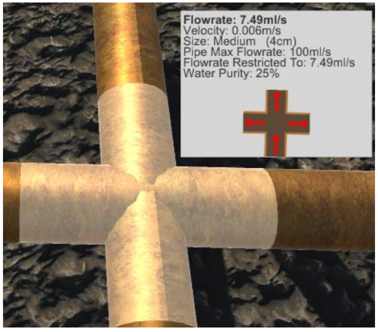
Village: My Village 1
Input Flowrate: 2.08ml/s
Demand: 2.08ml/s
Residents: 0 / 20
Population Growth: -20people/day
*based on incoming water & food
→ Max Population: 50

Housing Block
(x: 6, z: 20)
Requires:
Input


Flowrate: 4.86ml/s
Velocity: 0.0039m/s
Size: Medium (4cm)
Pipe Max Flowrate: 100ml/s
Flowrate Restricted To: 4.86ml/s
Water Purity: 25%


Flowrate: 0.54ml/s
Velocity: 0.0004m/s
Size: Medium (4cm)
Pipe Max Flowrate: 100ml/s
Flowrate Restricted To: 0.54ml/s
Water Purity: 25%


Flowrate: 2.08ml/s
Velocity: 0.0017m/s
Size: Medium (4cm)
Pipe Max Flowrate: 100ml/s
Flowrate Restricted To: 2.08ml/s
Water Purity: 25%


Flowrate: 7.49ml/s
Velocity: 0.006m/s
Size: Medium (4cm)
Pipe Max Flowrate: 100ml/s
Flowrate Restricted To: 7.49ml/s
Water Purity: 25%

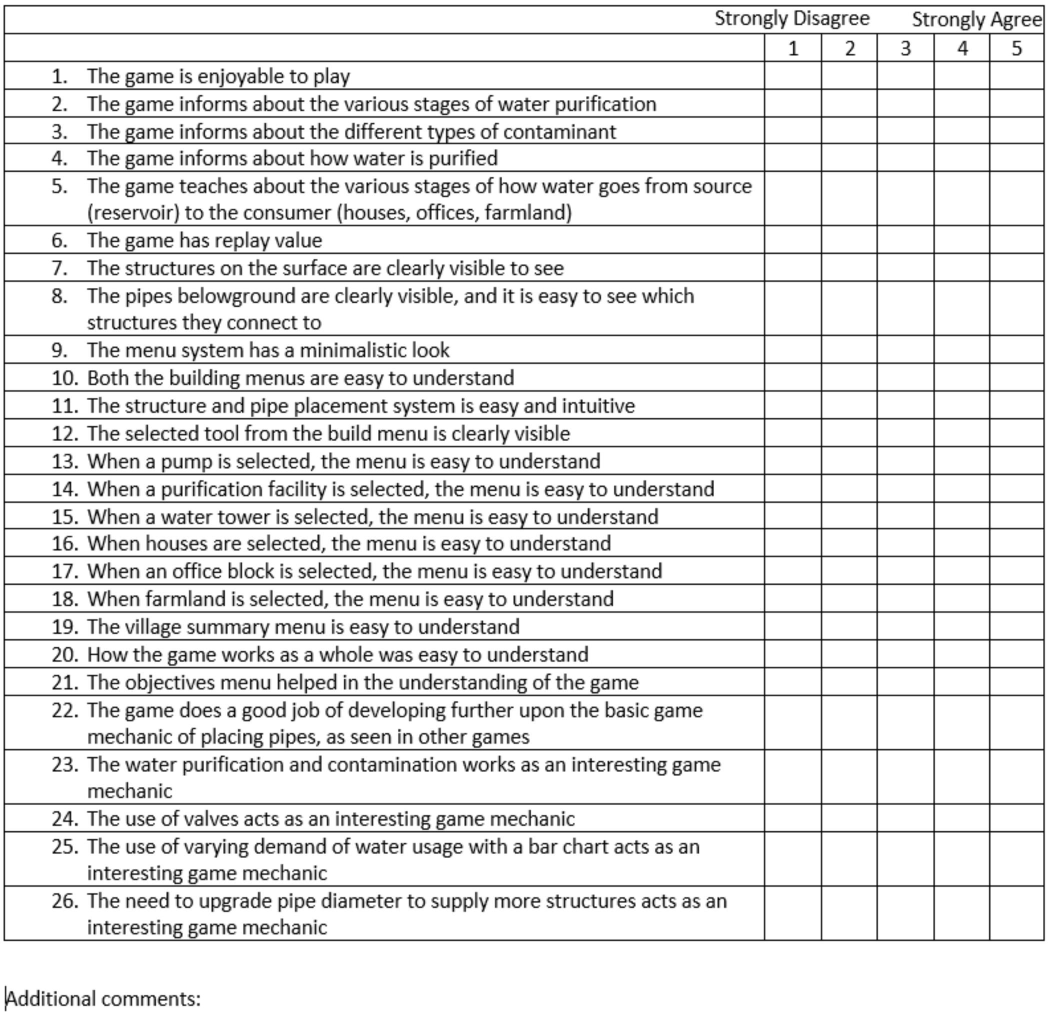
Purpose of test: To see if the demand per second is correct, and to see if the pipe network provides that correct amount.

Result: Farmland: (420Litres * 0.00417) / 3600 = 4.86ml/s. Offices: (32Litres * 0.0061)/3600 = 0.54ml/s. Houses: (120Litres * 0.00625) / 3600 = 2.08mg/l. All flowrates are correct. 4.86+0.54+2.08 = 7.48, which is 0.01 different because of intermittent rounding. Correct.

