Water Reuse

Water Reuse Vol 13 No 2, 107 doi: 10.2166/wrd.2023.063

Smart water network infrastructures

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ABSTRACT

This paper presents a solution to convert the conventional water network into a smart water network (SWN). Scenarios are synthesized for water recycling inside buildings with less water consumed, minimizing the overall cost. Multiphysics modelling and simulation are conducted with Hysys and Ansys - Fluent in calculating the water flow quantity, pressure of the water network and velocity of water inside the pipe network. Four scenarios are synthesized and modelled for a selected mall building case study. These scenarios reduce the water consumption in the mall from 100% to 29.4%, with a cost-saving of more than 60%.

Key words: smart infrastructures, smart water networks, water-energy nexus, water semantic networks

HIGHLIGHTS

- Design of smart water network framework.
- Synthesis and evaluation of smart water network design scenarios.
- Modeling and simulation of water networks.

NOMENCLATURE

z	The height between source and pump destination (m)
γ	The specific weight of water
ρ	Density of water (kg/m^3)
g	Gravitational acceleration (m/s^2)
A	The cross-sectional area of the pipe (m^2)
V	water velocity (m^2/s)
Q	Flow rate (m^3/s)
P	Pressure (pa)
η	Efficiency
Sh	Sherwood number
Re	Reynolds number
Sc	Schmidt number
K_m	Mass transfer coefficient (m/s)
d	Diameter of pipe (m)
D	Diffusion constant (m^2/s)
U	Mean flow velocity (m/s)
ρ_l	Density of liquid (kg/m^3)
ρ_{Fe}	Density of iron (kg/m^3)
μ	Dynamic viscosity (kg/ms)
$C_{(b.O)}$	Bulk concentration of oxygen (kg/m^3)
M_{Fe}	Molar mass of iron (g/mol)
CR	Corrosion rate (mm/year)

ABBREVIATIONS

SWN Smart water network.
KPIs key performance indicators
WSN Water semantic network
HVAC (heating, ventilation and airconditioning)

1. INTRODUCTION

Water stress or scarcity occurs when the demand for safe and available water exceeds the supply in a particular area. On the demand side, most of the world's freshwater (around 70%) is used for agriculture, with the remainder split between industrial use (19%) and domestic use, including drinking (11%). On the supply side, water sources include surface water such as rivers, lakes and reservoirs, and groundwater accessible from aquifers. However, global warming is expected to increase the number of water-stressed areas and exacerbate water stress in areas already affected. Subtropical regions such as Australia, the southern United States, and some countries in European and North African countries are expected to experience warmer temperatures and more frequent and prolonged droughts. However, if precipitation does occur in these areas, it is expected to be more intense. Weather in the tropics is also becoming more variable, climate researchers say (Klobucista & Robinson 2022). Therefore, water conservation has become necessary and inevitable, especially nowadays, after the world is exposed to drought and the depletion of some rivers. Canada and worldwide are experiencing climate and environmental changes directly linked to water networks. The Government of Canada is committed to achieving net-zero emissions by 2050. These factors motivated governments, municipalities, companies, and the public to analyze water supply and conservation strategies with an effective transition to smart water networks (SWNs). Water is critical to humans, animals, and plants; its importance is reflected in associated industries, and residential and community infrastructures, including energy, food, agriculture, transportation, recreation, health, and waste processes. Typically, the most recognized goal of wastewater reclamation and reuse is to produce water of sufficient quality for use in potential applications that do not require drinking water quality standards, such as urban uses (Sala & Serra 2004).

As the extension of cities in Canada, the request for water increments and can stretch groundwater or surface water sources. Climate changes are diminishing the masses of ice, and the source of a regular supply of water within the west of Canada territories is at hazard. The Canadian reaction to reuse was considered in 2015 (Velasquez & Yanful 2015). The ponder appeared that a more significant part of the college community was in support of utilizing reuse water, be that as it may, they were more likely to acknowledge reuse wastewater for applications that do not include drinking or near individual contact. Otherwise, the province of Ontario published the Water and Energy Conservation Guidance Manual for Sewage Works, of which Part 4 is on Water recovery and reuse (Water and Energy Conservation Guidance Manual for Sewage Works 2012). One of the existing cases was considered, ponders of six golf courses all through Canada, and it was stated within the report. A Canadian standard, CAN/-CSA-B128.1–06/B128.2–06 (R2016), shows the Plan and Establishment of Non-Potable Water Systems/Maintenance and Field Testing of Non-Potable Water Frameworks (B128.1-2006/B128.2-2006 2016). It can be utilized for non-potable water frameworks for applications such as flushing toilets, flooding gardens and gardens, washing automobiles, showering, showering, washing dress, or warming and cooling. In 1991, The 'Toronto Healthy House' established a competition design as a project for recycling the water of houses, including a cistern beneath the backyard deck. It was done by filtering the water collected from rain and gray water, then reused in the house again (Boake 2008). About 80% of the water used at home is recycled. Reuses in London, Ontario, include 3-M offices and Fanshawe College. 3M offices use reservoir water from an underground sump tile system to flush toilets. These efforts have reduced the building's drinking water consumption by 25% per year for 600 on-site employees (approximately 200 m^3 per month since 2017) (Rossum 2020).

Moreover, Ottawa's Conservation Cooperative had begun a case study for the reuse of domestic water by treatment of light gray water (bath and shower wastewater). It was reused in eight units of apartment complexes for flushing toilets. The system separates the bathroom drain, from those toilets and sinks to showers, while two supply lines separate the recovered toilet flush water from all other water sources in the building. Preliminary treatment results indicated that all had recovered Water quality targets met, except for bacteriological quality (Salah & Waller 1999). In some cases, treated wastewater is indirectly used for drinking purposes. For example, injecting into aquifers increases treatment capacity and minimizes saltwater intrusion. Water recycling and reuse are critical to climate change adaptation, as increasingly unpredictable weather patterns and their impacts, such as severe drought and sea-level rise, are likely to adversely affect the quantity and quality of freshwater resources (UN Environment-DHI Center 2017). Water reclamation or recycling primarily makes non-potable wastewater useful. Hence, provide cost saving with enhanced environmental benefits. The economic impact mainly depends on the power consumption to produce and pump fresh water. This relationship between energy and water is analyzed and KPIs are assessed (Gabbar & Abdelsalam 2020).

From the previous survey, the process of water recycling is considered the mean cornerstone for living on the earth. Therefore, the paper presents a practical solution to analyze, plan, and manage water networks. Most solutions for water conservation from the literature depend on recycling rainwater and some output from sinks to toilets for flushing. This recycling saves water and costs with a rate not more than 25% of the AS–IS model. The paper has conducted potential scenarios to enhance the water conservation system and make it less costly than other solutions in the literature. It is done with a low rate of capital and running costs. An integrated modeling and simulation tool is proposed using Multiphysics modeling to define and evaluate all possible water recycling scenarios.

Moreover, the authors focus on the analysis, development, and management of water networks and their interactions with community infrastructures to support decision-making and planning of transitioning SWN. It includes environment and health adaptation in water systems where SWN will ensure the capacity to include and account for climate change impacts on water systems as linked with community infrastructures. Multiphysics modeling and simulation is used to evaluate and assess water cycles, processes, treatment, storage, transportation, and utilization systems and define associated model parameters and key performance indicators (KPIs). Water semantic network (WSN) is studied and adopted to answer questions with learning capabilities from experts, real-time data, simulation, and historical data. The proposed solution will support the transitioning of smart water networks in Canada and make it as a model for worldwide deployment.

2. SMART WATER NETWORK FRAMEWORK

The work is divided into seven modules, as shown in Figure 1.

Module-1: Multiphysics Modeling and Simulation: This module will enable to practice computational and Multiphysics modeling and simulation of water networks and discuss water properties in all relevant processes with other scientists and experts and define and assess KPIs. Modeling will cover nano, micro, and macro levels including physical infrastructures of water networks. Model parameters and coupling among them will be linked within WSN. This module will practice model parameters and interfaces between water networks processes of energy-transportation-food-health-social infrastructures. **Module-2: Water Semantic Network:** This module will support transforming knowledge associated with models into WSN. This module will provide AI, learning, and reasoning techniques for optimization and data analytics of water networks and discuss dynamic updates of WSN, which will be used to integrate all views from all scientists and experts. **Module-3: Environmental Assessment:** This module will enable to practice environmental assessment techniques for water processes, systems, facilities, and infrastructures. It will acquire knowledge related to the environmental degradation of water processes and systems and link to environmental impacts. The assessment is based on performance measures

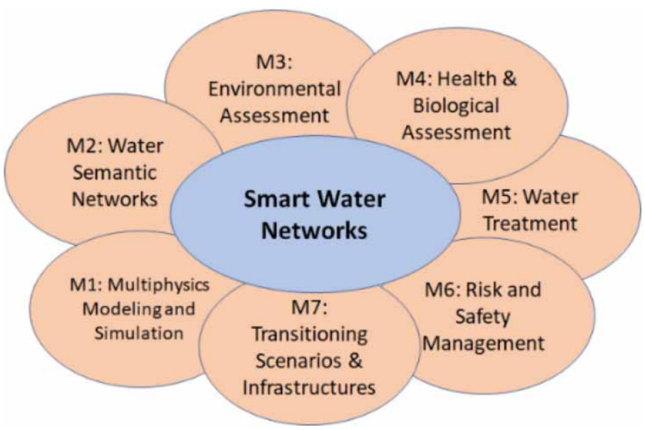

Figure 1 | Smart water networks modules.

which are linked to water quality and properties. **Module-4: Health & Biological Assessment:** This module will enable to practice health and biological assessment techniques for water processes, systems, facilities, and infrastructures. This will acquire knowledge related to biodegradation of water processes and systems and link to health impacts. Health assessment is based on KPIs related to human and animal health and plants, which are linked to water quality and properties. **Module-5: Water Treatment:** This module will enable water treatment techniques, processes, and technologies. It will practice different storage and transportation options and technologies and assess water quality and link to performance measures. The module will practice water treatment process technologies and the integration within interconnected infrastructures. It will practice different water sensor technologies, and how to evaluate water properties and diagnose water networks. The module will include models and technologies for water treatments and quality control. **Module-6: Risk and Safety Management:** This module will enable to practice risk assessment and management techniques, probabilistic approaches, hazard scenarios, and safety and protection layers for water networks and infrastructures. It will practice risk and safety management approaches on water networks, treatment facilities, water transportation, water storage, and link to design and operation decision-making. **Module-7: Transitioning Scenario & Infrastructures:** This module will enable to practice the synthesis and analysis of transition scenarios of SWN in different community applications and infrastructures. This will acquire knowledge about developing and evaluating potential scenarios to deploy SWNs, assure water security, and process technologies and evaluate their performance to ensure successful implementations. It will practice water technologies to support and manage changes in water networks. It will understand relations between water networks and community development, supported by the circular economy with integrated views of water networks within community applications.