6.2 - User testing & results

Like previously stated in methodology, a questionnaire is how the data is being collected, using a Likert scale with an 'additional comments' section. To develop the questionnaire, it was broken down into sections: generic, teaching, understanding, usability and game mechanics. Generic questions are needed, to allow participants to give their general opinion on the game. The following four sections were added, to compare the project against its objectives to see if they've been achieved. As the aim is based primarily on game mechanics, the final five questions are related to specific game mechanics found within the game.

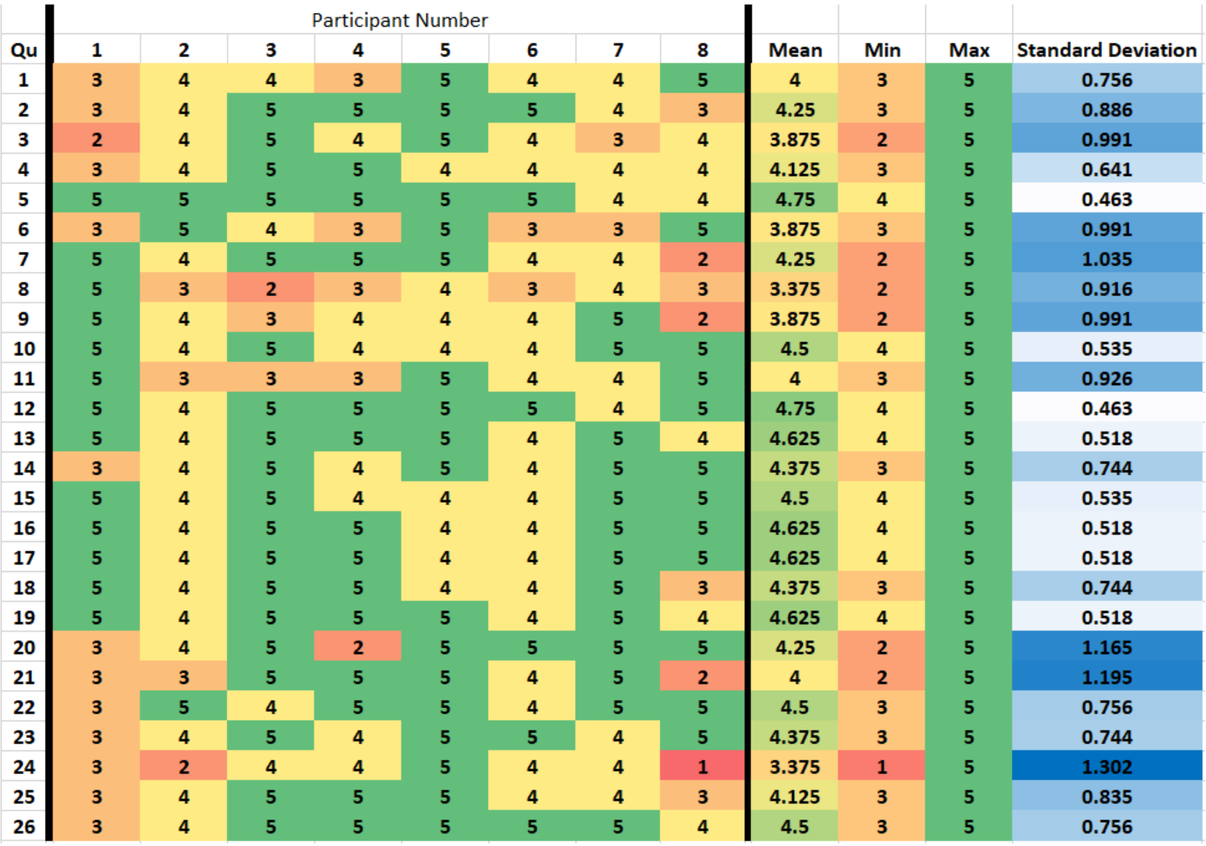
The survey was completed by 8 participants. To complete the questionnaire, a mixed demographic was used: partly students and partly adults, some of which were gamers, and others weren't; this provided a mixed response so it wouldn't be biased. I had no need to document whether or not they were students or gamers for the purposes of my questionnaire.



	Strongly Disagree				Strongly Agree
	1	2	3	4	5
1. The game is enjoyable to play					
2. The game informs about the various stages of water purification					
3. The game informs about the different types of contaminant					
4. The game informs about how water is purified					
5. The game teaches about the various stages of how water goes from source (reservoir) to the consumer (houses, offices, farmland)					
6. The game has replay value					
7. The structures on the surface are clearly visible to see					
8. The pipes belowground are clearly visible, and it is easy to see which structures they connect to					
9. The menu system has a minimalistic look					
10. Both the building menus are easy to understand					
11. The structure and pipe placement system is easy and intuitive					
12. The selected tool from the build menu is clearly visible					
13. When a pump is selected, the menu is easy to understand					
14. When a purification facility is selected, the menu is easy to understand					
15. When a water tower is selected, the menu is easy to understand					
16. When houses are selected, the menu is easy to understand					
17. When an office block is selected, the menu is easy to understand					
18. When farmland is selected, the menu is easy to understand					
19. The village summary menu is easy to understand					
20. How the game works as a whole was easy to understand					
21. The objectives menu helped in the understanding of the game					
22. The game does a good job of developing further upon the basic game mechanic of placing pipes, as seen in other games					
23. The water purification and contamination works as an interesting game mechanic					
24. The use of valves acts as an interesting game mechanic					
25. The use of varying demand of water usage with a bar chart acts as an interesting game mechanic					
26. The need to upgrade pipe diameter to supply more structures acts as an interesting game mechanic					

Additional comments:

Questionnaire



	Participant Number											
Qu	1	2	3	4	5	6	7	8	Mean	Min	Max	Standard Deviation
1	3	4	4	3	5	4	4	5	4	3	5	0.756
2	3	4	5	5	5	5	4	3	4.25	3	5	0.886
3	2	4	5	4	5	4	3	4	3.875	2	5	0.991
4	3	4	5	5	4	4	4	4	4.125	3	5	0.641
5	5	5	5	5	5	5	4	4	4.75	4	5	0.463
6	3	5	4	3	5	3	3	5	3.875	3	5	0.991
7	5	4	5	5	5	4	4	2	4.25	2	5	1.035
8	5	3	2	3	4	3	4	3	3.375	2	5	0.916
9	5	4	3	4	4	4	5	2	3.875	2	5	0.991
10	5	4	5	4	4	4	5	5	4.5	4	5	0.535
11	5	3	3	3	5	4	4	5	4	3	5	0.926
12	5	4	5	5	5	5	4	5	4.75	4	5	0.463
13	5	4	5	5	5	4	5	4	4.625	4	5	0.518
14	3	4	5	4	5	4	5	5	4.375	3	5	0.744
15	5	4	5	4	4	4	5	5	4.5	4	5	0.535
16	5	4	5	5	4	4	5	5	4.625	4	5	0.518
17	5	4	5	5	4	4	5	5	4.625	4	5	0.518
18	5	4	5	5	4	4	5	3	4.375	3	5	0.744
19	5	4	5	5	5	4	5	4	4.625	4	5	0.518
20	3	4	5	2	5	5	5	5	4.25	2	5	1.165
21	3	3	5	5	5	4	5	2	4	2	5	1.195
22	3	5	4	5	5	4	5	5	4.5	3	5	0.756
23	3	4	5	4	5	5	4	5	4.375	3	5	0.744
24	3	2	4	4	5	4	4	1	3.375	1	5	1.302
25	3	4	5	5	5	4	4	3	4.125	3	5	0.835
26	3	4	5	5	5	5	5	4	4.5	3	5	0.756

Table 7. Collected questionnaire data from Likert scale section.

Participant	Additional Comments
1	Pressure, roughness of pipes, overhead height, the cost, water flow rate to be decided.
3	Clearly a well thought out game. I found the purification interesting; it prompted me to research the subject further. The game features interesting mechanics: furthermore it clearly as well designed platform on which further mechanics can be developed.
4	Perspective was tricky, pipes joining together worked really well.
8	Easy to understand how the pump from the reservoir connects to purification facility and then to water tower to supply fresh water to village. Control of village gets more intense the more office blocks and farmland that are created. The structures and instructions could be more detailed.

Table 8. Collected questionnaire data from additional comments section

7 - Evaluations and Conclusions

To assess whether the project was a success, it is necessary to analyse the given feedback provided by the questionnaires, and to then compare the project along with those results against the aim and objectives, which allows for final conclusions to be made.

7.1 - Evaluation of User feedback

One of the questions that received a low mean was related to: how visible pipes were and how easily you can tell which structures they are connected to. Participant 4 also noted, “perspective was tricky”, which is related to the problem. This is because when placing I/O Pipes the camera perspective can trick you, making you think the pipe is below a structure, when in fact it’s not, only when you rotate the camera perspective does it allow the player to see their error. A way to mitigate this issue would have been to project a square/rectangle below each structure.

Valve game mechanic received a low mean and the highest standard deviation, meaning some difference on opinion. This is justified, the valve was implemented early in development, use of it will restrict flowrate making a negative effect on village blocks, which is undesirable.

Questions 10 to 21 detailed about the usability and understanding of the game. Questions 10 to 12 lists about the building and placement which generally received positive feedback with placement slightly less, but this is most likely due to the perspective as previously discussed. Questions 13 to 19 are about the selected structure GUIs, all of which received positive feedback, with water purification and farmland being the lowest. The water purification menu can seem a bit anti-intuitive, especially as you don’t know which processors you’ve placed and which ones you haven’t from within the menu. Questions 20 and 21, which relate to how easy the game is to understand and how the objectives help with the understanding both have a larger standard deviation, meaning there isn’t conformity.

Further analysis of additional comments from participant 1 has shown that more realistic physics were requested such as pressure and pipe friction, as well as the fact that the prices of the structures need to be balanced further. Additionally, participant 8 noted that the instructions could be clearer to help new users get used to the game.

7.2 - Evaluation of the Project Compared to the Aim

Project Aim – To explore interesting game mechanics around the topic of water flow with pipes through the medium of a fun and engaging water resource management game which will promote water conservation while teaching about water purification, contaminants and the life cycle of water.

Questions 22 to 26 refer to the implementation of game mechanics. Question 22 specifically compares this game mechanics to basic game mechanics as seen in other games, this was the problem to begin with as mentioned in the introduction. The results show this to be highly rated with moderate agreement. For the remaining features, they were generally positively received except for the valve, previously mentioned. The other aspects of this aim are detailed further in the next section.

7.3 - Evaluation of the Project Compared to the Objectives

Objective 1 - To make sure to have a comprehensible UI so that it has minimalistic coherent navigation with features like: clear outline of selected tools, tool tips when hovering, current objectives and an in-game help button.

Question 9 shows that this is some disagreement (based on standard deviation) on whether it has a minimalistic look. Navigation is all in the corner for different game modes and viewing objectives, except for speeding up time and selected structure, which appear in the other corners. Question 12 shows the selected tool is visible and easy to see, as there is positive feedback with low standard deviation. Tool tips have simply been replaced with a tag underneath the build menu item, which allows you to see the information without needing to hover. The help button, is effectively the objectives button as it tells the player what you need to do, of which in question 21 shows there is a general positive response, with some agreement.

Objective 2 - To educate the users about the serious problem that water wastage and to inform them about how much effort it put into processing their water so they should be more conservative about the water they use.

The game does in fact inform about the various stages of purification as seen in Questions 2 and 4 which received a positive result, however this doesn't necessarily mean people will read about how the purification works (as seen within water purification selected structure GUI) and it also doesn't mean they'll conserve water more because of playing the game.