3. METHODOLOGY

This paper discusses smart water infrastructures to analyze, plan, and manage water networks. The objectives of the paper include the analysis of water networks and their interactions with other systems in community applications. The identification of coupling mechanisms between water and other interconnected systems includes deterministic and probabilistic models to be able to evaluate optimum water management scenarios and associated policies. The paper is prepared for the integrated modeling and simulation using Multiphysics, which is used to evaluate interactions of water flow conversions and define associated model parameters with performance measures. A WSN is developed with a knowledge base to accumulate related models and parameters for water cycles to be able to answer questions with learning capabilities from real-time data, simulation, and historical data. The paper's framework analyzes and discusses the preparation of the following focal areas: (a) Coupling between water infrastructures and community systems; (b) Model water properties in all processes and assess the performance measures; (c) Develop a knowledge base for WSNs for learning and reasoning about water systems and interfaces; (d) Model different water management schemes for sustainable communities with optimization to achieve the highest performance; and (e) Study water treatment process technologies and their integration with WSNs.

To create a multi-physical model of a physical water network, an initial model outlining the physical water flow from cradle to grave must first be defined. This part will discuss the process from node to node and from one process step to the next. To begin, we must consider each source of water. For this model, both surface-level water (rivers, ponds, lakes) and groundwater are considered. The water network model is defined and drawn due to the water supply process and residual one. The model has a color code and can be seen in Table 1.

The water process steps differ based on the source of water; however, for this model, the water process is designed to take both source types into account. The treated water is then sent to storage tanks, out of a distribution network, then to each customer nodes (residential and commercial). The model also considers the internal water networks for each node to account for interactions at node level (i.e., interaction with building piping, faucets, etc.). The residual water (waste, excess water, and stormwater in cities) then is fed into wastewater treatment facilities where they are treated and released back into the environment. The overall process can be viewed in Figure 2.

The article offers new ways to model water networks with extracted knowledge from experts, simulation, real-time data, and technologies, which are updated dynamically within WSNs. The training will enable experts and public inputs to WSNs to support design, operation, management, and transition scenarios for community projects of smart water networks. The Multiphysics modeling in nano, micro, and macro levels of water networks will enable accurate evaluation of different scenarios and assessment of relevant KPIs.

Table 1 | The color code of the SWN

Color	Physical system
Blue	1. Boiler and Main Storage Tank 2. Cooling and Heating water system (drinkable) 3. Sprinkler system (input) 4. Basin, Sink inlet (input) 5. Shower bath (input) 6. Washing machine (input)
Orange	1. Toilets/Urinal (input) 2. Basin (output) 3. Shower bath (output) 4. Washing machine (output)
Green	The output of Sewage water treatment to the Irrigation system
Brown	Sink output
Gray	Toilets/Urinal Output
Purple	1. Raw water source 2. Rain and storm water 3. Industrial treated water

3.1. KPIs (A_1&A_2)

Since both sources are considered at node A, their KPI are similar. Thus, we can group both KPIs together. Just like the model parameters, we can have both physical KPI and chemical KPI (water properties). Table 1 illustrates physical KPI (of water capture and pump station) while Table 2 covers KPI for water quality (Goldoni *et al.* 2014; Khalil 2021) (A_1: Design, A_2: Alternative Component). Otherwise, Table 3 indicates the water quality chemically.

Each of these KPIs can be evaluated either by the formula used in simulation or by direct measurements, details of each are described below.

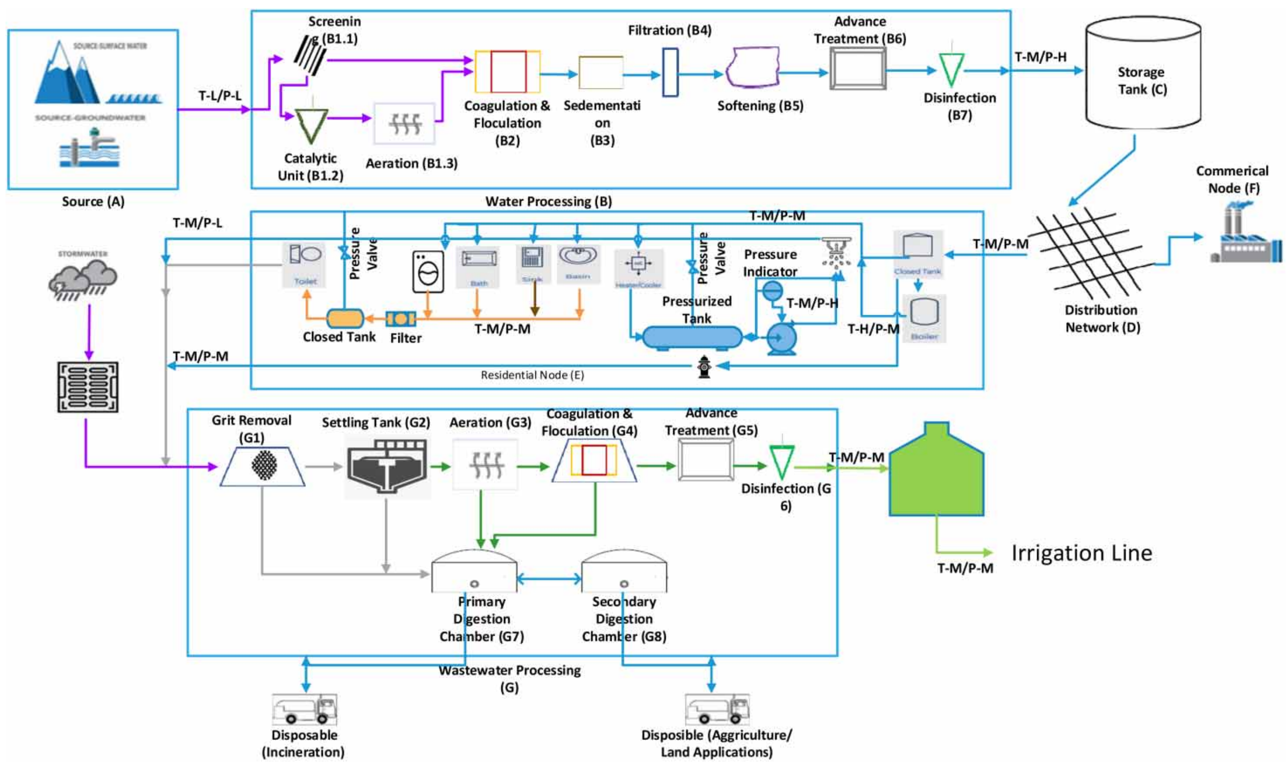

Figure 2 | Process diagram of a water system in buildings.

Table 2 | Physical KPIs

KPI	Description	Criteria
P_{A1}, P_{A2}	Pump pressure head	Enough to capture water
Q_{A1}, Q_{A2}	Flow rate	Match required flow rate for capture tank
Pw_{A1}, Pw_{A2}	Hydraulic power of pump	Match required power needed to pump influent
η_{A1}, η_{A2}	Efficiency of pump	Higher efficiency the better
V_{A1}, V_{A1}	Volume of tank used to capture source	Volume > current water demand/day

3.1.1. Evaluating required pump pressure KPI

The required pump pressure (also known as total pressure over the pump, PT) can be evaluated using the hydrostatic pressure equation from (White 2011), which states that:

$$P_T = \gamma z \tag{1}$$

where z is the height between the source and pump destination, while γ is the specific weight of water (evaluate as $\gamma = \rho \times g$, where ρ is the density of water and g is gravitational acceleration). Pressure can also be obtained by simulation as well (Hadad *et al*. 2004).

3.1.2. Evaluating flow rate KPI

The flow rate can be determined by flow sensors situated before and after the pump or can be calculated using Bernoulli equation from White (2011), applied to the capture tank (given that the required fluid height is known):

$$\frac{P_1}{\rho} + \frac{1}{2}V_1^2 + gh_1 = \frac{P_2}{\rho} + \frac{1}{2}V_2^2 + gh_2 \tag{2}$$

where the velocity term can be expressed as flow rate by this relationship: $Q = V \times A$, where A is the cross-sectional area of pipe. Flow rate can also be found in simulation by getting velocity from a cut plane and post-processing rule to calculate flow rate.

3.1.3. Evaluating hydraulic power KPI

With both pressure and flow rate known, hydraulic power (for our case it's also called pump waterpower) can be evaluated by this equation (Lopes & Costa 2019):

$$P_W = Q_F \times \rho \times g \times z = Q_F \times P_T \tag{3}$$

Table 3 | Water quality KPIs (chemical)

KPI	Description	Criteria (The Grand River Conservation Authority n.d.) (TRC Groundwater Quantity and Quality 2010)
DO_{A1}	Dissolved oxygen content	−4–6 mg/L (depending on temperature for surface water)
NTU_{A1}	Turbidity in surface water	<20 NTU
$N\text{-}Cs_{A1}$	Nitrate content in surface water	<3.0 mg/L of nitrate
$A\text{-}Cs_{A1}$	Ammonia content in surface water	<20 μg/L of ammonia
pH_{A1}	pH levels of surface water	6–9 (depending on sea life)
TDS_{A2}	Concentration of total dissolvable solids	239–1175 mg/L
Hd_{A2}	Hardness of ground water	246–803 mg/L
$N\text{-}Cs_{A2}$	Nitrate concentration in GW	0.01–0.09 mg/L
$Na\text{-}Cs_{A2}$	Sodium concentration in GW	11.9–27.7 mg/L
$Fe\text{-}Cs_{A2}$	Iron concentration in GW	0.002–7.9 mg/L

This value can also be computed computationally in simulation.

3.1.4. Evaluating pump efficiency KPI

The pump efficiency can be computed using the following equation (Lopes & Costa 2019):

$$\eta = \frac{P_W}{P_S} \times 100 \tag{4}$$

where P_s is the shaft power of the pump which can be calculated using this relationship:

$$P_S = \frac{P_W}{\eta} \tag{5}$$

The technique proposed is use a framework of both process simulation software (Aspen Hysys) and computational fluid dynamics software (Ansys Fluent) to consider both aspects of analysis. This will allow for the flexibility of analyzing chemical processes and interaction of tanks, pipes, destination nodes, etc. while giving the ability to simulate details in each node via computational fluid dynamics (CFD) techniques. This process can be iterative in a sense that we can use Ansys Fluent software to model each component in detail and use the results in (Aspen Hysys) to set up and run a process simulation of the whole network.

To actualize this plan, a development flow chart was created for us to follow to make sure we reach each milestone.

Based on Figure 3, the development plan for the model is as follows. Start off using the proposed model along with preliminary known values. Add in additional assumptions based on similar worked examples, which should allow for a full simulation setup for each node in fluent. This should allow for the calculation of model parameters at boundary conditions for each component (in each node). Verify solutions with physical, operational, or experimental measurement (this includes changing initial conditions, applying mesh and convergence studies, etc.). Once solutions match, the result from fluent can be used to setup an Aspen Hysys process simulation (i.e., taking resulting flow conditions across a pipe or tank and defining them in Hysys pipe/tank module for simulation). With the water network defined in Hysys, steady state simulation can be run to define and verify KPIs (as listed previously). Once it is verified, this model can be used for life cycle analysis (LCA) for the water network and provide a baseline LCA mode to be compared to possible To-Be models (Naghedolfeizi 1991).

In addition to the above, consideration on the possibility of creating an interface between fluent results and Hysys for automated data handling will be tested and described as well.