Objective 3 - Research the steps involved to purify dirty water within a facility and simulate the key stages of the process within the game through the form of a purification

facility upgrade system. Each stage of the process within the facility should purify the water more and more removing different unwanted impurities from the water.

The game implements a purification facility which cleans the water to a certain standard, based upon the configuration. Additionally, water is given a contamination status at all stages of the simulation, this stores different groups of contamination info within it. The levels of contamination at the reservoir is far from pure, the levels of contamination are set based upon data from the literature review stating natural levels of contamination.

Objective 4 - Research the physics behind how water flows through pipes and implement some of the key features into the water flow simulation of the game, this would include things like pipe circumference, water velocity and volume per unit time.

The game implements some of the key features of fluid mechanics, such as flowrate, velocities and cross-sectional area. Other water mechanic features include: splitting and combining of water at junctions; potential flowrate of a water based upon gravity, height and circumference of pipe; water restrictions due to smaller pipes, demand of the users.

Adding these features to the game created a simplified version of fluid mechanics. It would be almost impossible to compute a game like this to in a fully realistic way (particle physics), which requires massive amounts of computing performance, unnecessary for this game. More features could be added such as water pressure (ideas behind it are somewhat implemented in terms of pipe restrictions, due to pseudo-backpressure), water viscosity, temperature of water, and more realistic pipe junction intersections based on directions of pipes.

The objective set out to only implement *some* of the key features, therefore this objective was fairly well completed.

Objective 5 - To try and make sure that the game is enjoyable, to do this, a variety of attributes to make it engaging. Randomness of weather conditions and the placement of resources/structures within the world will add replay value.

Question 1, shows a mean enjoyment value of 4, with *some* disagreement, but in general fairly positive. Within the additional comments, feedback from participant 8, even described the game as “intense”, which is a good response for a CMS game.

Question 6, which is related to replay value has a mean value of 3.875, with slightly more disagreement, this is fair as randomness wasn't implemented into the game in any kind of way.

Randomness of weather conditions wasn't implemented due to time constraints. Randomness of resources and structures wasn't implemented because design decisions were made to instead allow the players to place village structures for themselves.

Objective 6 - [Stretch Objective] To implement an oil system into the game, similar to the water mechanics, so this will involve obtaining the oil, purifying it and piping it to its desired destination.

This objective was not achieved, simply because it was overly ambitious to do it in the first place (hence why it was a stretch objective), given the time constraints.

Objective 7 - [Stretch Objective] To achieve a fluid gameplay experience, previews of structures or pipes should be shown when the player is deciding where to place them, this can be done by showing the object on the centre of the tile that the mouse is pointing on at a deduced opacity, additionally when placing pipes, previews of nearby pipes connecting to the preview pipe will make the game seem more fluid. Secondly the underground view of pipe placement should be clear: you should be able to see the pipes in the dirt while still showing what structures they connect to in the above ground.

When players are deciding to place structures, a preview of the structure does appear where the cursor is, but it's it at full opacity. When placing pipes a preview of the current pipe is shown on top of the cursor, seeing how it would connect to other pipes. When in the underground view, above ground structures appear translucent, allowing for greater visibility of pipes, however seeing which pipes connect to which structures is difficult to see because of the camera perspective, as previously state in the 'evaluation of user feedback' section.

7.4 - Conclusion

Over all this project was a success, it achieved its aim and most of its objectives. The finished product is a working unique game that implements a variety of interesting game mechanics, while at the same time informing players about contaminants, purification and the process of obtaining water. The game acts as a good base for further development of features and game mechanics to be added in the future.

7.5 - Potential Further Work

7.5.1 - Pipe Materials

One aspect of the game that wasn't fully implemented was different pipe materials (metals, plastic concrete, etc.) that would range in price and have different attributes such as: higher max flowrate, contaminating the water with pipe debris, and rusting depending on the corrosiveness of the water, compared to the pipes material.

Pipes with copper, iron, brass and lead settings

The additional of alternatives pipes might add confusion to the player given that they need to pick shape and size already. Also 'bad pipes' (pipes that are low level) aren't necessarily the cheap ones in real life, as lead is very harmful, but expensive, this would make for nonsensical pricing within the game.

7.5.2 - Sewage System, Adaptive Reservoir, Weather System

Once the water has been sent to houses and offices, it essentially disappears from the system and gets used up. In reality, most of that used water will be turned into dirty water and sent down the sewers, an output pipe could be added to offices and homes to take the dirty water and put it into a sewage treatment plant. This plant could clean the water to an acceptable state to put back into the reservoir.

This would effectively complete the whole water cycle, meaning the reservoir could have a varying height, as water goes into the system it drains, until it is returned from the sewage treatment. If sewage treatment isn't used, it would make it harder to clean later on, contaminating the reservoir further.

A weather mechanic could be added, evaporating farmland and emptied water tower water, to be held to rain at a later point, this would add for interesting game play such as drought and flooring, making water more of a scarce resource, while flooding could affect people getting to work (loss of income).

7.5.3 - Oil, Generators and Hydropower

There is no form of power in the game, pumps and purification facility operate without power; this is where generators come in, making power a 4th resource for players to conserve. There could by varying types of generator, such as a wood burning, oil powered or hydro powered, which would vary in price. For wood generators, a certain number of office residents would have to work as lumberjacks instead, impeding potential income.

Oil could be a 5th resource found in the world just like water; this would be in keeping with the theme of liquid management. Finding the oil could require having to dig around with a drill to find where it is, or use some form of technique to determine its location. Once found and a hole has been dug, a pump could be used to extract the oil into pipes. Like water, oil can be purified too, to allow better power efficiency, for this an oil purification rig could be placed, alongside tankers for the oil to be stored in.

Alternatively, power could be generated with the means of hydropower, given that the terrain can have varying height, a body of water high up could be linked to a dam that could generate large amounts of power, a cheaper alternative would be a water wheel.

8 - Reflective Analysis

Overall in general I feel like the project was fairly successful as I achieved my aim, implementing most of the features I wanted, which allowed me to explore new interesting game mechanics based around pipe flow. I was slightly disappointed that I couldn't implement a sewage system into the game, this is because then the game would show the whole cycle of water flow from start to finish and the water level of the reservoir could then change, making water more of a scarce resource. But I feel like that it was too much of an ambitus task to implement given the time constraints.

I feel like selecting an AGILE methodology was a good choice, my original ideas changed quite a lot compared to the final result. If I had gone for more of waterfall methodology, then my some of my original designs might not have worked, resulting in more design time, delaying the project further.

I'm happy with the choice of Unity as the game engine to develop the game, as I previous knowledge with the UI, it allowed me to focus all of my time on the project itself, rather than having to learn how to use the engine.

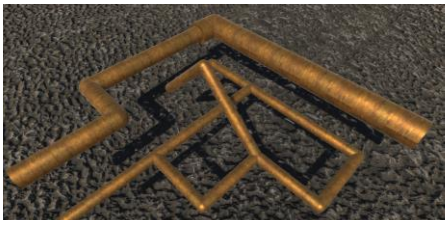
One of the major challenges when developing the game was getting my head around the different scales of water compared to the scales of time. This is because the pipes are on a city scale so they're larger than normal, but they can branch off to supply a single village block, making it a small amount of water. Time in the game can go from real-time speed, to up to 3600 times faster, so trying to test whether the quantity of water on a city size scale is filling up at an accurate amount proved to be very difficult.

One of the ways in which my simulation differs from reality, is the water consumption. I used statistical data to get the amount of water used per person, per day, and statistical data for the percentage of daily use, which is used to calculate hourly use. The problem occurs when converting from hourly use to secondly, my simulation simply divides it by 3600 to get ml/s use, whereas in reality there would be no use for a long period of time, then a large burst use of water.

8.1 - What went well

Pipe shapes, sizes and placement

I'm happy with how the variation on pipes turned out, players can pick from 8 different pipe sizes in 3 different sizes; this was done with simply two basic primitive types: a cylinder and a sphere, which is dynamically arranged and scaled depending on the shape and size to create the pipe prefab on the fly. Additionally, when an 'over pipe' is added, nearby pipes will automatically change their shape to connect to them. Overall I think the pipe shapes look nice and the mixing of cylinder and sphere textures blend seamlessly. The placement system work well, pipes are aligned to a grid, when the cursor is on the grid it shows a preview of the pipe placement, once placed it aligns seamlessly to neighbouring pipes to give the effect of one continuous pipe, rather than many individual pieces.



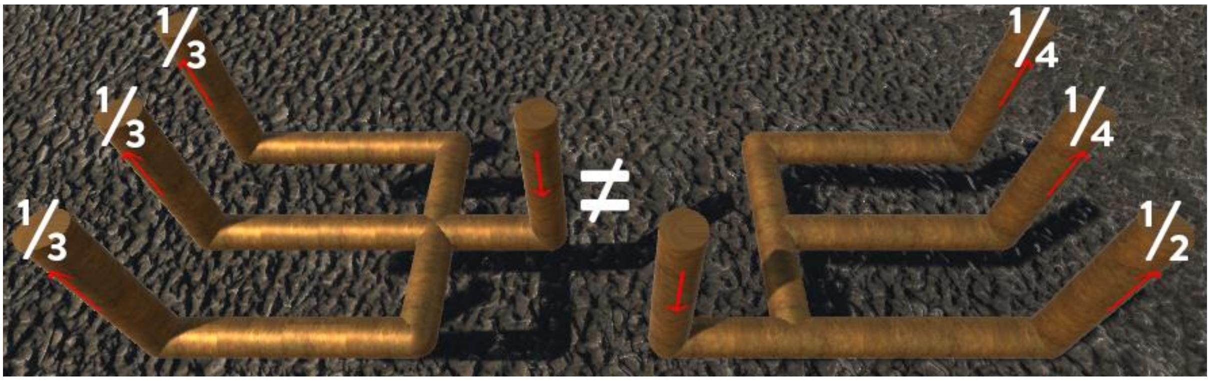
Explored interesting game mechanics

I'm happy with how I've adapted the basic idea of a pipe placement game, added more realistic physics to it and created a whole new unique game, different to any other I've seen.

8.2 - What didn't go well

Pipe water distribution

When trying to implement the main game loop for water transportation I knew that fluid mechanics is an advanced topic and that I could never make it 100% accurate, and so I needed to use simplified water mechanics. When implementing the game loop, originally I only implemented 'step 1' detailed in my implementation section, and for that I had to design a way to handle the directions of water flow, and how to manage the splitting and combining of water in the multisided pipes. The way that I implemented it, meantthat if water is flowing in one direction, then another pipe can't feed back into that pipe in the wrong direction. Additionally, there's a multi-sided pipe, the water is distributed in half (2 sinks) or thirds (3 sinks) at that junction (if both output pipes are the same size), however this means the order in which you split the pipes can dictate how much water goes to each, see below diagram. This is different to reality; in reality, the order of splitting will have *some* effect on the distribution, but not to the extent that my game does it. Thankfully when the 'step 2' was implemented, this meant that water that was not 'used up' on the first destination, can be carried to the subsequent destinations, meaning this effect would be only visible when there's not an access of water, compared to the demand of village structures.