3.2. Multiphysics model for node: fluent

For this paper, collaboration was done with Yorkdale mall, and as such the commercial node is modeled after Yorkdale mall's water network. Based on the information given by Yorkdale energy report from 2018, an AS–IS model was created (as shown in Figure 4). It is seen that the network can be divided into four zones, and as such the strategy for implementing a simulation can be broken down into four zones as well, with each element in the process flow diagram being coupled to a parameter in Table 4.

- Each zone contains water-consuming objects such as faucets, washing machines, toilets, etc.
- Taking each object's water use as a boundary condition, computational fluid dynamics was used to calculate the flow through the distribution pipeline to pumps and tanks.
- Tanks and pumps were modeled in processing software to obtain operation conditions and then used to calculate operational costs.

The proposed network begins with inflow from the city into a tank, which then feeds water into both a heated tank and the cold-water pipe system. From a preliminary analysis of the tank component, it was deduced that a required outlet flow condition for the tank is required to be able to provide a full analysis of the cold storage tank. The idea proposed is working backwards from each terminating component from the tank feed line (i.e., heater, pump, pipeline, toilet, and faucet urinal.), where each inlet condition from the components becomes our outlet condition for the previous component

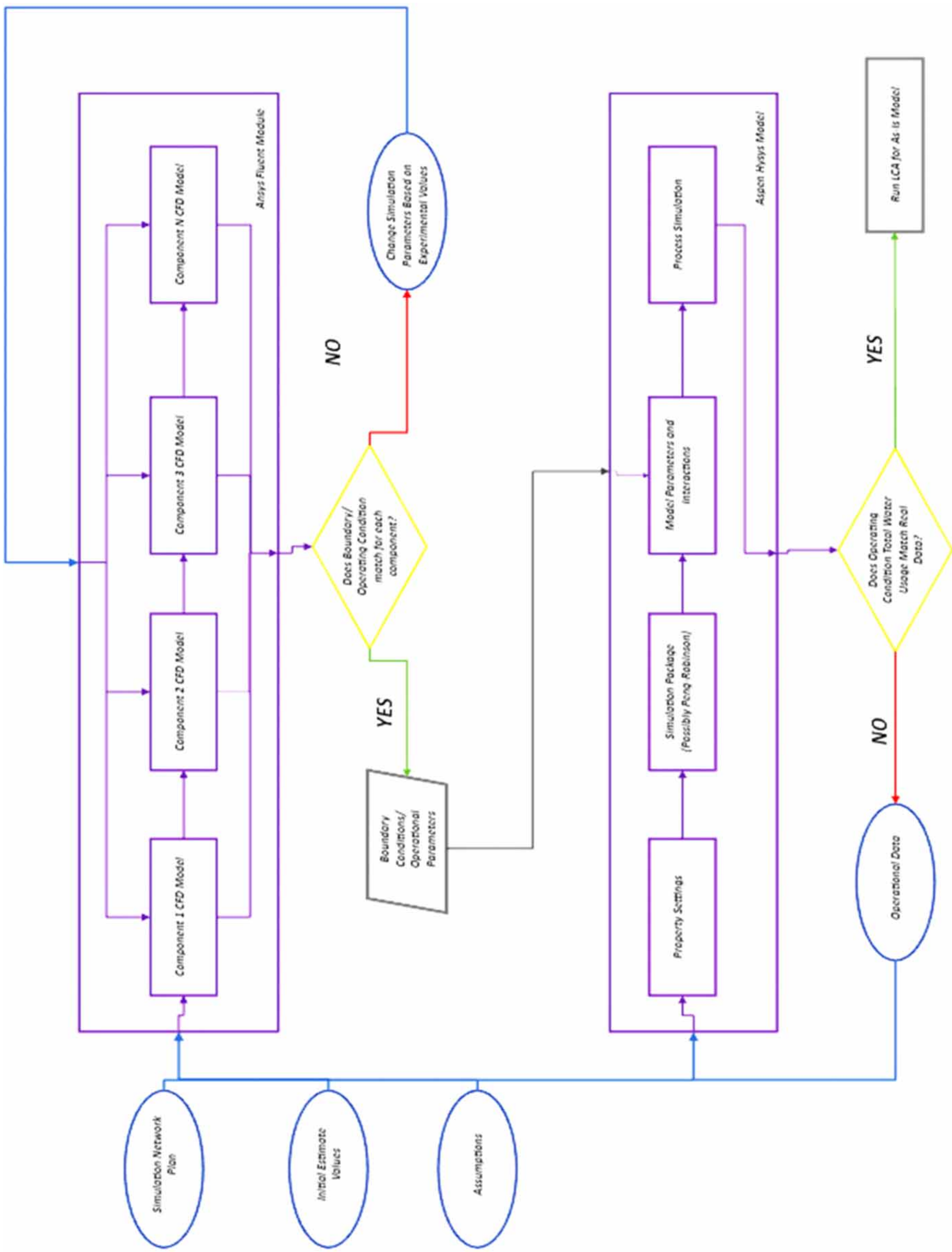

Figure 3 | Methodology of water network modeling.

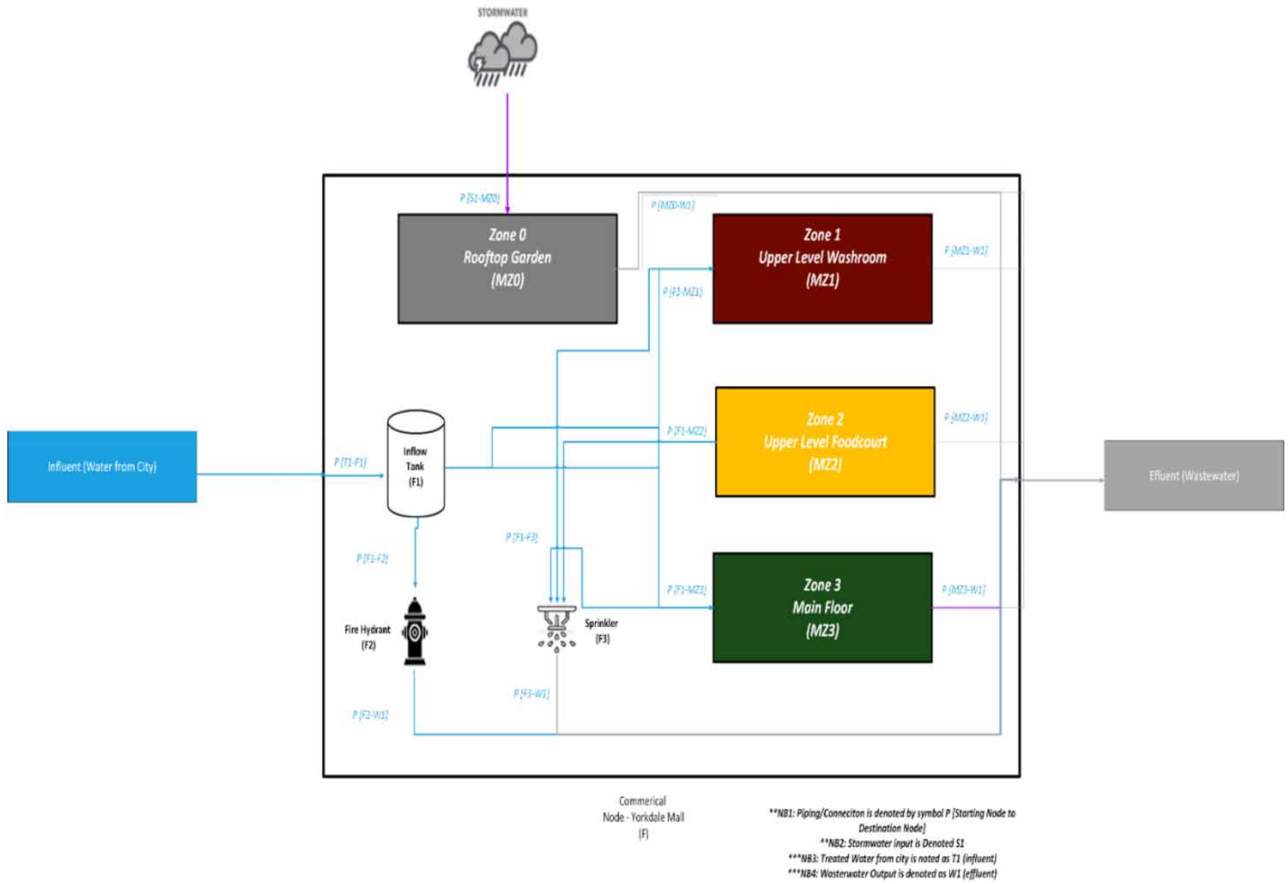

Figure 4 | Schematic diagram for AS–IS model.

Table 4 | Description of different zones

Zone	Description
Zone 0	Rooftop garden area (mapping rainwater tanks and irrigation system)
Zone 1	Upper-level washroom (mapping both men and women's washroom)
Zone 2	Upper-level food court (mapping food court kitchen and sanitary stations)
Zone 3	Main floor (mapping water systems in storefronts, sanitary stations, and additional washrooms)

(i.e., working backwards from toilet/urinal/faucet → distribution pipe → heater → pump → storage tank). Once the solution is verified, these results can be used in Hysys for process simulation. Table 5 shows the viscous model and physics setup for the simulation of fluent.

Table 5 | Physical model setup for fluent simulation

Fluent setup parameter	Option/value
Gravity	Enabled ($a_y = 9.81$ m/s^2)
Energy equation	ON
Viscous model	K-Epsilon realizable standard wall function
Method	Coupled (second-order based)

The model can show operational conditions and the cost of a water network; the building is assumed to stand for 45 years and work 12 h/day. The hydraulic calculation is conducted to calculate the flow rate in every item of the water network. This allows for the analysis of new or improved nodes in the network for comparison.

There are four different scenarios are tested and they briefly are:

1. Changing elbow pipe at faucets (changing 90° bends to either 45° or 120°).
2. Changing pipe material for distribution pipes within washrooms, stores, or restaurants (changing to PVC as an example).
3. Recycling the water output and treating it through a small wastewater plant in or beside the building.
4. Residual water from the building with three different sub-scenarios.

4. RESULTS AND DISCUSSIONS

In terms of faucets, pipes, toilet tanks, and water tank geometries, 3D models are estimated using a modified T-Junction in some pipes and faucets (which should facilitate mixing hot and cold-water streams). Geometries are created using SolidWorks. The simulation is divided into two parts, the first one is for the AS–IS model. AS–IS model considers the actual and existing case of the building, and calculation is performed to get the flow rate and actual cost of water consumption. The second one is the To-Be model, this model after conducting four scenarios for water consumption and cost analysis for these changes.

The geometries are meshed using Ansys workbench. The mesh method used is automatic with mesh refinement. Mesh structure is chosen by software to be mostly triangular with a refinement level of 2. The mesh properties and quality reported by fluent are shown in Table 5.