Pipe pressures

Originally when trying to implement the fluid mechanics, pressure information was added to water along with information like flowrate and velocity. Pressure would be built up from a water tower, or added from a pump. This meant that the direction of water could be moved based on pressure differentials, making it more realistic to how water flows in reality. Along with different heights affecting pressure, different pipe diameters can also effect the pressure of the pipe, for this I tried to implement the Bernoulli equation (as aforementioned in my literature review); this seemed to work in theory, but when trying to implement a whole model that can work for an endless variety of configurations, this was more difficult. As pressure wasn't implemented, to help simulate the effects of back-pressure I added flowrate restrictions based upon pipe sizes, but this isn't a perfect solution.

Removing contaminants with water purification processes, and the effects of contaminants on residents

One of the big challenges of the project was to link contaminants into groups, find how the purification process cleans which type of contaminant from the water supply and how those remaining contaminants affect residents and crops. For the purposes of this game I've had to do a lot generalisation, this is because there's an almost endless list of contaminants that can be found within nature and so I've had to group them together, the problem with this is making a group called 'metals' is so general as some metals will be good for you while other will kill you. Additionally, for purification processes it was difficult for me to know exactly what, and how much was removed at each stage of the process. Therefore, my implementation of removing a certain percent of a group type of contaminant was a big generalisation.

Communicating what's happening to users

I find that I struggled to implement a way to communicate to the users why certain things are happening within the game. For example, there can be 5 different reason for why there isn't as much water as expected flowing through a pipe to a village block, these are: the water tower can't supply enough; the valve is turned to restrict water; there water is at its maximum flowrate for a certain pipe piece; there isn't enough demand; another structure is taking most of the water. However, the user isn't directly told which one of the 5 reasons that this is happening, instead they must work it out by inspecting the information about various pipes, valves and structures.

I've often wondered why there isn't enough water flowing, thinking there's a bug, when in fact it's due to an intentional restriction within the game, for a reason. The mitigate these issues, there should be pipeline analysis that will identify to the user where bottle-necks in the system exist, or if it's the fault of the structure as to why there isn't enough water flowing.

8.3 - Things I would do differently next time

Make purification facilities better

I feel like the design of how the water purification facility functions could be better. It should clean the water in batches, having a dirty water input which fills up over time, and then a clean water storage to store the water before passing it on further, this would make it more realistic to real life and also make it more intuitive for users as currently if the destination storage (e.g. water tower) is full, the processing stops. Also, players pretty much need to buy most/all of the purification processors as soon as the game start, to make sure that they are providing clean water, the only part that is upgraded over time is the main part (to allow more to be processed at once), which doesn't expand upon the purification side. Additionally, it would be better if the users had a better indication of the inner working of the purification, listing what it would be at each stage and what each stage would remove from the water.

Code Efficiency when finding items within the Grid

When designing the code for how the pipe and structure data should be stored, I decided to have a 2-dimensional array for structures and a 3-dimensional array for pipes (using the 3rd dimension for the two height levels); this meant that I could index the position of the item with just two or three indexing coordinates. At first this seemed like the best way to implement it, but later when I was trying to optimise code efficiency I realised that this wasn't the best, this is because whenever a function needs to find objects within the world, it must search through the whole grid space to find the items, if instead there were a list of the created pipes and a list of the created structures, then a search function would be able to find the items quicker, this would also mean performance would stay the same if the map size were to increase, unlike before. To be able to access items with coordinates there should still be a 2-dimensional/3-dimensional, however this should contain a pointer to the item within the list instead.

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10 - Appendix A

[redacted] Participant 1

	Strongly Disagree			Strongly Agree	
	1	2	3	4	5
1. The game is enjoyable to play				✓	
2. The game informs about the various stages of water purification				✓	
3. The game informs about the different types of contaminant				✓	
4. The game informs about how water is purified				✓	
5. The game teaches about the various stages of how water goes from source (reservoir) to the consumer (houses, offices, farmland)					✓
6. The game has replay value					✓
7. The structures on the surface are clearly visible to see				✓	
8. The pipes belowground are clearly visible, and it is easy to see which structures they connect to			✓		
9. The menu system has a minimalistic look				✓	
10. Both the building menus are easy to understand				✓	
11. The structure and pipe placement system is easy and intuitive			✓		
12. The selected tool from the build menu is clearly visible				✓	
13. When a pump is selected, the menu is easy to understand				✓	
14. When a purification facility is selected, the menu is easy to understand				✓	
15. When a water tower is selected, the menu is easy to understand				✓	
16. When houses are selected, the menu is easy to understand				✓	
17. When an office block is selected, the menu is easy to understand				✓	
18. When farmland is selected, the menu is easy to understand				✓	
19. The village summary menu is easy to understand				✓	
20. How the game works as a whole was easy to understand				✓	
21. The objectives menu helped in the understanding of the game			✓		
22. The game does a good job of developing further upon the basic game mechanic of placing pipes, as seen in other games					✓
23. The water purification and contamination works as an interesting game mechanic				✓	
24. The use of valves acts as an interesting game mechanic		✓			
25. The use of varying demand of water usage with a bar chart acts as an interesting game mechanic				✓	
26. The need to upgrade pipe diameter to supply more structures acts as an interesting game mechanic				✓	

Additional comments:

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[redacted] Participant 2

		Strongly Disagree			Strongly Agree
	1	2	3	4	5
1. The game is enjoyable to play			✓		
2. The game informs about the various stages of water purification			✓		
3. The game informs about the different types of contaminant		✓			
4. The game informs about how water is purified			✓		
5. The game teaches about the various stages of how water goes from source (reservoir) to the consumer (houses, offices, farmland)					✓
6. The game has replay value			✓		
7. The structures on the surface are clearly visible to see					✓
8. The pipes belowground are clearly visible, and it is easy to see which structures they connect to					✓
9. The menu system has a minimalistic look					✓
10. Both the building menus are easy to understand					✓
11. The structure and pipe placement system is easy and intuitive					✓
12. The selected tool from the build menu is clearly visible					✓
13. When a pump is selected, the menu is easy to understand					✓
14. When a purification facility is selected, the menu is easy to understand			✓		
15. When a water tower is selected, the menu is easy to understand					✓
16. When houses are selected, the menu is easy to understand					✓
17. When an office block is selected, the menu is easy to understand					✓
18. When farmland is selected, the menu is easy to understand					✓
19. The village summary menu is easy to understand					✓
20. How the game works as a whole was easy to understand			✓		
21. The objectives menu helped in the understanding of the game			✓		
22. The game does a good job of developing further upon the basic game mechanic of placing pipes, as seen in other games			✓		
23. The water purification and contamination works as an interesting game mechanic			✓		
24. The use of valves acts as an interesting game mechanic			✓		
25. The use of varying demand of water usage with a bar chart acts as an interesting game mechanic			✓		
26. The need to upgrade pipe diameter to supply more structures acts as an interesting game mechanic			✓		

Additional comments:

Pressure, roughness of pipes, overhead height

The Cost, water flow rate to be decided.

[redacted] Participant 3

	Strongly Disagree				Strongly Agree
	1	2	3	4	5
1. The game is enjoyable to play				✓	
2. The game informs about the various stages of water purification					✓
3. The game informs about the different types of contaminant					✓
4. The game informs about how water is purified					✓
5. The game teaches about the various stages of how water goes from source (reservoir) to the consumer (houses, offices, farmland)					✓
6. The game has replay value				✓	
7. The structures on the surface are clearly visible to see					✓
8. The pipes belowground are clearly visible, and it is easy to see which structures they connect to		✓			
9. The menu system has a minimalistic look			✓		
10. Both the building menus are easy to understand					✓
11. The structure and pipe placement system is easy and intuitive			✓		
12. The selected tool from the build menu is clearly visible					✓
13. When a pump is selected, the menu is easy to understand					✓
14. When a purification facility is selected, the menu is easy to understand					✓
15. When a water tower is selected, the menu is easy to understand					✓
16. When houses are selected, the menu is easy to understand					✓
17. When an office block is selected, the menu is easy to understand					✓
18. When farmland is selected, the menu is easy to understand					✓
19. The village summary menu is easy to understand					✓
20. How the game works as a whole was easy to understand					✓
21. The objectives menu helped in the understanding of the game					✓
22. The game does a good job of developing further upon the basic game mechanic of placing pipes, as seen in other games				✓	
23. The water purification and contamination works as an interesting game mechanic					✓
24. The use of valves acts as an interesting game mechanic				✓	
25. The use of varying demand of water usage with a bar chart acts as an interesting game mechanic					✓
26. The need to upgrade pipe diameter to supply more structures acts as an interesting game mechanic					✓

Additional comments:

Clearly a well thought out game. I found the purification interesting: it prompted me to research the subject further. The game featured interesting mechanics: furthermore its clearly a well designed Platform on which further mechanics can be developed.

[redacted] Participant 4

	Strongly Disagree				Strongly Agree
	1	2	3	4	5
1. The game is enjoyable to play			✓		
2. The game informs about the various stages of water purification					✓
3. The game informs about the different types of contaminant				✓	
4. The game informs about how water is purified					✓
5. The game teaches about the various stages of how water goes from source (reservoir) to the consumer (houses, offices, farmland)					✓
6. The game has replay value			✓		
7. The structures on the surface are clearly visible to see					✓
8. The pipes belowground are clearly visible, and it is easy to see which structures they connect to			✓		
9. The menu system has a minimalistic look				✓	
10. Both the building menus are easy to understand				✓	
11. The structure and pipe placement system is easy and intuitive			✓		
12. The selected tool from the build menu is clearly visible					✓
13. When a pump is selected, the menu is easy to understand					✓
14. When a purification facility is selected, the menu is easy to understand				✓	
15. When a water tower is selected, the menu is easy to understand				✓	
16. When houses are selected, the menu is easy to understand					✓
17. When an office block is selected, the menu is easy to understand					✓
18. When farmland is selected, the menu is easy to understand					✓
19. The village summary menu is easy to understand					✓
20. How the game works as a whole was easy to understand		✓			
21. The objectives menu helped in the understanding of the game					✓
22. The game does a good job of developing further upon the basic game mechanic of placing pipes, as seen in other games					✓
23. The water purification and contamination works as an interesting game mechanic				✓	
24. The use of valves acts as an interesting game mechanic				✓	
25. The use of varying demand of water usage with a bar chart acts as an interesting game mechanic					✓
26. The need to upgrade pipe diameter to supply more structures acts as an interesting game mechanic					✓

Additional comments:

Perspective was tricky, pipes Joining together worked really well.

[redacted] Participant 5

	Strongly Disagree			Strongly Agree	
	1	2	3	4	5
1. The game is enjoyable to play					✓
2. The game informs about the various stages of water purification					✓
3. The game informs about the different types of contaminant					✓
4. The game informs about how water is purified				✓	
5. The game teaches about the various stages of how water goes from source (reservoir) to the consumer (houses, offices, farmland)					✓
6. The game has replay value					✓
7. The structures on the surface are clearly visible to see					✓
8. The pipes belowground are clearly visible, and it is easy to see which structures they connect to				✓	
9. The menu system has a minimalistic look				✓	
10. Both the building menus are easy to understand				✓	
11. The structure and pipe placement system is easy and intuitive					✓
12. The selected tool from the build menu is clearly visible					✓
13. When a pump is selected, the menu is easy to understand					✓
14. When a purification facility is selected, the menu is easy to understand					✓
15. When a water tower is selected, the menu is easy to understand				✓	
16. When houses are selected, the menu is easy to understand				✓	
17. When an office block is selected, the menu is easy to understand				✓	
18. When farmland is selected, the menu is easy to understand				✓	
19. The village summary menu is easy to understand					✓
20. How the game works as a whole was easy to understand					✓
21. The objectives menu helped in the understanding of the game					✓
22. The game does a good job of developing further upon the basic game mechanic of placing pipes, as seen in other games					✓
23. The water purification and contamination works as an interesting game mechanic					✓
24. The use of valves acts as an interesting game mechanic					✓
25. The use of varying demand of water usage with a bar chart acts as an interesting game mechanic					✓
26. The need to upgrade pipe diameter to supply more structures acts as an interesting game mechanic					✓