In addition to the above built-in settings, a few custom field functions are created to solve for corrosion rate (CR) of elbow. The method to solve for CR is to use mass transfer coefficient (which measures how much material is diffused to the bulk fluid flow). The idea has been exercised in (Lopes & Costa 2019) case studies (assuming corrosion agent is Iron), thus taking inspiration from this, a CR can be obtained by using the following equations:

$$\mathrm{Sh} = 0.0165 \times \mathrm{Re}^{0.86} \times \mathrm{Sc}^{0.33} \tag{6}$$

$$\mathrm{Sh} = \frac{k_\mathrm{m} \times d}{D} \tag{7}$$

$$\mathrm{Sc} = \frac{\mu \times d}{\rho_l \times D} \tag{8}$$

$$\mathrm{Re} = \frac{\rho_l \times d \times U}{\mu} \tag{9}$$

$$\mathrm{CR} = \frac{k_\mathrm{m} \times C_\mathrm{b,O} \times M_\mathrm{Fe}}{\rho_\mathrm{Fe}} \times 60 \times 60 \times 24 \times 365 \times 1,000 \tag{10}$$

where each variable is defined in Table 6.

4.1. AS–IS model of building simulation

Currently, the commercial node of an existing mall is taken as AS–IS model to simulate it in the ANSYS Fluent by assuming no friction, but this will change once more data about the actual material of items and their physical dimensions are given. This model allows us to predict the flow conditions required to maintain each item's required mass flow rate. AS–IS model components are shown in Figures 4 and 5. The simulation in fluent is performed item by item on each floor. The simulation is conducted on mass flow rate and material specification for the faucets, pipes and pipes connection, and toilets tanks, as illustrated in the next section.

4.1.1. Faucet simulation

Figures 6–12 show the simulation of the faucet system with pressure, velocity, mass transfer coefficient, and wall shear.

The audit states that faucets have installed aerators, which reduce the flow rate to 0.5 US GPM (US gallons per minute) (TRC, Groundwater Quantity and Quality 2020). By feeding the fluent with the outlet flow rate and material of faucets and pipes. Then it provides the mass flow rate and the pressure difference between the inlet and outlet according to the

Table 6 | Variable definitions for Equations (6)–(10)

Variable	Description
Sh	Sherwood number
Re	Reynolds number
Sc	Schmidt number
Km	Mass transfer coefficient (m/s)
d	Diameter of pipe (m)
D	Diffusion constant (m^2/s)
U	Mean flow velocity (m/s)
ρ_l	Density of liquid (kg/m^3)
ρ_{Fe}	Density of iron (kg/m^3)
μ	Dynamic viscosity (kg/ms)
$C_{b.O}$	Bulk concentration of oxygen (kg/m^3)
M_{Fe}	Molar mass of iron (g/mol)
CR	Corrosion rate (mm/year)

friction coefficients. The output results indicate the reduction in both flow rate and pressure and how much water consumption is in the simulated system.

With the above simulation output, an approximate value for water usage in faucets (based on volume flow) can be used for comparison, along with an approximate material lifespan based on the CR. These properties will be used to compare the changes for a To-Be model in the next section.

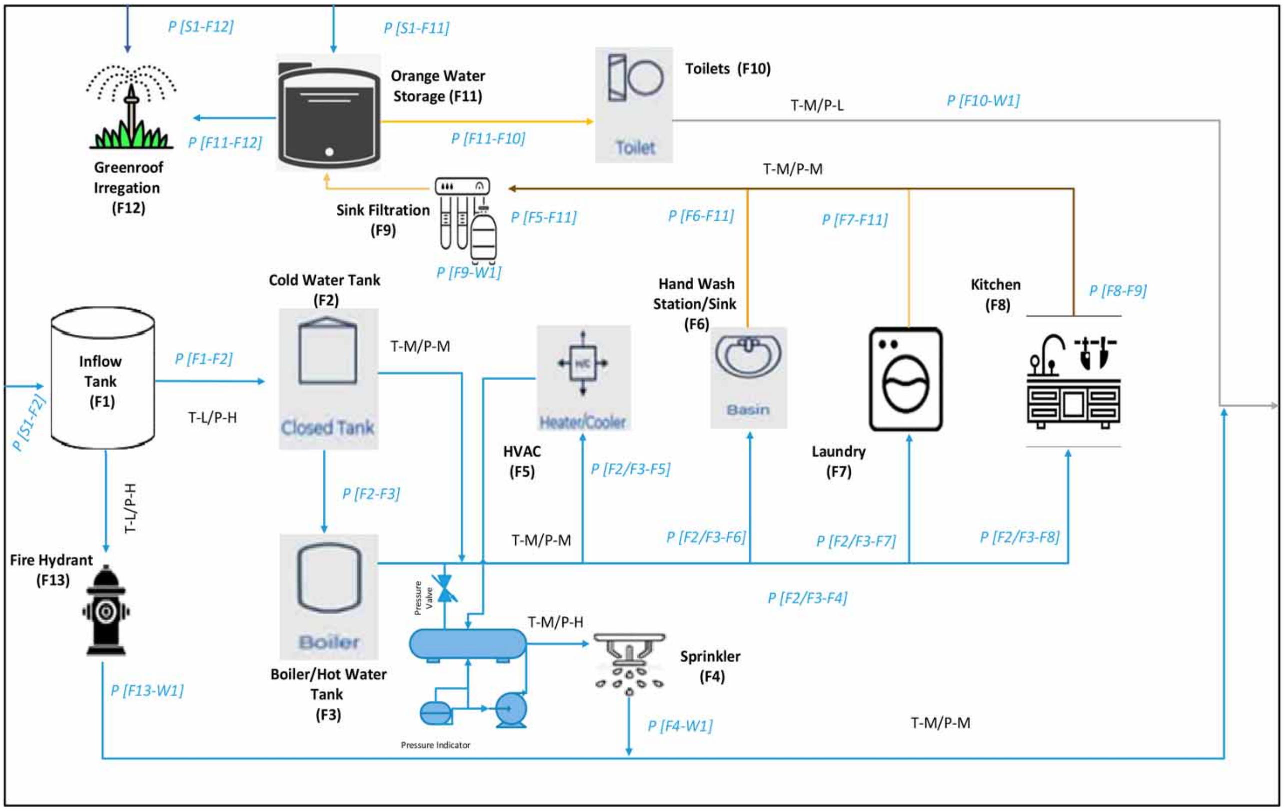

Figure 5 | Commercial node – mall example.

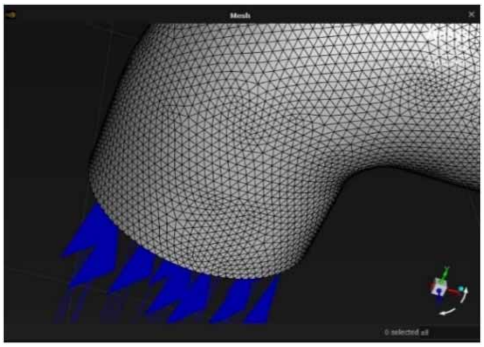

Figure 6 | Close-up of faucet mesh structure.

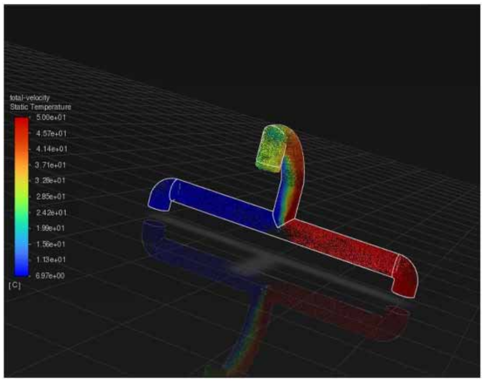

Figure 7 | Velocity vector of water through faucet.

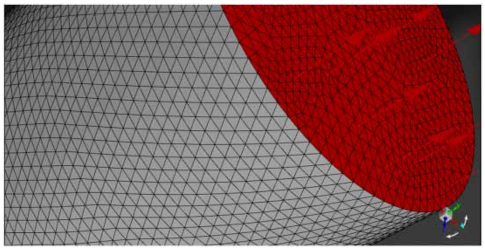

Figure 8 | Mesh structure close-up of faucet elbow pipe.

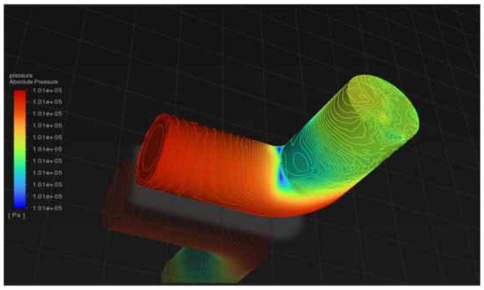

Figure 9 | Pressure contour along faucet elbow.

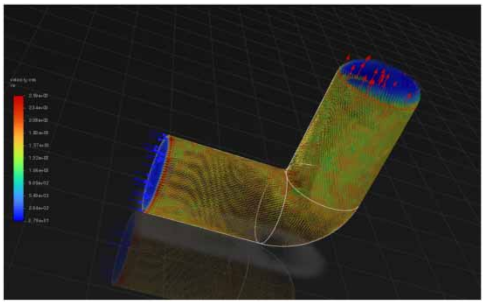

Figure 10 | Velocity vector colored in pressure.

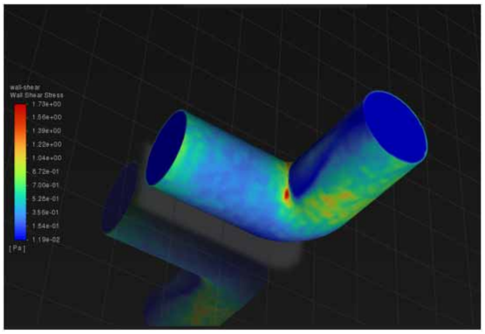

Figure 11 | Wall shear stress on elbow.

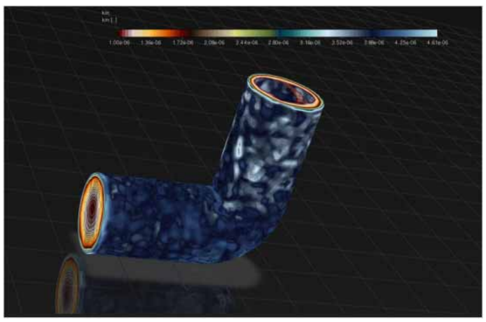

Figure 12 | Mass transfer coefficient on elbow wall.

4.1.2. Faucet distribution pipe

The faucet distribution pipe is first created in SOLIDWORKS by assembling small pipe segments, tee, elbow, and a reduction fitting to facilitate changes in geometry. Then are meshed to prepare them for fluent simulations, as in Figures 13–17.

4.1.3. Model for tankless toilet

Yorkdale Mall uses a tankless toilet model for all their washrooms. Each toilet is designed to use approximately 4.8 L/flush. Then are meshed to prepare them for fluent simulations, as in Figures 18 – 20. To convert this number into something we can use to define our model, first, it is assumed that this consumption is water consumption at the inlet; next, it is assumed a flush normally last about 30 s. With this information, the flow rate into this node from the distribution pipeline. Table 7 is summarizing the assumptions for this case.

According to the above assumptions, a fluent model of this node, it is assessed in calculating the actual output mass flow rate during a flush for the wastewater model portion in Aspen Hysys.

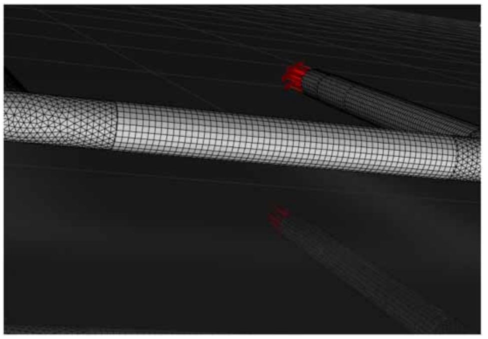

Figure 13 | Mesh structure close-up of faucet distribution pipe.

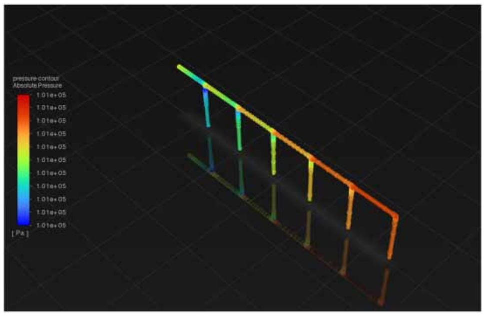

Figure 14 | Pressure contour along pipe.

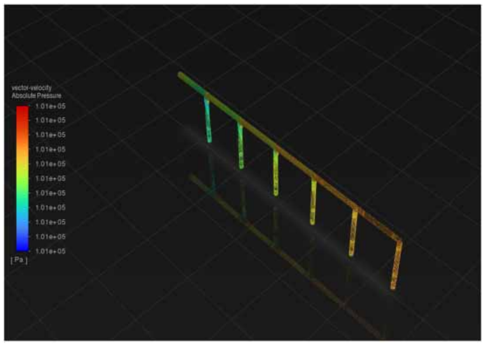

Figure 15 | Velocity vector colored in pressure.

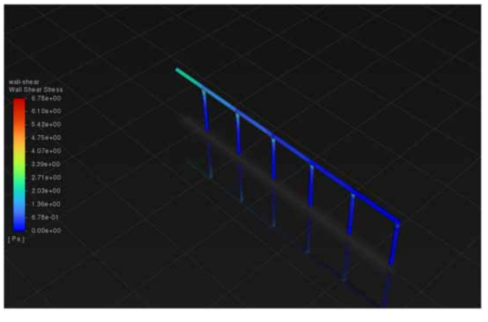

Figure 16 | Wall shear of faucet distribution pipe.

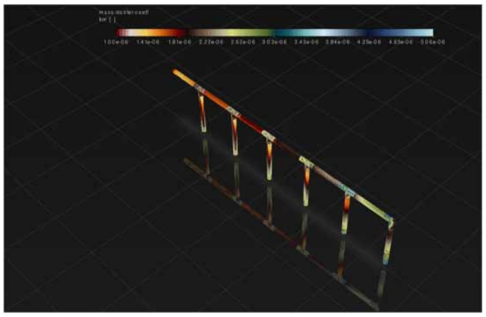

Figure 17 | Wall mass transfer coefficient of faucet distribution pipe.

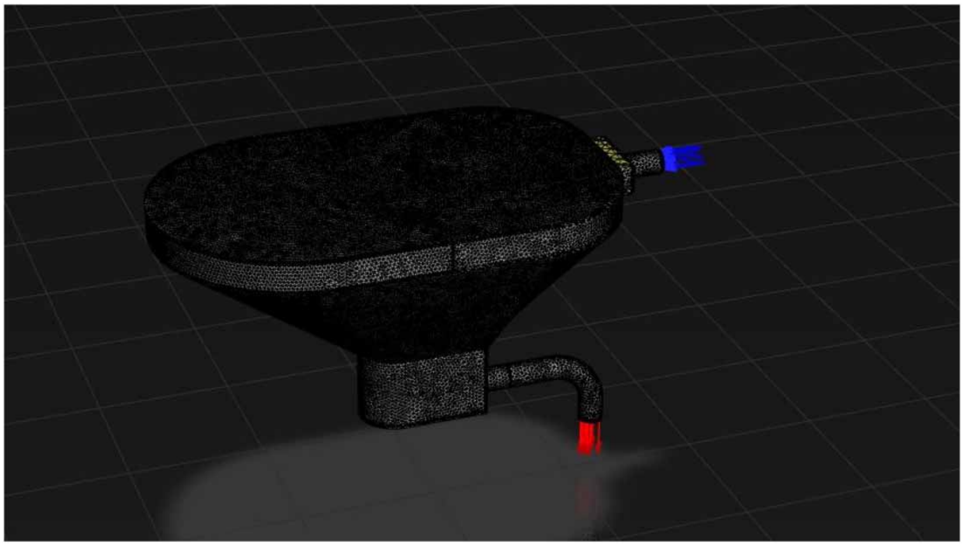

Figure 18 | Mesh of tankless toilet.

Similarly, the model of all components in the main floor is created the same for every floor of the Yorkdale Mall.

Once the full flow conditions for each component are computed by Fluent and/or supplied by the collaborator (Yorkdale Mall), it is then used to setup a Hysys worksheet. This should allow for a full analysis of each component in a network where changes in one component also show changes in other components. This should also allow for dynamic simulation which will offer more details about the network's performance over time.

Referring to Figure 21, we can see that each component can be modeled in Hysys by dragging and dropping them into the worksheet. Each of these components can be programed with specific flow conditions and properties to mimic real-like components. In addition, in and out streams between each component can be programed to follow certain properties that can either be constant or vary over time. These properties can be observed over time in either steady state simulation or in dynamic simulation by adding control valves.

This is a sample for every hydraulic calculation done for whole items in every floor for AS–IS or To-Be models.

Table 8 is the summary of data output from both simulation and calculation programs for AS–IS model. These data are taken as reference for comparison with To-Be model. The output and simulation show that, the total usage water and its annual cost is 581,959 ($/year).

4.2. To-be model of the building simulation

With each node modeled with both fluent and Hysys, we now have an overall picture of the performance of the As–Is Model for each network. This section discusses the possible changes to apply to each network and uses the simulation model from above to evaluate possible KPI's to illustrate the feasibility of the change.

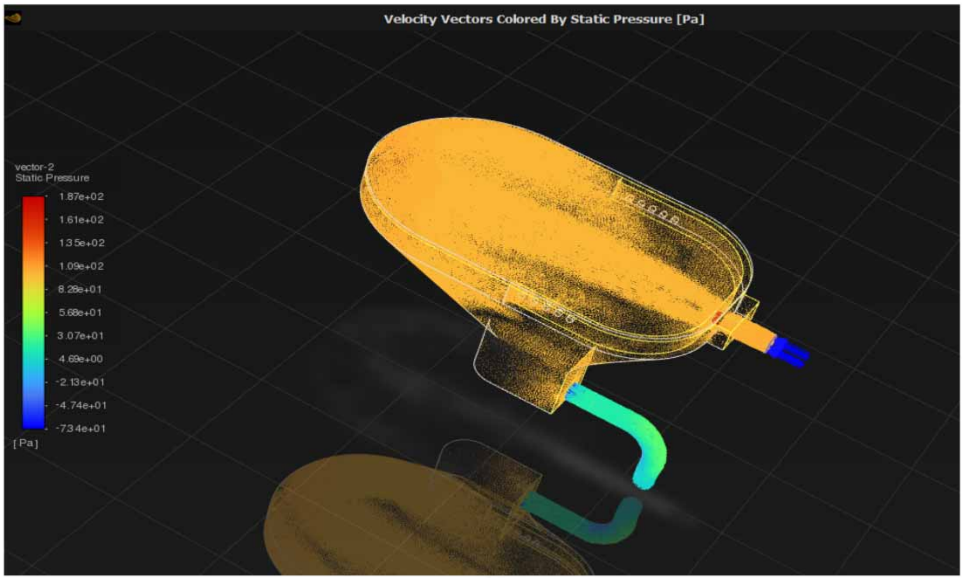

Figure 19 | Velocity vector of water flow of tankless toilet.

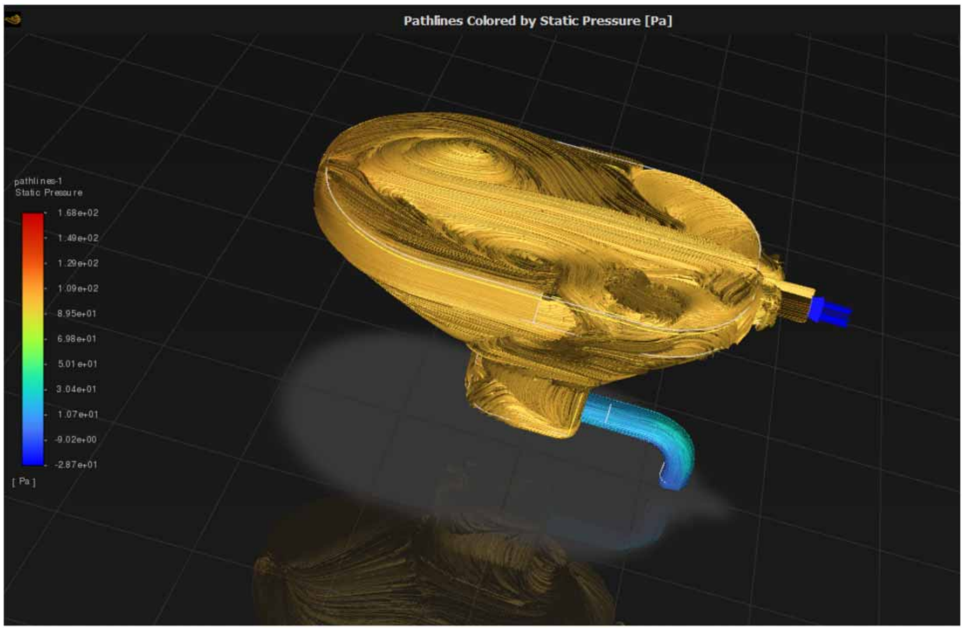

Figure 20 | Velocity path line ribbon of water flow (colored by pressure) of tankless toilet.

Table 7 | Assumed parameter for toilet

Assumed parameter	Assume value
Water consumption at inlet	4.8 L/flush
Flush duration	30 s
Required mass flow rate per flush	0.16 kg/s

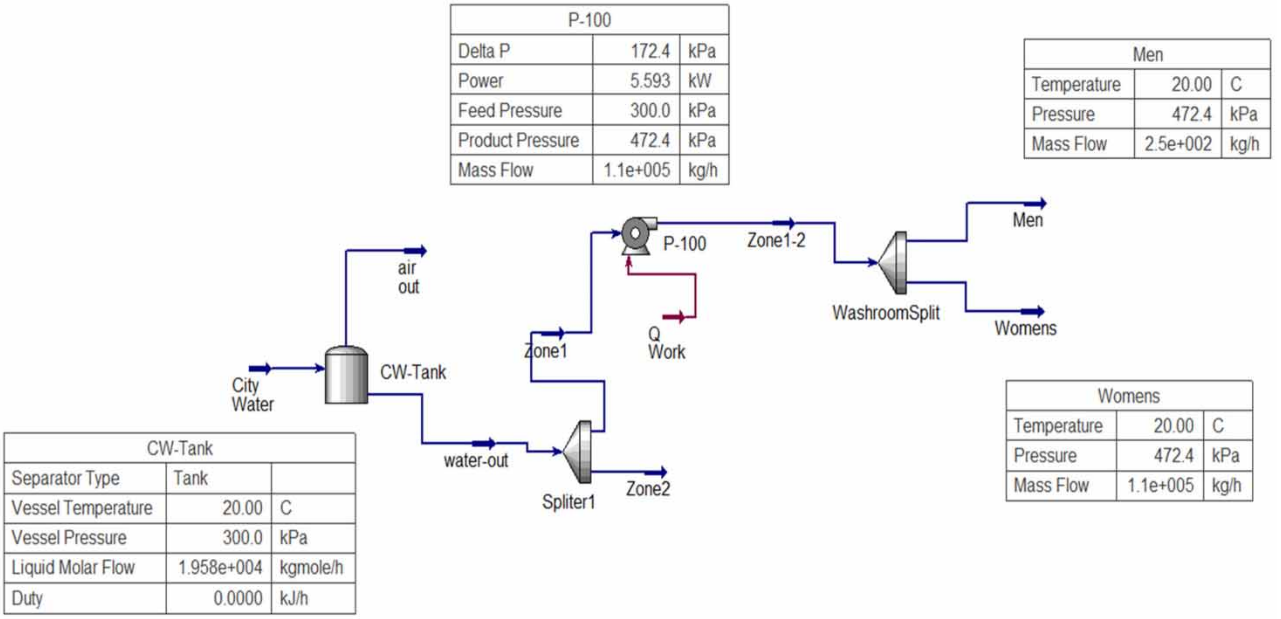

Figure 21 | A sample Hysys simulation worksheet.