Additional comments:

[redacted] Participant 6

	Strongly Disagree				Strongly Agree
	1	2	3	4	5
1. The game is enjoyable to play				✓	
2. The game informs about the various stages of water purification					✓
3. The game informs about the different types of contaminant				✓	
4. The game informs about how water is purified				✓	
5. The game teaches about the various stages of how water goes from source (reservoir) to the consumer (houses, offices, farmland)					✓
6. The game has replay value			✓		
7. The structures on the surface are clearly visible to see				✓	
8. The pipes belowground are clearly visible, and it is easy to see which structures they connect to			✓		
9. The menu system has a minimalistic look				✓	
10. Both the building menus are easy to understand				✓	
11. The structure and pipe placement system is easy and intuitive				✓	
12. The selected tool from the build menu is clearly visible					✓
13. When a pump is selected, the menu is easy to understand				✓	
14. When a purification facility is selected, the menu is easy to understand				✓	
15. When a water tower is selected, the menu is easy to understand				✓	
16. When houses are selected, the menu is easy to understand				✓	
17. When an office block is selected, the menu is easy to understand				✓	
18. When farmland is selected, the menu is easy to understand				✓	
19. The village summary menu is easy to understand				✓	
20. How the game works as a whole was easy to understand					✓
21. The objectives menu helped in the understanding of the game				✓	
22. The game does a good job of developing further upon the basic game mechanic of placing pipes, as seen in other games				✓	
23. The water purification and contamination works as an interesting game mechanic					✓
24. The use of valves acts as an interesting game mechanic				✓	
25. The use of varying demand of water usage with a bar chart acts as an interesting game mechanic				✓	
26. The need to upgrade pipe diameter to supply more structures acts as an interesting game mechanic					✓

Additional comments:

[redacted] Participant 7

	Strongly Disagree			Strongly Agree	
	1	2	3	4	5
1. The game is enjoyable to play				✓	
2. The game informs about the various stages of water purification				✓	
3. The game informs about the different types of contaminant			✓		
4. The game informs about how water is purified				✓	
5. The game teaches about the various stages of how water goes from source (reservoir) to the consumer (houses, offices, farmland)				✓	
6. The game has replay value			✓		
7. The structures on the surface are clearly visible to see				✓	
8. The pipes belowground are clearly visible, and it is easy to see which structures they connect to				✓	
9. The menu system has a minimalistic look					✓
10. Both the building menus are easy to understand					✓
11. The structure and pipe placement system is easy and intuitive				✓	
12. The selected tool from the build menu is clearly visible				✓	
13. When a pump is selected, the menu is easy to understand					✓
14. When a purification facility is selected, the menu is easy to understand					✓
15. When a water tower is selected, the menu is easy to understand					✓
16. When houses are selected, the menu is easy to understand					✓
17. When an office block is selected, the menu is easy to understand					✓
18. When farmland is selected, the menu is easy to understand					✓
19. The village summary menu is easy to understand					✓
20. How the game works as a whole was easy to understand					✓
21. The objectives menu helped in the understanding of the game					✓
22. The game does a good job of developing further upon the basic game mechanic of placing pipes, as seen in other games					✓
23. The water purification and contamination works as an interesting game mechanic				✓	
24. The use of valves acts as an interesting game mechanic				✓	
25. The use of varying demand of water usage with a bar chart acts as an interesting game mechanic				✓	
26. The need to upgrade pipe diameter to supply more structures acts as an interesting game mechanic					✓

Additional comments:

Participant 8

	Strongly Disagree			Strongly Agree	
	1	2	3	4	5
1. The game is enjoyable to play					✓
2. The game informs about the various stages of water purification			✓		
3. The game informs about the different types of contaminant				✓	
4. The game informs about how water is purified				✓	
5. The game teaches about the various stages of how water goes from source (reservoir) to the consumer (houses, offices, farmland)				✓	
6. The game has replay value					✓
7. The structures on the surface are clearly visible to see		✓			
8. The pipes belowground are clearly visible, and it is easy to see which structures they connect to			✓		
9. The menu system has a minimalistic look		✓			
10. Both the building menus are easy to understand					✓
11. The structure and pipe placement system is easy and intuitive					✓
12. The selected tool from the build menu is clearly visible					✓
13. When a pump is selected, the menu is easy to understand				✓	
14. When a purification facility is selected, the menu is easy to understand					✓
15. When a water tower is selected, the menu is easy to understand					✓
16. When houses are selected, the menu is easy to understand					✓
17. When an office block is selected, the menu is easy to understand					✓
18. When farmland is selected, the menu is easy to understand			✓		
19. The village summary menu is easy to understand				✓	
20. How the game works as a whole was easy to understand					✓
21. The objectives menu helped in the understanding of the game		✓			
22. The game does a good job of developing further upon the basic game mechanic of placing pipes, as seen in other games					✓
23. The water purification and contamination works as an interesting game mechanic					✓
24. The use of valves acts as an interesting game mechanic	✓				
25. The use of varying demand of water usage with a bar chart acts as an interesting game mechanic			✓		
26. The need to upgrade pipe diameter to supply more structures acts as an interesting game mechanic				✓	

Additional comments:

Easy to understand how the pump from resevoir connects to purification facility and then to water tower to supply fresh water to village. Control of village gets more intense the more office blocks and farmland that are created. The structures and instructions could be more detailed.