Table 8 | AS–IS model data

AS–IS parameter	Value
Total water usage (m^3/day)	391
Cost per volume (\$/m^3)	4
Cost per day (\$/day)	1,594
Cost per year (\$/year)	581,959
Total flow loss (L/day)	21,799
%Loss per day	6

4.2.1. Scenario 1: changing elbows, diameters and faucets

As seen previously, the model can show operational conditions and the cost of a water network. The building is assumed to stand for 45 years and work 12 h/day. This allows for a comparative analysis of new or improved nodes in the network. There are two sub-scenarios tested, and they briefly are:

1. Changing elbow pipe at faucets (changing 90° bends to either 45° and 120°).
2. Changing pipe material for distribution pipes within washrooms, stores, or restaurants (changing to PVC as an example).

For each faucet angle, the model is run, and each updated operational parameter is propagated to each node in our model till we finally reach the city tank, where total water usage can be calculated and costs can be determined. Figure 22 illustrates the simulation of scenario (1) from the city tank to Yorkdale mall.

4.2.1.1. Elbow pipes of 45°. For 45° elbow, pipes are installed (scenario 1.1), Table 9 shows briefly KPIs for this scenario.

The 45° elbow is mounted so that the fluid direction can be changed to 45°. Compared to a 90° elbow, a 45° elbow produces less friction and lower pressure. A decrease in pressure means less water consumption.

4.2.1.2. Elbow Pipe of 120°. Similarly, if 120° elbow pipes are installed (scenario 1.2), Table 10 presents KPI's for this scenario.

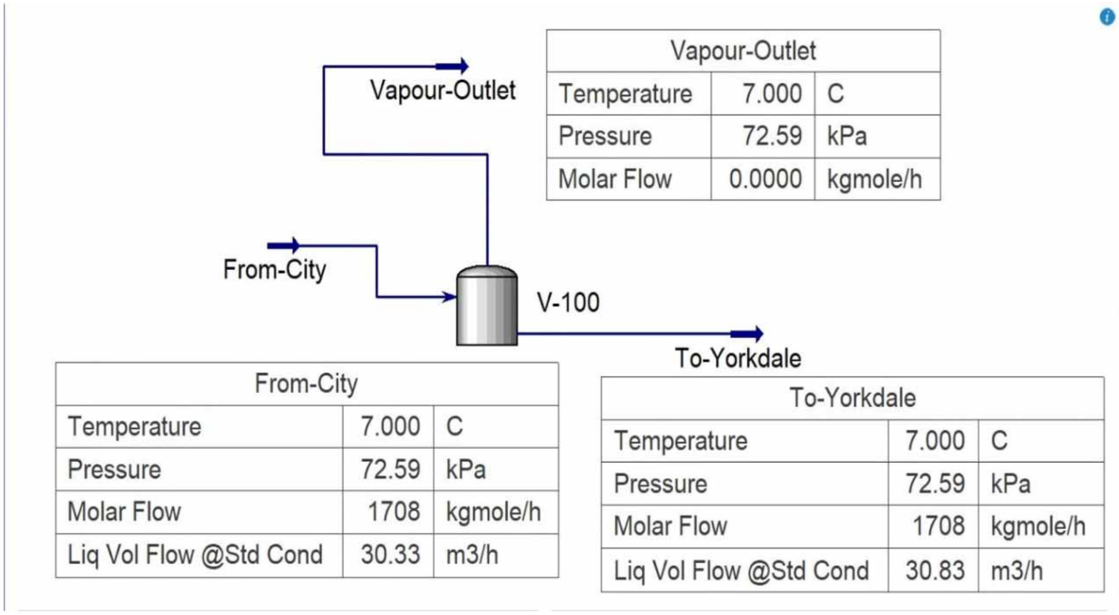

Figure 22 | A Hysys simulation worksheet scenario 1.

Table 9 | Scenario 1.1 data

Total water usage (m^3/day)	391
Operational cost per volume ($/$m^3$)	4
Operational cost per day ($/day)	1593
Operational cost per year ($/year)	581,536
Total flow loss (L/day)	20,919
Capital cost ($)	2,307
Cost saving per year ($/year)	424

Table 10 | Scenario 1.2 data

Total water usage (m^3/day)	390
Cost per volume ($/$m^3$)	4
Cost per day ($/day)	1,592
Cost per year ($/year)	581,157
Total flow loss (L/day)	20,978
Capital cost ($)	3,968
Cost saving per year ($/year)	802

The 120° elbow directed the fluid flow into smooth streams with a reduction in the pressure difference due to the open bent of the elbow compared to the 90°. This led to conserve of the water flow with less water flow loss.

4.2.1.3. Changing pipe diameter to 14 mm. In this scenario, it is changing pipe diameter for the washroom, kitchen, and sanitation for the main and upper levels to be 14 mm (scenario 1.3). The output data can be seen in Table 11.

The head loss is roughly proportional to the square of the flow rate in most engineering flows (fully developed. For laminar flow, the head loss is proportional to velocity rather than velocity squared. Thus, the friction factor is inversely proportional to velocity.

Table 11 | Scenario 1.3 data

Total water usage (m^3/day)	391
Cost per volume ($/$m^3$)	4
Cost per day ($/day)	1,594
Cost per year ($/year)	581,688
Total flow loss (L/day)	21,348
Capital cost ($)	3,968
Cost saving per year($/year)	299

Table 12 | Scenario 1.4 data

Total water usage (m^3/day)	334
Cost per volume ($/$m^3$)	4
Cost per day ($/day)	1,361
Cost per year ($/year)	496,618
Total flow loss (L/day)	16,816
Capital cost ($)	13,440
Cost saving per year ($/year)	85,341

4.2.1.4. Changing the intermittent faucet only. Changing the Intermittent Only component changed for the washroom, kitchen, and sanitation are only changed; all pipe sizes and diameters remained the same as AS-IT is (scenario 1.4). This type of faucet is characterized by pulsed water flow, not a continuous one like the conventional one. Therefore, it saves the unused water which is lost during washing. The cost and amount of water consumed are presented in Table 12. This led to saving in water consumption of about 14.7% of AS–IS usage water.

4.2.2. Scenario 2: changing pipe material to PVC and/or galvanize iron

For each distribution pipe inside the washroom, restaurants, stores, etc., the piping material was changed to PVC/Galvanized Iron (this in technical terms, meant a change in friction inside the pipe).

The change was quantified by measuring estimated volume loss based on flow rate loss between the input and output of each tank, pump, and pipe system. Figure 23 illustrates the simulation of scenario (2) from the city tank to Yorkdale Mall.

4.2.2.1. Pipe material change to PVC (scenario 2.1). PVC allowed for a drop in volume loss percentage from 5.58 to 5.33% with everything else being equal. This can be seen in Table 13, the difference between AS–IS model and the scenario 2.1 is considered a very small rate. This led to save in water consumption of about 1% of AS–IS usage water.

4.2.2.2. Pipe material change to galvanized iron (scenario 2.2). Galvanized iron allowed for a drop in volume loss percentage from 5.58 to 5.42%, with everything else equal; this can be seen in Table 14. This led to saving in water consumption of about 1% of AS–IS usage water.

From the previous results and data output from the simulation, there is no difference between PVC and galvanized iron pipes in the water consumption and saving. Due to the same cross-sectional areas, wet surfaces, and the roughness of the surfaces – there cannot be notice significant difference in friction head loss in steel and plastic PVC pipes. The difference varies with the size of the pipe and flow rate. Therefore, these scenarios aren't considered economical of exciting buildings or even new ones.

4.2.3. Scenario 3: recycling the water of the shower, bath, and sink

This process depends on recycling the building water from the bath, shower, sink, and kitchen to reuse in the main line of building feeding. This is assumed by conducting a small wastewater plant in or beside the building, as shown in Table 15. This led to saving in water consumption of about 64% of AS–IS usage water.

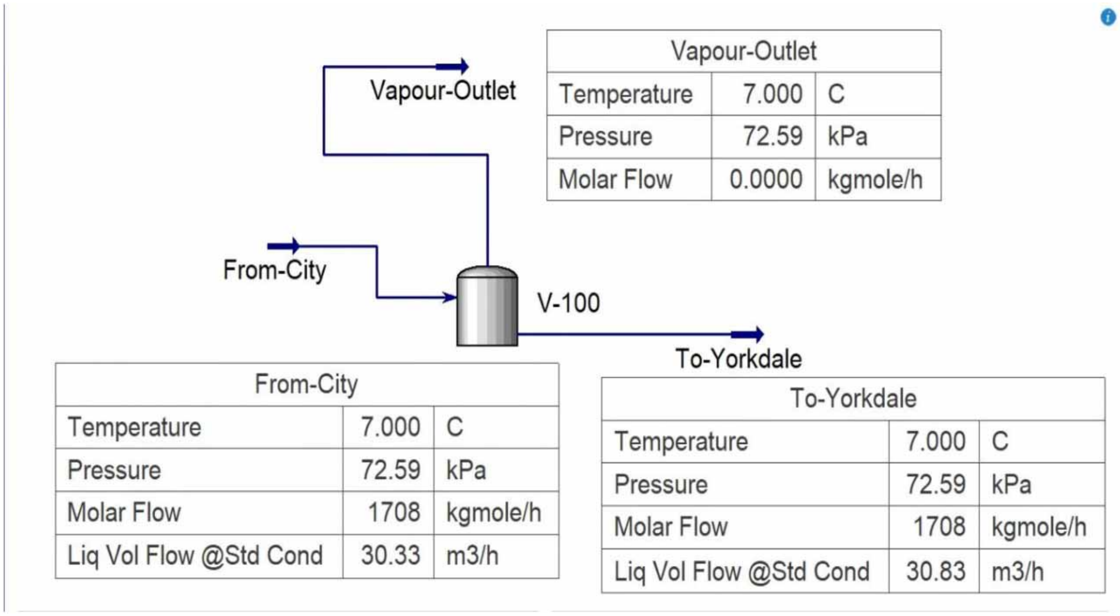

Figure 23 | A Hysys simulation worksheet scenario 2.

Table 13 | Scenario 2.1 data

Total water usage (m^3/day)	391
Cost per volume ($/$m^3$)	4
Cost per day ($/day)	1,594
Cost per year ($/year)	581,825
Capital cost ($)	2,037
Cost saving per year ($/year)	135

Table 14 | Scenario 2.2 data

Total water usage (m^3/day)	391
Cost per volume ($/$m^3$)	4
Cost per day ($/day)	1,594
Cost per year ($/year)	581,785
Capital cost ($)	2,137
Cost saving per year ($/year)	174

4.2.4. Scenario 4: reuse the residual water of shower, kitchen, cooling system, and sink

Residual water of the building is a new way of operation for the water conservation system. The process relies on recycling the building's wastewater for reuse. This process has many benefits for both water conservation and energy savings in treating wastewater. Water coming from heating, ventilation and airconditioning (HVAC), sink, etc. is reused in some applications with some auxiliary such as in sprinkler, toilet flushing.

This scenario is developed based on water residual and filtering it in the same place to be reused for toilet flushing.

4.2.4.1. Residual water from washroom, sink, and kitchen to toilet (scenario 4.1). The process of scenario 4.1 depends on the residual water from the washroom, sink, and kitchen and is reused after filtering to toilet flushing. It is conducted by saving

Table 15 | Scenario 3 data

Total water recycled (m^3/day)	141
Total water usage (m^3/day)	397
Total water from city (m^3/day)	257
Cost per volume ($/$m^3$)	4
Cost per day ($/day)	1,047
Cost per year ($/year)	382,055
Capital cost ($)	42,154
Running cost ($/year)	13,140
Savings per year from city ($/year)	185,827

Table 16 | Scenario 4.1 data

Total water recycled (m^3/day)	64
Total water usage (m^3/day)	397
Total water from city (m^3/day)	333
Cost per volume ($/$m^3$)	4
Cost per day ($/day)	1,358
Cost per year ($/year)	495,703
Capital cost ($)	10,000
Savings per year from city ($/year)	79,958

this water in a closed tank; the tank is connected to the freshwater line to keep the flow rate of toilets flushing. Table 16 and Figure 24 illustrate this scenario's process and amount of savings. This led to save in water consumption to about 14.8% of AS–IS usage water.

4.2.4.2. Residual water from HVAC to sprinkler (scenario 4.2). This scenario assumes that the HVAC system is an open water system. It means recycling the water output from the HVAC system to the sprinkler system is possible. This lead to

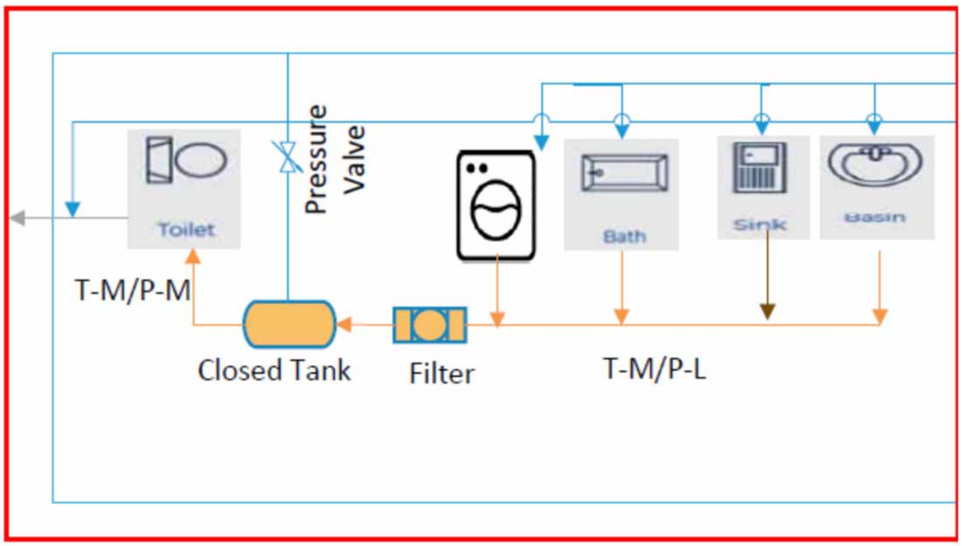

Figure 24 | Flowchart of scenario 4.1.

Table 17 | Scenario 4.2 data

Total water recycled (m^3/day)	196
Total water usage (m^3/day)	397
Total water from city (m^3/day)	201
Cost per volume ($/$m^3$)	4
Cost per day ($/day)	820
Cost per year ($/year)	299,200
Capital cost ($)	20,000
Savings per year from city ($/year)	276,460

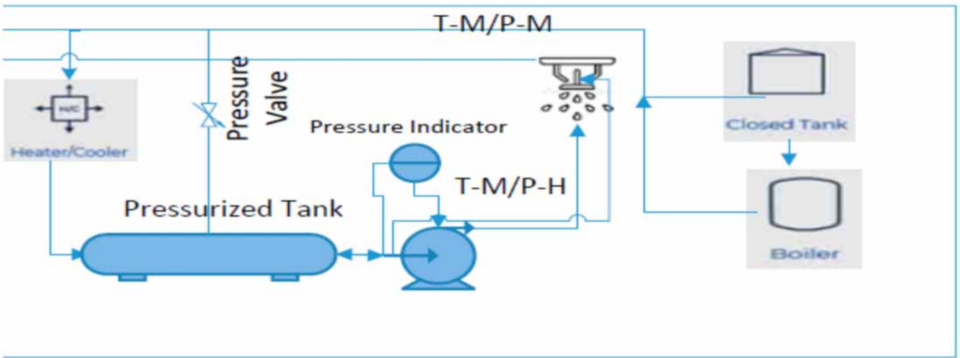

Figure 25 | Flow chart of scenario 4.2.

save in water consumption to about 48.6% of AS–IS usage water. Table 17 and Figure 25 illustrate this scenario's process and amount of savings.

4.2.4.3. Residual water from HVAC to water supply line (scenario 4.3). In this scenario, it is assumed that the HVAC system is an open water system. The residual HVAC water is linked to the water network of the mall to feed the whole building with keeping the central feeding to get the exact flow rate of the building demand. Table 18 and Figure 26 illustrate this scenario's process and amount of savings.

4.3. The full comparison results for all scenarios in the AS–IS model

The following figures show the comparison between all scenarios according to the rate of water usage in the building, rate of saving, and the cost saving from recycling it.

Table 18 | Scenario 4.3 data

Total water recycled (m^3/day)	282
Total water usage (m^3/day)	397
Total water from city (m^3/day)	115
Cost per volume ($/$m^3$)	4
Cost per day ($/day)	469
Cost per year ($/year)	171,225
Capital cost ($)	30,000
Savings per year from city ($/year)	404,436

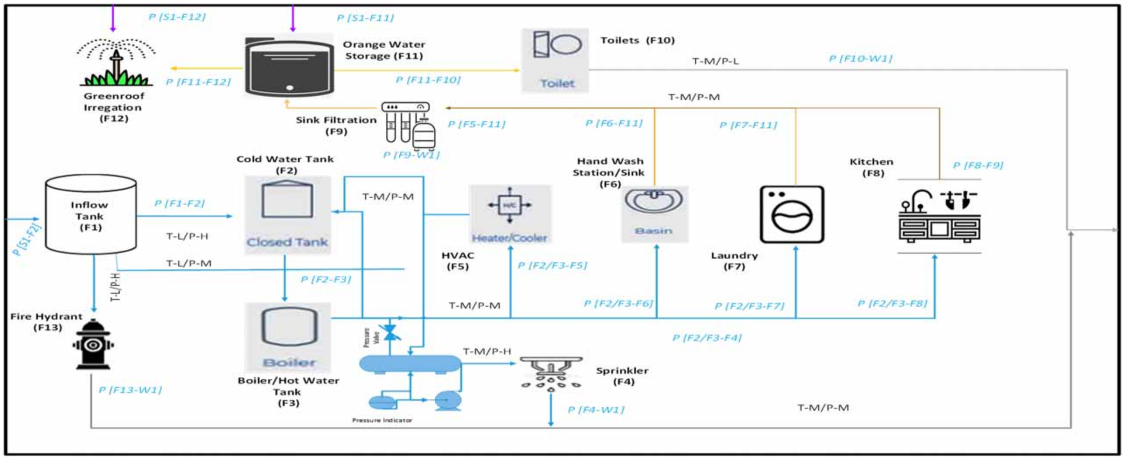

Figure 26 | Flowchart of scenario 4.3.

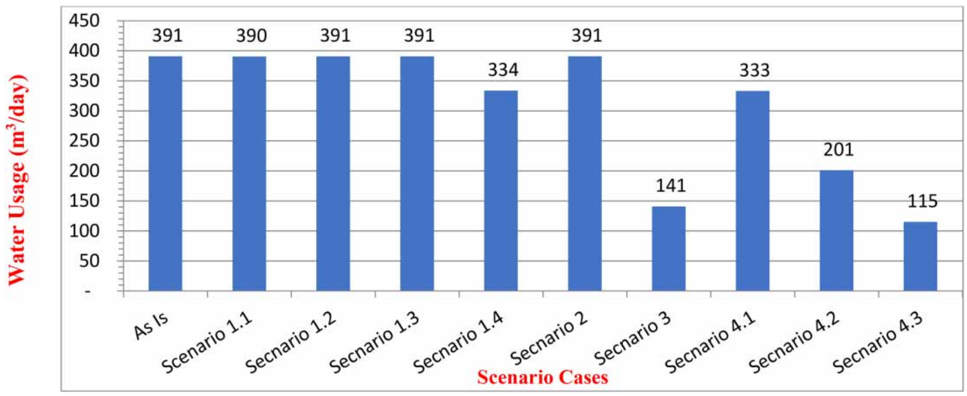

Figure 27 | Water usage from water network (m^3/day).

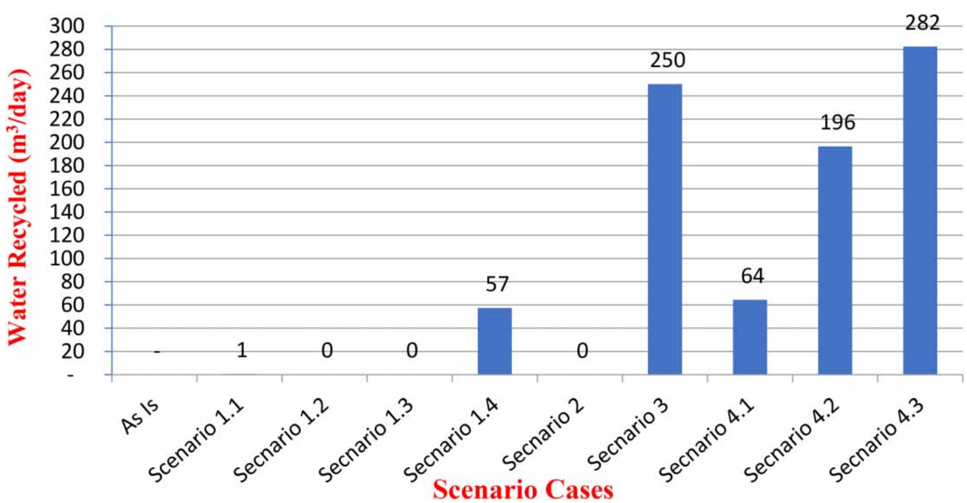

Figure 28 | Total water recycled (m^3/day).

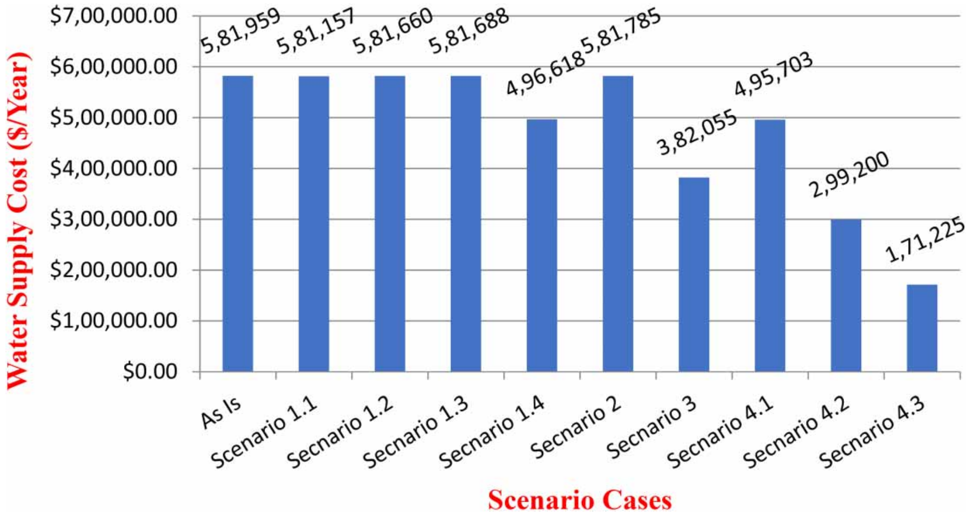

Figure 29 | Water supply cost per year ($/year).

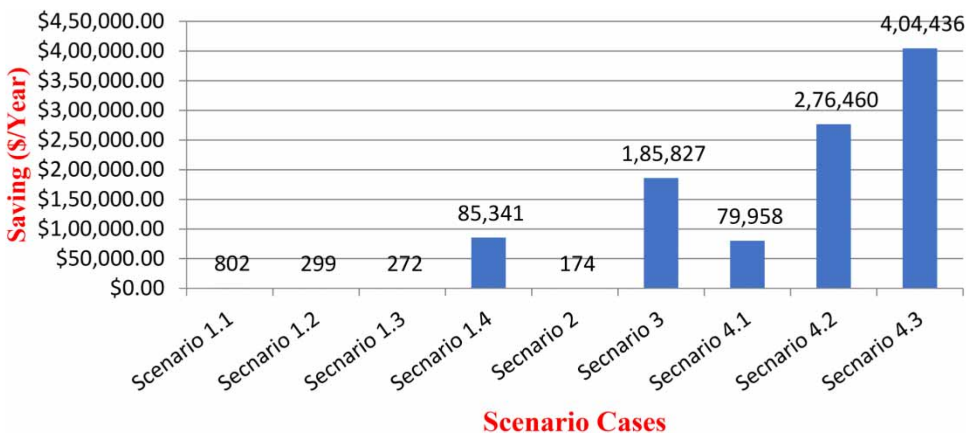

Figure 30 | Savings per year from costs paid to city ($/year).

Figures 27–32 show the comparison in detail. Scenarios 4.1 and 4.3 are more practical and lower costs even after calculating the capital and running costs. Although scenario has 65% water less than the AS–IS model, still less than 4.1 and 4.3 scenarios due to the capital cost of construction and running cost of the small wastewater plant.

A sensitivity analysis is conducted for scenarios 1.4, 3, 4.1, 4.2, and 4.3, which have highly saved costs. This analysis concerns the capital and running costs with an impact on the saving cost. Table 19 shows these results of analysis.

5. CONCLUSION

Water conservation and beneficial reuse can reduce freshwater diversion from rivers (Anderson 2003). There are many direct and indirect benefits from reduced diversion and improved downstream water quality. These benefits should be considered when evaluating the benefits of new water reuse projects. Water reuse increases the available water supply, allows more human needs to be met with less fresh water and reduces human impact on the global water environment. There is a reason for optimism that humanity will focus efforts to reverse the deterioration of the earth's water environment and hit the world's water sustainability needs. This paper presents a solution to transform a building's traditional water network into an SWN. Many scenarios for water recycling in buildings with low water consumption while minimizing costs are

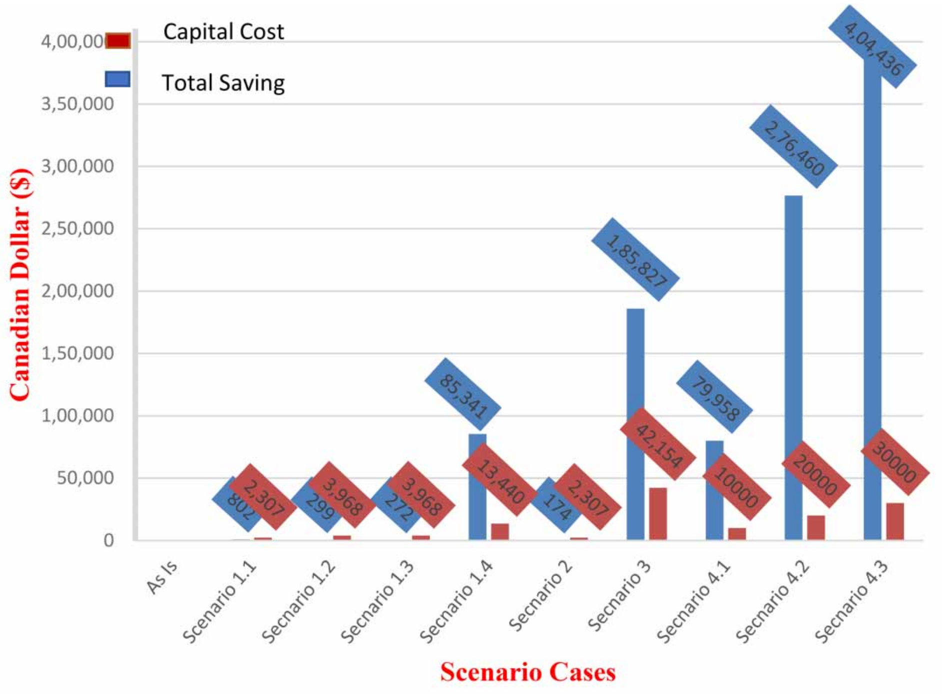

Figure 31 | Total saving ($/year) vs capital cost ($).

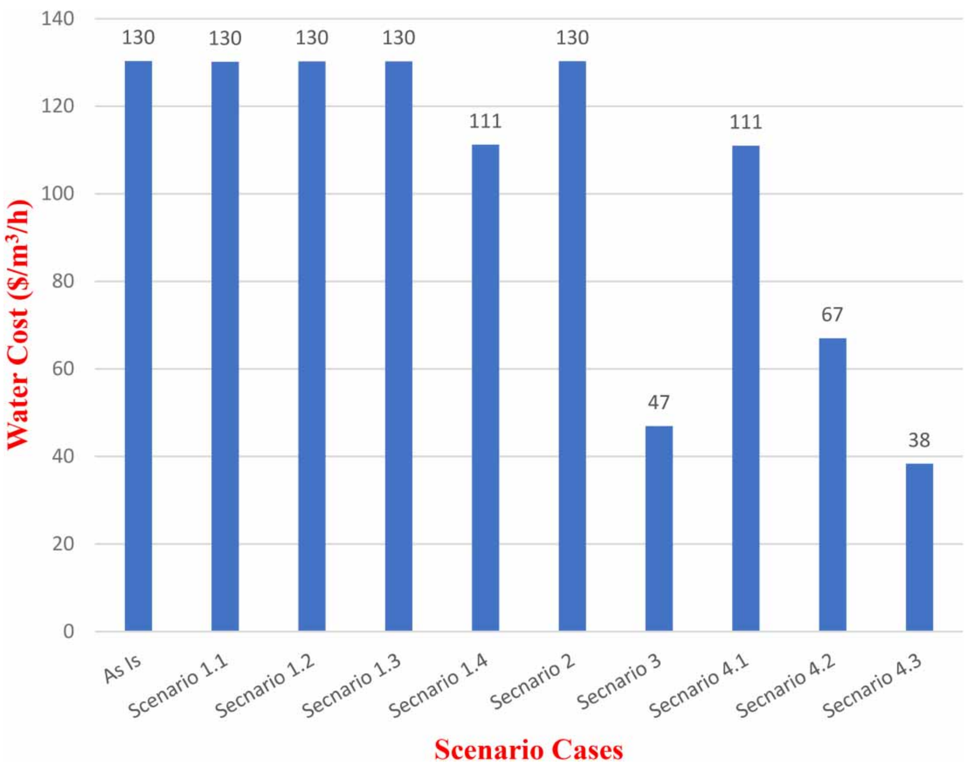

Figure 32 | Water cost ($/m^3/h).

Table 19 | Sensitivity analysis of different scenarios

The estimated percent growth	Capital cost ($)	Savings per year from city ($/year)
Sensitivity analysis scenario 1.4		
5%	14,112	71,229
7%	14,381	70,960
9%	14,650	70,691
11%	14,918	70,423
13%	15,187	70,154
Sensitivity analysis scenario 3		
5%	57,402	128,425
7%	58,245	127,582
9%	59,088	126,739
11%	59,931	125,896
13%	60,774	125,053
Sensitivity analysis scenario 4.1		
5%	10,500	69,458
7%	10,700	69,258
9%	10,900	69,058
11%	11,100	68,858
13%	11,300	68,658
Sensitivity analysis scenario 4.2		
5%	21,000	255,460
7%	21,400	255,060
9%	21,800	254,660
11%	22,200	254,260
13%	22,600	253,860
Sensitivity analysis scenario 4.3		
5%	31,500	372,936
7%	32,100	372,336
9%	32,700	371,736
11%	33,300	371,136
13%	33,900	370,536

therefore being discussed. Five scenarios out of nine are considered the most saving and practical for use in the water recycling of the building. The simulation and hydraulic calculation for these scenarios results are summarized as follows:

1. Decrease the water usage from the main water line to feed the water demand in buildings.
2. Contributing to the development of the economy by adding new, stable, low-cost residual water usage.
3. Scenarios 1.4, 3, 4.1, 4.2, and 4.3 have a Total Water Recycled of 15, 64, 16, 50, and 72%, respectively.
4. Scenarios 1.4, 3, 4.1, 4.2, and 4.3 are cost saving 14.67, 32, 13.7, 47.5, and 69.5%, respectively.
5. The cost saving leads to more water supply investment and enhances the environmental issue.
6. Revenue from water consumption increases for local communities.

ACKNOWLEDGEMENT

The research team would like to thank Ontario Tech University and members in the Smart Energy Systems Lab (SESL).

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 26 September 2022; accepted in revised form 16 February 2023. Available online 22 March 2023